

Cloud cavitation dynamics with varying incidence

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Ἐν οἶδα, ὅτι οὐδὲν οἶδα.

—Σωκράτης, 469/470 π.Χ. – 399 π.Χ.^{1,2}

I know that I know nothing.

—Socrates, 469/470 BC – 399 BC

¹Kopidakis, M.Z., Patrikiou, E., Lypourlis, D. & Moraitou, D. (2021, pp. 27, 29, 83). *Αρχαία Ελληνικά Φιλοσοφικός Λόγος. Γ' Γενικού Λυκείου* [Ancient Greek Philosophical Discourse. Grade 12]. Computer Technology Institute and Press “DIOPHANTUS” (CTI).

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Vorwort des Herausgebers

Kontext

Ist der Entstehungsmechanismus und der Kollaps von Kavitationswolken verstanden, dann ist auch hydrodynamische Kavitation zu einem großen Teil verstanden. Kavitationswolken entstehen jenseits einer kritischen Reynoldszahl. Diese ist von der Kavitationszahl und der Gestalt des umströmten Körpers abhängig: $Re > Re_c(\sigma, \text{Gestalt})$. Aus Arbeiten meiner Forschungsgruppe und auch von anderen Gruppen sind die räumlich und zeitlich größten Skalen eines periodischen Wolkenablösens bekannt. Diese Kenntnis ist ähnlich der bei einem turbulenten Freistahl, bei dem die größte Zeitskala durch Austrittsdurchmesser geteilt durch die mittlere Strömungsgeschwindigkeit und die größte räumliche Skala durch den Austrittsdurchmesser selbst gegeben ist. Die kleinsten Skalen werden als sogenannte Kolmogorow-Skalen bezeichnet und beschreiben die kleinsten Wirbel, die sich aus einer Dimensionsanalyse ergeben.

In der Kavitation sind die kleinsten Skalen durch die einzelne Blase einer „bubbly cloud“ gegeben. Die räumlichen und zeitlichen Frequenzen und ihre Entstehung zwischen dem Kleinen und Großen sind bisher weitgehend unerforscht. Das Erforschen dieser Spektren haben Herr Hatzissawidis und ich uns vor einigen Jahren vorgenommen. Die Antwort von Herrn Hatzissawidis darauf ist ausgezeichnet.

Experimente

Die experimentellen Ergebnisse der vorliegenden Arbeit hat Herr Hatzissawidis am vergleichsweise großen Kavitationskanal der University of Tasmania, Australien, gewonnen. Herr Hatzissawidis hat dort einen mehrmonatigen Forschungsaufenthalt, der von der Deutschen Forschungsgemeinschaft im Rahmen des Sonderforschungsbereichs 1194 gefördert wurde, absolviert. Das symmetrische NACA 0015 Profil (Sehnenlänge 120 mm, Breite 250 mm) wurde bei der Firma Bergmaier GmbH in Bruchsal sowie in der Darmstädter Institutswerkstatt vorbereitet und in die 600 mm × 600 mm Teststrecke eingebaut. In seiner Zeit als wissenschaftlicher Mitarbeiter hat Herr Hatzissawidis den neuen Darmstädter Kavitationskanal aufgebaut. Der Kanal zeichnet sich durch eine hohe Strömungsgeschwindigkeit von bis zu 30 m s^{-1} aus. Das dort verbaute NACA 0015 Profil hat allerdings nur eine Sehnenlänge von 46 mm bei einer Tiefe von sogar nur 25 mm. Die Hypothese, dass ein Kondensationsstoß dann stromauf läuft, wenn die Kavitationsschicht das Profilende erreicht, wurde durch die Ergebnisse am kleinen Kanal validiert.

Methode

Herr Hatzissawidis ist ein Pionier in der Anwendung von Spektralmethoden zur Analyse von zeitlichen und räumlichen Skalen der hydrodynamischen Kavitation. Die Nutzung der Spectral Proper Orthogonal Decomposition (SPOD) ermöglicht ihm in der Tat, mit scharfer Brille auf seine Kavitationsmessungen zu schauen. So analysiert er den Frequenzinhalt von Auftriebsmessungen und zerlegt seine Bilder in Moden.

Einsichten

Herr Hatzissawidis erkennt, dass die generalisierte Kavitationszahl $\sigma/2\alpha$ sehr gut in der Lage ist, um den Einfluss von Kavitationszahl σ und Anstellwinkel α bei konstanter Reynoldszahl $Re > Re_c$ zu studieren. Weiterhin erkennt er, dass die Strouhalzahl idealerweise mit der Schichtgeschwindigkeit $U_\infty\sqrt{1+\sigma}$ gebildet wird. Dies sind wichtige Erkenntnisse, die die zukünftige experimentelle Arbeit deutlich vereinfachen. Herr Hatzissawidis identifiziert Wolkenkavitation, die durch den sogenannten Re-Entrant-Flow bestimmt und die durch Kondensationsstöße geprägt sind. Herr Hatzissawidis erkennt, dass bei der von ihm betrachteten fortgeschrittenen Kavitation der Keimgehalt keine Rolle spielt.

Nachhaltigkeit und Nachvollziehbarkeit

Große Teile der Forschungsdaten von Herrn Hatzissawidis sind vorbildlich auf dem Repositorium der TU Darmstadt, TUdataLib, abgelegt. Weiterhin sind Hochgeschwindigkeitsaufnahmen als Zusatzmaterial im Repositorium offen zugänglich. Herr Hatzissawidis hat eine von ihm genutzte SPOD-Methode open source auf einem Git-Repositorium für die Forschungsgemeinschaft verfügbar gemacht. Die soziale Grundlage von Wissenschaft ist Vertrauen und Vertrauen wird über Nachvollziehbarkeit erreicht. Die Arbeit von Herrn Hatzissawidis ist in dieser Hinsicht vorbildlich.

Nutzen der Ergebnisse für Wissenschaft und Industrie

Hydrodynamische Kavitation bestimmt die Funktion und Verfügbarkeit von Pumpen, Propellern und Turbinen. Förderhöhe, Schub oder Turbinenleistung reduzieren sich mit zunehmender Kavitation. Kavitationswolken verursachen Lärm, Schwingungen und Materialschäden. Die vorliegende Arbeit von Herrn Hatzissawidis liefert 1.) Werkzeuge, um die Dynamik von Kavitation zu untersuchen und 2.) Einsichten in Frequenzen und die dazugehörigen Moden.

Aufgabe der Industrie ist die Gestaltung von Fluidenergiemaschinen. In den vergangenen 40 Jahren wurden hierfür immer feiner granulare numerische Strömungslöser eingesetzt. Das Streben nach einer direkten numerischen Simulation ist nach meinem Dafürhalten eine Sackgasse. Es wird auf absehbare Zeit nicht möglich sein, die Entstehung und Dynamik jeder einzelnen Blase zu berechnen. Zumindest ist dies aus Gründen der

Zeit- und Energieeffizienz verboten. Ein zukunftsweisender Weg sind statistische Verfahren kombiniert mit numerischen Verfahren. Dabei geht es darum, Mesoskalenmodelle bei kavitierenden Strömungen abzuleiten. Dies wird derzeit bereits sehr erfolgreich in der Verbrennungsforschung eingesetzt und harret der Anwendung in der Kavitationsforschung. In meiner Forschungsgruppe haben wir vor einigen Jahren bereits die Dynamik von Ringwirbeln mit einer Mittelungsmethode berechnet. Es bleibt abzuwarten, ob die reichhaltige Dynamik kavitierender Strömungen damit beschrieben werden kann. Die Methoden von Herrn Hatzissawidis stehen für die Validierung bereit. Die Industrie sollte sich aber auch die Frage stellen, wie bestimmte Oberflächendruckverläufe einphasiger Strömungen bestimmte Moden verursachen. Hier weist Herr Hatzissawidis Wege. Einphasige Strömungen sind besonders einfach zu berechnen. Damit wird die Fluidenergiemaschine im Rechner optimierbar.

Letztlich bleibt noch anzumerken, dass in der vorliegenden Arbeit die Untersuchungen von Herrn Hatzissawidis zur Oberflächenrauheit nicht enthalten sind. Die Gestalt des Schaufelgitters, aber auch die Oberflächenstruktur sind lohnende Gestaltungsfelder.

Darmstadt, im Februar 2026
Peter F. Pelz

Declarations

Declaration of originality pursuant to section 9 (1) of the General Doctoral Regulations (PO/AT), as amended for the 9th time in the version dated 15 November 2023

I hereby declare that I wrote this thesis independently – apart from the aids expressly mentioned in the dissertation, and that I observed the ‘Grundsätze zur Sicherung guter wissenschaftlicher Praxis an der Technischen Universität Darmstadt – Principles for Safeguarding Good Scientific Practice at Technical University of Darmstadt’ and the ‘Leitlinien zum Umgang mit digitalen Forschungsdaten an der TU Darmstadt – Guidelines on Digital Research Data at TU Darmstadt’ in their current versions when writing the dissertation.

Statement regarding publications

I hereby declare that the content of this thesis is extended, adapted, or directly reproduced from the following manuscripts, which have been submitted to the *Journal of Fluid Mechanics* and are currently under review: Hatzissawidis, Russell, Venning, Pelz, and Brandner (2025a, 2025b). The abstract of this thesis is taken and adapted from both manuscripts. In the introductory sections at the beginning of each chapter, relevant citations are provided. The results presented in chapter 4 and chapter 5 are taken from Hatzissawidis, Russell, Venning, Pelz, and Brandner (2025a) and Hatzissawidis, Russell, Venning, Pelz, and Brandner (2025b), respectively.

Declaration of the use of Artificial Intelligence in the writing process

I acknowledge the use of the large language models GPT-4o and GPT-5 by OpenAI in order to generate suggestions for improvements in writing style and proofreading. After using these tools and services, I reviewed and edited the content as needed and take full responsibility for the content of the publication.

Darmstadt, 02.12.2025
Grigorios Hatzissawidis

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My PhD has been the most formative journey of my life – deepening my knowledge of core engineering disciplines and redefining me as an engineer. This thesis was undertaken while I served as a research assistant at the Chair of Fluid Systems, Technische Universität Darmstadt, and as a visiting researcher at the Australian Maritime College, University of Tasmania. While it is often said that only results matter, this journey was shaped by the people who supported and inspired me.

First and foremost, I want to thank my supervisors: Prof Peter Pelz, whose passion for fluid mechanics and inspiring guidance have shaped me as a researcher. I value your advice, constructive discussions, and the trust you have placed in me to explore my own path. I also thank my second supervisor, Prof Paul Brandner, for hosting me and enabling experiments in a world-class cavitation tunnel. I am grateful to have come to know you during my PhD; your ideas, advice, and warm hospitality – especially the dinner at Lou’s place – made my stay both personally and professionally enriching.

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Darmstadt, 02.12.2025
Grigorios Hatzissawidis

Abstract

Cloud cavitation dynamics about a three-dimensional NACA 0015 hydrofoil with varying incidence are investigated in a variable-pressure water tunnel. The incidence is relevant for off-design operation of pumps, turbomachinery, and marine propellers, yet experimental investigations in this area remain scarce. The experiments were conducted at a fixed Reynolds number of 8×10^5 , with the incidence α varied between 0° and 16° , covering cavitation inception to supercavitation, at four cavitation numbers ($\sigma = 0.50, 0.76, 0.88, 1.01$). Unsteady force measurements were conducted simultaneously with high-speed photography to analyse shedding physics. Characteristic length- and time-scales were extracted from high-speed photographs and the power spectral density of the lift coefficient, respectively. The transient analysis was performed using continuous wavelet transform. The topology of the shedding modes was identified through the spectral proper orthogonal decomposition technique applied to high-speed photographs. Four modes, (i), (ii), (iii), and (iv), were identified: (i) at low cavitation numbers, the fundamental shockwave-driven shedding mode at a chord-based Strouhal number St of 0.19 to 0.29 dominates, characterised by the development and stagnation of a re-entrant flow during cavity growth, followed by the triggering of a shockwave at the trailing edge; (ii) a low-frequency mode describing the excursion of the cavity tip which occurs only in conjunction with mode (i); (iii) a high-frequency mode which can be either a harmonic artefact or a physical mode linked to three-dimensional shedding; (iv) at high cavitation numbers, the fundamental coupled re-entrant flow and condensation shockwave-driven mode at $St = 0.51$ to 0.56 dominates, where the re-entrant flow penetrates the cavity sheet just downstream of its leading edge, initiating a shockwave that condenses the remaining cavity. The parameter $\sigma/2\alpha$ derived from linear theory yields a good prediction: the cavity velocity-based Strouhal numbers associated with the four modes collapse onto distinct curves, consolidating the information from the four spectrograms of each σ . A gradual transition from mode (iv) to (i) is observed as $\sigma/2\alpha$ decreases, where the modes occur exclusively and simultaneously, with shockwaves becoming more dominant. Mode (ii) is characterised by a complex interaction with mode (i): In mode (i), shockwaves originating from the tip and root intersect to form a ‘cross’-shaped pattern in the space-time diagram; a disruption of this pattern coincides with the emergence of mode (ii) and a weakening of mode (i). Mode (i) exhibits a plateau in St and the maximum cavity sheet length as the maximum cavity sheet length equals the chord length, which coincides with the disappearance of mode (ii). Capturing the three-dimensional behaviour at high incidence and cavitation number requires consideration of higher-order spectral proper orthogonal decomposition eigenmodes. Cloud cavitation dynamics vary strongly with incidence, exhibiting multiple mechanisms and modes, as well as complex, interacting dynamics with three-dimensional behaviour – an observation that should inform modelling, control, and design.

Zusammenfassung

Die Dynamik von Wolkenkavitation in Abhängigkeit vom Anstellwinkel wurde an einem dreidimensionalen NACA 0015 Auftriebskörper in einem Kavitationskanal untersucht. Der Anstellwinkel α ist für den Betrieb von Pumpen, Turbomaschinen sowie Schiffspropellern der beschreibende Parameter, wenn sie außerhalb ihres Auslegungspunktes betrieben werden. Dennoch liegen hierzu bislang nur wenige experimentelle Untersuchungen vor. Die Experimente wurden bei konstanter Reynoldszahl von 8×10^5 durchgeführt. Der Anstellwinkel α wurde im Bereich von 0° bis 16° bei vier Kavitationszahlen ($\sigma = 0.50, 0.76, 0.88, 1.01$) variiert und umfasste damit sämtliche Betriebszustände von Kavitationsbeginn bis Superkavitation. Kraftmessungen mit einer Sechskomponenten-Kräftewaage sowie Hochgeschwindigkeitsaufnahmen zur Aufklärung der zugrunde liegenden Strömungsphysik wurden durchgeführt. Aus den Daten wurden jeweils charakteristische Zeit- sowie Längenskalen identifiziert. Eine transiente Analyse wurde mittels der kontinuierlichen Wavelet-Transformation durchgeführt. Die Topologie der Moden wurde mittels spectral proper orthogonal decomposition identifiziert. Vier Moden, (i), (ii), (iii) und (iv), wurden identifiziert: (i) Bei niedriger Kavitationszahl dominiert die schockwellengetriebene Mode mit einer auf die Profilschneckenlänge bezogene Strouhalzahl St von 0.19 bis 0.29. Dabei entsteht ein Re-Entrant Flow während des Schichtwachstums, der schließlich stagniert; anschließend wird an der Profilhinterkante eine Schockwelle getriggert. (ii) Eine niederfrequente Mode, die nur in Verbindung mit Mode (i) auftritt und die Oszillation der Schichtspitze beschreibt. (iii) Eine hochfrequente Mode, die entweder ein harmonisches „Artefakt“ oder eine physikalische Mode ist. (iv) Bei hohen Kavitationszahlen dominiert die mit einer Schockwelle gekoppelte, vom Re-Entrant Flow-getriebene Mode mit $St = 0.51$ bis 0.56. Der Re-Entrant Flow durchbricht die Kavitationsschicht kurz vor dem Schichtbeginn und eine darauffolgende Schockwelle kondensiert die übrige Schicht. Der aus der linearen Theorie stammende Parameter $\sigma/2\alpha$ erlaubt eine gute Verallgemeinerung der Ergebnisse, da die auf die Schichtgeschwindigkeit bezogenen Strouhalzahlen der vier Moden gut übereinander liegen. Der Übergang von Mode (iv) zu (i) erfolgt fließend, wenn $\sigma/2\alpha$ verringert wird und Schockwellen zunehmend dominieren. Die Moden treten dabei sukzessive und simultan auf. Mode (ii) tritt in Zusammenspiel mit Mode (i) auf: In Mode (i) entstehen zwei schräge Schockwellen, ausgehend vom oberen und unteren Ende der Schicht und formen ein kreuzförmiges Muster im Ort-Zeit-Diagramm. Mode (i) weist ein Plateau in St sowie der maximalen Schichtlänge auf, sobald die maximale Schichtlänge der Profilschneckenlänge entspricht; dieser Zustand geht mit dem Verschwinden von Mode (ii) einher. Um das dreidimensionale Verhalten bei hohem Anstellwinkel und Kavitationszahl zu erfassen, müssen spectral proper orthogonal decomposition Eigenmoden höherer Ordnung berücksichtigt werden. Die Dynamik von Wolkenkavitation variiert stark mit dem Anstellwinkel und weist mehrere Mechanismen und Moden sowie komplexe, miteinander wechselwirkende Dynamiken mit 3D-Verhalten auf – eine Beobachtung, die Modellierung, Regelung und Auslegung maßgeblich beeinflussen sollte.

Contents

1	Introduction	1
1.1	Background and research gap	1
1.2	Aims and research questions	5
1.3	Methodology and thesis outline	6
2	A review of the literature	9
2.1	Cloud cavitation shedding mechanisms	9
2.1.1	Re-entrant flow-driven cloud cavitation	12
2.1.2	Shockwave-driven cloud cavitation	13
2.1.3	Transition and origin of shockwaves	16
2.2	Characteristic frequencies	18
2.2.1	Strouhal number and dimensional analysis	18
2.2.2	Inter-study comparison	20
2.3	Shedding behaviour of cloud cavitation	24
2.3.1	Two-dimensional and three-dimensional topology	24
2.3.2	Temporal behaviour and multimodality	25
2.3.3	Existing studies on cavitation behaviour with varying incidence . .	26
2.4	Modal decomposition techniques in cavitation	28
2.5	Synthesis of literature and research gaps	29
2.5.1	Summary of key findings	29
2.5.2	Research gaps and future studies	30
3	Experimental overview and data analysis techniques	33
3.1	Experimental set-up and design	33
3.1.1	CRL cavitation tunnel	33
3.1.2	Hydrofoil and six-component force balance	38
3.1.3	Experimental design	41
3.2	Spectral and transient analysis	43
3.3	Cavitation topology	43
3.3.1	High-speed and still photography	44
3.3.2	Spectral proper orthogonal decomposition for modal analysis . . .	45
4	Cavity topology and spectral analysis	51
4.1	Global cavitation topology	51
4.2	Force measurements, spectral content, and characteristic frequencies . . .	55
4.2.1	Steady and unsteady analysis of the force measurements	55
4.2.2	Spectral content and modes	58

4.2.3	Characteristic frequencies	61
4.3	Transient behaviour and correlation between modes	65
4.3.1	Transient analysis using continuous wavelet transform	65
4.3.2	Ratio of mode frequencies	70
4.3.3	Correlation between modes	73
4.4	Summary of key findings	75
5	Shedding mechanisms and mode transition	77
5.1	Coupled re-entrant flow and condensation shockwave	79
5.1.1	Phenomenological analysis	80
5.1.2	Invariance of the shedding frequency	85
5.2	Fundamental shockwave-driven mode and tip shedding mode	90
5.3	Condensation shock initiation at the trailing edge	102
5.4	Transition from re-entrant flow to condensation shockwave	106
5.5	Top-bottom cloud shedding	109
5.6	Summary of key findings	114
6	Conclusion	117
6.1	Restating the aims of the study and approach	117
6.2	Summary of the main results and answers to the research questions	118
6.3	Practical implications of the results	121
6.4	Limitations and recommendations for future research	122
6.5	Final thoughts	122
	References	125
	Own publications	137
A	Uncertainty analysis	139
B	Scientific method and research data management	149
C	Spectral analysis tools	153
C.1	Parameter study for Welch's method	153
C.2	Parameter study for the continuous wavelet transform	154
D	Fluid properties	157
E	Additional figures	159
E.1	Inter-study comparison for chord-based Strouhal numbers	159
E.2	Spectrograms of the lift coefficients over the incidence	160
E.3	Power spectral density for the same $\sigma/2\alpha$	161

List of Figures

1.1	Still photograph of cloud cavitation about a NACA 0015 hydrofoil	2
2.1	Schematic overview of the three fundamental forms of cloud cavitation . .	11
2.2	Still photographs of re-entrant flow-driven and shockwave-driven cloud cavitation	14
2.3	The speed of sound in a gas/water mixture as a function of the gas volume fraction	15
2.4	Strouhal numbers of previous studies of cloud cavitation about a NACA hydrofoil	21
2.5	Still photographs of two-dimensional and three-dimensional shedding . . .	25
3.1	Schematic of the cavitation tunnel	34
3.2	Microbubble measurements for different nuclei populations in the cavitation tunnel	35
3.3	Schematic of the test section with the mounted NACA 0015 hydrofoil . .	36
3.4	Schematic of the entire measurement system and the test section	37
3.5	Schematic of the bottom-side view of the NACA 0015 hydrofoil with coordinate systems, forces, and moments	39
3.6	Boundary layer measurements in the cavitation tunnel at four different positions	40
3.7	Schematic of the spectral proper orthogonal decomposition technique . .	46
3.8	Reconstruction of an instantaneous high-speed photography using the ‘frequency-domain approach’	48
4.1	Array of still photographs depending on σ and α	52
4.2	Maximum cavity sheet length over $\sigma/2\alpha$	53
4.3	Cavity spanwise extent over $\sigma/2\alpha$	54
4.4	Mean and standard deviation of the lift and drag coefficient	56
4.5	Spectrograms of the power spectral density of the lift coefficient for $\sigma = 1.01, 0.88, 0.76, 0.50$	59
4.6	Chord-based Strouhal number St and cavity velocity-based Strouhal number St^* over $\sigma/2\alpha$	62
4.7	Inter-study comparison of studies on a NACA 0015 hydrofoil	64
4.8	Wavelet spectrograms for $\sigma = 1.01$ and $\alpha = 10^\circ, 12^\circ$ and 14°	66
4.9	Wavelet spectrograms for $\sigma = 0.50$ and $\alpha = 6^\circ, 8^\circ$ and 14°	67
4.10	Wavelet spectrograms for $\sigma/2\alpha \approx 2.10$	69
4.11	Frequency ratio St_{ii}/St_{iii} over $\sigma/2\alpha$	71
4.12	Frequency ratio St_{ii}/St_i over $\sigma/2\alpha$	72

List of Figures

4.13	Pearson correlation coefficient between the continuous wavelet transform coefficients	74
4.14	Absolute values of the components of the continuous wavelet transform of mode (i) against (ii), (iii), and (iv)	75
5.1	Absolute value of the leading SPOD eigenmodes at representative operation points	78
5.2	Visualisation of the coupled re-entrant flow and condensation shockwave in a stacked figure of the lift and pitching coefficient, continuous wavelet transform, and space-time diagram for $\sigma = 1.01$ and $\alpha = 10^\circ$	81
5.3	Space-time diagrams of the re-entrant flow impinging the cavity sheet leading to the subsequent condensation shockwave	82
5.4	Sequence of high-speed photographs of the coupled re-entrant flow and condensation shockwave mechanism	83
5.5	Detailed chordwise space-time diagram of the coupled re-entrant flow and condensation shockwave cycle with annotations	84
5.6	Detailed spanwise space-time diagram of the coupled re-entrant flow and condensation shockwave cycle with annotations	85
5.7	Spanwise space-time diagrams of $\alpha = 9^\circ$, 10° and 11° and $\sigma = 1.01$ showing the coupled re-entrant flow and condensation shockwave cycle . .	86
5.8	Chordwise space-time diagrams of $\alpha = 9^\circ$, 10° and 11° and $\sigma = 1.01$ showing the coupled re-entrant flow and condensation shockwave cycle . .	88
5.9	Strouhal numbers of the coupled re-entrant flow and condensation shockwave mechanism over $\sigma/2\alpha$	89
5.10	Leading SPOD eigenmodes of mode (i), (ii), and (iii) as absolute values and phase for $\sigma = 0.50$ and $\alpha = 6^\circ$, 8° and 14°	91
5.11	Stacked figure of the lift and pitching coefficient, continuous wavelet transform, and space-time diagrams for $\sigma = 0.50$, $\alpha = 6^\circ$	92
5.12	Sequence of high-speed photographs showing the condensation shockwave mechanism	93
5.13	Detailed spanwise space-time diagram of the condensation shockwave mechanism exhibiting the ‘cross’-shape	94
5.14	Stacked figure of the lift and pitching coefficient, continuous wavelet transform, and space-time diagrams for $\sigma = 0.50$, $\alpha = 6^\circ$ showing the transition from mode (i) to mode (ii)	95
5.15	Temporal mean and standard deviation of the high-speed photographs over 50 cycles for dominant mode (i) and (ii)	97
5.16	Stacked figure of the lift and pitching coefficient, continuous wavelet transform, and space-time diagrams for $\sigma = 0.50$, $\alpha = 14^\circ$ showing the occurrence of mode (i) and (ii)	98
5.17	Power spectral density of the lift coefficient for similar $\sigma/2\alpha$ across four cavitation numbers	99
5.18	Comparison of spanwise space-time diagrams and continuous wavelet transform components for similar $\sigma/2\alpha$ across four cavitation numbers . .	100

5.19	Peaks of the power spectral density and relative SPOD variance for mode (i) and (ii) as a function of $\sigma/2\alpha$ showing the diminishing of mode (ii)	103
5.20	Chord-based Strouhal number and maximum cavity sheet length for $\sigma = 0.50$ and $\sigma = 0.76$ as a function of $\sigma/2\alpha$ showing the ‘lock-in’ effect	103
5.21	Stacked figure with the lift and pitching coefficient, the real part of the CWT of the lift coefficient and space-time diagrams showing the shockwave triggering at the trailing edge of the hydrofoil	104
5.22	Peaks of the power spectral density of the lift coefficient and the relative SPOD variance for mode (i), (ii), and (iv) as a function of $\sigma/2\alpha$ showing the transition from (iv) to (i)	107
5.23	Leading SPOD eigenmodes for $\sigma = 1.01$ and $\alpha = 10^\circ, 12^\circ, 14^\circ$	108
5.24	Spanwise space-time diagram for the transitional operation point where mode (i) and mode (iv) occur together	108
5.25	Leading and second order SPOD eigenmodes for $\sigma = 1.01$ and $\alpha = 10^\circ, 15^\circ$ and 16°	110
5.26	Relative variance of modes (i), (iii), and (iv) of the leading and the second order SPOD eigenmode	111
5.27	Relative mode variance as a function of the eigenmode number and the corresponding spectrum for $\sigma = 1.01$ and $\alpha = 10^\circ, 15^\circ$ and 16°	112
5.28	Space-time diagrams showing for $\sigma = 1.01$ and $\alpha = 10^\circ, 15^\circ$ and 16° . . .	113
A.1	Contributions of the uncertainty as a bar chart	141
A.2	Uncertainty analysis of the lift force, drag force, and pitching moment . .	143
A.3	Uncertainty analysis of the lift, drag, and pitching coefficient	144
B.1	Schematic of the scientific method and the research data management . .	150
C.1	The effect of zero-padding on the Welch PSD	153
C.2	The effect of the window size on the Welch PSD	154
C.3	Real and imaginary part of the complex Morlet wavelet for increased bandwidth	155
C.4	The effect of the bandwidth on the time-averaged CWT	156
D.1	Dependence of the fluid properties on the temperature	158
E.1	Inter-study comparison of studies on a NACA 0015 hydrofoil of the chord-based Strouhal number	159
E.2	Spectrograms of the estimated power spectral density of the lift coefficient for $\sigma = 1.01, 0.88, 0.76, 0.50$ over α	160
E.3	Power spectral density over for the same $\sigma/2\alpha$ across the four cavitation numbers	161

List of Tables

2.1	Overview of previous studies on a NACA 0015	23
3.1	Experimental design with the different run types	42
5.1	Overview of mode (i) to (iv): their $\sigma/2\alpha$ and St ranges	79
A.1	Uncertainty quantification for free-stream velocity (U_∞) calculation	145
A.2	Uncertainty quantification for Reynolds number (Re) calculation	145
A.3	Uncertainty quantification for cavitation number (σ) calculation	145
A.4	Uncertainty quantification for lift coefficient (C_L) calculation	146
A.5	Uncertainty quantification for drag coefficient (C_D) calculation	146
A.6	Uncertainty quantification for pitching coefficient (C_P) calculation	147

Notation

List of Symbols

The table below summarises the symbols used in the mathematical and physical expressions throughout the thesis. The first column lists the symbols, the second column offers a description of their meanings along with the page numbers where they are mentioned, and the third column shows their dimensions. Dimensions are expressed in terms of the base quantities: length (L), mass (M), time (T), temperature (Θ), amount of substance (N), and electric current (I). A dimension of 1 indicates that the quantity is dimensionless, while ‘depends’ means that the quantity varies based on other input quantities.

Symbol	Description	Dimension
a	Uncertainty bounds, 140	depends
$\hat{a}$	Maximum cavity sheet length, 10, 11, 16, 19, 53, 80, 85, 89, 103	L
$\hat{a}_+$	Non-dimensionalised maximum cavity sheet length, 16, 18–20, 27, 53–55, 59, 70, 72, 80, 84, 88, 89, 99, 102–105, 160	1
α	Incidence, xiii, xv, xviii–xxi, xxiii, 2, 5–8, 14, 16, 19–23, 29–31, 33, 37–39, 41, 42, 44, 48, 51–81, 83, 85–95, 97–100, 102–104, 106–114, 117–121, 140, 143–145, 153, 154, 156, 159–161	1
b	Span of the hydrofoil, 23, 38–40, 56, 57, 141, 146, 147	L
BW	Bandwidth, 43, 154–156	T ²
C	Cumulative distribution of nuclei and microbubbles, 34, 35	L ^{−3}
c	Dissolved oxygen concentration, 36, 37	ML ^{−3}
c	Speed of sound, 13, 14	LT ^{−1}
C_D	Drag coefficient, xxiii, 39, 56, 140–142, 146	1
C'_D	Fluctuating part of the drag coefficient, 56, 57	1
$\overline{C}_D$	Mean part of the drag coefficient, 56, 57, 141, 144, 146	1
$\overline{C}_P$	Mean part of the pitching coefficient, 141, 144, 147	1
c_G	Speed of sound of the gas, 14	LT ^{−1}
C_L	Lift coefficient, xxiii, 39, 55, 56, 58, 59, 61, 65, 71, 72, 77, 79, 81, 92, 95, 96, 98–100, 102–104, 106, 107, 140–142, 146, 153, 154, 160, 161	1
c_L	Speed of sound of the liquid, 13, 14	LT ^{−1}
C'_L	Fluctuating part of the lift coefficient, 56, 57	1
$\overline{C}_L$	Mean part of the lift coefficient, 56, 57, 141, 144, 146	1

List of Symbols

Symbol	Description	Dimension
C_P	Pitching coefficient, xxiii, 39, 81, 92, 95, 96, 98, 102, 104, 140–142, 147	1
$c_p(x)$	Pressure distribution along the hydrofoil, 19	1
CWT	Continuous wavelet transform, 43, 65–67, 69, 71, 72, 74, 75, 80, 81, 92, 95, 98, 100, 104, 156	1
d_c	Critical bubble or nuclei diameter, 34, 35	L
δ	Thickness of the boundary layer where the velocity reaches 99 % of U_∞ , 40	L
δ	Scales, 43	1
Δp	Differential pressure, 35–37, 141, 145	$ML^{-1}T^{-2}$
Δp_0	Offset of the differential pressure, 141, 145	$ML^{-1}T^{-2}$
Δt	Duration, 41, 42	T
Δy	Expanded uncertainty, 140	depends
η	Vertical direction of the flow-fixed coordinate system, 39	L
η'	Transverse direction of the hydrofoil-fixed coordinate system, 39	L
f	Frequency, xxvi–xxviii, 18, 19, 21, 43, 46–49, 58, 61, 62, 64, 66, 67, 69–72, 74, 75, 80, 81, 85, 87, 92, 95, 96, 98–104, 107, 109, 153, 154, 156, 159	T^{-1}
f_c	Centre frequency, 43, 154–156	T^{-1}
F_D	Drag force, 37, 39, 141, 146	MLT^{-2}
$\overline{F}_D$	Mean drag force, 143	MLT^{-2}
f_{HSI}	Frame rate, 41, 42	T^{-1}
F_L	Lift force, 37, 39, 141, 146	MLT^{-2}
$\overline{F}_L$	Mean lift force, 143	MLT^{-2}
F_S	Side force, 37, 39	MLT^{-2}
f_{TU}	Acquisition rate, 41, 42	T^{-1}
H	Height of the test section, 23, 40	L
K	Contraction coefficient, 35, 36, 141, 145	1
k	Coverage factor, 35, 140, 143–147	1
L	Chord length of the hydrofoil, 10, 11, 16, 18, 19, 21, 23, 36, 38–40, 43, 48, 53–58, 61, 62, 64, 78, 80–89, 91, 92, 94, 95, 97, 98, 100, 101, 103, 104, 108, 110, 113, 141, 145–147, 159	L
λ	SPOD variance, 112	depends
$\mathbf{\Lambda}_{f_k}$	Diagonal matrix with the diagonal elements being the variances of the SPOD for f_k , xxvi, 47	depends
$\tilde{\mathbf{\Lambda}}_{f_k}$	Same as $\mathbf{\Lambda}_{f_k}$ containing only the non-zero elements from the reduced eigenvalue problem, xxvii, 46–48	depends
λ_{f_k}	Cumulative variance at frequency f_k , 48, 49	depends
λ_{+, f_k}	Non-dimensionalised cumulative variance at frequency f_k , 49, 103, 107	1

Symbol	Description	Dimension
$\lambda_{f_k}^{(i)}$	SPOD variance, diagonal elements of $\tilde{\mathbf{\Lambda}}_{f_k}$ for i -th eigenmode at a frequency of f_k , 48, 49	depends
$\lambda_{+,f_k}^{(i)}$	Non-dimensionalised SPOD variance, 48, 110–112	1
M	Number of snapshots, 45	1
M_P	Pitching moment, 37, 39, 141, 147	ML^2T^{-2}
$\overline{M}_P$	Mean pitching moment, 143	ML^2T^{-2}
M_R	Rolling moment, 37, 39	ML^2T^{-2}
M_Y	Yawing moment, 37, 39	ML^2T^{-2}
n	Number of independent observations, 139	1
N	Number of input quantities, 140	1
N	Number of pixel, 45, 47	1
n	Polytropic index, 13–15	1
N_b	Number of blocks, 45–47, 49	1
N_f	Window size, 45–47, 49	1
N_o	Overlap, 45	1
ν	Kinematic viscosity, 23, 36, 38, 141, 157, 158	L^2T^{-1}
p	Pressure, 13, 14	$\text{ML}^{-1}\text{T}^{-2}$
p_c	Blake’s critical pressure, 34, 35	$\text{ML}^{-1}\text{T}^{-2}$
ϕ_G	Gas volume fraction, 13–15	L^3L^{-3}
$\Phi_{f_k}^{(i)}$	i -th spatial SPOD mode at frequency f_k , columns of $\tilde{\Phi}_{f_k}$, 47	depends
Φ_{f_k}	Spatial mode matrix where the columns are the spatial modes for f_k , xxvii, 47	depends
$\tilde{\Phi}_{f_k}$	Same as Φ_{f_k} , containing only the non-zero elements from the reduced eigenvalue problem, xxvii, 46, 47	depends
p_∞	Free-stream static pressure at midspan of the hydrofoil, 11, 34–39, 141, 145	$\text{ML}^{-1}\text{T}^{-2}$
PSD	Power Spectral Density, 59, 71, 72, 99, 103, 107, 153, 154, 160, 161	T
ψ	Wavelet function, 43, 155	1
p_v	Vapour pressure of water, 34, 35, 38, 141, 157, 158	$\text{ML}^{-1}\text{T}^{-2}$
$\mathbf{Q}$	Data matrix containing the SPOD snapshots $\mathbf{q}_i$, xxvii, 45, 46	depends
q	Random variable, 139	depends
$\hat{\mathbf{Q}}$	Matrix with the DFT components of the data matrix $\mathbf{Q}$, 46, 47	depends
$\mathbf{q}_k$	k -th snapshot at time t_k of the input data for the SPOD, 45	depends
$\hat{\mathbf{q}}_k$	k -th DFT component associated with frequency f_k , 46	depends
R	Coefficient of determination, 84	1
r	Pearson correlation coefficient, 73–75, 90, 99	1

List of Symbols

Symbol	Description	Dimension
R	Resolution, 41, 42	L
Re	Reynolds number, xxiii, 2, 14, 20, 23, 36, 59, 63, 140, 141, 145, 157, 160	1
ϱ	Density, 36, 38, 39, 141, 157, 158	$ML^{-1}T^{-2}$
ϱ_G	Density of the gas, 13	ML^{-3}
ϱ_L	Density of the liquid, 13	ML^{-3}
$\hat{s}$	Spanwise cavity extent, 54, 55, 61, 87	L
S	Surface tension, 34, 35	MT^{-2}
$\mathbf{S}_{f_k}$	Estimated cross-spectral density tensor at frequency f_k , 47	depends
σ	Cavitation number, xiii, xv, xviii–xxi, xxiii, xxviii, 2, 5–8, 10, 11, 14, 16, 19–23, 25, 29–31, 33, 38, 40–42, 44, 48, 51–81, 83, 85–95, 97–104, 106–114, 117–121, 140, 141, 143–145, 149, 153, 154, 156, 157, 159–161	1
$\sigma_{I,II}$	Critical cavitation number for the transition from sheet cavitation to re-entrant flow-driven cloud cavitation, 10, 11	1
$\sigma_{II,III}$	Critical cavitation number for the transition from re-entrant flow-driven cloud cavitation to shockwave-driven cloud cavitation, 10, 11	1
$\hat{s}_+$	Nondimensionalised spanwise cavity extent, 54, 55, 59, 61, 70, 72, 87, 160	1
St	Chord-based Strouhal number, xiii, xv, xix, xxiii, 10, 11, 18–21, 58, 59, 62, 65–72, 78–81, 83, 86, 87, 89, 91–93, 95, 96, 98, 99, 102–104, 108, 112, 153, 154, 156, 159, 160	1
St^*	Cavity velocity-based Strouhal number, xix, 61, 62, 64, 87, 89, 161	1
$\hat{St}$	Cavity length-based Strouhal number, 19, 20, 86, 87, 89	1
T	Period of a cycle, 86–88, 95, 96, 98, 100, 104, 108, 113	T
t	Physical time, xxvii, 11, 43, 45, 46, 82, 155	T
T	Temperature of water, 37, 141, 145–147, 157, 158	Θ
τ	Translation time, 43	T
θ_i	Derivative of the output quantity with respect to the i -th input estimate or sensitivity coefficient, 140, 141, 145–147	depends
Θ_{f_k}	Eigenvector matrix of the reduced eigenvalue problem to calculate the SPOD, 47	depends
t_+	Nondimensionalised time, 43, 66–69, 80–86, 88, 92–101, 104, 106, 108, 109, 111, 113	1
$\tilde{t}$	Thickness to the chord ratio of the NACA geometry, 38	1
u	Local velocity in ξ -direction within the test section, 40	LT^{-1}
$u_A(x_i)$	Standard uncertainty of Type A of the input estimate x_i , 139	depends

Symbol	Description	Dimension
$u(x_i)$	Standard uncertainty of the input estimate x_i , 140	depends
$u_B(x_i)$	Standard uncertainty of Type B of the input estimate x_i , 140	depends
$u_c(y)$	Combined uncertainty of the estimate y , 140, 141, 143–147	depends
U_∞	Free-stream velocity, xxiii, xxvi, 11, 18, 19, 21, 35–40, 43, 58, 61, 62, 64, 80–82, 84–88, 92, 94, 95, 98, 100, 104, 108, 113, 140, 141, 145–147, 157, 159	LT^{-1}
W	Weight matrix, 47	depends
w	Width of the test section, 23	L
w	Window function, xxix, 45, 46	1
w_i	Component i of the window function w , 46	depends
x	Streamwise direction of the coordinate system with origin at the leading edge, 11, 39, 48, 78, 80–82, 84–86, 88, 91, 92, 94, 95, 97, 98, 100–102, 104, 108, 110, 113	L
$\bar{X}_i$	Arithmetic mean of the individual observation for the i -th input quantity, 139, 140, 145–147	depends
x_i	Input estimate, xxviii, xxix, 139–141, 145–147	depends
X_i	Input quantity, 139–141, 145–147	depends
ξ	Streamwise direction of the flow-fixed coordinate system, xxviii, 39, 40	L
$\hat{\xi}$	Re-entrant flow coordinate, 10, 11	L
$X_{i,k}$	k -th individual observation for the i -th input quantity, 139	depends
ξ'	Chordwise direction of the hydrofoil-fixed coordinate system, 39	L
$\tilde{x}$	Chordwise coordinate of the NACA geometry, 38	1
Y	Measurand, 140	depends
y	Output estimate, xxix, 140, 141, 143, 144	depends
$\tilde{y}$	Thickness coordinate of the NACA geometry, 38	1
z	Transverse direction of the coordinate system with origin at the leading edge, 39, 48, 78, 81–88, 91, 92, 94, 95, 97, 98, 100, 104, 108, 110, 113	L
ζ	Transverse direction of the flow-fixed coordinate system, 39, 40	L
ζ'	Spanwise direction of the hydrofoil-fixed coordinate system, 39	L

Special sets

Imaginary part of a complex number ($\Im$) 155

Real numbers ($\mathbb{R}$) 45, 47

Real part of a complex number ($\Re$) 81, 92, 95, 98, 100, 104, 155

Abbreviations

2D Two-dimensional xvii, xix, 4, 7, 9, 20, 23–26, 28–31, 47, 51, 68, 70, 73, 81, 90, 99, 106, 109, 110, 113, 115, 120, 122

3D Three-dimensional xiii, xvii, xix, 3–7, 9, 21, 23–26, 28–31, 47, 49, 51, 53, 54, 68, 70, 71, 73, 76, 81, 84, 87, 101, 109, 110, 113, 114, 118, 120–122

AMC Australian Maritime College 33

BEP Best efficiency point 1

CRL Cavitation Research Laboratory xvii, 7, 23, 33–35, 40, 149, 150

CROM Cluster-based reduced-order modelling 26

CSM Cavitation susceptibility meter 34, 35

CWT Continuous wavelet transform xiii, xviii, xx, xxi, 7, 29, 43, 51, 65, 66, 68–71, 73, 76, 80, 92, 93, 95–98, 100–102, 104, 118–120, 151, 153–155

DFT Discrete Fourier transform 45, 46, 118

DMD Dynamic mode decomposition 26, 28, 45

FFT Fast Fourier transform 150, 154

GUM Guide to the Expression of Uncertainty in Measurement 139, 140

HDF Hierarchical data format 149, 151

K-H instability Kelvin-Helmholtz instability 3, 9–11, 13, 29, 58

LED Light-emitting diode 37

MSI Mie-scattering imaging 34, 35

NACA National Advisory Committee for Aeronautics xiii, xv, xix, xxi, xxiii, xxviii, xxix, 2, 4, 6, 7, 9, 14, 16, 18, 20, 21, 23–27, 29, 33, 36–39, 51, 62–64, 76, 79, 81, 82, 87, 118, 149, 159

NI National Instruments 36, 37, 39, 44

PCC Pearson correlation coefficient xx, 65, 73–75, 118, 119

- PCI** Peripheral Component Interconnect xxxi
- PIV** Particle image velocimetry 12, 28, 45
- POD** Proper orthogonal decomposition 26, 28, 45
- PSD** Power spectral density xiii, xviii–xxi, 21, 43, 58–61, 70–73, 99–103, 106, 107, 119, 120, 151, 153, 154, 160, 161
- PXIe** PCI eXtensions for Instrumentation Express 36, 37, 39, 44
- RDM** Research data management 8, 149
- SPOD** Spectral proper orthogonal decomposition xiii, xv, xvii, xix–xxi, 5, 7, 8, 26, 28, 29, 33, 42–49, 77, 82, 90, 91, 97, 99, 101–103, 106–111, 114, 115, 118, 120, 121, 150, 151
- TB** Terminal block 37, 39
- UTAS** University of Tasmania 33
- XWT** Cross-wavelet transform 28, 29

Chapter 1

Introduction

This chapter contextualises the study, identifies the research gap, and formulates five research questions investigated in this thesis. It introduces the two fundamental drivers of cloud cavitation – re-entrant flow and condensation shockwave – and examines their technical relevance to pump and marine applications under varying incidence, which is rarely addressed in the literature. It emphasises that re-entrant flow and shockwave phenomena are coupled and often coexist; moreover, the shedding is multimodal, further complicating the analysis of cloud cavitation. Accordingly, modal decomposition methods are introduced as a tool to reveal coherent structures from high-speed photographs that are otherwise hidden by direct observation. The chapter concludes with an outline of the thesis and a brief chapter-by-chapter summary.

Parts of this chapter are adapted from the following manuscripts, which have been submitted to the *Journal of Fluid Mechanics*: Hatzissawidis, Russell, Venning, Pelz, and Brandner (2025a, 2025b).

1.1 Background and research gap

Hydrodynamic cavitation denotes the tensile rupture of a fluid when the local static pressure falls below a critical pressure – Blake’s threshold (Blake, 1949) – a mechanism already envisaged by Leonhard Euler (1754, p. 266) nearly three centuries ago. Since the end of the 19th century, cavitation has preoccupied engineers, after early observations of damage to ship propellers and associated performance losses brought the phenomenon to light (Thornycroft & Barnaby, 1895; Parsons, 1911). To this day, cavitation research remains vibrant and understanding its physics is essential for performance prediction, erosion mitigation, and control. This historical perspective frames today’s challenges posed by cavitation in engineering applications, particularly in pumps and marine propulsion systems.

Today, the growing prevalence of off-design pump operation – particularly in boiler feed pumps of coal-fired power plants – is driven by the integration of sustainable energy sources in response to climate change, which in turn increases the susceptibility of these pumps to cavitation (Haese et al., 2023). The pumps do not operate at the best efficiency point (BEP), implying that the incidence between the incoming flow and the camber line of the impeller vanes is not equal to zero, i.e., it deviates from the condition of ‘shockless entry’ (Karassik et al., 2008, p. 2.89), see also Gülich (2020). Similarly, variations in incidence are likewise relevant in marine propellers as the inflow velocity varies due to

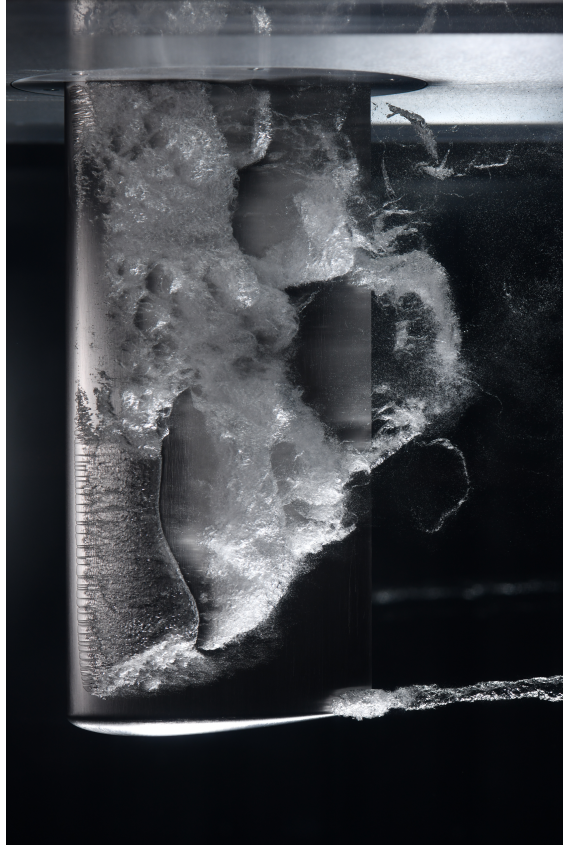


Figure 1.1: Cloud cavitation about a NACA 0015 hydrofoil (chord length 120 mm) at a cavitation number σ of 1, Reynolds number Re of 8×10^5 , and incidence α of 13° . The flow direction is from left to right and the hydrofoil is vertically mounted on the ceiling of the test section. The cavitation topology is highly three-dimensional. The cavity sheet is condensed at the hydrofoil's root, probably due to a preceding condensation shockwave, whereas the cavity sheet still exists at the tip. A supplementary movie 1 is available.

the operation in the ship's wakes rather than in 'open water' (Knapp et al., 1970). Thus, a thorough understanding of the cavitation dynamics with varying incidence of lifting bodies is essential, as it directly affects both the efficiency and erosion risk of these crucial systems. The predominant form of cavitation occurring about pump impellers or ship propellers is *cloud cavitation*, which is the focus of this study.

One could think that the goal is to completely avoid cavitation; however, this is unrealistic in practice due to prohibitive costs and operational constraints (Franc & Michel, 2005, p. 6). Consequently, a limited level of cavitation, depending on the application, is acceptable, provided it occurs under controlled conditions (Franc & Michel, 2005, p. 6) – hence the need for a rigorous physical understanding.

Cloud cavitation represents one of the most technically relevant forms of cavitation

(Brennen, 2013, p. 196) characterised by its chaotic, three-dimensional, and intermittent nature, involving small-scale and large-scale hydrodynamic instabilities, turbulence, and shockwave formation, as shown in the high-resolved still photograph acquired in this study, figure 1.1. This still photograph illustrates several hallmarks of cloud cavitation. A corresponding supplementary movie 1 is available in the TUdataalib repository (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025d), together with all other movies referenced in this study. At the root, the cavity is condensed, probably due to a preceding condensation shockwave, while at the tip a growing cavity sheet is formed, exhibiting the three-dimensional (3D) shedding behaviour of cloud cavitation. Small-scale hydrodynamic instabilities, particularly at the cavity leading edge, manifest as spanwise separated cells, where the nuclei are ‘produced in a self-sustaining manner’ (Russell et al., 2026), which are trapped in the separated boundary layer (Ram et al., 2020). Nucleation may also arise from surface crevices (Groß & Pelz, 2017). Further downstream, the wake is populated by numerous large-scale clouds, interspersed with small-scale structures in a chaotic manner. In addition to cloud cavitation, tip-vortex cavitation also arises, figure 1.1. Together, these characteristics underscore the complexity of cloud cavitation and the difficulty of isolating and capturing its dominant dynamics.

Cloud cavitation is described as the periodic shedding of large-scale vortex cavities (Kubota et al., 1989) that fulfil the Helmholtz’s theorems (Helmholtz, 1858; Buttenbender, 2012) and can be divided into three phases: (i) cavity growth due to nucleation at the leading edge; (ii) cloud shedding due to the re-entrant flow or condensation shockwave; (iii) advection due to the bulk flow and collapse.

Two mechanisms for large-scale cloud cavitation are well established and widely accepted: (i) re-entrant flow-driven cloud cavitation, characterised by an upstream-directed flow beneath the cavity sheet, which pinches off the cavity at its leading edge (Callenaere et al., 2001; Pelz et al., 2017); (ii) condensation shockwave due to a decrease in speed of sound at low cavitation numbers (Ganesh, 2015; Ganesh et al., 2016). A third mechanism, termed *sheet cavitation* – namely, the Kelvin-Helmholtz instability (K-H instability) within the interfacial shear layer between the bulk flow and the cavity sheet – acts as an alternative mechanism for cavity breakdown into small-scale clouds (Avellan et al., 1988; Brandner et al., 2010).

Since its introduction and early popularisation by Knapp (1955) 70 years ago, the re-entrant flow mechanism has attracted sustained research attention (e.g. Furness & Hutton, 1975; Lush & Skipp, 1986; Le et al., 1993a). The re-entrant flow is a viscous flow film, which develops at the cavity trailing edge, flows upstream beneath the cavity sheet, breaks the cavity surface at the leading edge, resulting in large-scale cloud shedding and downstream advection. Kawanami et al. (1997) provided indirect experimental evidence for the re-entrant flow. They placed a spanwise obstacle to block the upstream propagation of the re-entrant flow to the leading edge of the cavity, thereby suppressing cloud cavitation. Callenaere et al. (2001) conducted an extensive experimental study on the dynamics of the re-entrant flow, identifying that a strong adverse pressure gradient and a sufficiently thick cavity sheet are necessary for the re-entrant flow to develop and lead to large-scale cloud cavitation. Brandner et al. (2010) observed at specific conditions re-entrant flow-driven cloud cavitation about a sphere, where the adverse

pressure gradient is strong. Pelz et al. (2017) proposed – based on an experimental-theoretical analysis – an analytical criterion expressed as a ‘kinematic condition’: When the re-entrant flow has sufficient momentum to propagate to the cavity leading edge, periodic cloud cavitation occurs; otherwise, sheet cavitation occurs.

For decades, the re-entrant flow was regarded as the sole fundamental mechanism of periodic cloud cavitation; condensation shockwaves were not considered, despite early observations by Jakobsen (1964). Reisman et al. (1998) observed shockwaves propagating through the gas/water mixture during cloud cavitation and identified them as a primary source of noise and erosion. However, they did not treat condensation shockwaves as an alternative mechanism to re-entrant flow; instead, shockwaves were regarded as a distinct phenomenon accompanying cloud cavitation.

It is a known fact that the speed of sound in a gas/water mixture drops sharply and can be of the same order as the free-stream velocity (Crespo, 1969; Brennen, 2013). In cloud cavitation, this occurs when the cavitation number falls below a critical threshold, making the flow susceptible to condensation shockwaves (Ganesh et al., 2016). Ganesh et al. (2016) provided the first direct evidence that condensation shockwaves are an independent shedding mechanism, distinct from re-entrant flow. Over the years, this distinction was not made, and periodic cloud cavitation was related to the re-entrant flow – due both to the two mechanisms having characteristic velocities of the same order of magnitude (Zhang et al., 2022; Bhatt et al., 2023; Hatzissawidis, Kuhr, & Pelz, 2025) and to the difficulty of discriminating them using high-speed photography alone. Among the first to distinguish re-entrant flow-driven cloud cavitation from shockwave-driven cloud cavitation were Arndt et al. (2000), Kjeldsen et al. (2000), and Leroux et al. (2005). They associated shockwave-driven cloud cavitation with a low shedding frequency that is approximately independent of the cavitation number, whereas re-entrant flow-driven cloud cavitation exhibits a higher shedding frequency that decreases as the cavitation number is reduced.

The transition from re-entrant flow to shockwave-driven cloud cavitation remains not fully understood and is an active topic of research. Recent experiments on a NACA 0015 hydrofoil by Bhatt et al. (2023) indicate a probabilistic transition, with condensation shockwaves becoming more dominant as the cavitation number is reduced. Hatzissawidis, Kuhr, and Pelz (2025) identified the trailing edge of the hydrofoil as a shockwave trigger: When the cavity sheet length equals the chord length, a shockwave is initiated. The classical view – where a collapsing cloud generates the shockwave – is supported by Zhang et al. (2022) and the numerical study by Budich et al. (2018); however, they also reported condensation shockwaves through the cavity sheet without preceding cloud collapse.

Despite the complexity of the transition process, much of the literature analyses cloud cavitation in nominally unimodal, two-dimensional (2D) case to separate the mechanisms and simplify interpretation. In practice, however, cloud cavitation frequently exhibits 3D behaviour and multimodality – even over nominally 2D hydrofoils – so that multiple modes may arise simultaneously or intermittently (Kawanami et al., 1998; Prothin et al., 2016; Wu et al., 2019; Venning et al., 2022; Hatzissawidis, Sieber, Oberleithner, & Pelz, 2025). These modes interact and influence one another (Venning et al., 2022), or complex transient behaviour between modes has also been reported (Barwey et al., 2020). Due to

advances in computational resources and high-speed photography, coherent structures in cloud cavitation – previously obscured in direct observation – can now be extracted using modal decomposition techniques, e.g., spectral proper orthogonal decomposition (SPOD) by Towne et al. (2018), which is applied in this study; see also Prothin et al. (2016), Barwey et al. (2020), Smith et al. (2020a), Smith et al. (2020b), Venning et al. (2022), and Hatzissawidis, Sieber, Oberleithner, and Pelz (2025).

The aforementioned phenomena – 3D behaviour, multimodality, and transition mechanism – remain comparatively less explored; where they are considered, studies predominantly vary the cavitation number while keeping the incidence fixed. The study of cavitation dynamics, motivated by marine applications, dates back to the 1950s and 1960s (Kermeen, 1956; Parkin, 1956; Meijer, 1959; Kermeen, 1961; Wade & Acosta, 1966). Franc and Michel (1985, 1988) conducted an extensive study on boundary layer development and leading edge cavity separation about steady and oscillating hydrofoils. They systematically varied incidence and cavitation number, but did not focus on the global cavitation dynamics; moreover, the now-standard distinction between re-entrant flow- and condensation shockwave-driven shedding had not yet been established.

At the heart of this study is a clear gap: we lack systematic data on how incidence affects cloud cavitation dynamics. In particular, the dependence of characteristic frequencies or Strouhal numbers on incidence has not been comprehensively mapped. Flat plate scaling $\sigma/2\alpha$ (Brennen, 2013, p. 230) is often used to account for the change in pressure distribution with incidence and to collapse experimental data. However, its validity for hydrofoils other than a flat plate remains uncertain, especially when the cavitation number and the incidence are varied over a wider range. Incidence also controls the adverse pressure gradient; at high incidence, the adverse pressure gradient can become strong and is known to strongly influence re-entrant flow shedding (Callenaere et al., 2001; Pelz et al., 2017). Under strong adverse pressure gradients on spheres, de Graaf et al. (2017) reported a coupled mechanism: a re-entrant flow impinges on the cavity sheet before reaching the leading edge, followed by a condensation shockwave that condenses the remaining sheet. In addition, the trailing edge trigger (Hatzissawidis, Kuhr, & Pelz, 2025) is not investigated for an incidence sweep. Finally, the complex, chaotic 3D dynamics of cloud cavitation remain under-analysed with modern modal decomposition techniques.

1.2 Aims and research questions

The overarching aim of this thesis is to investigate and understand cloud cavitation dynamics with varying incidence. The spectral content with the associated modes is characterised as a function of the incidence and the cavitation number. Further, the parameter $\sigma/2\alpha$ from the linear flat plate theory is evaluated for its efficacy in collapsing and generalising cavitation behaviour. Particular emphasis is placed on the fundamental shedding mechanisms – re-entrant flow and condensation shockwaves – depending on the incidence and their governing physics, which are examined in greater detail than in previous studies. The spatiotemporal behaviour of cloud cavitation is likewise analysed.

Five research questions are formulated as follows:

- RQ1. Does the hydrofoil's trailing edge act as a trigger for condensation shockwaves when the maximum cavity sheet length impinges on it, and how does its influence vary with incidence α ?*
- RQ2. How do the characteristic Strouhal numbers of re-entrant flow-driven and shockwave-driven cloud cavitation vary with incidence α ?*
- RQ3. Does the dimensionless ratio $\sigma/2\alpha$ from linear flat plate theory uniquely characterise the cavitation behaviour about a NACA 0015 hydrofoil?*
- RQ4. How does the shedding mechanism associated with the re-entrant flow evolve with varying incidence α , particularly at high α where the adverse pressure gradient is strong?*
- RQ5. How do 3D topology, multimodality, and transient behaviour (simultaneously or exclusively occurrence of modes) evolve with varying α , and can modal decomposition techniques reliably identify the coherent structures under these conditions?*

1.3 Methodology and thesis outline

This thesis builds on the studies by Venning et al. (2022) and Hatzissawidis, Kuhr, and Pelz (2025). In these works, the cavitation number was varied and the resulting dynamics analysed; here, the emphasis is placed on the incidence.

To the best of the author's knowledge, this is the first extensive, systematic investigation of spectral content and underlying mechanisms under a carefully controlled, fine-grained variation of the incidence. To address the aims and research questions, a dense incidence sweep is performed on the benchmark NACA 0015 hydrofoil, developed by the National Advisory Committee for Aeronautics (NACA), at four cavitation numbers. This isolates the influence of incidence while accounting for the effect of the cavitation number.

An extensive preliminary study using high-resolution still photography provides an initial picture of the cavitation topology and dynamics. High-speed photography is then acquired in complementary settings – (i) high temporal resolution with short duration to resolve physics, and (ii) lower temporal resolution with long duration to enable robust averaging and modal decomposition to identify the coherent structures hidden with direct observation. Simultaneous force measurements supply spectra that are cross-references with the high-speed photographs; the force balance further enables the fine incidence sweep to resolve the dynamics and reveal mode transitions. Further, a time-frequency analysis of the force signal identifies the instantaneous spectral content in time and allows a direct link to the high-speed photographs.

This thesis is organised into six chapters; Chapter 2 – chapter 6 constitute the main body:

Chapter 2 provides a structured survey of prior work relevant to this study, organised into four major sections. Section 2.1 summarises the mechanisms of cloud cavitation

and their historical development: first, the two fundamental shedding mechanisms – re-entrant flow (section 2.1.1) and condensation shockwaves (section 2.1.2); then, studies on the transition between these mechanisms and competing explanations for the origin of shockwaves (section 2.1.3). Section 2.2 examines the characteristic frequencies of both mechanisms; the associated Strouhal numbers are reviewed, and a dimensional analysis is provided for the chord-based and maximum cavity length-based Strouhal number (section 2.2.1). An extensive inter-study comparison for the NACA 0015 hydrofoil across numerous set-ups in the literature is presented, exhibiting strong data scatter (section 2.2.2). While unimodal and nominally 2D cavitation behaviour is preferred in many studies, as it simplifies the analysis and helps isolate the mechanisms, many cavitating flows instead display 3D topology, multimodality, and transient behaviour. These aspects are reviewed in section 2.3 (section 2.3.1 and section 2.3.2). All of these phenomena emerge and vanish with varying incidence, and the lack of data on cavitation dynamics with varying incidence is summarised in section 2.3.3. The analysis of such complex structures relies on modal decomposition techniques, reviewed in section 2.4. This section outlines their historical development and cavitation-specific applications and assesses their suitability for identifying coherent structures that are hidden by direct observation. Finally, section 2.5 summarises and synthesises the findings across sections (section 2.5.1) and highlights the research gaps, leading to the research questions addressed in this thesis (section 2.5.2).

Chapter 3 provides a detailed description of the experiments and the data analysis techniques used in this study. Section 3.1 introduces the experimental set-up, including the measurement system, the description of the main components of the Cavitation Research Laboratory (CRL) water tunnel (section 3.1.1), the test model and force balance (section 3.1.2), and the experimental design (section 3.1.3). The spectral analysis of time-resolved data is performed using Welch’s method, and the time-frequency analysis using continuous wavelet transform (CWT) (section 3.2). Section 3.3 presents the set-up and techniques for analysing cavitation topology. The topology is determined from high-speed photography and high-resolved still photography introduced in section 3.3.1. Finally, the modal decomposition technique SPOD by Towne et al. (2018) used to identify the coherent structures in cloud cavitation is described in detail in section 3.3.2.

Chapter 4 presents the first part of the results. The cavitation topology, including still photographs taken under various operation conditions and the characteristic lengths of the cavity, is analysed and compared to the linear theory for a flat plate using the parameter $\sigma/2\alpha$ in section 4.1. Force measurements are examined in section 4.2: the steady and unsteady components of the lift and drag coefficients exhibit peaks in the unsteady component, where the modes have the energy maximum (section 4.2.1). The force spectra reveal the modes as function of incidence across the four cavitation numbers (section 4.2.2). An extensive comparison is carried out to contextualise the results of this study with respect to data reported in earlier studies (section 4.2.3). The transient behaviour of the modes – exclusive versus concurrent occurrence – is addressed in section 4.3. The time-frequency analysis using CWT is conducted in section 4.3.1. Frequency ratios are examined to identify harmonic artefacts (section 4.3.2). The relation between the modes can be expressed using the correlation coefficients, which are determined and discussed

in section 4.3.3. The chapter concludes with a summary of the results and key findings (section 4.4).

Chapter 5 presents the second part of the results. First, the spatial modes are identified applying SPOD, which exhibit similar topology across the four cavitation numbers (chapter 5). Next, the shedding physics are investigated. Section 5.1 describes re-entrant flow-driven cloud cavitation coupled with a leading-edge extinction due to a condensation shockwave. A phenomenological analysis (section 5.1.1) is conducted, and notes the unexpected invariance of its frequency at varying $\sigma/2\alpha$ (section 5.1.2). Section 5.2 analyses shockwave-driven cloud cavitation and the behaviour of the corresponding low-frequency tip mode. Trailing edge shock initiation, and its associated plateau in frequency and cavity sheet length is addressed in section 5.3. The transition from re-entrant-flow-driven to shockwave-driven cloud cavitation as $\sigma/2\alpha$ is reduced is treated in section 5.4. Finally, section 5.5 identifies and discusses the top-bottom shedding that emerges at high incidence and cavitation number. The chapter concludes with a summary of the results and key findings, and synthesises the outcomes of this chapter with those of chapter 4 (section 5.6).

Chapter 6 restates the aims of the study (section 6.1), provides its main results, addresses the research questions, and highlights the thesis's contributions to the analysis and understanding of cloud cavitation (section 6.2). Further, the practical implications of the results are explored, highlighting how they can be applied in real-world application (section 6.3). Additionally, limitations are discussed and directions for future work are outlined (section 6.4). To conclude the thesis, some final thoughts are offered (section 6.5).

Among the supplementary information provided in the appendix, a detailed uncertainty analysis of the data is provided in appendix A. The scientific method applied in this study alongside with the research data management (RDM) is outlined in appendix B. It also includes information about the parts of the data and the corresponding metadata which have been published in the TUdatalib repository.

Chapter 2

A review of the literature

The literature review surveys the current state of knowledge on the driving shedding mechanisms, i.e., K-H instability, re-entrant flow and condensation shockwave, of cloud cavitation, section 2.1. Next, studies on the transition from re-entrant flow-driven cloud cavitation to shockwave-driven cloud cavitation are listed and critically discussed, section 2.1.3. Competing theories for the origin of the condensation shockwaves which are linked to the transition process are summarised and discussed in the same section. After introducing the fundamental mechanisms, an extensive comparison between previous publications of the characteristic frequencies of re-entrant flow-driven and shockwave-driven cloud cavitation is conducted for a NACA 0015 hydrofoil, showing pronounced scatter among published studies with the data failing to collapse onto a single curve, section 2.2. The global shedding behaviour – 2D/3D topology and temporal behaviour – is reviewed, with emphasis on multimodality, whereby distinct modes can occur simultaneously or exclusively, section 2.3. Given the central role of incidence in cloud cavitation and in the occurrence of the aforementioned effects, section 2.3.3 reviews previous studies on incidence variation effects on cloud cavitation dynamics and notes that the influence of the incidence is comparatively underexplored, often overshadowed by the prevailing focus on the cavitation number. Finally, modal decomposition techniques as applied to cloud cavitation are reviewed; enabled by increased computational resources in recent decades, these methods reveal structures not identifiable by direct observation, section 2.4. Section 2.5 concludes by synthesising the findings of the literature review, identifying the research gaps, and situating the present study accordingly. Finally, the aims and the scope of the thesis are defined.

The content of this chapter is adapted and extended from the following manuscripts, which have been submitted to the *Journal of Fluid Mechanics*: Hatzissawidis, Russell, Venning, Pelz, and Brandner (2025a, 2025b).

2.1 Cloud cavitation shedding mechanisms

Marine propulsors, water turbines or pump impellers, operating under off-design conditions and experiencing local pressure drops below Blake’s critical threshold (Blake, 1949), are more prone to developing into periodic cloud cavitation – one of the most severe cavitation forms (Brennen, 2013, pp. 196–197). It is accompanied by severe efficiency losses, vibrations, and a substantial risk of erosion – a problem that has preoccupied

engineers since the end of the 19th century (Thornycroft & Barnaby, 1895; Parsons, 1911).

Cloud cavitation is defined as the periodic shedding of vortex cavities that fulfil the Helmholtz’s theorems (Helmholtz, 1858; Buttenbender, 2012) and can be divided into three phases: (i) cavity formation and growth at the cavity leading edge; (ii) cloud shedding; (iii) cloud advection and collapse.

There are three fundamental forms of cloud cavitation (figure 2.1), namely: (I) K-H instability-driven cloud cavitation, also referred to as sheet cavitation; (II) re-entrant flow-driven cloud cavitation (see section 2.1.1); (III) shockwave-driven cloud cavitation (see section 2.1.2). Figure 2.1 provides a schematic overview of the three cavitation forms and the transition between them, according to Pelz et al. (2017) and Hatzissawidis, Kuhr, and Pelz (2025). A brief overview is given here; the latter two mechanisms are treated in detail in sections 2.1.1 and 2.1.2.

As the cavitation number σ is reduced under otherwise constant operation conditions, cavitation inception occurs. At some stage, a quasi-steady cavity sheet develops with only small-scale break-up at the trailing edge due to interfacial instabilities, such as K-H instabilities (Brandner et al., 2010; Russell et al., 2016; de Graaf et al., 2017), regime (I), see figure 2.1. This regime is termed (I) sheet cavitation.

A further reduction of σ below a critical value, $\sigma \leq \sigma_{\text{I,II}}$, results in (II) re-entrant flow-driven cloud cavitation. The re-entrant flow is a viscous liquid film that forms at the cavity closure – hereafter called the cavity trailing edge – and travels upstream beneath the cavity sheet (see coordinate of the re-entrant flow front, $\hat{\xi}(t)$, in figure 2.1). When this film has sufficient momentum to reach the cavity leading edge, it breaks through the cavity sheet and triggers the shedding of a large-scale cavitation cloud that is then advected downstream. In this regime, the maximum cavity sheet length is usually less than the chord length of the hydrofoil, $\hat{a} < L$. If the re-entrant flow momentum is insufficient for the re-entrant flow to reach the leading edge, then the cavity may be quasi-steady (Pelz et al., 2017) with only small-scale break-up corresponding to regime (I).

When σ falls below a second critical value, $\sigma \leq \sigma_{\text{II,III}}$, condensation shockwaves become the dominant shedding mechanism (Hatzissawidis, Kuhr, & Pelz, 2025), see figure 2.1. This transition is attributed to a pronounced drop in the speed of sound in the gas/water mixture, making the fluid susceptible to shockwaves (Ganesh et al., 2016). If the hydrofoil trailing edge acts as a trigger, the condition $\hat{a} \geq L$ holds for this regime; however, as will be shown below, shockwaves may also occur for $\hat{a} < L$.

The shedding frequency associated with re-entrant flow-driven cloud cavitation is a function of σ and the shape of the hydrofoil, the latter including the incidence when a lifting surface is used as the test model. The chord-based Strouhal number, St , decreases as σ is reduced. By contrast, the characteristic frequency of shockwave-driven cloud cavitation exhibits little to no dependence on σ . This offers an initial overview of the shedding frequencies; a detailed comparison and discussion is given in section 2.2.

These two fundamental mechanisms – re-entrant flow and condensation shockwaves – are widely accepted as the primary drivers of large-scale cloud cavitation and constitute the subject of this study. However, the classification in figure 2.1 is only a simplified picture of cloud cavitation. In reality, cloud cavitation is not invariably unimodal

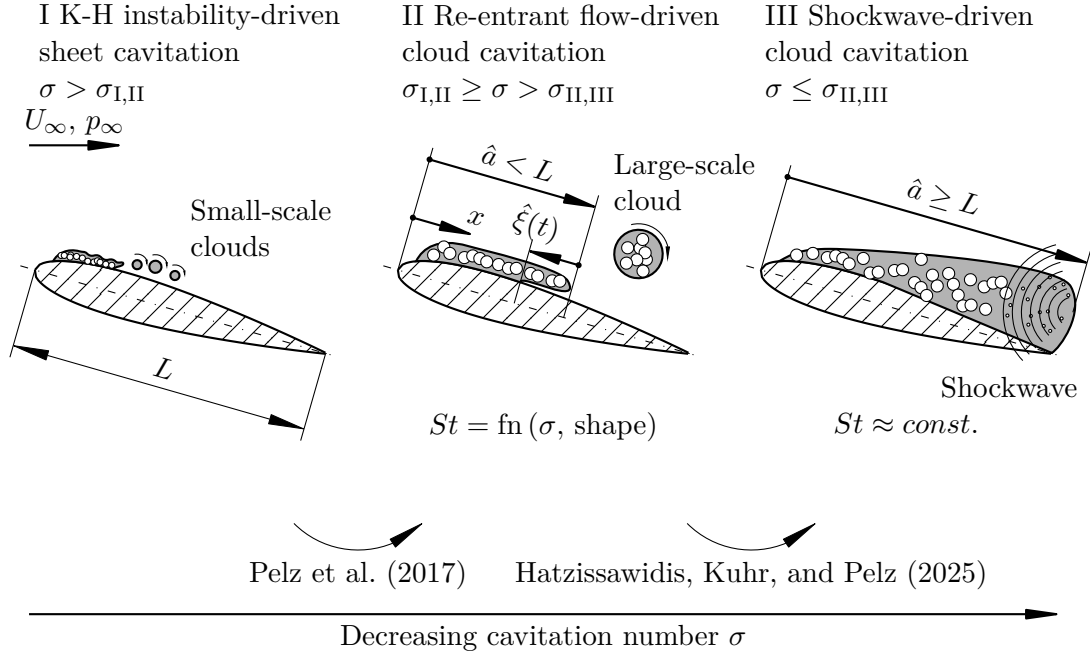


Figure 2.1: Schematic overview of the three fundamental forms of cloud cavitation: (I) K-H instability-driven cloud cavitation, also referred to as sheet cavitation; (II) re-entrant flow-driven cloud cavitation; (III) shockwave-driven cloud cavitation. As the cavitation number σ is reduced, cavitation inception arises and regime (I) is reached, where interfacial instabilities, i.e., K-H instabilities, lead to small-scale cloud shedding. A decrease in σ below a critical value, $\sigma \leq \sigma_{I,II}$, results in (II) re-entrant flow-driven cloud cavitation. In this regime the chord-based Strouhal number St is a function of σ and the shape of the test model. Typically, the cavity sheet length is less than the chord length L of the hydrofoil, $\hat{a} < L$. As far as the re-entrant flow (coordinate $\hat{\xi}(t)$) reaches the leading edge, a cavitation cloud is formed and shed, see Pelz et al. (2017). A further decrease in σ below the second critical value, $\sigma \leq \sigma_{II,III}$, results in the occurrence of shockwaves as the dominant mechanism for cloud shedding referred to as (III) shockwave-driven cloud cavitation. In this regime the cavity sheet length is larger than in regime (II). If the shockwave trigger is the trailing edge of the hydrofoil, it follows $\hat{a} \geq L$ (Hatzissawidis, Kuhr, & Pelz, 2025). The schematic is adapted from Hatzissawidis, Kuhr, and Pelz (2025).

with a well-defined periodicity; It can be multimodal with interacting shedding modes, intermittent and chaotic, and – in transitional regimes – modes may be mutually exclusive or concurrent, see section 2.3. Because this study investigates cloud cavitation dynamics across variations in incidence and cavitation number, a detailed review of key studies is provided, outlining the historical development and the mechanisms underlying re-entrant

flow-driven and shockwave-driven cloud cavitation.

2.1.1 Re-entrant flow-driven cloud cavitation

In the classical picture of periodic cloud cavitation, re-entrant flow has traditionally been regarded as the sole driver of cloud shedding. This thin, viscous film forms at the cavity trailing edge and propagates upstream beneath the cavity sheet. Upon reaching the leading edge it penetrates the sheet, detaching a vapour cloud that is advected downstream by the bulk flow. Penetration does not necessarily occur at the leading edge. The re-entrant flow can break through earlier, producing shedding, as reported by Knapp (1955) and many other researchers.

Knapp (1955) was the first to describe the periodic mechanism of the re-entrant flow in his pioneering study, using high-speed photography within the framework of pitting tests designed to quantify the intensity of cavitation erosion. Notably, the periodic nature of hydrodynamic cavitation had already been reported years earlier for a cavitating Venturi nozzle by Nowotny (1942). This initiated a sustained body of research on the dynamics of cloud cavitation about lifting bodies, converging-diverging geometries, and axisymmetric bodies or spheres, with ongoing investigations into the underlying shedding mechanisms.

For specific conditions Wade and Acosta (1966) observed periodic cloud cavitation about a lifting body, although the phenomenon was not described using the modern terminology. Furness and Hutton (1975) predicted the kinematics of the re-entrant flow from their experimental data using irrotational flow theory. Lush and Skipp (1986) confirmed the observations of Knapp (1955) for both a convergent-divergent geometry and a wedge, proposing the re-entrant flow as the driving mechanisms behind the shedding. Le et al. (1993a) and de Lange et al. (1994) observed both re-entrant flow shedding and irregular shedding, the latter occurring when the re-entrant flow has insufficient momentum to reach the cavity leading edge – typically in thin cavities (Le et al., 1993a) or at low incidence or low Reynolds numbers (de Lange et al., 1994).

Kawanami et al. (1997) provided experimental evidence for the presence of the re-entrant flow by introducing a spanwise bar that hindered its upstream motion, thereby suppressing cloud cavitation. This was confirmed by Pham et al. (1999), who measured the thickness of the re-entrant flow and observed a reduction in the spectral peak associated with the dominant cloud shedding when a spanwise bar was introduced. They attributed the frequency decrease to a loss of re-entrant flow momentum. Gopalan and Katz (2000) used particle image velocimetry (PIV) to resolve the velocity field around the cavity trailing edge, providing clear evidence of the re-entrant flow.

The influential study of Callenaere et al. (2001) linked the occurrence of the re-entrant flow to the ratio between the cavity thickness and the re-entrant flow thickness, as well as the adverse pressure gradient, which must be sufficiently large. For the former, if the thickness of the re-entrant flow and the cavity are similar, they interact, and the cavity breaks up into small-scale structures as the re-entrant flow passes beneath it. Although the overall cavitation behaviour is not periodic, the re-entrant flow itself is periodic (Callenaere et al., 2001). For the latter, if the adverse pressure gradient is too low, no re-entrant flow can form, and cloud cavitation is suppressed, referred to as an

‘open’ cavity, where probably K-H instability lead to cavity break up. More recently Gawandalkar and Poelma (2022) confirmed the results regarding the re-entrant flow dynamics of Callenaere et al. (2001) using tomographic imaging, determining re-entrant flow thickness and velocity.

Pelz et al. (2017) developed an analytical model to describe the dynamics of the re-entrant flow. According to their findings, cloud cavitation occurs when the momentum of the re-entrant flow is sufficient to reach the cavity leading edge; otherwise, shedding is suppressed. This condition leads to a critical Reynolds number, above which cloud cavitation occurs. The same analytical model to identify the characteristic time of the re-entrant flow was recently applied by Hatzissawidis, Kuhr, and Pelz (2025) to predict the shedding frequency, showing good agreement.

In summary, the onset of the re-entrant flow shedding is governed by a kinematic condition: A re-entrant flow that develops from the stagnation point flow at the cavity trailing edge must carry sufficient momentum to reach the leading edge and to penetrate the cavity sheet, thereby detaching a cloud.

2.1.2 Shockwave-driven cloud cavitation

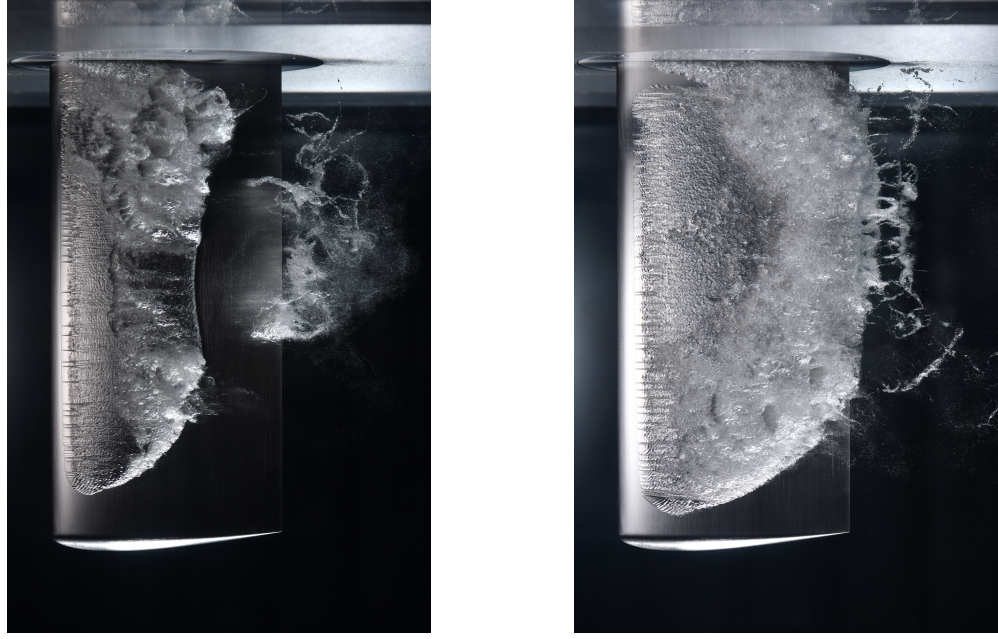
Over the years following the work of Knapp (1955), the re-entrant flow was widely regarded as the sole driving mechanism for cloud cavitation. Condensation shockwaves were not considered to cause periodic cloud cavitation, even though the presence of shockwaves in cavitating flows had already been postulated by Jakobsen (1964). This is not surprising, since direct observation with high-speed photography alone makes it difficult to distinguish the re-entrant flow from a condensation shockwave. Another point, that makes the distinction difficult is that the characteristic velocities of both mechanisms are of the same order of magnitude and comparable to the bulk flow velocity (Pham et al., 1999; Bhatt et al., 2023; Hatzissawidis, Kuhr, & Pelz, 2025).

Two high-resolved still photographs from the present study illustrate the difference in the occurrence of re-entrant flow and shockwave-driven cloud cavitation, figure 2.2 (a) and (b), respectively. The cavity sheet above the upstream moving re-entrant flow is translucent at midspan, and the re-entrant flow front is clearly visible beneath the cavity sheet, figure 2.2 (a); at the hydrofoil root, the re-entrant flow interacts with the cavity sheet, which is broken upstream of the re-entrant flow front. By contrast, in figure 2.2 (b), the cavity sheet upstream of the shockwave front appears frothy.

The question arises as to why shockwaves occur in cavitating flows with velocities being of the same order of magnitude as the bulk flow. The presence of bubbles in a flow markedly lowers the speed of sound relative to a single-phase flow, reaching values of the order of the free-stream velocity $\mathcal{O}(10 \text{ m s}^{-1})$ (Crespo, 1969; Brennen, 2013; Prosperetti, 2015). Brennen (2013, p. 148) derived an expression to calculate the speed of sound, c , of a homogeneous ‘two-component gas/liquid mixture’:

$$\frac{1}{c^2} = [\varrho_L (1 - \phi_G) + \varrho_G \phi_G] \left[\frac{\phi_G}{np} + \frac{(1 - \phi_G)}{\varrho_L c_L^2} \right], \quad (2.1)$$

where the density of the liquid and the gas are ϱ_L and ϱ_G , respectively, the gas volume



(a) Re-entrant flow-driven cloud cavitation

(b) Condensation shockwave-driven cloud cavitation

Figure 2.2: Cloud cavitation about a NACA 0015 hydrofoil (chord length 120 mm) driven by (a) re-entrant flow at a cavitation number σ of 1 and an incidence α of 10° and (b) condensation shockwave at $\sigma = 0.5$ and $\alpha = 8^\circ$. Two photographs were chosen where the re-entrant flow (a) and the condensation shockwave (b) are moving upstream, respectively. The Reynolds number Re is 8×10^5 .

fraction is ϕ_G , the polytropic index is n , the speed of sound of the liquid is c_L and the pressure is p . Figure 2.3 demonstrates the steep decrease in the effective speed of sound in a mixture. For example, the speed of sound drops to $c \approx 20 \text{ m s}^{-1}$ for a typical gas volume fraction of $\phi_G = 50\%$ (Ganesh et al., 2016). This is one to two orders of magnitude lower than the speed of sound in the single-phase of vapour and water at room temperature, with $c_G \approx 380 \text{ m s}^{-1}$, $c_L \approx 1500 \text{ m s}^{-1}$, respectively (Franc & Michel, 2005, p. 167). Equation (2.1) provides a rough estimate of the speed of sound. Bhatt et al. (2021) employed the ‘homogeneous frozen model’ from Brennen (2013, pp. 149–152) to estimate the speed of sound while accounting for phase change without heat transfer between the phases. In contrast, the ‘homogeneous equilibrium model’ (Brennen, 2013, pp. 149–152) assumes the heat transfer between the phases to be instantaneously. The former yielded better Mach number predictions for cloud cavitation in a backward facing step, whereas the latter overestimated them (Bhatt et al., 2023).

The dramatic drop in the speed of sound in a bubbly mixture implies that cavitating flows become susceptible to shockwave phenomena. Despite decades of earlier research on shockwaves in bubbly flows (Campbell & Pitcher, 1958; Crespo, 1969; Noordzij & Van Wijngaarden, 1974; van Wijngaarden, 1980), their role as a driving mechanism for cloud

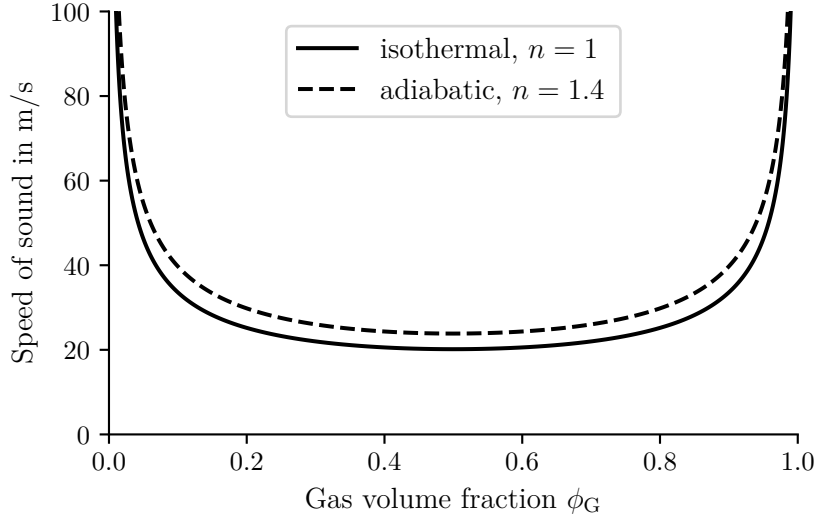


Figure 2.3: The speed of sound in a gas/water mixture as a function of the gas volume fraction according to equation (2.1) for the isothermal case ($n = 1$) and the adiabatic case ($n = 1.4$). The gas is vapour with data taken from Franc and Michel (2005, pp. 88, 167). The speed of sound in the gas/water mixture drops one to two orders of magnitude relative to the single-phase. The figure is adapted from Brennen (2013, pp. 148–149), with permission from Cambridge University Press. © 2014 Christopher Earls Brennen.

shedding was only recognised much later, around the 2000s. Le et al. (1993b) measured the pressure pulses from shockwaves occurring in cavitation about a hydrofoil. Reisman et al. (1998) paved the way for the recognition of shockwaves in cloud cavitation and their role in governing cavitation dynamics. They associated the formation of shockwaves with cloud collapse and observed their propagation through the bubbly mixture. However, at this stage shockwaves were not considered as an alternative mechanism to re-entrant flow, but rather a distinct phenomenon.

The distinction between shockwave-driven and re-entrant flow-driven cloud cavitation was made by Arndt et al. (2000) and Kjeldsen et al. (2000), who classified them as ‘type 1’ and ‘type 2’ oscillations, respectively. The former is characterised by a low chord-based Strouhal number being independent of the cavitation number, whereas the latter exhibits a constant cavity length-based Strouhal number, see section 2.2. Leroux et al. (2004, 2005) also observed two distinct ‘dynamics’ and linked the low-frequency shedding (type 1) to the re-entrant flow and the subsequent shockwave emitted during cloud collapse, condensing the remaining cavity sheet.

Brandner et al. (2010) observed that, at low cavitation numbers, the cavity sheet about a sphere subjected to a strong adverse gradient collapses due to a shockwave. They showed that a re-entrant flow impinges upon the cavity sheet, initiating the condensation of the remaining cavity sheet.

A decade ago, the seminal studies by Ganesh (2015) and Ganesh et al. (2016) provided

the first direct evidence that condensation shockwaves can induce cloud shedding, using X-ray densitometry to track their propagation within the cavity. They reported a strong dependence on the local Mach number, with shockwave phenomena being most pronounced when it exceeds unity. Additional indirect evidence of shockwaves was provided by Ganesh et al. (2017), who placed an obstacle intended to block re-entrant flow while allowing shockwaves to pass; the continued observation of cloud shedding under these conditions – contrary to earlier findings, cf. Kawanami et al. (1997) – supports the presence of shockwaves as the driving mechanism. Budich et al. (2018) corroborated the experiments with a detailed numerical study of the same convergent-divergent geometry.

These two main mechanisms, i.e., re-entrant flow and condensation shockwaves, can also occur together (Smith et al., 2020a). The authors reported that the re-entrant flow is involved in the primary shedding process of shockwave-driven cloud cavitation about a NACA 0009 hydrofoil. During the growth phase of the cavity, a re-entrant flow develops; although it does not break through the sheet, it preconditions the flow by destabilising the cavity’s upper surface, promoting a more dispersed cavity sheet and thereby increasing susceptibility to shockwave formation.

Overall, since the work of Ganesh et al. (2016), a plethora of experimental studies regarding shockwave-driven cloud cavitation followed, confirming the occurrence of shockwaves as the fundamental shedding mechanism in various geometries (Jahangir et al., 2018; Wu et al., 2019; Smith et al., 2020a; Smith et al., 2020b; Bhatt et al., 2021; Gawandalkar & Poelma, 2024; Hatzissawidis, Kuhr, & Pelz, 2025).

2.1.3 Transition and origin of shockwaves

Thus far, the two dominant mechanisms for large-scale cloud shedding – re-entrant flow (section 2.1.1) and the condensation shockwaves (section 2.1.2) – were discussed separately; this section relates them, focusing on the regime transition from re-entrant flow-driven to shockwave-driven cloud cavitation, and the trigger of the shockwaves. Shock initiation is tightly coupled to the transition: once shockwaves are triggered, re-entrant-flow shedding weakens and may be suppressed.

As mentioned above, the re-entrant flow-driven shedding exhibits a higher frequency that depends on the cavitation number, whereas the shockwave-driven cloud shedding occurs at a lower that is independent of the cavitation number as already observed by Arndt et al. (2000); see section 2.2 for a detailed discussion of the characteristic frequencies. This is important to distinguish these two mechanisms from a spectrogram.

One of the first explanations of the transition between these two regimes was given by Arndt et al. (2000) and Kjeldsen et al. (2000). A transition was reported at $\sigma/2\alpha = 4$ corresponding to a non-dimensionalised maximum cavity length by the chord length, $\hat{a}_+ := \hat{a}/L$, of 0.75. The latter is theoretically predicted by Watanabe et al. (1998) and Watanabe et al. (2001), who attributed it to the negative cavitation compliance, i.e., the volume of the cavity sheet decreases as the cavitation number is reduced. The experiments by Fujii et al. (2007) for different foils confirmed a transition at $\hat{a}_+ = 0.75$. However, other studies – including the present study – have not confirmed any change in dynamics at $\hat{a}_+ = 0.75$ or $\sigma/2\alpha = 4$ (Kawakami, Fuji, et al., 2008; Smith et al., 2020a;

Bhatt et al., 2023; Hatzissawidis, Kuhr, & Pelz, 2025). Callenaere et al. (2001) suggested that the negative cavitation compliance may be a ‘mathematical artefact’. Although Arndt et al. (2000) and Arndt (2012) mentioned shockwaves to be the driver of periodic cloud cavitation, they also referred to the negative cavitation compliance. However, how these two different mechanisms, i.e., shockwaves and negative cavitation compliance, can be related has not been discussed.

Today, it is widely accepted – supported by experimental evidence and simulations – that the transition is initiated by the onset of condensation shockwaves. Recently, Bhatt et al. (2023) have shown that as the cavitation number is reduced and the cavity Mach number exceed unity, shockwaves dominate while re-entrant flow-driven cycles become increasingly unlikely. They quantified the likelihood of each shedding mechanism by assigning occurrence probabilities. This can be interpreted as a ‘transitional regime’, in which either mechanism occurs with a certain probability – consistent with previous reports (Jahangir et al., 2018; Wu et al., 2019; Smith et al., 2020a; Smith et al., 2020b; Hatzissawidis, Kuhr, & Pelz, 2025; Hatzissawidis, Sieber, Oberleithner, & Pelz, 2025).

This raises the question of the origin of the shockwaves and the mechanisms that trigger them. As already shown by Ganesh et al. (2016) and Bhatt et al. (2023), a necessary condition is that the local Mach number exceeds unity.

The literature presents a broad spectrum of explanations for the origin of shockwaves, reflecting the diversity of geometries and operation conditions examined across different studies. The classic view holds that a cloud collapse from the previous cycle triggers the shockwave propagation and shedding, as shown by Leroux et al. (2004) and Jahangir et al. (2018) and recently by Zhang et al. (2022) and Gawandalkar and Poelma (2024). Zhang et al. (2022) observed both cloud collapse-driven shedding and shedding event without a preceding collapse. They further distinguished between shock and pressure waves, concluding that the disturbance emitted by a cloud collapse is a pressure wave rather than a shockwave; this wave impinges on the cavity sheet and triggers shedding. Beyond this, more complex scenarios can lead shock propagation to become a multistep process as reported by Wu et al. (2019) and Barwey et al. (2020). In contrast, de Graaf et al. (2017) reported, for a cavitating sphere, no coupling between the prior cloud collapse and the cavity sheet. In the numerical study by Budich et al. (2018), conducted for the same configuration as Ganesh et al. (2016), it was reported that a cloud collapse may induce the formation of a shockwave; however, shockwaves have also been observed without such a collapse. Zhang et al. (2022) also showed experimentally that a cloud collapse is not necessary for shockwave-driven cloud cavitation.

Ganesh (2015) provides another explanation for shockwave formation, suggesting that the cavity sheet grows asymptotically with decreasing cavitation number, such that the instantaneous growth and then arrest of the cavity trigger a shockwave. Hatzissawidis, Kuhr, and Pelz (2025) demonstrated experimentally and theoretically that a shockwave can be triggered when the maximum cavity length equals the chord length of the hydrofoil. This represents another recently proposed mechanism for shockwave formation. A similar mechanism was observed by Venning et al. (2022).

In summary, a necessary condition for shockwaves to occur is that the local Mach number exceeds unity. Several explanations have been proposed for the transition from

re-entrant flow-driven to shockwave-driven cloud cavitation:

- I *Negative cavitation compliance*, an intrinsic instability that does not invoke condensation shockwaves (Watanabe et al., 1998; Arndt et al., 2000; Kjeldsen et al., 2000);
- II *Cloud collapse as the trigger* of the condensation shockwave (Leroux et al., 2004; Jahangir et al., 2018; Zhang et al., 2022; Gawandalkar & Poelma, 2024);
- III *Adverse pressure gradient* as a trigger of shockwaves (Budich et al., 2018; Zhang et al., 2022);
- IV *Growth dynamics of the cavity sheet*, asymptotic increase of the cavity sheet with decreasing cavitation number and rapid growth-and-arrest behaviour (Ganesh, 2015); and
- V *Hydrofoil trailing edge trigger*, a shockwave is initiated when the maximum sheet length equals the chord length of the hydrofoil (Venning et al., 2022; Hatzissawidis, Kuhr, & Pelz, 2025).

Together, these mechanisms may act in combination, or one may dominate over the others depending on the geometry and experimental arrangement. In the present study, no coupling was observed between the cloud collapse and the cavity sheet; rather, a shockwave is triggered at the trailing edge of the hydrofoil, consistent with Venning et al. (2022) and Hatzissawidis, Kuhr, and Pelz (2025), mechanism V. Shockwaves were also observed for cavity sheet lengths shorter than the chord, $\hat{a}_+ < 1$.

2.2 Characteristic frequencies

Having discussed the two fundamental shedding mechanisms and their transition, this section analyses the characteristic frequencies of each mechanism and compares results from numerous prior studies. To enhance comparability and keep the scope manageable, only studies employing a NACA 0015 hydrofoil are considered.

2.2.1 Strouhal number and dimensional analysis

Arndt et al. (2000) observed two patterns in the frequency spectrum of cloud cavitation about a NACA 0015 hydrofoil. The re-entrant flow-driven cloud cavitation (referred to as ‘type 2’) is associated with a chord-based Strouhal number,

$$St := \frac{fL}{U_\infty}, \quad (2.2)$$

where f is the characteristic shedding frequency that is dependent on the cavitation number, among other parameters (see below). Shockwave-driven cloud cavitation (referred to as ‘type 1’) exhibits a chord-based Strouhal number that is independent of the cavitation number, as observed by numerous researchers (Arndt et al., 2000; Kjeldsen et al., 2000;

Leroux et al., 2005; Kawakami, Fuji, et al., 2008; Smith et al., 2020a; Hatzissawidis, Kuhr, & Pelz, 2025), among others. The former is characterised by a low chord-based Strouhal number of about $0.1 - 0.2$, whereas the latter can vary from about 0.1 up to 1.4 depending on the cavitation number or the cavity length.

A kinematic explanation of the variation of St associated with re-entrant flow-driven cloud cavitation is that, as σ is reduced, and the maximum cavity sheet length grows, the re-entrant flow must travel upstream farther from the trailing edge to the leading edge of the cavity; hence the shedding frequency – and the chord-based Strouhal number – decreases (Franc & Michel, 2005). This, in fact, is only valid if a constant re-entrant flow velocity is assumed.

Non-dimensionalising the shedding frequency with the maximum cavity sheet length $\hat{a}$ yields the maximum cavity length-based Strouhal number,

$$\hat{St} := \frac{f\hat{a}}{U_\infty}, \quad (2.3)$$

which tends to collapse the data to a constant value in the case of re-entrant flow-driven cloud cavitation, see Franc and Michel (2005). This implies $f \propto U_\infty/\hat{a}$. According to Franc and Michel (2005), a typical value is $\hat{St} \approx 0.3$.

Throughout the literature, the values for the cavity length-based Strouhal numbers for re-entrant flow-driven cloud cavitation vary from about 0.25 to 0.4 , see Arndt (2012) and Hatzissawidis, Kuhr, and Pelz (2025). As derived by Hatzissawidis, Kuhr, and Pelz (2025) from a dimensional analysis, the shedding frequency f is a function of the maximum cavity sheet length $\hat{a}$, the characteristic length, which is the chord length L , the free-stream velocity U_∞ , and the shape:

$$f = \text{fn}(\hat{a}, L, U_\infty, \text{shape}). \quad (2.4)$$

The shape includes the contour of the lifting surface such as a hydrofoil model (or the contour of a convergent-divergent nozzle) and the incidence α (in the case of a lifting surface), i.e., $\text{shape} = \{\text{model}, \alpha\}$, fully considered by the pressure distribution along the surface $c_p(x)$. From a dimensional analysis (Spurk, 1992) of equation (2.4), it follows that the chord-based Strouhal number is not solely a function of the non-dimensionalised maximum cavity sheet length, $\hat{a}_+$, non-dimensionalised by the chord length, L , but also of the shape,

$$St = \text{fn}(\hat{a}_+, \text{shape}), \quad (2.5a)$$

or, using the relation $\hat{a}_+ = \text{fn}(\sigma, \text{shape})$, it can be expressed as a function of the cavitation number σ and the shape as

$$St = \text{fn}(\sigma, \text{shape}). \quad (2.5b)$$

It is noteworthy that kinematic quantities are now coupled to dynamic quantities through the cavitation number.

It should be mentioned that the dimensionless nucleation rate is not considered here as a parameter; for a detailed treatment of this, including the calculation of an

analytic relationship between the maximum cavity length and the cavitation number, see Hatzissawidis, Kuhr, and Pelz (2025).

From equation (2.5a) and the well-known relation $St \propto 1/\hat{a}_+$, it follows the relationship between the chord-based and the maximum cavity length-based Strouhal number:

$$St = \frac{1}{\hat{a}_+} \hat{St}(\text{shape}). \quad (2.6)$$

Thus, the cavity length-based Strouhal number would be expected to depend only on shape, which could explain the variation reported in the literature. However, as shown below, even for identical hydrofoils, the data exhibit substantial scatter; hence facility-specific conditions, manufacturing tolerances, and water quality (e.g. dissolved oxygen concentration, nuclei content) may also contribute.

The characteristic chord-based Strouhal number of shockwave-driven cloud cavitation also varies throughout the literature, typically appearing about 0.1 or higher about 0.2 – as observed by Kawakami, Fuji, et al. (2008) in different cavitation tunnels and is attributed to differences in aspect ratios of the hydrofoils investigated.

2.2.2 Inter-study comparison

Data from numerous studies on cloud cavitation about a NACA 0015 hydrofoils are considered to demonstrate their scatter, figure 2.4. The studies, together with important information such as model and test section dimensions, blockage ratio and operation conditions (Re , σ), incidence α , and the content are summarised in table 2.1. A comparison with the results of the present study is conducted later in section 4.2.3.

The chord-based Strouhal numbers as a function of $\sigma/2\alpha$ are plotted in figure 2.4, providing a global picture of the frequencies observed in various experiments. The parameter $\sigma/2\alpha$ can be derived for linear theory for a flat plate (Acosta, 1955) to correct the cavitation number for the incidence. The first notable aspect is the scatter in the data across various experiments, despite using the same hydrofoil. These differences may arise from variations in blockage ratios, water quality, i.e., dissolved and free-stream nuclei, scale effects, and operation conditions.

However, the well-known trend remains observable. The data are arranged into two distinct regions: low-frequency shedding, which exhibits weak or no dependence on $\sigma/2\alpha$ and is associated with condensation shockwaves, and high-frequency shedding, which shows a strong dependence on $\sigma/2\alpha$ and is associated with the re-entrant flow. Also, the transition from one to the other mechanism does not happen at a specific $\sigma/2\alpha$, rather it varies throughout the literature. The experiments conducted by Smith et al. (2020a) reveal a maximum Strouhal number around 0.6, which is lower than the values observed for 2D NACA 0015 hydrofoils by Kawanami et al. (1998), Arndt et al. (2000), Bhatt et al. (2023), and Hatzissawidis, Kuhr, and Pelz (2025). Further, no correlation between the blockage ratio, see table 2.1, and the Strouhal numbers can be discerned. The blockage ratio in the experiments by Bhatt et al. (2023) is similar to the blockage ratio in Hatzissawidis, Kuhr, and Pelz (2025); however, the characteristic frequencies

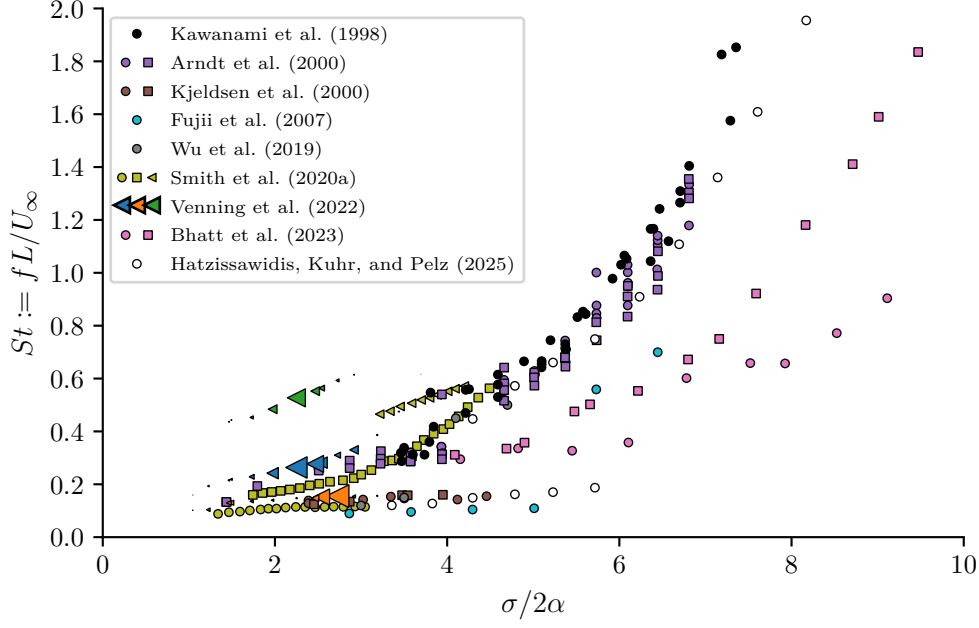


Figure 2.4: Comparison of previous studies of the chord-based Strouhal numbers associated with the dominant shedding in cloud cavitation about a NACA 0015 hydrofoil (except for Smith et al., 2020a, which is a NACA 0009 hydrofoil). Data from Venning et al. (2022) for varying cavitation number and otherwise constant parameters are plotted, where the fundamental shockwave-driven shedding is represented by the blue leftward triangles, a low- and high-frequency mode by the orange and blue leftward triangles, respectively. The size of the dots represents the energy from the peak of the power spectral density (PSD) of the lift coefficient. The other reference data include: Kawanami et al. (1998) for four different free-stream velocities (black circles); Arndt et al. (2000), with free-stream velocities of 8 m s^{-1} and 10 m s^{-1} (purple squares and circles); Kjeldsen et al. (2000), at incidences of 6° and 7° (brown circles and squares); Fujii et al. (2007), at an incidence of 8° (cyan circles); Wu et al. (2019), at an incidence of 10° (grey circles); Smith et al. (2020a), using a 3D trapezoidal NACA 0009 hydrofoil at 6° for shockwave, re-entrant flow with root/tip shedding modes (yellow circles, squares and leftward triangles); Bhatt et al. (2023), at incidences of 7° and 10° (pink circles and squares); and Hatzissawidis, Kuhr, and Pelz (2025), at 12° (white circles).

observed are significantly different. The same is observed between the experiments of Smith et al. (2020a) and Venning et al. (2022).

The Strouhal numbers associated with shockwaves are scattered near two values: at ~ 0.1 (Kjeldsen et al., 2000; Fujii et al., 2007; Wu et al., 2019; Smith et al., 2020a; Hatzissawidis, Kuhr, & Pelz, 2025) and ~ 0.2 (Arndt et al., 2000; Venning et al., 2022; Bhatt et al., 2023). Kawakami, Fuji, et al. (2008) observed a difference in the low-

frequency shedding between low (~ 7 ppm) and high (~ 13 ppm) gas content. This cannot be confirmed by the data in the literature and the findings of Mäkiharju et al. (2017), where the shedding frequency did not show any dependence on the gas content.

The scattering of the data can also be attributed to the varying shedding mechanisms observed in the different experiments, such as the multistep shedding described by Barwey et al. (2020), which has not been observed in other studies, including the present one.

In summary, despite inter-study scatter, a clear trend emerges: (i) a frequency that depends on $\sigma/2\alpha$ associated with the re-entrant flow and (ii) a frequency that does not depend on $\sigma/2\alpha$ associated with condensation shockwaves. This distinction allows for discrimination between the mechanisms based on frequency trends alone. However, this trend was not observed by Ganesh et al. (2016) about a convergent-divergent nozzle and the fundamental frequencies of re-entrant flow-driven and shockwave-driven cloud cavitation can be similar (Bhatt et al., 2023). Thus, optical diagnostics are necessary to distinguish between the two mechanisms. However, in the present study, the two mechanisms exhibit clearly separated frequency ranges, as shown later.

Researcher	Tunnel	Model	Chord $\times$ span $L(\text{mm}) \times b(\text{mm})$	Test section $H(\text{mm}) \times w(\text{mm})$	Blockage ratio in %	$Re (\times 10^6)$	σ	α	Content
Kawanami et al. (1998)	Marine Propeller Cavitation Tunnel, University of Tokyo	2D	80×150	150×600	3	0.35, 0.46, 0.58, 0.69	1.14 – 2.15	8.36°	Re-entrant flow-driven shedding
Arndt et al. (2000)	Obernach	2D	128×300	300×300	8	1.02, 1.28	0.28 – 2.37	8°	Two types: low-frequency ('type 1') and high- frequency ('type 2') shedding see Arndt et al. (2000)
Kjeldsen et al. (2000)	SAFL	2D	81×190	190×190	6 – 8	0.87	0.2 – 1.8	2° to 8°	
Fujii et al. (2007)	Osaka University	2D	70×70	100×70	13	0.35	0.78 – 2.23	8°	Same as Arndt et al. (2000) for various geometries
Wu et al. (2019)	9-in. water tunnel, Michigan	2D	50×76.8	76×76.8	14	0.4	1 – 1.6	10°	Multistep process, with cloud collapse influencing the cavitation dynamics
Smith et al. (2020a)	CRL	3D	90×300	600×600	1	0.8	0.2 – 1.2	6°	Re-entrant flow and shockwaves, and coupled mechanism
Venning et al. (2022)	CRL	3D	150×300	600×600	2	1.4	0.18 – 1	6°	Shockwaves with presence of re-entrant flow, multimodal behaviour
Bhatt et al. (2023)	9-in. water tunnel, Michigan	2D	165.6×209.6	210×210	14, 17	1.3	1 – 3.7	7°, 10°	Probability of either re-entrant flow or shockwave dominance
Hatzissawidis, Kuhr, and Pelz (2025)	TU Darmstadt	2D	46×25	70×25	16	0.8	1 – 5	12°	Transition from re-entrant flow to shockwave
Present study	CRL	3D	120×241	600×600	1 – 3	0.8	0.5, 0.75, 0.875, 1	0° to 16°	Re-entrant flow, shockwaves, coupled, intermittent and exclusive behaviour

Table 2.1: Overview of previous studies on a NACA 0015 (except for Smith et al., 2020a which involved a NACA 0009) compared to the present work. The table summarises the dimensionality of the geometry (2D or 3D), chord and span of the hydrofoil, test section dimensions, the parameter variation in Re , σ , and α , as well as the reported content of the paper. Parameters are calculated based on available data and missing Reynolds numbers were estimated using the kinematic viscosity $\nu = 1 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$.

2.3 Shedding behaviour of cloud cavitation

So far, cloud cavitation driven by the re-entrant flow or the condensation shockwave has been regarded as periodic, unimodal and two-dimensional; however, cloud cavitation may exhibit transient behaviour with a three-dimensional topology and multiple shedding modes involved. Three-dimensional topologies of cloud cavitation reported in the literature are summarised in section 2.3.1, while multimodality and the behaviour over time, which can be highly transient, are discussed in section 2.3.2. The shedding behaviour with varying incidence and the lack of data on the incidence variation are reviewed in section 2.3.3. Variation in incidence and its effect on cloud cavitation dynamics – including transitions between mechanisms, 2D/3D topology, multimodality, and transient behaviour – constitute the research gap addressed in the present study, as outlined at the end of this chapter.

2.3.1 Two-dimensional and three-dimensional topology

Cloud cavitation is intrinsically 3D. For classification, the shedding is regarded as 2D when the spanwise variation is small over a substantial fraction of the span, and a single global mode sheds a large-scale cavity at approximately the same spanwise position, see figure 2.5 (a). In this regime, the spanwise-average flow field is strictly periodic with a single dominant frequency and no out-of-phase events. By contrast, at the same incidence for a larger cavitation number, the shedding loses spanwise coherence – multiple spanwise modes and/or distinct shedding locations appear – and the behaviour is 3D, see figure 2.5 (b).

The distinction between 2D and 3D models presents an additional challenge that influences cavitation dynamics and adds more complexity to their understanding. Laberteaux and Ceccio (2001a, 2001b) conducted a study about a hydrofoil and a wedge with a 2D and a 3D geometry, respectively. They found that cavity topology and the direction of the re-entrant flow were significantly influenced by the presence of a spanwise pressure gradient. De Lange and de Bruin (1997) also observed a redirected re-entrant flow, explaining the ‘reflection’ of the re-entrant flow at the cavity closure. The so-called ‘side-entrant’ flow was later confirmed on a 3D twisted hydrofoil by Foeth (2008), Foeth et al. (2008), and Kadivar et al. (2020). As noted by Smith et al. (2020a) and Venning et al. (2022), even nominally 2D geometries can exhibit 3D flow structures, a finding that has also been recently demonstrated by Hatzissawidis, Sieber, Oberleithner, and Pelz (2025) and many other researchers.

Another 3D phenomenon reported by Kawanami et al. (1998) is the occurrence of multiple shedding locations along the hydrofoil span. This has been described as the ‘compatibility’ condition between cavity length and the hydrofoil’s span (Smith et al., 2020a).

In practical devices such as marine propellers and pump impellers, cloud cavitation is typically 3D, because both blade geometry and inflow are inherently 3D (Breslin & Andersen, 1993; Brennen, 2011). This is why 3D effects in cloud cavitation are important to understand. In this study, a finite-span 3D NACA 0015 hydrofoil is investigated that,

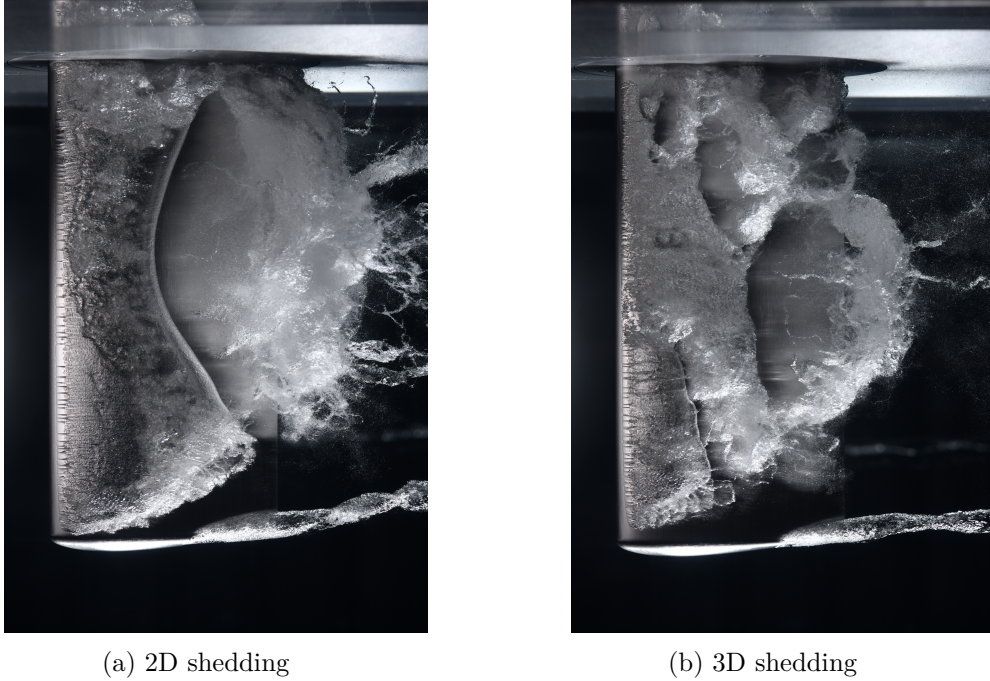


Figure 2.5: Shockwave-driven cloud cavitation about a NACA 0015 hydrofoil (chord length 120 mm) in case of (a) 2D shedding at a lower cavitation number σ of 0.75 and (b) 3D shedding at a higher cavitation number σ of 1. The incidence is 14° and the Reynolds number is 8×10^5 .

depending on the operation conditions, exhibits both 2D and 3D shedding behaviour. Although acknowledged in the literature, these 3D effects remain insufficiently investigated, largely because studies on shedding mechanisms (see section 2.1) are experimentally and analytically more tractable in nominally 2D cases.

2.3.2 Temporal behaviour and multimodality

Beyond its 3D topology, cloud cavitation can also be multimodal – multiple global shedding modes may occur simultaneously or exclusively in time – posing an additional challenge for analysis and interpretation. Multimodal behaviour is often accompanied by 3D behaviour, indicating that temporal dynamics and spatial topology are tightly coupled. As discussed in section 2.1.3, the transition from re-entrant flow-driven to shockwave-driven cloud cavitation is not abrupt; within the transitional regime both mechanisms occur, yielding multimodal behaviour. Arndt et al. (2000) were among the first to identify multimodal behaviour in the transitional regime between re-entrant flow-driven and shockwave-driven cloud cavitation using time-frequency analysis, with the two fundamental modes occurring exclusively. In recent years, numerous researchers have reported multimodality in cloud cavitation, enabled by increased computational capability and use of modal decomposition techniques; the latter is reviewed in section 2.4.

The modal content of cloud cavitation depends on numerous conditions such as geometry, shape, operation point, dissolved O_2 concentration, number and size of free-stream nuclei (Venning et al., 2022). Shedding modes may occur exclusively, intermittently or simultaneously, and manifest as either unimodal or multimodal, as shown in numerous recent studies (Prothin et al., 2016; Wu et al., 2019; Barwey et al., 2020; Smith et al., 2020a; Venning et al., 2022; Bhatt et al., 2023; Hatzissawidis et al., 2024; Hatzissawidis, Sieber, Oberleithner, & Pelz, 2025). Earlier studies focused primarily on the fundamental shedding mode of unimodal shedding, often overlooking additional modes.

Prothin et al. (2016) identified numerous modes about a 2D NACA 0015 hydrofoil by applying proper orthogonal decomposition (POD) (Lumley, 1970) and dynamic mode decomposition (DMD) (Schmid, 2010) to high-speed photographs, demonstrating that even for a 2D geometry, the leading mode is not enough to represent the behaviour of cloud cavitation.

Wu et al. (2019) have shown in their experimental study using X-ray densitometry about a 2D NACA 0015 hydrofoil that cloud cavitation exhibits multistep and multimodal behaviour. They reported a ‘three-step process’ in shockwave-driven cloud cavitation where the collapse of a cloud, shed due to the re-entrant flow, interacts with the growing cavity sheet as an intermittent step. In the transitional regime, the ‘three-step process’ and a ‘two-step process’ occur exclusively in the time-frequency analysis of an acoustic signal. Barwey et al. (2020) detected two so-called ‘styles’ through a modal decomposition technique called cluster-based reduced-order modelling (CROM) where the transition between the ‘styles’ occurs spontaneously. They identified the cloud collapse to be responsible for the transition.

Smith et al. (2020a) and Venning et al. (2022) applied a technique called SPOD by Towne et al. (2018) to high-speed photographs and identified several modes in cloud cavitation about 3D NACA hydrofoils, occurring both simultaneously and exclusively. Recently, the same trend has been reported by Hatzissawidis, Sieber, Oberleithner, and Pelz (2025) and Hatzissawidis, Sieber, and Pelz (2025) who identified multiple modes, some coexisting simultaneously and others appearing exclusively about a 2D NACA 0015 hydrofoil. Using SPOD by Sieber et al. (2016), they analysed a sequence of cloud cavitation regimes as the cavitation number was reduced.

In summary, most studies have concentrated on unimodal shedding because it is easier to isolate and analyse the underlying mechanisms. However, multimodality – and its associated temporal behaviour – has been widely documented over the past decade. Despite this progress, multimodality under varying incidence remains underexplored. The following section reviews studies that perform an incidence-sweep.

2.3.3 Existing studies on cavitation behaviour with varying incidence

This section reviews prior work on cavitation behaviour with varying incidence, aligning with the focus of this thesis. Changes in incidence govern the occurrence of 2D/3D topology, the temporal behaviour, and the multimodality all of which are especially relevant for marine propellers and pump impellers operating under off-design operation conditions.

Although many studies have investigated cavitation dynamics with respect to the cavitation number at fixed incidence and otherwise constant operation conditions (see table 2.1), investigations involving systematic incidence sweeps remain relatively scarce – especially in the context of the underlying physics of the shedding mechanisms. Pioneering efforts in the 1950s and 1960s laid the groundwork for such investigations, using force measurements and photography to study cavitation dynamics (Kermeen, 1956; Parkin, 1956; Meijer, 1959; Kermeen, 1961; Wade & Acosta, 1966). These studies were primarily motivated by applications in marine propellers, but also extended to pump design. Notably, even earlier work on cavitating hydrofoils and force measurements dates back to the 1930s in Göttingen (Walchner, 1932).

Wade and Acosta (1966) have already performed an extensive study about a plano-convex hydrofoil, measuring the forces and capturing the cavitation behaviour using high-speed photography at various cavitation numbers, Reynolds numbers, and varying incidence. They identified three regimes – supercavitation and sheet cavitation, both exhibiting no oscillations in the force, and an intermediate regime with strong oscillation, corresponding to cloud cavitation – though without using the terminology commonly adopted today. Le et al. (1993a) also investigated a plano-convex hydrofoil and developed a regime map as a function of cavitation number and incidence. The ‘periodic zone’ corresponds to a narrow region where the non-dimensionalised cavity length lies between 0 and 1, while supercavitation occurs beyond a cavity length of 1. This result differs from the observations in the present study as discussed later – periodic cloud cavitation still occurs, even for a cavity length beyond the trailing edge of the hydrofoil. The ‘periodic zone’ was found to extend over a wider range of incidences and shifts towards higher incidences as the cavitation number is increased. For high enough cavitation numbers, the ‘periodic zone’ transitions to shear cavitation (Le et al., 1993a; Franc & Michel, 2005), aligning with the results of this study. Moreover, the authors did not distinguish between the two shedding mechanisms, namely re-entrant flow and condensation shockwaves, but rather classified all the periodic regimes as a single type.

Franc and Michel (1985, 1988) conducted an extensive study on the interaction between cavitation and the boundary layer about a NACA 16012 hydrofoil. They developed a map as a function of cavitation number and incidence at fixed Reynolds number that distinguishes between ‘partial cavitation’ and, at higher incidence, a ‘two-phase cavity’ regime – likely corresponding to conditions where cavitation exhibits chaotic and irregular spanwise shedding approaching the shear cavitation regime (Franc & Michel, 1985; Franc & Michel, 2005). Briançon-Marjollet et al. (1990) studied in a subsequent work the differences between unseeded and seeded flows regarding cavitation dynamics, where the line between ‘partial cavitation’ and ‘supercavitation’ is drawn at $\hat{\alpha}_+ = 1$. As noted previously, this finding is in contrast to the results of this study obtained with a similar hydrofoil. Contrary to the studies previously mentioned, Leroux et al. (2005) reported both low- and high-frequency shedding with varying incidence in an experimental-numerical study, although the experimental design was too sparse to clearly resolve the conditions under which the two types occur.

In summary, research on cavitation dynamics with varying incidence remains fragmentary and often prioritises other objectives than cavitation dynamics. Here, the focus

is explicitly on the cavitation dynamics themselves – the underlying physical shedding mechanisms, topology (2D/3D), and the temporal behaviour. A brief review of the modal decomposition techniques in fluid mechanics and the application in cavitation research to identify the aforementioned effects is provided.

2.4 Modal decomposition techniques in cavitation

Over the past two decades, advances in computational resources and high-speed photography have broadened and accelerated the scope of modal decomposition techniques, enabling them to interrogate vast datasets and unveil coherent flow structures that were formerly beyond reach. Coherent, energetically dominant features in spatiotemporal flow fields can be extracted with modal decomposition techniques – most notably POD (Lumley, 1970) and DMD (Schmid, 2010). This review is limited to application of modal decomposition techniques in cavitation. An in-depth review of the most important modal decomposition techniques in fluid mechanics, usually being variants of POD and DMD, are given by Taira et al. (2017).

For turbulent flows, where coherent structures occur on multiple length and time scales, POD was introduced in turbulence research by Lumley (1970). The same method appears in other fields under different names (Holmes et al., 2012, p. 68). POD is commonly applied to identify the dominant spatial and temporal features of flow fields, thereby aiding physical interpretation of the underlying dynamics. Consequently, POD results should be critically evaluated for physical plausibility.

Modal decomposition methods are usually applied to velocity fields from PIV or numerical simulation (Taira et al., 2017). Over the past years, modal decomposition methods have been applied more and more to cavitation research. Because cavitating flows are inherently multiphase, time-resolved, quantitative measurements of the flow field are difficult and, therefore, rare; consequently, high-speed photography is widely used to analyse the dynamics. The resulting pixel intensity fields can be interpreted as the local void fraction – a high intensity corresponds to high void fraction, a low intensity to a low void fraction – but they remain qualitative; consequently, physical interpretation must be made with care.

One of the first studies to apply modal decomposition techniques to high-speed photography of cloud cavitation was performed by Prothin et al. (2016). The authors analysed cloud cavitation for various cavitation regimes by varying the cavitation number and compared POD and DMD results. Both methods were suitable to capture the dominant dynamics of cloud cavitation. Smith et al. (2020a), Smith et al. (2020b), Venning et al. (2022), and Hatzissawidis et al. (2024) applied SPOD by Towne et al. (2018) (see section 3.3.2) to high-speed photographs of cloud cavitation about 3D hydrofoils, where multiple modes occur. This technique draws on the strengths of POD and DMD for ‘statistically stationary flows’ and are ‘optimally averaged DMD modes’ (Towne et al., 2018). They demonstrated that SPOD is suitable for identifying the dominant modes in cloud cavitation. Recently, Venning et al. (2024) conducted a combined modal decomposition techniques with cross-wavelet transform (XWT), see Grinsted et al. (2004).

2.5 Synthesis of literature and research gaps

The XWT was calculated from the CWTs of two signals obtaining the coherence and the phase (Venning et al., 2024). In their study, they conducted the XWT between pixel intensities of a cavitating bluff body and a pressure signal that enables improved temporal analysis due to the relative phase between the signal and the high-speed photographs.

Hatzissawidis, Sieber, Oberleithner, and Pelz (2025) applied SPOD by Sieber et al. (2016) to high-speed photographs of a cavitating NACA 0015 hydrofoil, showing the multimodality of cloud cavitation. It should be mentioned that this method is not the same as the SPOD by Towne et al. (2018). SPOD by Sieber et al. (2016) has the intrinsic feature to allow a time-frequency analysis by using the temporal coefficients. Hatzissawidis, Sieber, Oberleithner, and Pelz (2025) analysed the temporal behaviour of the dominant modes, which occurred either simultaneously or exclusively.

Numerous other studies have applied modal decomposition to cavitation to identify the dominant features; to mention some of these: Danlos et al. (2014), Esposito et al. (2021), and Kumar et al. (2025).

In summary, modal decomposition techniques in cavitating flow are applied to reveal the dominant coherent structures that are hidden by direct observation. This includes the phenomena discussed above, i.e., 2D/3D topology (section 2.3.1) and multimodality (section 2.3.2). These techniques are indispensable in this study: they provide the primary tool for detecting dominant modes because cloud cavitation with varying incidence exhibits these phenomena.

2.5 Synthesis of literature and research gaps

2.5.1 Summary of key findings

The literature indicates three well-established fundamental mechanisms of cloud cavitation, ordered from higher to lower cavitation numbers: (I) K-H instability-driven cloud cavitation or sheet cavitation; (II) Re-entrant flow-driven cloud cavitation; (III) Condensation shockwave-driven cloud cavitation. This study focuses on (II) and (III), since they produce large-scale cloud cavitation – the primary source of noise, vibration, efficiency loss, and erosion in marine propellers and pump impellers. The transition from (II) to (III) occurs as the local Mach number exceeds unity: the re-entrant flow becomes less dominant and condensation shockwaves govern the shedding process. It was recently reported by Bhatt et al. (2023) that the transition is probabilistic. However, the origin or trigger of these shockwaves remains debated, with competing explanations across the literature. Hatzissawidis, Kuhr, and Pelz (2025) recently identified that the trailing edge can act as a shockwave trigger, i.e., when the maximum cavity sheet length reaches the trailing edge a shockwave is triggered. A similar effect has been reported by Venning et al. (2022).

A detailed inter-study comparison of the characteristic Strouhal number for cloud cavitation is conducted from numerous studies with different dimensions on the benchmark hydrofoil NACA 0015, also used in this study showing scattering across the data. The data were plotted over $\sigma/2\alpha$. According to linear flat-plate theory, the incidence effects on the pressure distribution are compensated for by using $\sigma/2\alpha$: however, this scaling

is generally not valid for the hydrofoil in the present study and should be considered. The inter-study scatter may also arise due to differences in the experimental set-up, scale effects, water quality, i.e., dissolved oxygen concentration and free-stream nuclei, blockage ratio, and operation conditions. However, a clear trend is observed: The characteristic chord-based Strouhal number of condensation shockwave-driven cloud cavitation does not depend on $\sigma/2\alpha$, while the re-entrant flow does. Using the maximum cavity sheet length rather than the chord length to calculate the Strouhal number compensates the dependence of the characteristic shedding frequency on $\sigma/2\alpha$ with values between 0.25 and 0.4. However, this Strouhal number is recently found to be dependent on the hydrofoil shape, which includes the hydrofoil model and the incidence (Hatzissawidis, Kuhr, & Pelz, 2025).

Further, a coupled mechanism – re-entrant flow followed by a condensation shockwave as the re-entrant flow breaks through the cavity sheet – has been demonstrated for a sphere by de Graaf et al. (2017), where the adverse pressure gradient is strong. For hydrofoils, especially under increasing incidence where the adverse pressure gradient becomes strong, direct evidence of the same coupling is limited. Existing studies rarely perform controlled incidence sweeps.

The global shedding behaviour shows that cloud cavitation may exhibit complex 3D topology and multimodality rather than idealised unimodal 2D shedding. Multiple modes may occur simultaneously and/or exclusively in time, which complicates analysis and understanding. Over the past two decades, modal decomposition has emerged as a powerful tool to reveal the coherent structures in cavitation that are hidden by direct observation.

Despite its importance, incidence has received comparatively little attention in the literature; most studies emphasise variations of the cavitation number at fixed incidence. However, the phenomena noted above – 2D/3D transitions, multimodality, and associated temporal dynamics – are strongly expressed with varying incidence, motivating the present focus.

2.5.2 Research gaps and future studies

The following research gaps arise from the literature review from which the research questions RQ1, RQ2, RQ3, RQ4, and RQ5 in section 1.2 are derived:

- The initiation of cloud cavitation and the mechanisms governing regime transition remain contested, particularly regarding their dependence on geometry. While transitions observed with decreasing cavitation numbers are well documented, systematic studies of transitions with varying incidence are scarce. This gap motivates the question of whether the triggering at the trailing edge as the maximum cavity length reaches the chord length is also observed as the incidence is varied. This can also be extended to other geometries, as, for example, a convergent-divergent nozzle (see RQ1).
- Despite a substantial inter-study scatter, a consistent trend emerges: for condensation shockwave-driven cloud cavitation, the chord-based Strouhal number

remains approximately constant as the cavitation number is varied, whereas for the re-entrant flow-driven cavitation it decreases with decreasing cavitation number. For the latter, the maximum cavity length-based Strouhal number is approximately constant. However, most of these findings come from sweeps in the cavitation number; systematic behaviour as a function of incidence remains largely unexplored (see RQ2).

- Cloud cavitation dynamics under varying incidence remain insufficiently characterised; most studies vary the cavitation number at fixed incidence. Consequently, the validity and limits of the parameter $\sigma/2\alpha$ from the linear flat plate theory to predict shedding are unresolved (see RQ3).
- The physical behaviour of the re-entrant flow under varying incidence is insufficiently characterised. Higher incidence likely strengthens the adverse pressure gradient, potentially intensifying the re-entrant flow and modifying the shedding mechanism – yet systematic evidence is lacking for a hydrofoil (see RQ4).
- The global shedding behaviour has been predominantly analysed for unimodal, 2D shedding, where the mechanisms are easier to isolate and examine. By contrast, the temporal behaviour of 3D topology and multimodality remains largely unexplored, particularly as a function of the incidence. Accordingly, a clear research gap exists: both the capability of modal decomposition techniques to isolate the dominant coherent shedding in complex, multimodal, 3D cloud cavitation and the systematic characterisation of mode evolution with varying incidence remain insufficiently established (see RQ5).

Chapter 3

Experimental overview and data analysis techniques

Experiments of cloud cavitation about a NACA 0015 hydrofoil were conducted at the CRL variable-pressure water tunnel at the University of Tasmania (UTAS) to investigate the influence of the incidence α on cloud cavitation dynamics. Besides α , the cavitation number σ was also varied as a key parameter in cavitation research. Force measurements using a six-component force balance were conducted to capture the hydrodynamic response of the hydrofoil under cavitation. Simultaneous high-speed photography was performed to link the force data to the cavitation dynamics and understand the shedding physics. This chapter presents the facility and its main components, the experimental set-up including the data acquisition system, the high-speed photography set-up, the test model, the experimental design, and the data analysis techniques such as the SPOD by Towne et al. (2018) which was applied in this study to identify the dominant flow structures from the high-speed photography.

This chapter is adapted and extended from the following manuscripts, which have been submitted to the *Journal of Fluid Mechanics*: Hatzissawidis, Russell, Venning, Pelz, and Brandner (2025a, 2025b).

3.1 Experimental set-up and design

This section presents the experimental set-up, including the CRL cavitation tunnel, its key characteristics, the measurement equipment and techniques, the NACA 0015 hydrofoil used as the test model, and the experimental design.

3.1.1 CRL cavitation tunnel

The experiments were conducted in the closed, recirculating, variable-pressure water tunnel at the CRL of the Australian Maritime College (AMC), UTAS. A schematic of the cavitation tunnel together with all main components is shown in figure 3.1. The test section is 2600 mm long and has a square inlet cross-section with a side length of 600 mm. The free-stream velocity and the free-stream static pressure within the test section can be varied from 2 to 12 m s⁻¹ and 4 to 400 kPa absolute, respectively. The tunnel contains 365 m³ of demineralised water and is equipped with a continuous nuclei removal system (figure 3.1), the downstream tank removing large nuclei (> 100 μ m) via

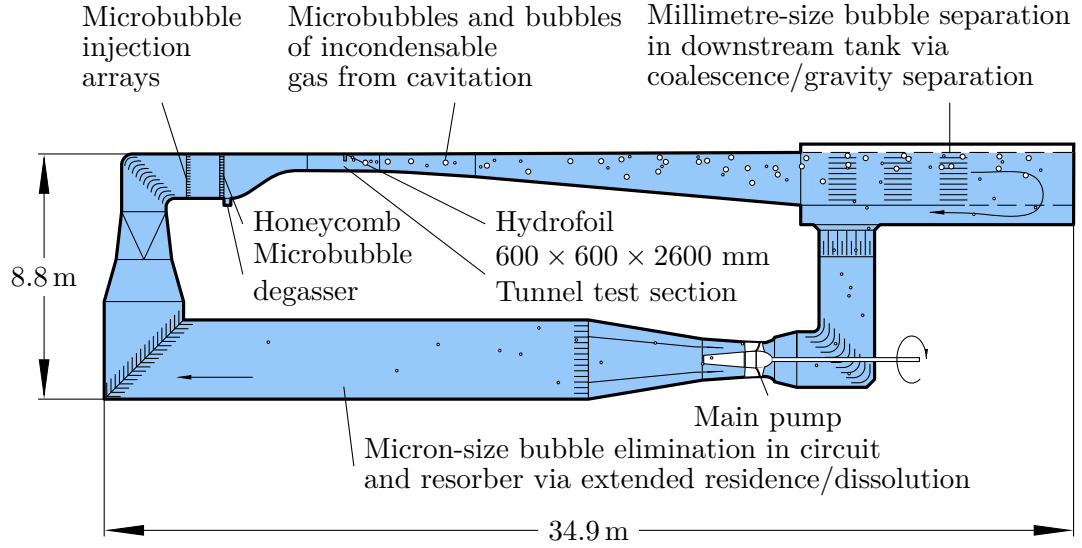


Figure 3.1: Schematic of the CRL closed, recirculating, variable-pressure water tunnel with all main components. Cavitation-induced bubbles about the hydrofoil are continuously removed in the downstream tank through gravitational separation and coalescence, or in the resorber by diffusion, located behind the main pump.

coalescence and gravity separation, and the resorber removing small nuclei ($< 100 \mu\text{m}$) via dissolution at low flow velocities (Brandner et al., 2007). Nuclei generated artificially using the upstream microbubble generators or through the cavitating model within the test section are eliminated to avoid recirculation, since this, depending on the number and size of nuclei, may affect the cavitation behaviour as shown by Arndt and Keller (2003), Russell et al. (2018) and Venning et al. (2022). Natural nuclei remain present in the water and their size varies with a power law distribution (Venning et al., 2018). Abundant small nuclei require tensile stresses that are far too high to activate, while larger nuclei are too scarce. The nuclei population at the CRL was measured using the cavitation susceptibility meter (CSM) (Khoo et al., 2020) for the natural nuclei or ‘background nuclei’ and the Mie-scattering imaging (MSI) (Russell et al., 2020) for the abundant, sparse, and monodisperse cases, see figure 3.2. Data are presented in terms of the cumulative distribution C as a function of the tension $p_c - p_v$, with p_c being Blake’s critical pressure (Blake, 1949), and p_v being the saturated vapour pressure of water. Blake’s critical pressure can be converted to a critical bubble diameter, d_c , depending on an ambient pressure – here the free-stream pressure p_∞ is used – by solving

$$p_c - p_v = \frac{-2}{3\sqrt{3}} \sqrt{\frac{(4S/d_c)^3}{p_\infty - p_v + 4S/d_c}}, \quad (3.1)$$

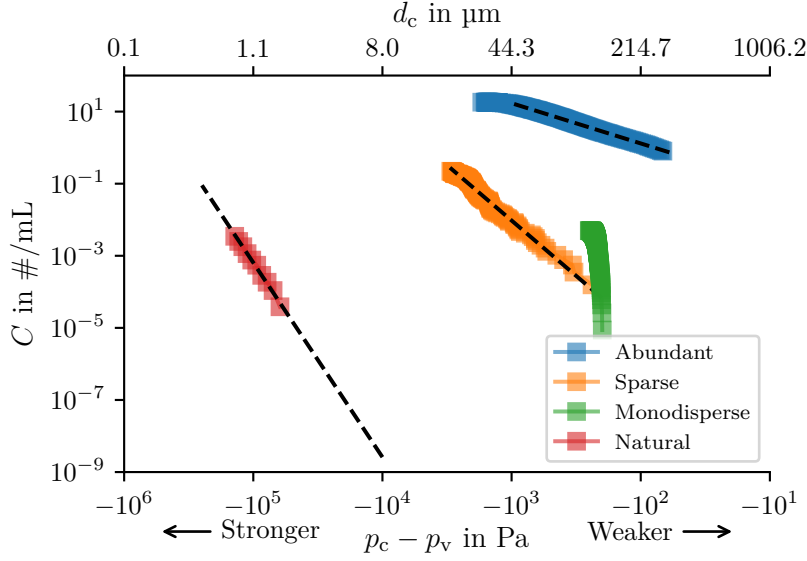


Figure 3.2: Microbubble measurements for different nuclei populations in the CRL cavitation tunnel. The cumulative distribution C from the large, weak bubbles to the small, strong bubbles as a function of the tension $p_c - p_v$. The natural population was measured with a CSM, the abundant, sparse and monodisperse were measured with MSI. The upper axis shows the calculated diameter for a cavitation number of 1 according to equation (3.1).

with S being the surface tension, see Franc and Michel (2005, p. 19). In this thesis, no artificial seeding is added and only the ‘background nuclei’ are present. For a cavitation number of 1, the diameter of the nuclei in the water is of the order of magnitude of 1 μm , see figure 3.2.

A detailed schematic of the test section is shown in figure 3.3, with a square cross-sectional area of 600 mm $\times$ 600 mm at the inlet and a length of 2600 mm. The free-stream static pressure p_∞ , defined at the hydrofoil’s midspan, was measured using two absolute pressure transducers, Siemens Sitrans P DSIII models 7MF4333-1FA02-2AB1 (range 0 to 130 kPa) and 7MF4333-1GA02-2AB1 (range 0 to 500 kPa), depending on the actual value of p_∞ , less or larger than 120 kPa, respectively. The maximum ‘expanded uncertainty’ of p_∞ over all operation points based on the ‘law of propagation of uncertainty’ is 0.14 kPa and 0.53 kPa (coverage factor $k = 2$), respectively, calculated according to the ISO/IEC Guide 98-3:2008 (International Organization for Standardization, 2008), as are all the uncertainties of the tunnel data. The details of the uncertainty analysis are provided in appendix A.

The free-stream velocity U_∞ was calculated from the differential pressure, Δp , using a differential pressure transducer Siemens Sitrans P DSIII model 7MF4433-1FA02-2AB1 (range 0 to 160 kPa) and by applying ‘Bernoulli’s theorem’ (Batchelor, 2000). The differential pressure was measured across the contraction between the cross-section of height 1600 mm and 600 mm, see figure 3.3, with a calibrated contraction coefficient K

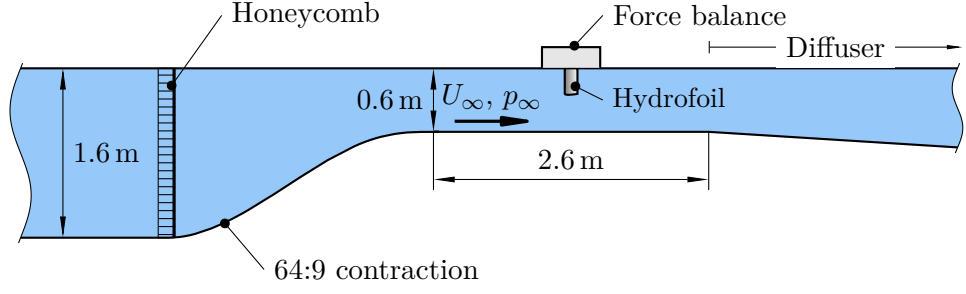


Figure 3.3: Schematic of the test section showing the NACA 0015 hydrofoil mounted on the ceiling on the six-component force balance at mid-length of the test section. Flow enters from the nozzle into the test section, at a contraction ratio of 64:9, and exits downstream to a diffuser. To maintain a constant streamwise flow velocity U_∞ along the test section, the bottom wall of the test section is inclined at about 0.44° relative to the streamwise direction, resulting in a gradual expansion of the test section height from 600 mm to 620 mm.

(Brandner, 2013) across all operating velocities:

$$U_\infty = K \sqrt{2 \frac{\Delta p}{\rho}}. \quad (3.2)$$

The free-stream velocity was approximately 7.2 m s^{-1} during all measurements. The maximum expanded uncertainty of U_∞ over all operation points is 0.017 m s^{-1} . To maintain a constant streamwise flow velocity along the test section, the bottom wall of the test section is inclined at 0.44° , expanding the height of the test section from 600 mm at the inlet to 620 mm at the outlet. This compensates for the reduction in effective cross-sectional area caused by the growth of the boundary layer thickness.

The dissolved O_2 concentration, c , was measured and monitored using an Endress + Hauser Liquiline CM442-AAM2A2F260A transmitter with an Endress + Hauser COS61D-AAA1A3 optical O_2 sensor. The water degassing process was always conducted prior to the experiments by initially generating a large free surface, lowering the tunnel's static pressure to its minimum value (4 kPa), and the velocity to 4 m s^{-1} . Next, air was injected at a volumetric flow rate of 20 L s^{-1} to generate shedding on the surface and therefore a large amount of bubbles. Air diffuses from the water into the bubbles due to the strong supersaturation at the low pressure. The bubbles are finally removed in the downstream tank. To avoid altering the dynamics of cloud cavitation – as shown by Kawakami, Fuji, et al. (2008) and Kawakami, Qin, and Arndt (2008) – the dissolved O_2 content was maintained between 3 to 3.3 mg L^{-1} with an expanded uncertainty of $\pm 0.038 \text{ mg L}^{-1}$. Tunnel data were acquired using a NI PXIe-6341 module connected to a PXIe-1073 chassis, see figure 3.4. An overview of the measurement system, including all key components and their wiring, is presented in figure 3.4.

The chord-based Reynolds number, $Re := U_\infty L / \nu$, was maintained at 8×10^5 , where

3.1 Experimental set-up and design

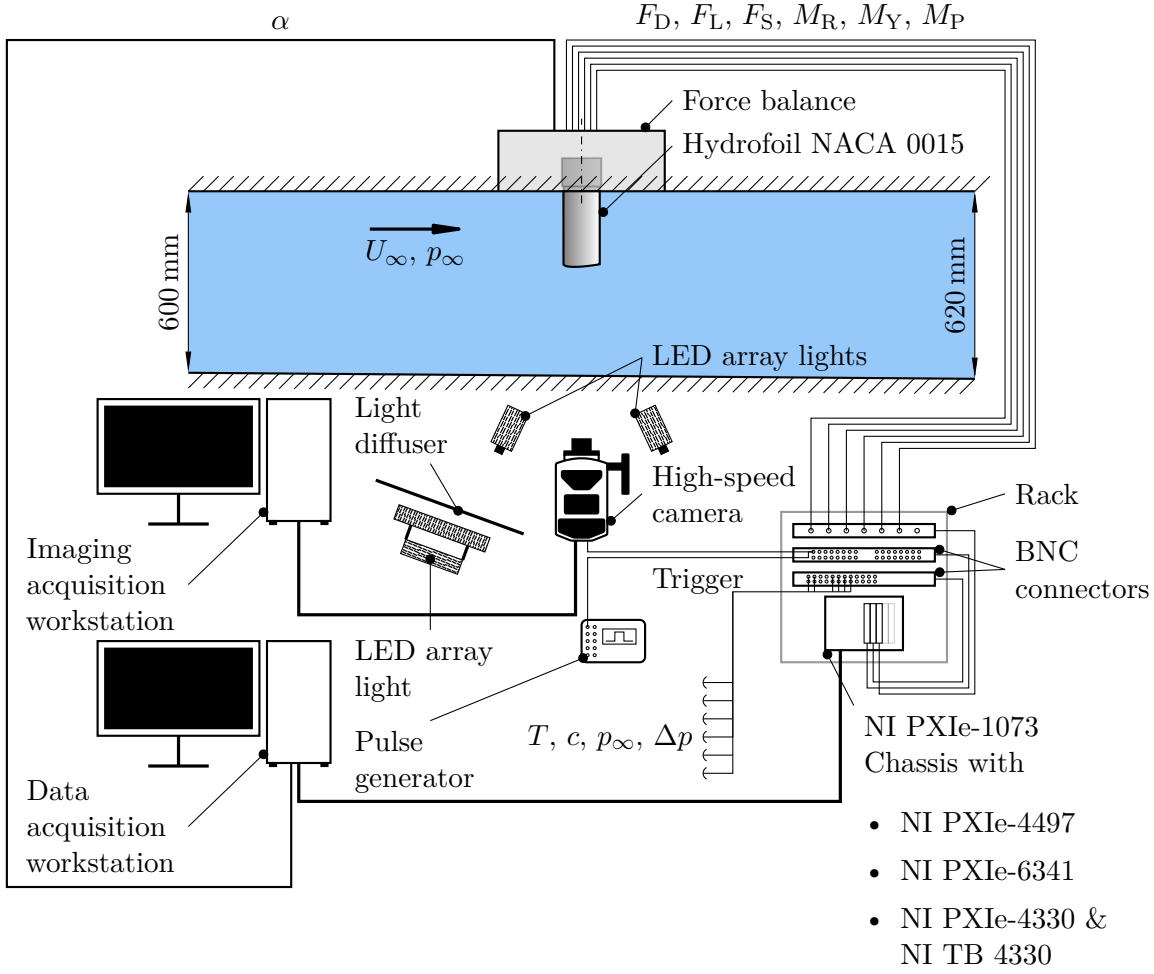


Figure 3.4: Schematic of the measurement system and the test section, including the data acquisition components, the cabling and the high-speed photography set-up. The tunnel data, i.e., temperature T , dissolved oxygen concentration c , differential pressure Δp to calculate the free-stream velocity U_∞ , free-stream static pressure p_∞ in the test section were recorded by a National Instruments (NI) PXIe 6341 card connected to a BNC 2090 terminal block. High-speed photography was performed simultaneously using a Phantom v2640 camera. A BNC model 575 Pulse generator provided the trigger signal to the high-speed camera, which was recorded by the NI PXIe-6341 card connected to a BNC 2144 terminal block. Illumination was provided by two Veritas constellation 120 5600K light-emitting diode (LED) array lights and one HANECO SKYPAD LED array light with a diffuser sheet. The force balance data were recorded simultaneously using a NI PXIe 4330 card.

L is the chord length of the hydrofoil and ν is the kinematic viscosity of water. The corresponding expanded uncertainty of the Reynolds number is approximately 1.2×10^4 or 1.5% of the mean value. The incidence α was varied from no cavitation to supercavitation or shear cavitation, spanning a range from 0° to 16° . The cavitation number, $\sigma := 2(p_\infty - p_v) / \rho U_\infty^2$, where p_v and ρ are the saturated vapour pressure and the density of the water, respectively, was varied in several steps, see table 3.1, to include the influence of the cavitation number additionally to the fine-resolved incidence. Reference measurements for the single-phase flow were also conducted. The corresponding expanded uncertainty of the cavitation number ranges between 0.005 and 0.031 or between 0.6% and 1% of the mean value. The temperature dependence of the water properties, i.e., ν , ρ , p_v , is calculated using data by Warneck and Williams (2012), see appendix D. The temperature was slightly increasing during the experiments within the range from 16.5 to 17.6 °C, with an expanded uncertainty of approximately 0.6 °C.

3.1.2 Hydrofoil and six-component force balance

The model hydrofoil has a rectangular planform with a constant NACA 0015 cross-sectional area with a chord length L of 120 mm and submerged span b of 250 mm, figure 3.5. The tip is faired by rotating half of the NACA profile about its chordwise axis. The aspect ratio of the hydrofoil’s rectangular part is approximately 2, as it is the case in Venning et al. (2022). The blockage ratio for an incidence between 0 and 16° varies from approximately 1 to 3 %, ensuring that there are no effects on the dynamics.

The model was made of stainless steel 1.4301 according to the standard DIN EN 10088-1:2024-04 (Deutsches Institut für Normung e.V. (Hrsg.), 2024) with an average surface roughness and a standard deviation of $0.46 \mu\text{m} \pm 0.07 \mu\text{m}$ measured with a Keyence VK-X3000 3D surface profiler and tolerances in manufacturing smaller than 100 μm to 400 μm depending on the lengths.

The NACA four-digit section profile equation (Abbott & von Doenhoff, 1959, p. 113) is modified,

$$\pm \tilde{y} = \frac{\tilde{t}}{0.2} \left(0.2969 \sqrt{\tilde{x}} - 0.1260 \tilde{x} - 0.3516 \tilde{x}^2 + 0.2843 \tilde{x}^3 - 0.1003 \tilde{x}^4 \right), \quad (3.3)$$

adapting its last coefficient to obtain a thicker trailing edge from 378 μm to 594 μm for robustness and manufacturing (Zarruk et al., 2014; Smith et al., 2020a). Here, $\tilde{t}$ is the thickness to the chord ration (0.15 for a NACA 0015), and $\tilde{x}$ and $\tilde{y}$ are the coordinates of the NACA geometry, where the chord length has been normalised to unity.

In this study, transient force measurements were conducted. The model hydrofoil was attached to a six-component force balance (Butler et al., 2021), mounted on the test section ceiling vertically at mid-length, i.e., 1.3 m downstream of the test section inlet, as shown in figure 3.3. The hydrofoil, together with the force balance, was lowered through a penetration hole of 160 mm into the test section. On the wetted part of the force balance, a fairing disk made of stainless steel was flush mounted to the test section wall with a constant gap of 500 μm to the hydrofoil, avoiding any contact and disturbance of the force measurements. The forces were captured from strain-gauge beam load cells and

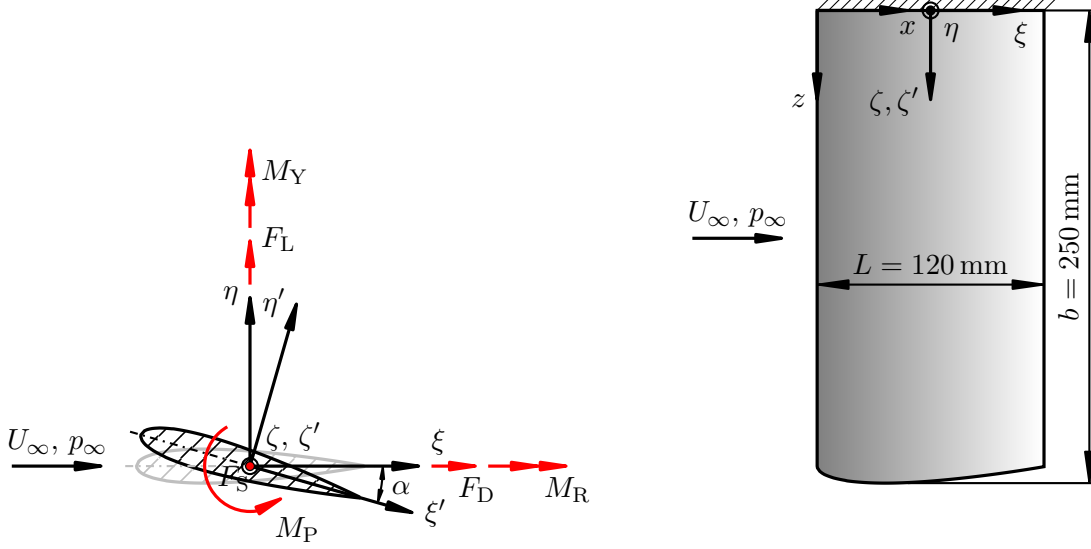


Figure 3.5: The left-hand side presents the bottom view of the NACA 0015 hydrofoil, while the right-hand side shows its side view as mounted on the six-component force balance on the ceiling of the test section. Both coordinate systems are illustrated at the left-hand side: the hydrofoil-fixed coordinate system ξ', η', ζ' , which rotates with the incidence angle α , and the flow-fixed coordinate system ξ, η, ζ . All forces and moments from the force-balance are denoted: lift force F_L , drag force F_D , side force F_S , yawing moment M_Y , rolling moment M_R , and pitching moment M_P , all based on the flow-fixed coordinate system. Additionally, the free-stream velocity U_∞ and static pressure p_∞ at midspan are depicted. The hydrofoil has a span b and a chord length L . The coordinate system at the leading edge at the hydrofoil's root, x, z , is used for the space-time diagrams.

flexures (Butler et al., 2021) instrumented in Wheatstone-bridge configurations with a NI PXIe 4330 card and a NI TB 4330 terminal block connected to the NI PXIe 1073 chassis, see figure 3.4.

Forces (lift force F_L , drag force F_D , side force F_S) and moments (yawing moment M_Y , rolling moment M_R , pitching moment M_P) are defined with respect to the flow-fixed coordinate system ξ, η, ζ (figure 3.5), calculated by transforming the forces and moments in the hydrofoil-fixed coordinate system ξ', η', ζ' . In this study, the dimensionless coefficients defined as $C_L := 2 F_L / \rho U_\infty^2 L b$ (lift coefficient), $C_D := 2 F_D / \rho U_\infty^2 L b$ (drag coefficient), and $C_P := 2 M_P / \rho U_\infty^2 L^2 b$ (pitching coefficient) are used. Since high-speed photography is conducted normal to the flow from the side view, the flow-fixed coordinate system was placed at the root of the hydrofoil's leading edge, x, z (figure 3.5), and is used when extracting information from the high-speed photographs, such as cavity lengths or space-time diagrams.

The force balance was calibrated using precision masses and a first order calibration

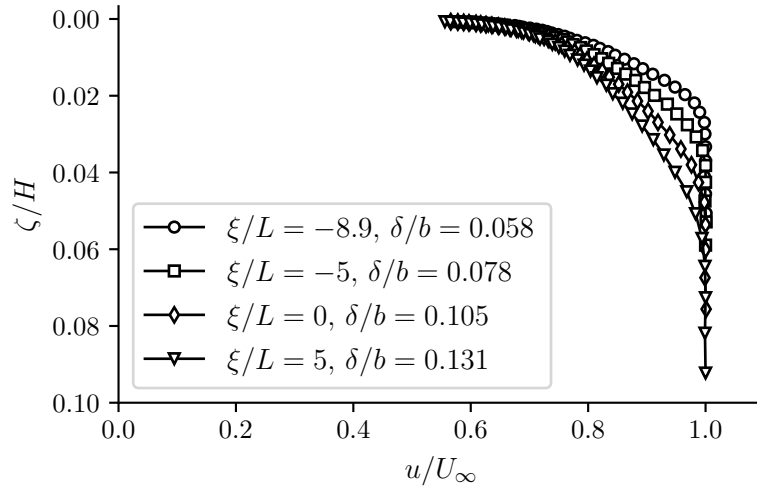


Figure 3.6: Boundary layer measurements from Belle et al. (2016) in the CRL cavitation tunnel at four different positions, $\xi/L = -8.9, -5, 0, 5$. The local velocity u in ξ -direction is non-dimensionalised with the free-stream velocity U_∞ . The thickness of the boundary layer δ where the local velocity reaches 99 % of the free-stream velocity is given.

between the load cell voltages and the load forces (Butler et al., 2021). The uncertainties were calculated according to the ISO/IEC Guide 98-3:2008 (International Organization for Standardization, 2008), considering all sources of uncertainty given by Butler et al. (2021), for details see appendix A. The expanded uncertainty was determined to be less than 1 % for the lift coefficient and 4 % for the drag and pitching coefficient, for the four cavitation numbers investigated ($\sigma = 0.50, 0.76, 0.88, 1.01$) as well as the single-phase flow, being valid for an incidence larger than 6° , where the interesting operation points in this study lie. Generally, the expanded uncertainty as a percentage increases for lower incidences (i.e. low forces and moments) (Butler et al., 2021). The bias of the incidence resulting from the alignment uncertainty from the set-up is eliminated by ‘zeroing’ the incidence at zero lift coefficient. The remaining combined uncertainty of the incidence is 0.0049° on a full scale (Butler et al., 2021).

Measurements of the boundary layer thickness were conducted by Belle et al. (2016) at various positions, see figure 3.6. Data were obtained in the plane ξ, ζ at mid-depth, with $\xi = 0$ corresponding to the hydrofoil rotational axis and $\zeta = 0$ to the ceiling. The coordinate ζ , non-dimensionalised by the height of the test section H , is presented as a function of the local velocity non-dimensionalised by the free-stream velocity, u/U_∞ . For $\xi/L = 0$, the local velocity reaches 99 % of the free-stream velocity by 10.5 % of the hydrofoil’s span, indicating that boundary layer effects will be visible.

3.1.3 Experimental design

To capture the full range of cavitation regimes, the incidence was incrementally varied from single-phase flow – starting at 3.25° or 4° depending on the cavitation number – up to 16° , where almost supercavitation or shear cavitation occurs and the maximum load of the force balance is reached. ‘Long’-duration force measurements were conducted in increments $\Delta\alpha$ of 0.25° for 240 s at 1000 Hz acquisition rate to obtain well-converged, high-resolved spectra and reduce statistical uncertainty. These measurements include of the order of $10^3 - 10^4$ cycles of the fundamental shedding depending on the operation point. Additionally, ‘long’ measurements of the single phase-flow were also acquired as reference measurements to the cavitating flow. For the high-speed photography, two run types – ‘short’ and ‘medium’ – were recorded at high and low temporal resolution, respectively, see section 3.3.1. The run type ‘preliminary studies’ includes still photographs of the cavitation topology to obtain a first overview of the cavitation, see section 3.3.1. The experimental design is summarised in table 3.1, where the range of the incidence, α , cavitation numbers, σ , experiment duration, Δt , frame rate of the high-speed photography, f_{HSI} , acquisition rate of tunnel data including the force balance data, f_{TU} , and pixel resolution in the high-speed and still photography, R , are provided. The final pixel resolution was determined for each incidence by computing the pixel resolution using the span and the chord length and averaging the two values.

Table 3.1: Experimental design with the different run types. The nomenclature ‘long’, ‘medium’, and ‘short’ are the same as in Smith et al. (2020a). The table provides the range of the incidence, α , cavitation numbers, σ , experiment duration, Δt , frame rate of the high-speed photography, f_{HSI} , acquisition rate of tunnel data including the force balance data, f_{TU} , and resolution, R , obtained in the high-speed photography and the high-resolution still photography. The data from the run type ‘long’ are recorded over a long time to obtain high-resolved spectra and to reduce the statistical uncertainty. Two run types for the high-speed photography ‘medium’ and ‘short’ are conducted. The former is used to capture the cavitation topology with statistical sufficiency to conduct a statistical analysis and apply SPOD to identify the spatial modes and their corresponding frequency. The latter is used to obtain movies with high temporal resolution for a detailed analysis of the underlying physical mechanisms. The run type ‘preliminary studies’ is conducted prior to the main experiments to obtain an overview of the cavitation topology using high-resolution still photography.

Run type	α in $^\circ$	σ	Δt in s	f_{HSI} in Hz	f_{TU} in Hz	R in mm pixel $^{-1}$
Long	{0..0.25..16}	{0.50, 0.76, 0.88, 1.01, no cavitation}	240	N/A	1000	N/A
Medium	{5..1..16}	{0.50, 0.76, 0.88, 1.01}	50.924	1000	1000	0.14
Short	{5..1..16}	{0.50, 0.76, 0.88, 1.01}	1	6600	1000	0.14
Prel. studies	{0..1..16}	{0.25..0.25..2.5}	10	N/A	1000	0.04

3.2 Spectral and transient analysis

The PSD of the force data was estimated by Welch’s method (Welch, 1967) using a Hann window and a window size of 2048 points (2.048 s) with 50 % overlap (1.024 s) between the windows. Zero-padding was employed to smooth the PSD signal. This method was programmed using the Python package NumPy (Harris et al., 2020). Further details on the parameter selection in Welch’s method are provided in appendix C.1.

A time-frequency analysis was conducted by applying the CWT to the time-resolved force balance data using the Python package by Lee et al. (2019). This allows for a transient analysis to detect intermittent behaviour of the occurring modes at specific frequencies (Brandner et al., 2018; Smith et al., 2020a; Venning et al., 2022).

Due to the ‘Heisenberg-Gabor uncertainty principle’ (Gabor, 1946) there is a trade-off between frequency and time resolution (Mallat, 2009; Moca et al., 2021; Wong et al., 2023) for choosing the wavelet. A complex Morlet wavelet is chosen as a mother wavelet with a bandwidth of $BW = 14 \text{ s}^2$ and a centre frequency of $f_c = 1 \text{ Hz}$ denoted as ‘cmor14-1’ in the Python package (Lee et al., 2019),

$$\psi(t) = \frac{1}{\sqrt{\pi BW}} \exp\left(-\frac{t^2}{BW}\right) \exp(i 2\pi f_c t), \quad (3.4)$$

to be suitable to distinguish between the frequencies of interest and simultaneously localise the events in time accurately; see appendix C.2 for details on the parameter selection. Each octave (2^i to $2^{i+1} - 1$) consists of 256 scales from 2^0 to 2^7 Hz , evenly spaced on a logarithmic scale with base two, see Torrence and Compo (1998). The CWT is calculated by projecting the signal $f(t)$ onto the wavelet $\psi(t)$ ‘dilated’ throughout various scales δ and ‘translated’ by the times τ as

$$\text{CWT}(\tau, \delta) = \frac{1}{\sqrt{\delta}} \int_{-\infty}^{+\infty} f(t) \psi^*\left(\frac{t - \tau}{\delta}\right) dt, \quad (3.5)$$

Mallat (2009, p. 102), where $*$ denotes the conjugate complex. The CWT is a complex value which can be represented as the absolute value or the real and imaginary part. The latter allows the distinct periods to be visualised by high and low values on a spectrogram. The transformation of the scales to the frequencies is inversely proportional, $f = f_c/\delta$ (Wong et al., 2023).

The physical time t in seconds (s) is non-dimensionalised by the advection time L/U_∞ as $t_+ := t U_\infty / L$ for all time-resolved signals.

3.3 Cavitation topology

The cavitation topology was analysed using high-speed photography as well as high-resolution still photography. The still photographs serve as an overview regarding the global cavitation topology. The high-speed photographs are used to capture the transient behaviour of cloud cavitation as well as characteristic lengths as the cavity sheet length and its spanwise extent. Besides other image processing techniques, SPOD by Towne et al.

(2018) was applied to the high-speed photographs to capture the dominant dynamics of cloud cavitation behaviour.

3.3.1 High-speed and still photography

Simultaneous high-speed photography from the side view in increments $\Delta\alpha$ of 1° and force measurements were made to capture the cavitation topology and dynamics. The trigger signal generated by a BNC model 575 pulse/delay generator initiated the high-speed camera acquisition and was recorded using a NI PXIe-4497 module synchronised to the tunnel data and the force measurements, see figure 3.4. Two run types were performed for the high-speed photography, ‘medium’-duration acquisition with a reduced frame rate of 1000 Hz for 50.924 s resulting in 50924 frames, and ‘short’-duration acquisition with a high temporal resolution of 6600 Hz and reduced acquisition time of 1 s resulting in 6600 frames, see table 3.1. The former is used to capture the cavitation topology with statistical sufficiency by applying SPOD by Towne et al. (2018) to identify coherent structures as discussed below. The latter is used to reveal more details about the physical mechanisms occurring in cloud cavitation.

Besides SPOD, space-time diagrams were generated to conduct a spatiotemporal analysis of cloud cavitation behaviour. Space-time diagrams are chordwise (horizontal) or spanwise (vertical) ‘cuts’ through the high-speed photographs (Smith et al., 2019). These slices are arranged beside one another, where spatial and temporal information can be extracted. Characteristics of the flow such as the cavity length were extracted by following the maximum spatial extent of the cavity sheet, and slopes of spatial structures correspond to a characteristic velocity of the re-entrant flow or condensation shockwave.

High-speed photography was performed using a Phantom v2640 high-speed camera with a Nikon AF Nikkor 50 mm f/1.8D lens and an image size of $2048 \text{ pixel} \times 1952 \text{ pixel}$. The spatial resolution was $0.14 \text{ mm pixel}^{-1}$ for both ‘short’ and ‘medium’ run type. Illumination was provided by two IDT veritas constellation 120 560K LED lights and one Haneco skypad LED light combined with a diffusion sheet. The high-speed photography set-up including the main components is shown in figure 3.4.

Additionally, preliminary studies were conducted to gain insight into the cavitation topology depending on the operation conditions, i.e., cavitation number σ and incidence α , through high-resolution still photography for an incidence sweep from 0 to 16° in increments $\Delta\alpha$ of 1° where the cavitation number varied from 0.25 to 2.5 in increments $\Delta\sigma$ of 0.25 . In total, 40 still photographs per operation point were captured using a Nikon D850 45.7 megapixel camera with a Nikon AF-S Micro Nikkor 105 mm 1:2.8G ED lens, resulting in a spatial resolution of $0.04 \text{ mm pixel}^{-1}$. Illumination was provided by a triggered Drelloscop 3018 stroboscope with two light sources, a Drello lamp LE4040/20 and a Drello hand lamp HL4037/20. The overall experimental design is summarised above in table 3.1.

3.3.2 Spectral proper orthogonal decomposition for modal analysis

Since cloud cavitation exhibits intermittent, multimodal and chaotic behaviour, coherent structures can be difficult to identify through direct observation (Hatzissawidis, Sieber, Oberleithner, & Pelz, 2025). Thus, SPOD (Towne et al., 2018), a modal decomposition technique widely used in fluid mechanics, is applied to the high-speed photographs to identify spatial modes and their corresponding temporal frequencies. This technique has been successfully applied to cloud cavitation by Smith et al. (2020a), Venning et al. (2022), and Hatzissawidis et al. (2024).

SPOD offers benefits compared to the classically used methods such as DMD (Schmid, 2010) or POD (Lumley, 1970) outlined by Towne et al. (2018). SPOD provides single-frequency modes, rather than multi-frequency modes by POD, Lumley (1970), and ‘optimally represents the second-order space-time flow statistics’ (Towne et al., 2018). The so-called eigenmodes are ranked according to their energy at each frequency. In this study, pixel intensities are used as input values, and the general term ‘variance’ is preferred over ‘energy’, as no physical energy is obtained in this context. Only if velocity fields serve as input data, the variance equals to the turbulent kinetic energy. However, the two terms are used interchangeably for ease of understanding.

The SPOD algorithm averages the spectra by applying the discrete Fourier transform (DFT) to the time-varying data using Welch’s method (Welch, 1967). The resulting complex-valued data in the frequency domain are decomposed for each frequency using POD providing an amplitude and a phase, see Smith et al. (2020a). Usually, modal decomposition methods are applied to velocity fields obtained experimentally through PIV or in silico. Our input data are time-varying high-speed photographs of the cavitating flow field, i.e., pixel intensities. The translucency and reflection of the bubbly mixture leads to a high-pixel intensity at locations where cavitation is present.

The data from the run type ‘medium’, see table 3.1, are used that are recorded at a frame rate of 1000 Hz for 50.924 s resulting in 50924 frames, also called snapshots. The run duration includes of the order of $10^2 - 10^3$ cycles of the fundamental shedding to ensure convergence of the SPOD results. The spectra are estimated with Welch’s method, applying a Hann window with a window size N_f of 2048, and an overlap N_o of 50 %, resulting in 48 ‘blocks’, N_b (Towne et al., 2018), and a frequency resolution of 0.488 Hz. The data are zero-padded by factor 2 to double the number of frequency bins. The method is briefly introduced here as it is used in the present study; for a detailed description, see Towne et al. (2018) and Nekkanti and Schmidt (2021). A schematic of the SPOD methodology, adapted from Towne et al. (2018) is presented in figure 3.7.

The k -th snapshot at time t_k is denoted as $\mathbf{q}_k \in \mathbb{R}^N$ with N being the number of pixels. The data matrix

$$\mathbf{Q} = [\mathbf{q}_1, \mathbf{q}_2, \dots, \mathbf{q}_M] \in \mathbb{R}^{N \times M} \quad (3.6)$$

with M being the number of snapshots over time, is rearranged into smaller and overlapping blocks in time with a size of N_f , and the n -th windowed block reads

$$\mathbf{Q}^{(n)} \cdot \mathbf{w} = [w_1 \mathbf{q}_1^{(n)}, w_2 \mathbf{q}_2^{(n)}, \dots, w_{N_f} \mathbf{q}_{N_f}^{(n)}] \in \mathbb{R}^{N \times N_f}, \quad (3.7)$$

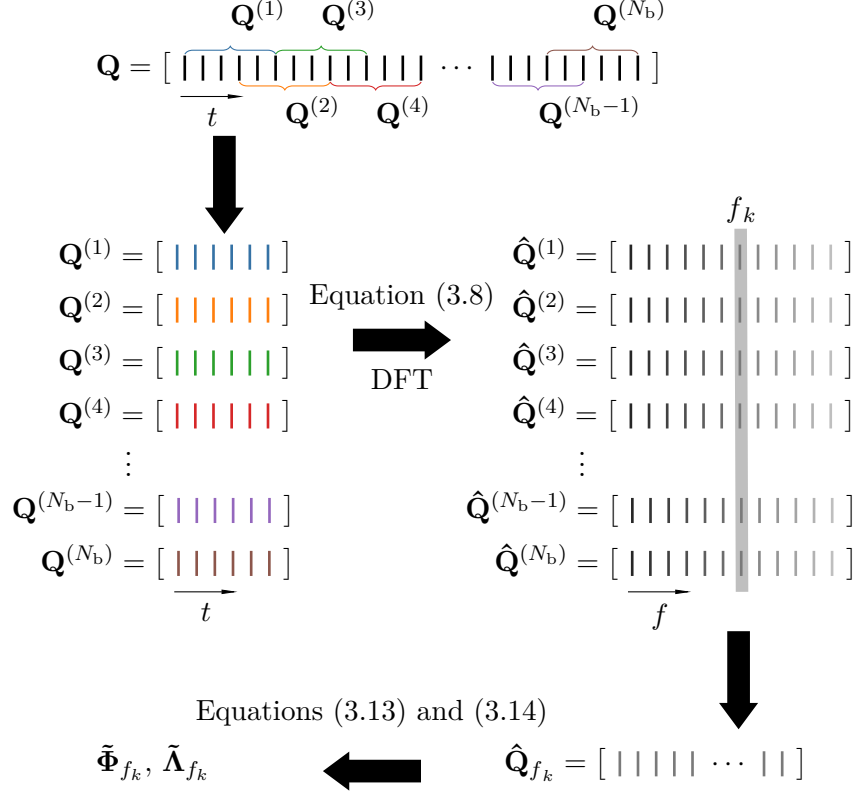


Figure 3.7: Schematic of the SPOD technique. First, the data matrix $\mathbf{Q}$ is rearranged into N_b pieces with an overlap of 50 %. These pieces are transformed into the frequency domain, by applying a DFT, leading to N_b Fourier blocks. As a result of the zero-padding, the Fourier blocks extend to twice the length of the corresponding time-domain signal, as shown schematically. The Fourier blocks are rearranged for the same frequency f_k : $\hat{\mathbf{Q}}_{f_k}$. From these, the SPOD spatial modes and the corresponding eigenvalues are calculated. The figure is adapted from Towne et al. (2018), with permission from Cambridge University Press. © 2018 Cambridge University Press.

where $\mathbf{w}$ is the window to decrease spectral leakage (Towne et al., 2018) and w_i are its components. Next, zero-padding is applied as mentioned above and the DFT of each block is calculated,

$$\hat{\mathbf{q}}_k^{(n)} = \frac{1}{2N_f \bar{\mathbf{w}}} \sum_{j=1}^{2N_f} w_j \mathbf{q}_j^{(n)} \exp \left(-i2\pi(k-1) \frac{(j-1)}{2N_f} \right) \quad (3.8)$$

where $w_j = 0$ and $\mathbf{q}_j^{(n)} = 0$ for $j > N_f$. The amplitude correction factor $\bar{\mathbf{w}}$ is $1/N_f \sum_{j=1}^{N_f} w_j$ for the Hann window, see Schmidt and Colonius (2020). The value $\hat{\mathbf{q}}_k^{(n)}$ is the k -th DFT component associated with the frequency f_k for the n -th block.

The resulting matrix in the frequency domain for the n -th block can be written as

$$\hat{\mathbf{Q}}^{(n)} = [\hat{\mathbf{q}}_1^{(n)}, \hat{\mathbf{q}}_2^{(n)}, \dots, \hat{\mathbf{q}}_{2N_f}^{(n)}] \in \mathbb{R}^{N \times 2N_f}. \quad (3.9)$$

Again, $2N_f$ discrete frequencies are obtained due to the zero-padding. The Fourier components are picked for the same frequency f_k for each block and the data are rearranged as

$$\hat{\mathbf{Q}}_{f_k} = [\hat{\mathbf{q}}_k^{(1)}, \hat{\mathbf{q}}_k^{(2)}, \dots, \hat{\mathbf{q}}_k^{(N_b)}] \in \mathbb{R}^{N \times N_b}. \quad (3.10)$$

The ‘estimated cross-spectral density tensor’ at a specific frequency f_k reads

$$\mathbf{S}_{f_k} = \frac{1}{N_b} \hat{\mathbf{Q}}_{f_k} \hat{\mathbf{Q}}_{f_k}^*, \quad (3.11)$$

where $*$ denotes its Hermitian transpose. Finally, the SPOD modes for frequency f_k can be computed from the eigenvalue problem:

$$\mathbf{S}_{f_k} \mathbf{W} \Phi_{f_k} = \Phi_{f_k} \Lambda_{f_k}. \quad (3.12)$$

$\mathbf{W}$ is a weight matrix, the columns of Φ_{f_k} are the spatial modes ranked by the corresponding variances, which are the diagonal elements of the diagonal matrix $\Lambda_{f_k} = \text{diag}(\lambda_{f_k}^{(1)}, \lambda_{f_k}^{(2)}, \dots, \lambda_{f_k}^{(N)})$. To decrease computational demands, Towne et al. (2018) proposed to solve the $N_b \times N_b$ eigenvalue problem,

$$\frac{1}{N_b} \hat{\mathbf{Q}}_{f_k}^* \mathbf{W} \hat{\mathbf{Q}}_{f_k} \Theta_{f_k} = \Theta_{f_k} \tilde{\Lambda}_{f_k}, \quad (3.13)$$

which computes the same non-zero eigenvalues (denoted by a tilde) as the $N \times N$ eigenvalue problem from equation (3.12), since usually $N_b \ll N$ is valid. This is the so-called ‘method of snapshots’ to compute the POD (Schmidt & Colonius, 2020) that dates back to Sirovich (1987). From this, the eigenvectors are computed as

$$\tilde{\Phi}_{f_k} = \frac{1}{\sqrt{N_b}} \hat{\mathbf{Q}}_{f_k} \Theta_{f_k} \tilde{\Lambda}_{f_k}^{-1/2}. \quad (3.14)$$

These eigenvectors are the spatial modes or eigenmodes. The N_b spatial modes are ranked in descending order according to their associated eigenvalues or mode variance:

$$\tilde{\Phi}_{f_k} = [\Phi_{f_k}^{(1)}, \Phi_{f_k}^{(2)}, \dots, \Phi_{f_k}^{(N_b)}]. \quad (3.15)$$

If the variance of the leading mode $\Phi_{f_k}^{(1)}$ captures the vast majority of the variance, it suffices alone to represent the dominant dynamics. Conversely, when higher order eigenmodes carry non-negligible variance, they have to be considered, which is typical for 3D shedding behaviour; by contrast, for 2D cases the leading eigenmode usually suffices. The complex SPOD modes provide information regarding the spatial occurrence of coherent structures associated with a discrete frequency. The modes are presented as absolute values, $|\Phi_{f_k}^{(i)}|$, together with the phase, $\arg(\Phi_{f_k}^{(i)})$, giving insight into the

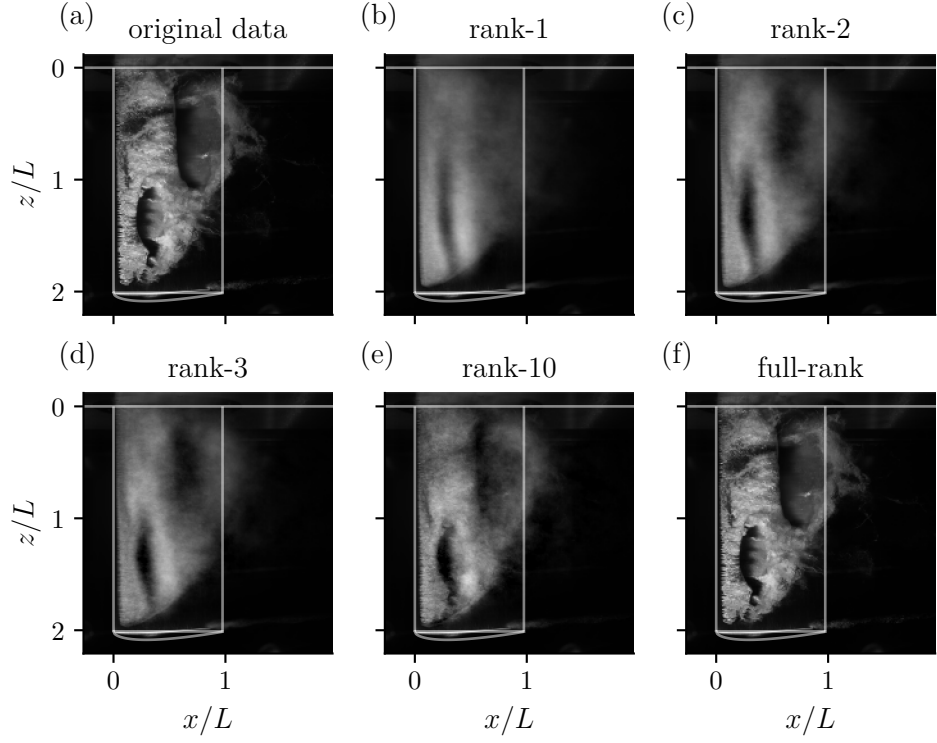


Figure 3.8: Reconstruction of an instantaneous high-speed photograph of cloud cavitation using the ‘frequency-domain approach’ (Nekkanti & Schmidt, 2021): (a) original flow field, (b) rank-1, (c) rank-2, (d) rank-3, (e) rank-10 and (f) full reconstruction of the flow field. In sum there are 48×2049 modes with 48 eigenmodes for 2049 frequencies. The operation point is $\sigma = 1.01$ and $\alpha = 13^\circ$.

shedding behaviour, as done by Smith et al. (2020a). The absolute values of the SPOD modes reveal the regions in the photograph where a particular mode has high intensity, or in other words, where the pixel intensity exhibits strong variation. They provide guidance in finding suitable locations for the space-time diagrams as mentioned above – the high-speed photographs are ‘cut’ where a high pixel intensity of the absolute value is observed. The corresponding phase reveals the relative timing of oscillation between different pixels in the flow field.

Finally, measures to quantify the ‘energy’ of the modes are introduced. $\lambda_{f_k}^{(i)}$ (diagonal elements of $\tilde{\mathbf{\Lambda}}_{f_k}$) is the variance of eigenmode i at frequency f_k . The non-dimensionalised modal ‘energy’ of eigenmode i at frequency f_k is

$$\lambda_{+,f_k}^{(i)} := \frac{\lambda_{f_k}^{(i)}}{\lambda_{f_k}}, \quad (3.16)$$

where λ_{f_k} is the cumulative variance at frequency f_k obtained by summing $\lambda_{f_k}^{(i)}$ over the

N_b eigenmodes:

$$\lambda_{f_k} = \sum_{i=1}^{N_b} \lambda_{f_k}^{(i)}. \quad (3.17)$$

The relation between the total ‘energy’ content at frequency f_k to the total ‘energy’ of the flow field reads

$$\lambda_{+, f_k} := \frac{\lambda_{f_k}}{\sum_{i=1}^{2N_f} \lambda_{f_i}}. \quad (3.18)$$

In general, the original flow field can be reconstructed from the SPOD results using the ‘frequency-domain approach’ by Nekkanti and Schmidt (2021), i.e., the inverse of the SPOD from the frequency-domain to the time-domain. In this example, the original photograph, figure 3.8 (a), is reconstructed using the leading eigenmode (rank-1 reconstruction), figure 3.8 (b), and the first two, three, and ten eigenmodes, figure 3.8 (c)-(e). The full-rank reconstruction recovers the original photograph using all 48 eigenmodes, figure 3.8 (f). The reconstruction is calculated for an instantaneous high-speed photograph exhibiting 3D behaviour of cloud cavitation in order to demonstrate that higher-order eigenmodes are necessary to represent the original photograph. At minimum, a rank-2 reconstruction is required to capture the 3D behaviour of cloud cavitation.

Chapter 4

Cavity topology and spectral analysis

This chapter provides the first part of the results, starting with the topology map and the characteristic lengths, namely the chordwise and spanwise cavity extents. The topology map of the high-resolved photographs across the four cavitation numbers and incidences is introduced as an overview. A detailed spectral analysis using the force data is conducted and spectrograms are generated for each cavitation number. Distinct peaks are identified from the spectrograms, and the four modes (i) to (iv) are introduced. The underlying physical mechanisms of the four modes are investigated in the following chapter 5. A transient analysis of the modes is conducted using the CWT of the lift coefficient. To quantify mutual mode interactions, the correlation between specific CWT coefficients is computed, indicating whether modes occur simultaneously or exclusively. The results are plotted against the parameter $\sigma/2\alpha$ derived from linear flat plate theory, which compensates for the differences in the pressure distribution with varying incidences.

The content of this chapter is taken and adapted from the following manuscript, which has been submitted to the *Journal of Fluid Mechanics*: Hatzissawidis, Russell, Venning, Pelz, and Brandner (2025a).

4.1 Global cavitation topology

As the cavitation number σ and the incidence α vary, various cavitation topologies are observed. Still photographs of the cavity topology of various operation points for varying σ and α are shown in figure 4.1, spanning cavitation regimes from incipient cavitation for high σ and low α , supercavitation for low σ and high α , and shear cavitation for high σ and α . Cloud cavitation occurs between these regimes and constitutes the focus of this study. The operation points investigated feature various shedding mechanisms and 2D and 3D behaviour, as will be described throughout this work.

The parameter $\sigma/2\alpha$, derived from the linear solution for a flat plate (Brennen, 2013, p. 230), is used to compare the operation points corresponding to different combinations of σ and α . This parameter can be imagined as a normalisation of σ that removes the incidence-induced pressure increase. Although the NACA 0015 used in this study differs from a flat plate, the agreement between the operation points for similar $\sigma/2\alpha$ is surprisingly good, as shown in figure 4.1 and the subsequent analysis. The oblique transparent lines are lines of identical $\sigma/2\alpha$. From direct observation, it can be seen that the parameter $\sigma/2\alpha$ describes fairly well the cavity topology in the cloud cavitation regime; however, as conditions approach desinent cavitation at low incidence and high cavitation

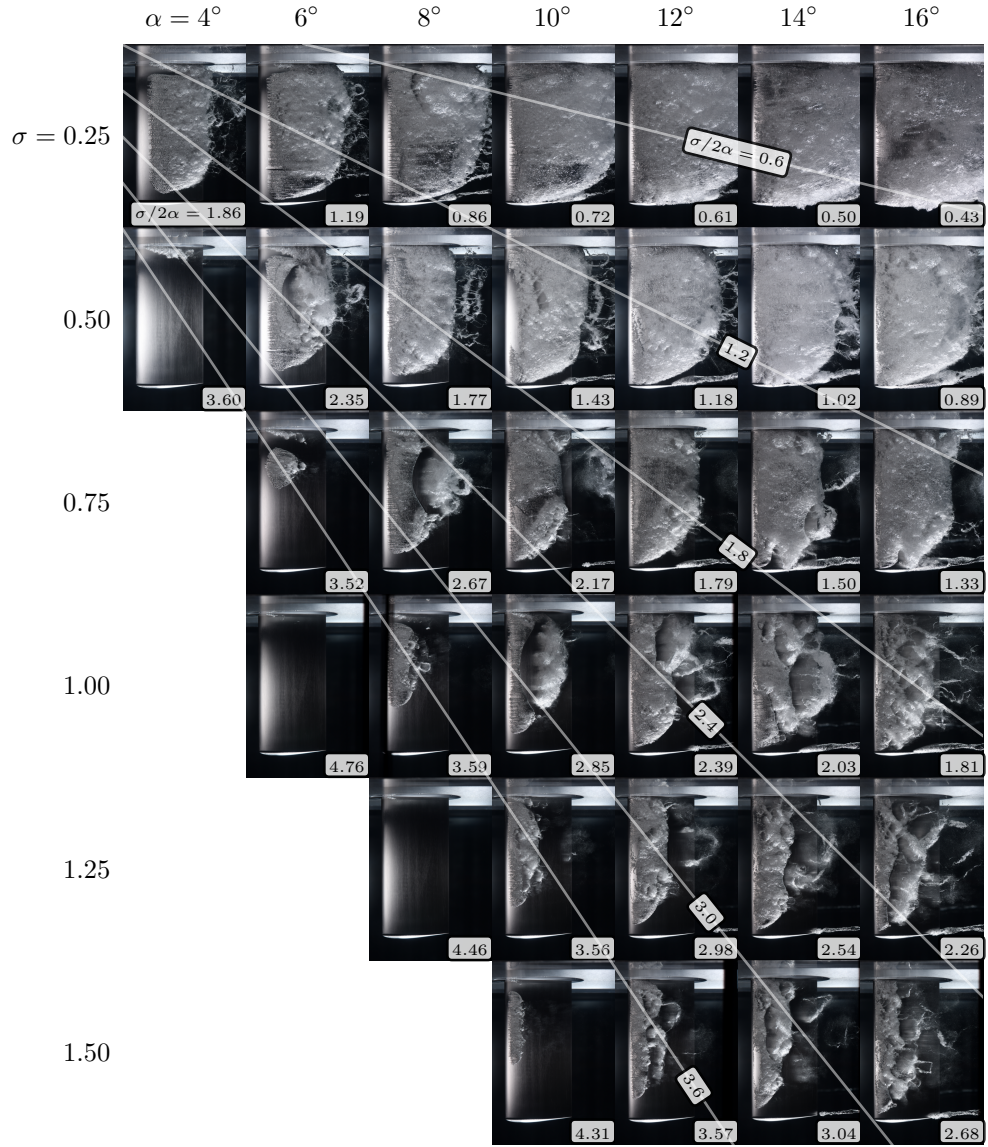


Figure 4.1: Array of still photographs showing the cavity extent and topology depending on the cavitation number σ and the incidence α . The flow direction is from left to right. The oblique transparent lines are lines of the same $\sigma/2\alpha$. The cavitation topology looks similar for similar $\sigma/2\alpha$ in the cloud cavitation regime. A supplementary movie 2 is available, showing the shedding for $\sigma = 0.75$ and $\alpha = 8^\circ, 12^\circ$ and 16° .

number or shear cavitation at high incidence and cavitation number, this parameter becomes less useful. A supplementary movie 2 from the high-speed photography is available showing the shedding for constant cavitation number and increasing incidence

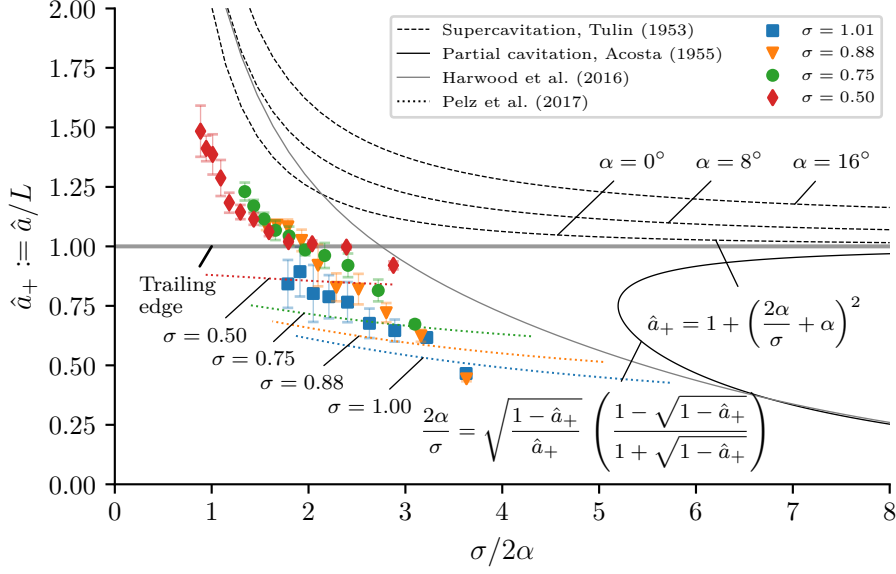


Figure 4.2: Experimentally determined maximum cavity sheet length $\hat{a}_+ := \hat{a}/L$ over $\sigma/2\alpha$ for four cavitation numbers $\sigma = 0.50, 0.76, 0.88$, and 1.01 . The cavity sheet length for $\sigma = 0.50$ exhibits a plateau when reaching the chord length. The cavity grows as σ is reduced or α is increased. For high σ and high α , the cavity growth stagnates since shear cavitation is approached. The error bars indicate the standard deviation of the identified maximum cavity lengths. The experimental data are compared to the flat plate theory by Acosta (1955) for ‘partial cavitation’ and Tulin (1953) for supercavitation, and the fitting by Harwood et al. (2016). The ‘asymptotic sheet growth model’ by Pelz et al., 2017 is also plotted. The data are available in the TUdatalib repository (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025c).

($\sigma = 0.75$ and $\alpha = 8^\circ, 12^\circ$ and 16°).

The row for $\sigma = 0.5$ shows the topology from no cavitation at $\alpha = 4^\circ$ (except for the corner vortex at the hydrofoil’s root), to almost supercavitation, 16° . Although the cavity extends beyond the hydrofoil’s trailing edge, periodic cloud cavitation is still present – contrary to what is reported in the literature, cf. Le et al. (1993a) and Franc and Michel (2005, pp. 132–133). Cavitation exhibits pronounced 3D topology at high cavitation numbers ($\sigma = 1.00, 1.25, 1.50$) and a high incidence of 16° , approaching the onset of shear cavitation.

Next, the characteristic lengths that govern the observed cavitation topologies are introduced and discussed. The non-dimensionalised maximum cavity sheet length, $\hat{a}_+ := \hat{a}/L$, is determined from the high-speed photographs of the run type ‘short’ (table 3.1), defined as the maximum streamwise extent of cavity in the cloud cavitation regime immediately prior to shedding, figure 4.2. The spanwise position used to determine the cavity length corresponds to the location of the maximum cavity extent, which may

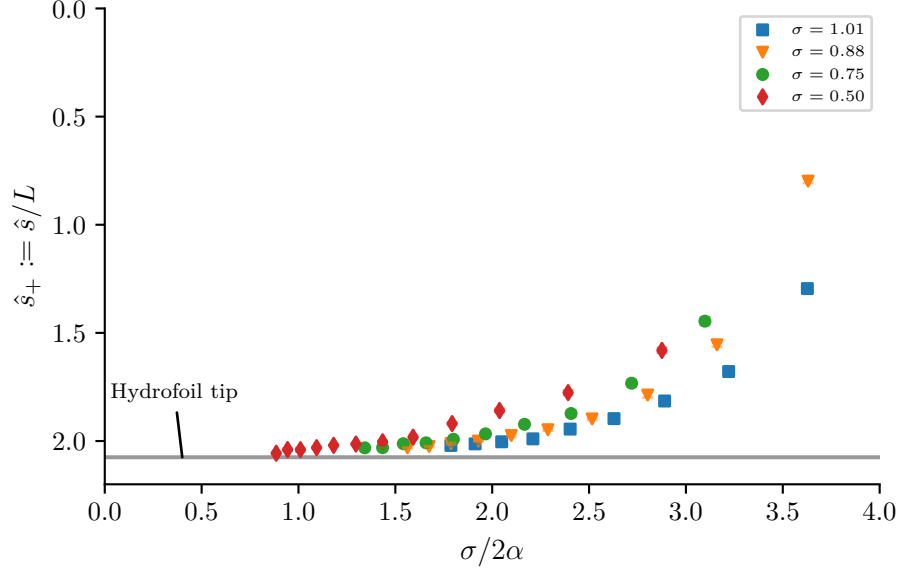


Figure 4.3: Experimentally determined cavity spanwise extent $\hat{s}_+ := \hat{s}/L$ over $\sigma/2\alpha$ for four cavitation numbers $\sigma = 0.50, 0.76, 0.88$, and 1.01 . The spanwise extent of the cavity approaches the hydrofoil’s tip as $\sigma/2\alpha$ is decreased. The data are available in the TUdataalib repository (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025c).

vary from cycle to cycle. Depending on the operation point, cycles of the order of 10^1 to 10^2 were included for the determination of the cavity length. The maximum cavity sheet length for cloud cavitation is obtained by averaging the maximum cavity sheet length determined in each cycle, yielding a mean value and a standard deviation. It should be mentioned that in cases approaching shear cavitation, however, the 3D behaviour of the cavitation made it difficult to identify distinct cycles. For the case of sheet cavitation, the time-average cavity length is determined. The error bars indicate the standard deviation of the identified maximum cavity lengths. The cavity sheet length $\hat{a}_+$ for four cavitation numbers is plotted as a function of $\sigma/2\alpha$, see figure 4.2. As foreseen, the maximum cavity sheet length increases as $\sigma/2\alpha$ decreases.

The experimental data are compared with the cavity sheet length predicted for a flat plate under ‘partial cavitation’ (Acosta, 1955) and supercavitation (Tulin, 1953), as well as with a fitted correlation proposed by Harwood et al. (2016). The experimental data and the models do not match well. A significant discrepancy is observed between the prediction for a flat plate under ‘partial cavitation’ and the experimental data.

The ‘asymptotic sheet growth model’ developed by Pelz et al. (2017) and applied in the recent study by Hatzissawidis, Kuhr, and Pelz (2025) is also plotted for the four cavitation numbers investigated in this study, figure 4.2 (dotted lines). For this model, the pressure distribution along the hydrofoil is needed. The pressure distributions with varying incidence are estimated using the XFLR5 software (Deperrois, 2023). The square

of the dimensionless nucleation rate is set to 0.25 which is of the same order of magnitude as in the study by Pelz et al. (2017). In general, the model reproduces the observed trend: the maximum cavity sheet length increases with decreasing $\sigma/2\alpha$ and decreasing σ .

For the larger cavitation numbers, 0.88 and 1.01, the fundamental shedding is primarily driven by the re-entrant flow (coupled with a condensation shockwave and introduced as mode (iv) in section 4.2.2) that is dominant in the range of approximately $\sigma/2\alpha = 2$ to 3, exhibiting the same trend in both cases. Here, the maximum cavity sheet length is always lower than the chord length of the hydrofoil. At lower values of $\sigma/2\alpha$ the regime transitions to shear cavitation, and the growth of the cavity length stagnates. For $\sigma = 0.88$ the shockwave-driven cloud cavitation mode (introduced as mode (i) in section 4.2.2) is more pronounced than for $\sigma = 1.01$, allowing the cavity length to grow beyond the chord.

Cloud cavitation at the lower cavitation numbers, 0.50 and 0.76, is primarily driven by condensation shockwaves, mode (i), and a stagnation in cavity growth – interpreted as a ‘lock-in’ effect in section 5.3 – can be observed around $\hat{a}_+ = 1$, consistent with the observation of Smith et al. (2020a) and Smith et al. (2020b). This stagnation in cavity growth is more pronounced for $\sigma = 0.50$, where the maximum cavity sheet remains about unity, i.e., $\hat{a}_+ \approx 1$ for about $1.6 < \sigma/2\alpha < 2.5$. As shown in section 5.3, the trailing edge of the hydrofoil acts as a trigger mechanism for a shockwave, being consistent with the observation of Hatzissawidis, Kuhr, and Pelz (2025). For lower values of $\sigma/2\alpha$, the cavity length curves become steeper, indicating a transition towards the onset of supercavitation. This trend can be observed for both cavitation numbers, 0.50 and 0.76, reaching values up to 1.5 and 1.25, respectively.

The non-dimensionalised spanwise extent of the cavity, $\hat{s}_+ := \hat{s}/L$, is also determined from the data with the run type ‘short’, see figure 4.3. For all cavitation numbers, the spanwise extent of the cavity approaches the hydrofoils tip with decreasing $\sigma/2\alpha$, following the same trend.

4.2 Force measurements, spectral content, and characteristic frequencies

After a first picture of the topology is obtained, the spectral content is determined and analysed. Starting with a simple analysis of the steady and unsteady parts of the force measurements, spectrograms using Welch’s method are generated, and the modes (i) to (iv) are introduced. The peaks of these spectra are identified and plotted against $\sigma/2\alpha$ to reveal the similarities between the four cavitation numbers. This summarises the spectrograms in one figure. The results are then compared with data from the literature for the same hydrofoil.

4.2.1 Steady and unsteady analysis of the force measurements

A first insight into the shedding dynamics is obtained by evaluating the mean, indicated by $\overline{(\cdot)}$, and the standard deviation, indicated by $(\cdot)'$, of the lift coefficient C_L , and the

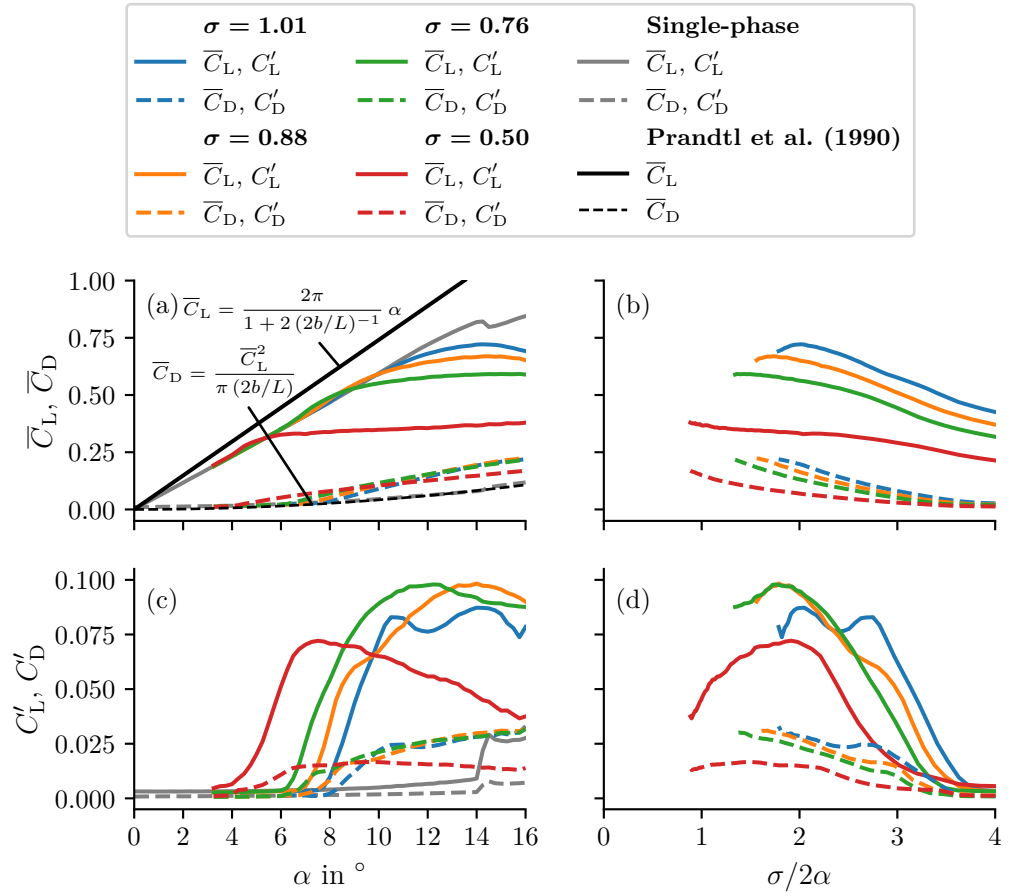


Figure 4.4: Mean, (a) and (b), and standard deviation, (c) and (d), of the lift and drag coefficient, denoted as $\overline{C}_L, C'_L, \overline{C}_D, C'_D$, respectively, over α , (a) and (c), and $\sigma/2\alpha$, (b) and (d), for the four cavitation numbers $\sigma = 0.50, 0.76, 0.88, 1.01$ and the single-phase flow. The black solid and dashed line represents the prediction of $\overline{C}_L$ and $\overline{C}_D$, respectively, from the airfoil theory with finite span and elliptical lift distribution (Anderson, 2017, p. 455) by Prandtl et al. (1990, pp. 448–449). The data are available in the TUDatalib repository (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025c).

drag coefficient C_D . The data used are from the run type ‘long’, during which forces were recorded for 240 s, see table 3.1. The mean and standard deviation of C_L and C_D for the four cavitation numbers investigated, as well as for the single-phase flow, are depicted in figure 4.4 as a function of incidence (figure 4.4 (a) and (c)) and as a function of $\sigma/2\alpha$ (figure 4.4 (b) and (d)).

For the single-phase flow, as α is increased, both $\overline{C}_L$ and $\overline{C}_D$ increase until stall occurs at about 14° , leading to a slight reduction in $\overline{C}_L$, figure 4.4 (a). The standard deviation of the lift coefficient, C'_L , which quantifies its unsteady component, increases abruptly

indicating the onset of stalled flow, figure 4.4 (c). For comparison, the airfoil-theory prediction of the lift and drag coefficient by Prandtl et al. (1990, pp. 448–449), assuming a ‘finite elliptic wing’ (Anderson, 2017, p. 455) with an elliptical lift distribution is plotted in figure 4.4 (a). The aspect ratio is set to $2b/L$ in the equations by Prandtl et al. (1990, pp. 448–449) (see figure 4.4 (a)), since the tunnel ceiling wall acts as a reflection plane. The predicted lift coefficient exhibits a higher slope of about $4/3\pi$ compared to the measured lift, which can be attributed to the effect of the ceiling boundary layer in reducing the effective aspect ratio. The theoretical drag coefficient seems to predict the measured value well; however, no firm conclusions can be drawn because it is computed from the theoretical lift coefficient, which is not realised. Compared to single-phase flow, the onset of cavitation results in a decrease in $\overline{C}_L$ and a corresponding increase in $\overline{C}_D$, figure 4.4 (a). As σ is reduced, $\overline{C}_L$ decreases. At high α and $\sigma = 0.50$, the onset of supercavitation is reached and $\overline{C}_D$ is lower than for the other cavitation numbers, despite the larger extent of cavitation, see figure 4.4 (a). This demonstrates the effect of drag reduction associated with supercavitation. The corresponding standard deviation of the drag coefficient, C'_D , decreases, see figure 4.4 (c) and (d).

The quantities are also plotted as functions of $\sigma/2\alpha$, which provides a better alignment between the four cavitation numbers. The standard deviations C'_L and C'_D initially increase as $\sigma/2\alpha$ is reduced, being one order of magnitude larger than in the single-phase flow. This reveals the influence of cavitation on the forces acting on the hydrofoil. The maximum lift fluctuations for $\sigma = 0.50$ and 0.76 are $C'_L = 0.072$ and 0.098 , respectively, observed at $\sigma/2\alpha = 1.92$ and 1.76 , figure 4.4 (d). As will be described later, cloud cavitation across this incidence range is driven by condensation shockwaves, mode (i), so the magnitude of the lift fluctuations reflects the intensity of this dominant shedding mechanism, see figure 4.5 (c) and (d).

For $\sigma = 1.01$, C'_L the curve is bimodal with two distinct peaks at $\sigma/2\alpha = 2.05$ ($\alpha=14^\circ$) and 2.75 ($\alpha=10.5^\circ$) and the corresponding values are $C'_L = 0.087$ and 0.083 , respectively, see figure 4.5 (c) and (d). For $\sigma = 0.88$, C'_L exhibits a stagnation around $\sigma/2\alpha = 2.7$; however, there is only one dominant peak at $\sigma/2\alpha = 1.79$ ($\alpha=14^\circ$), $C'_L = 0.098$. This is the intermediate behaviour between $\sigma = 0.75$ and 1.01 , where the former shows only one distinct peak. For these two larger cavitation numbers, 0.88 and 1.01 , the fundamental shedding transitions from coupled re-entrant flow/shockwave-driven (iv) to condensation shockwave-driven (i) as $\sigma/2\alpha$ is reduced or α is increased. This becomes evident in figure 4.5 (a) and (b), and the underlying mechanism will be discussed later in section 5.4. Interestingly, during the transition phase for $\sigma = 1.01$ at about $\sigma/2\alpha = 2.5$, where both modes (i) and (iv) occur, the unsteadiness (C'_L) exhibits a local minimum (see figure 4.5 (d)), and the most energetic shedding is located at the two distinct peaks associated with mode (i) and (iv).

It is evident that $\sigma/2\alpha$ from the linear flat plate theory cannot be applied to the hydrofoil in this study to collapse the curves, and the influence of the cavitation number on the mean and standard deviation of the force coefficients remains significant. However, the maximum values of C'_L for mode (i) occur at similar $\sigma/2\alpha$ around $1.8 - 2.1$. Further, a consistent trend is observed for all cavitation numbers: C'_L initially increases as $\sigma/2\alpha$ is reduced, reaching a maximum at the onset of cloud cavitation. With further reduction

of $\sigma/2\alpha$, the unsteadiness decreases due to the transition to supercavitation or shear cavitation. This trend is in agreement with the measurements by Venning et al. (2022), in which σ is varied at a fixed incidence.

4.2.2 Spectral content and modes

The spectrograms of C_L are generated for the four cavitation numbers using Welch's method to estimate the PSD as described in section 3.1.3. The spectrograms show the PSD as a function of $\sigma/2\alpha$ and both the frequency, f , and the chord-based Strouhal number, $St := fL/U_\infty$, in figure 4.5. For comparison, the corresponding spectrograms as a function of the incidence are shown in figure E.2 in the appendix E. It can be seen that the use of the parameter $\sigma/2\alpha$ results in a reasonable alignment of the spectrograms. Although the hydrofoil is far from a flat plate, this agreement is surprisingly good. However, as will be shown later, the modal characteristics, in terms of their relative dominance and ranges of occurrence, vary with cavitation number. The amplitude scale is kept the same for all cavitation numbers to allow for direct comparison. The data used are of the run type 'long' with 0.25° increments for α .

The spectrograms provide a global overview of the mode responses with varying $\sigma/2\alpha$. All four spectrograms are vertically aligned with respect to $\sigma/2\alpha$ to highlight the similarities between the cavitation numbers. For $\sigma = 1.01$ (figure 4.5 (a)), as $\sigma/2\alpha$ is decreased, immediately after inception and quasi-steady sheet cavitation, re-entrant flow-driven cloud cavitation (mode (iv)) occurs at about $\sigma/2\alpha = 3.5$. The frequency is invariant regarding a further reduction in $\sigma/2\alpha$, or equivalently an increase in incidence, see figure 4.5 (a).

Despite the presence of some periodic characteristics, quasi-steady sheet cavitation does not exhibit distinct peaks or strong oscillations in the forces; instead, it leads to a broadband increase in the spectrum (Smith et al., 2020a). Interfacial instabilities cause the shedding of small-scale horseshoe vortices, i.e., K-H instabilities, as reported by Brandner et al. (2010), see figure 4.1 for $\sigma = 1.00$ and $\alpha = 8^\circ$. This regime is observed within a narrow range of $\sigma/2\alpha$, since a modest increase in incidence (or a reduction in $\sigma/2\alpha$) leads to a growth in cavity length. At this point, the trailing edge of the cavity reaches an increased adverse pressure gradient leading to re-entrant flow-driven cloud cavitation (Gopalan & Katz, 2000; Callenaere et al., 2001), mode (iv), see figure 4.5 (a). Here, mode (iv) is the only mode present, i.e., the cavitation behaviour is unimodal, peaking at $\sigma/2\alpha = 2.81$ or $\alpha = 10.25^\circ$, with a Strouhal number of $St_{iv} = 0.53$. The increase in cavity length as $\sigma/2\alpha$ is reduced did not result in the expected decrease in the Strouhal number, which remains approximately constant, see figure 4.5 (a). This observation is discussed in detail in section 5.1.2.

The cavity length continues to increase as $\sigma/2\alpha$ is further reduced and condensation shockwaves appear: Mode (i) appears together with the low-frequency mode (ii) and high-frequency mode (iii), peaking at $\sigma/2\alpha = 1.98$ with $St_i = 0.34$. As expected from Venning et al. (2022), mode (ii) and (iii) are not simply the subharmonic and superharmonic of mode (i). Rather, mode (iii) contains both a harmonic artefact and physical modes, as discussed later in section 4.3 and in chapter 5. A further reduction in $\sigma/2\alpha$, achieved by

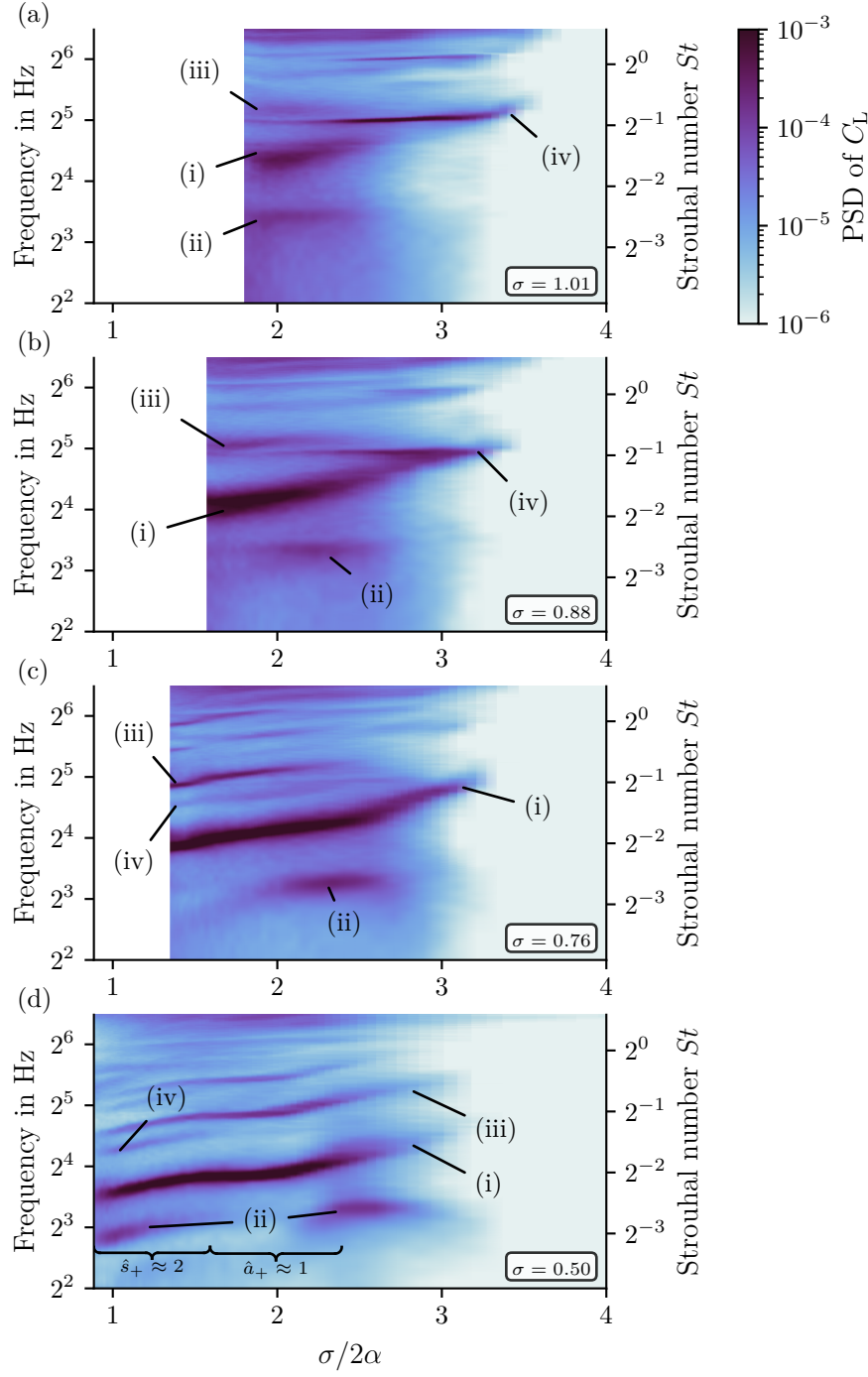


Figure 4.5: Spectrograms of the estimated PSD of the lift coefficient C_L showing the frequency and the Strouhal number over $\sigma/2\alpha$ for constant cavitation numbers $\sigma = 1.01, 0.88, 0.76, 0.50$, (a), (b), (c), (d), respectively, at constant Reynolds number of $Re = 8 \times 10^5$. The four modes (i) to (iv) are annotated within the spectrograms. It is also annotated where the cavity length equals the chord, $\hat{a}_+ = 1$, and the spanwise extent reaches the hydrofoil's tip, $\hat{s}_+ = 2$, see (d). The data are available in the TUdataLib repository (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025c).

increasing the incidence, leads to a decrease in the PSD of mode (i). At this point, the cavity length no longer increases, figure 4.2, and the cavitation becomes something akin to shear cavitation, characterised by the shedding of multiple clouds, see figure 4.1 for $\sigma = 1.00$ and $\alpha = 16^\circ$.

The same general behaviour observed for $\sigma = 1.01$, figure 4.5 (a), can be seen when reducing σ to 0.88, figure 4.5 (b), albeit with some differences. Mode (i) extends over a broader range of $\sigma/2\alpha$ and reaches its peak at $\sigma/2\alpha = 1.78$. The PSD associated with mode (i) is about four times larger than the peak observed for $\sigma = 1.01$. In contrast, mode (iv) peaks at $\sigma/2\alpha = 2.88$, with the corresponding PSD being four times lower than the peak for $\sigma = 1.01$ for mode (iv). Once again, the shedding frequency of mode (iv) is invariant with changes in $\sigma/2\alpha$. In contrast, the frequency of mode (i) varies with $\sigma/2\alpha$, which can be seen in the spectrograms for the two lower cavitation numbers, figure 4.5 (c) and (d).

The results fit into the existing literature, where re-entrant flow-driven and shockwave-driven cloud cavitation have been associated with a higher and lower Strouhal number, respectively, as shown by Arndt et al. (2000), and supported by recent studies (Smith et al., 2020a; Hatzissawidis, Kuhr, & Pelz, 2025). However, contrary to expectation, where the Strouhal number associated with shockwave-driven cloud cavitation was believed to exhibit no significant variation with $\sigma/2\alpha$ (see Kjeldsen et al., 2000 and many others), it is clearly evident here that it does.

One possible explanation for the apparent contradiction among studies regarding the Strouhal number trend in shockwave-driven cloud cavitation is the variation in dissolved oxygen concentration between the experiments. Kawakami, Fuji, et al. (2008) reported a dependence of the Strouhal number on the cavitation number for low gas content (≈ 7 ppm), while no such dependence was observed for higher gas content (≈ 13 ppm). The experiments in the present study are conducted at lower gas content (3 to 3.3 mg L⁻¹) and show a dependence, which is consistent with the findings of Kawakami, Fuji, et al. (2008). A similar trend was observed by Venning et al. (2022) at a dissolved gas content of about 3 ppm. However, Smith et al. (2020a) and Hatzissawidis, Kuhr, and Pelz (2025) did not report a significant dependence of the Strouhal number at about 3 – 4 ppm and 4 – 8 ppm, respectively. In these cases, the Strouhal number was about half the value observed in previous studies, see figure 4.7. The initial assumption relating the behaviour of the Strouhal number to the dissolved oxygen concentration can be discarded, as no clear trend is observed. This remains an open question that requires systematic measurements.

For the lower cavitation numbers, 0.50 and 0.76, mode (iv) appears only weakly in conjunction with mode (i) at lower values of $\sigma/2\alpha$, whereas mode (i) remains the fundamental mode. Since mode (i) is associated with condensation shockwaves, a critical cavitation number, somewhere between 0.88 and 0.76, is reached at which the re-entrant flow, as the fundamental shedding mechanism, is completely suppressed.

Mode (ii) occurs only in conjunction with mode (i) for all cavitation numbers. Interestingly, for the lowest cavitation number, 0.50, mode (ii) has two peaks at approximately $\sigma/2\alpha = 2.49$ and 1.01. Between these values, mode (ii) vanishes, while the frequency of mode (i) remains constant, exhibiting a plateau. This coincides with a stagnation of the

non-dimensionalised cavity length at unity, see figure 4.2. Additionally, the shockwave is triggered at the trailing edge of the hydrofoil and the shedding appears strongly coherent, see section 5.3. The range in which the cavity length is constant is highlighted in figure 4.5 (d). With a further reduction of $\sigma/2\alpha$, mode (ii) reappears. This coincides with the spanwise extent of the cavity, $\hat{s}$, reaching the tip of the hydrofoil, i.e., $\hat{s}_+ := \hat{s}/L \approx 2$, highlighted in figure 4.5 (d). Although this plateau is not observed for $\sigma = 0.76$, a similar effect can still be seen: At $\sigma/2\alpha \approx 2$, the cavity sheet length reaches unity and exhibits a slight stagnation in growth, see figure 4.2, accompanied by a diminishing mode (ii), figure 4.5 (c). As mode (ii) vanishes and the shedding becomes unimodal, the energy of mode (i) reaches its maximum at $\sigma/2\alpha \approx 1.9$ for both cavitation numbers, 0.50 and 0.76.

Mode (iii) also appears only in conjunction with mode (i) for all four cavitation numbers, figure 4.5, and might initially be interpreted as a superharmonic artefact of mode (i), as its frequency appears to be twice that of mode (i). However, the ratio of their frequencies does not consistently follow the expected factor of two, as detailed in section 4.3. In fact, mode (iii) is identified as a distinct physical mode in section 5.5, although it also exhibits a superharmonic component depending on the operation conditions.

The spectrograms for the four cavitation numbers show similar patterns; however, the transition from mode (iv) to mode (i) as fundamental shedding mode, or, in other words, from re-entrant flow to condensation shockwaves, as σ is reduced, becomes clearly evident. The parameter $\sigma/2\alpha$ aligns the spectrograms effectively, especially regarding cavitation inception. However, mode (ii) shifts towards higher values of $\sigma/2\alpha$ with decreasing σ . The characteristic frequencies of modes (i) to (iv) for the four cavitation numbers will be discussed in section 4.2.3.

4.2.3 Characteristic frequencies

The characteristic frequencies of mode (i) to (iv), along with the corresponding peaks of the estimated PSD of C_L , are extracted from the spectrograms in figure 4.5 for the four cavitation numbers and presented in figure 4.6 (a).

Non-dimensionalising the frequency by the chord (L) and the cavity velocity ($U_\infty\sqrt{1+\sigma}$), derived from ‘Bernoulli’s theorem’, the cavity velocity-based Strouhal number is defined as

$$St^* := \frac{fL}{U_\infty\sqrt{1+\sigma}} \quad (4.1)$$

(Breslin & Andersen, 1993). Using the cavity velocity-based Strouhal number results in better overlapping of the data compared to the chord-based Strouhal number, see figure 4.6 (a) vs. (b). For improved visualisation, selected spectra (PSD versus St^*) at identical values of $\sigma/2\alpha$ across the four cavitation numbers are shown in figure E.3 in appendix E.

The size of the dots are scaled for each mode independently based on PSD for better visualisation. The dots corresponding to modes (i) to (iv) for the four cavitation numbers are densely clustered in four distinct regions. Mode (ii) peaks at two different regions for $\sigma = 0.50$, as shown above. The reappearance of mode (ii) at low $\sigma/2\alpha$ coincides with a weakening of mode (i). Data from Venning et al. (2022) where the cavitation

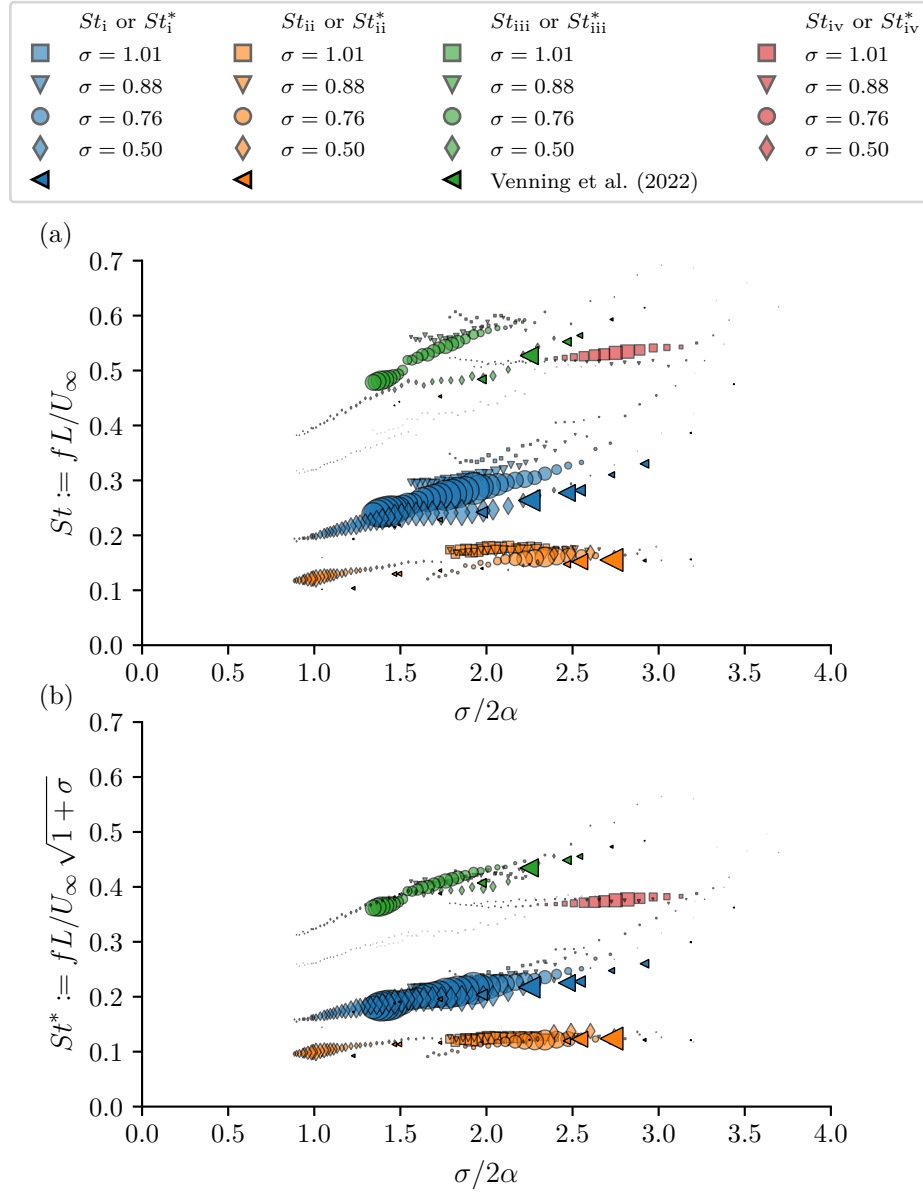


Figure 4.6: (a) Chord-based Strouhal number St and (b) cavity velocity-based Strouhal number St^* over $\sigma/2\alpha$ for the four cavitation numbers: $\sigma = 1.01$ (squares) 0.88 (downward-pointing triangles) 0.76 (circles) 0.50 (diamonds). The colours denote modes (i), (ii), (iii) and (iv). Data from Venning et al. (2022) (left-pointing triangles) are also included for a NACA 0015 hydrofoil with the same aspect ratio and a larger chord of 150 mm, with the occurrence of modes (i) to (iii). The marker sizes are scaled independently for each mode for better visualisation. The data show a better collapse when using the cavity velocity-based Strouhal number. The data are available in the TUDatalib repository (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025c).

number was varied are overlaid, exhibiting the same pattern for modes (i) to (iii). The diminishing of mode (ii) with its reappearance at lower $\sigma/2\alpha$ is also evident in the data by Venning et al. (2022), although the reappearance at low $\sigma/2\alpha$ is less pronounced. Interestingly, although Venning et al. (2022) used a NACA 0015 hydrofoil with the same aspect ratio and a larger chord length of 150 mm in the same cavitation tunnel, the observed pattern is shifted towards higher values of $\sigma/2\alpha$ and re-entrant flow-driven mode (iv) is absent. The shift may be attributed to the larger Reynolds number of 1.4×10^6 considered by Venning et al. (2022), as well as to scaling effects. The absence of mode (iv) can be attributed to the fixed low incidence of 6° in Venning et al. (2022). The adverse pressure gradient may be insufficient for the onset of re-entrant flow-driven cloud cavitation, with condensation shockwaves instead dominating the shedding. Furthermore, at such a small incidence, the cavitation number must be reduced substantially in order to induce cloud cavitation, exceeding the critical cavitation number (Pelz et al., 2017; Hatzissawidis, Kuhr, & Pelz, 2025) which defines the transition from re-entrant flow to shockwave-driven cloud cavitation. As a consequence, the fundamental shedding is dominated by condensation shockwaves. As becomes clear in the data, the critical cavitation number at which re-entrant flow does no longer appear as a fundamental mode lies between 0.76 and 0.88, see figure 4.5. The periodic shedding observed in Venning et al. (2022) occurs at $\sigma < 0.8$ which aligns with the findings of this study, where re-entrant flow is not observed. Although there are differences in operation conditions, including the variation of σ at fixed α versus α at fixed σ and differences in Re , the pattern aligns remarkably well when plotted against $\sigma/2\alpha$.

As shown in figure 4.6 (b), the slope of the frequency of mode (iv) is lower than that of mode (i), contrary to expectations. Specifically, the variation of the Strouhal number associated with shockwave-driven cloud cavitation exhibits a stronger dependence on $\sigma/2\alpha$ than re-entrant flow-driven cloud cavitation. However, mode (i) is associated with lower frequencies than mode (iv) and occurs at lower $\sigma/2\alpha$, as expected, see the inter-study comparison in section 2.2.2.

The characteristic frequencies identified in this study are compared with data from the inter-study comparison (section 2.2.2), which includes numerous studies on cloud cavitation about a NACA 0015 hydrofoil (except for Smith et al., 2020a, who investigated a NACA 0009), see figure 4.7. For this comparison, the cavity velocity-based Strouhal number, equation (4.1), is used, as it provides better data collapse than the chord-based Strouhal number, see figure 4.6. This can be attributed to the choice of the characteristic velocity, whereby the cavity velocity predicted by irrotational flow theory more accurately represents the re-entrant flow velocity and thus compensates for these differences. As will be shown in section 5.1.2, the irrotational flow theory alone does not fully explain the behaviour; the adverse pressure gradient and the initial momentum also affect the re-entrant flow velocity. For comparison, figure E.1 in appendix E presents the same data plotted using the chord-based Strouhal number. As noted previously, the data points exhibit inter-study scattering, see section 2.2.2.

The data of this study fall within a range of $\sigma/2\alpha$ from about 1 to 3, whereas the literature data extend up to 10. This discrepancy may arise because the present study focuses on lower cavitation numbers compared with the literature. The Strouhal number

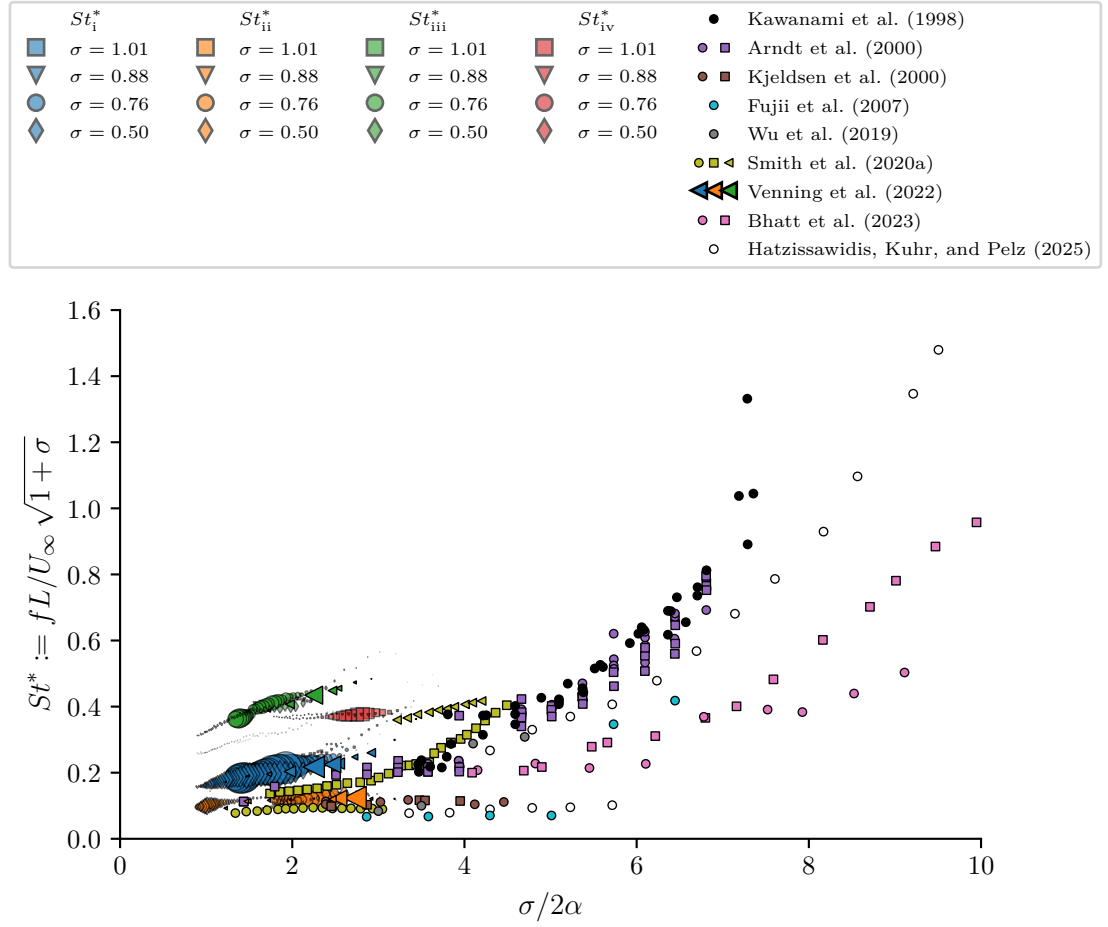


Figure 4.7: Comparison of studies on a NACA 0015 hydrofoil with the present work regarding the cavity velocity-based Strouhal number St^* over $\sigma/2\alpha$. Values are calculated based on the information provided within the respective studies. Results from the present study are shown for the four cavitation numbers: $\sigma = 1.01$ (squares), 0.88 (triangles), 0.76 (circles), 0.50 (diamonds). The colours (blue, orange, green, red) represent the four modes (i), (ii), (iii), (iv), respectively. For comparison, data from Venning et al. (2022) for varying cavitation number and otherwise constant parameters are plotted using the same colour scheme for modes (i) – (iii), represented by the leftward triangles. Additional reference data include: Kawanami et al. (1998) for four different free-stream velocities (black circles); Arndt et al. (2000), with free-stream velocities of 8 m s^{-1} and 10 m s^{-1} (purple squares and circles); Kjeldsen et al. (2000), at incidences of 6° and 7° (brown circles and squares); Fujii et al. (2007), at an incidence of 8° (cyan circles); Wu et al. (2019), at an incidence of 10° (grey circles); Smith et al. (2020a), using a three-dimensional trapezoidal NACA 0009 hydrofoil at 6° for shockwave, re-entrant flow with root and tip shedding modes (yellow circles, squares and leftward triangles); Bhatt et al. (2023), at incidences of 7° and 10° (pink circles and squares); and Hatzissawidis, Kuhr, and Pelz (2025), at 12° (white circles).

associated with shockwaves is also higher than that reported in the literature.

The studies in section 2.2.2 focus on the fundamental, dominant shedding. In addition to the fundamental shedding modes, as (i) and (iv) of our study, secondary modes, such as the low-frequency mode (ii) observed in our experiments, can be detected. This mode is approximately half the frequency of the fundamental mode (i). These secondary modes can also be more energetic than the fundamental modes, potentially leading to incorrect identification of the fundamental shedding dynamics. In general, cavitation is multimodal (Wu et al., 2019; Hatzissawidis, Sieber, Oberleithner, & Pelz, 2025), and a more detailed analysis is required to fully understand the shedding modes. Now, the aim is to investigate whether these modes occur simultaneously or exclusively, as well as to determine their frequency ratio to distinguish between superharmonics of the fundamental modes as artefacts or distinct physical modes.

4.3 Transient behaviour and correlation between modes

Thus far, time has not been treated as a parameter; this section conducts a transient analysis of the lift coefficient using CWT to represent the frequency spectrum as a function of time. This reveals whether the modes occur simultaneously, exclusively, or intermittently. The ratios of the mode frequencies are evaluated to determine whether a mode is a harmonic artefact or a physical mode; a ratio of two indicates a harmonic artefact. A physical mode is defined as a shedding event evident within the high-speed photographs, whereas a harmonic artefact occurs to rebuild a non-sinusoidal signal. Finally, the correlation between modes is computed using the CWT components at the specific mode frequencies, with the Pearson correlation coefficient (PCC) providing a measure of the correlation. In sum, this section relates the previously identified modes and clarifies their temporal behaviour and harmonic relation.

4.3.1 Transient analysis using continuous wavelet transform

The Morlet CWT, see section 3.2, of the lift coefficient C_L shows how the intensity of the modes varies over time. For the high cavitation number of 1.01, the absolute values of the CWT for the transition from unimodal mode (iv) to mode (i) shedding, corresponding to $\sigma/2\alpha = 2.89, 2.40$ and 2.05 , are plotted, figure 4.8 (a), (c), (e), with its corresponding time-averaged CWT, figure 4.8 (b), (d), (f). For $\sigma/2\alpha = 2.89$, which corresponds to an incidence of 10° , the cavitation is unimodal and highly coherent, with mode (iv), $St_{iv} = 0.54$, occurring throughout the whole time duration, figure 4.8 (a). The corresponding time-averaged CWT, figure 4.8 (b), exhibits exclusively one strong peak at this frequency. The shedding mechanism of mode (iv) corresponds to a coupled re-entrant flow with a condensation shockwave at the leading edge, as discussed in detail in section 5.1, see also de Graaf et al. (2017) for a similar mechanism about a sphere.

When $\sigma/2\alpha$ is reduced to 2.40 by increasing the incidence to 12° , the transitional regime from mode (iv) to mode (i) appears. As the maximum cavity length increases from 0.65 at $\alpha = 10^\circ$ to 0.77 at $\alpha = 12^\circ$ (figure 4.2) the re-entrant flow-driven cloud cavitation, mode (iv), weakens, with shockwaves becoming increasingly pronounced. While a higher

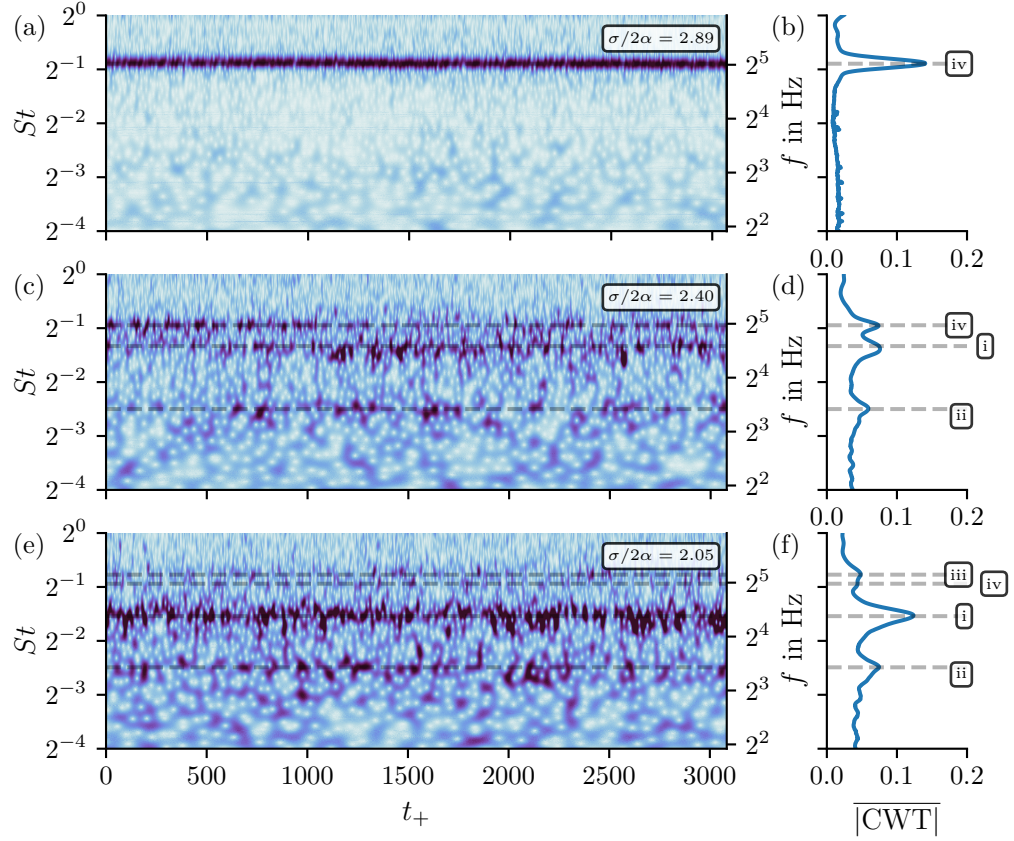


Figure 4.8: (a), (c), (e) show the absolute value of the CWT of the lift coefficient for a cavitation number σ of 1.01 and an incidence α of 10° , 12° and 14° , ($\sigma/2\alpha = 2.89, 2.40, 2.05$), respectively. (b), (d), (f) show the corresponding CWT averaged over the time. The fundamental shedding undertakes a transition from mode (iv) ($St_{iv} = 0.54$), (a) and (b), to mode (i) ($St_i = 0.34$), (e) and (f), respectively. Low mode (ii) ($St_{ii} = 0.18$, (c), (d) and (e), (f)) and mode (iii) ($St_{iii} = 0.59$, (e), (f)) occur in conjunction with mode (i). The physical duration corresponds to 51 s.

incidence results in a stronger adverse pressure gradient, the cavity sheet closes further downstream, where the adverse pressure gradient is lower, with the latter likely exerting a more dominant influence. Another mechanism is that a low void fraction reduces the speed of sound of the bubbly mixture, becoming increasingly susceptible for condensation shockwaves (Ganesh et al., 2016). The void fraction in the cavity is a function of the cavitation number, and values of 5 % to 50 % were observed by Ganesh et al. (2016), for high and low cavitation numbers, respectively. Although the cavitation number was fixed and the incidence varied, an effect on the void fraction can be inferred due to the occurrence of the shockwaves. In this transitional regime at $\sigma/2\alpha = 2.40$, fundamental modes (i) and (iv) are both evident in the CWT, figure 4.8 (c). Both modes exhibit highly

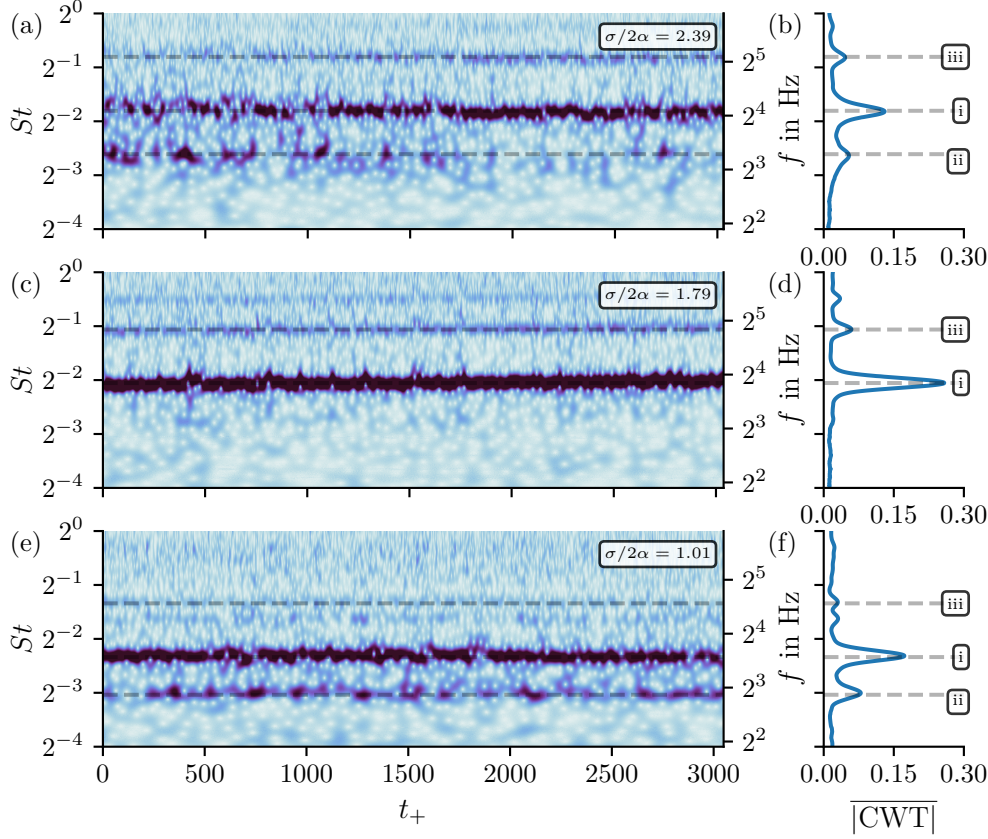


Figure 4.9: (a), (c), (e) show the absolute value of the CWT of the lift coefficient for a cavitation number σ of 0.50 and an incidence α of 6° , 8° and 14° , ($\sigma/2\alpha = 2.39$, 1.79, 1.01), respectively. (b), (d), (f) show the corresponding CWT averaged over the time. Mode (i) occurs in conjunction with mode (ii), (a) and (b), and (e) and (f). However, at an incidence of 8° , the shedding becomes highly two-dimensional and unimodal, (c) and (d), where the cavity sheet equals the chord. The Strouhal numbers are $St_i = 0.29$, 0.24 , 0.20 , $St_{ii} = 0.16$, 0.12 , $St_{iii} = 0.57$, 0.48 , 0.39 .

intermittent behaviour, with time instances where the modes occur and diminish. As demonstrated later, the modes display a negative correlation, suggesting that they occur exclusively. However, the space-time analysis in section 5.4 reveals that the modes occur both simultaneously and exclusively. This finding aligns with recent observations by Bhatt et al. (2023), where at specific operation points, both re-entrant flow and shockwaves were identified as shedding mechanisms. The occurrence of each mechanism follows a probability distribution that reflects the probability that one mechanism prevails over the other. For lower cavitation numbers, condensation shockwaves become increasingly dominant. The observation of Bhatt et al. (2023) is extended, demonstrating that this effect is evident for increasing incidence, complementing the findings for decreasing

cavitation number. In addition to the fundamental modes (i) and (iv), low-frequency mode (ii) is also evident in figure 4.8 (c), exhibiting highly intermittent behaviour. The time-averaged CWT, figure 4.8 (d), reveals that the fundamental modes (i) and (iv) exhibit approximately the same peak value, whereas mode (ii) is lower.

A further reduction in $\sigma/2\alpha$ by increasing α to 14° , results in the fundamental shedding transitioning to mode (i), with only slight evidence of mode (iv), figure 4.8 (e) and (f). It should be mentioned that the shedding becomes highly 3D, with large-scale clouds shed from multiple spanwise locations, due to the onset of shear cavitation at high incidence and cavitation number, see figure 4.1 for $\sigma = 1.00$ and $\alpha = 14^\circ$. Furthermore, shockwaves propagating both chordwise and spanwise are visible, exhibiting highly chaotic and incoherent behaviour. However, there are instances in time when 2D shedding is observed. Compared with the operating point where mode (iv) dominates, shown in figure 4.8 (a), mode (i) behaves differently at the operation point where it dominates, figure 4.8 (e). The 3D behaviour makes the shockwave-driven mode (i) less coherent and more intermittent. Mode (ii) remains evident, also showing highly intermittent behaviour.

The fundamental mode (i) has a Strouhal number St_i of 0.34 being lower than the Strouhal number of re-entrant flow-driven mode (iv) ($St_{iv} = 0.54$), as expected. The high-frequency mode (iii) also appears in conjunction with mode (i) with low intensity. The corresponding Strouhal number St_{iii} of mode (iii) is 0.59. Mode (iii) is not a higher harmonic artefact, as it does not correspond to twice the fundamental shedding frequency as shown later ($St_i = 0.34$ and $St_{iii} = 0.59$); rather, it is a physical mode that occurs occasionally, as demonstrated in section 5.5. Comparing these three operation points reveals that the transition from mode (iv) to (i) happens gradually. The cavity does not reach the trailing edge of the hydrofoil for $\sigma = 1.01$, figure 4.2, due the shear cavitation; thus, the cavity does not trigger the condensation shockwave, which is contrary to the case at $\sigma = 0.50$.

Next, the transition at low cavitation number, 0.50, is shown from the operation point where mode (i) occurs in conjunction with mode (ii), to unimodal shedding of mode (i), to the reappearance of mode (ii), by changing the incidence from 6° to 8° and finally to 10° , see figure 4.9. The corresponding parameters are $\sigma/2\alpha = 2.39, 1.79$ and 1.01 , respectively. This effect is visible in figure 4.5 (d) as discussed above. For $\sigma = 2.39$, which corresponds to an incidence of 6° , mode (i), (ii), and (iii) are visible in the CWT, as well as the spectrum calculated as the CWT averaged over time, figure 4.9 (a) and (b), respectively. The Strouhal numbers of mode (i), (ii), and (iii) are $St_i = 0.29$, $St_{ii} = 0.16$, $St_{iii} = 0.57$, respectively. From the absolute CWT, it can be seen that mode (ii) is highly intermittent. The presence of mode (ii) disturbs the coherence of mode (i), as seen for time instances within $0 < t_+ < 1700$, also reported by Venning et al. (2022). This is indicated by a negative correlation between mode (i) and (ii), such that each mode appears exclusively in the absence of the other, as detailed below. It is worth noting that the behaviour observed under these conditions is not universal. There are operation points where modes (i) and (ii) appear concurrently; the presence of mode (ii) does not suppress mode (i), and vice versa. This becomes clear from the correlation between mode (i) and (ii), figure 4.13 (a), as discussed later. From figure 4.9 (a) it can be seen that the shedding becomes highly coherent for $1700 < t_+ < 2600$, indicating

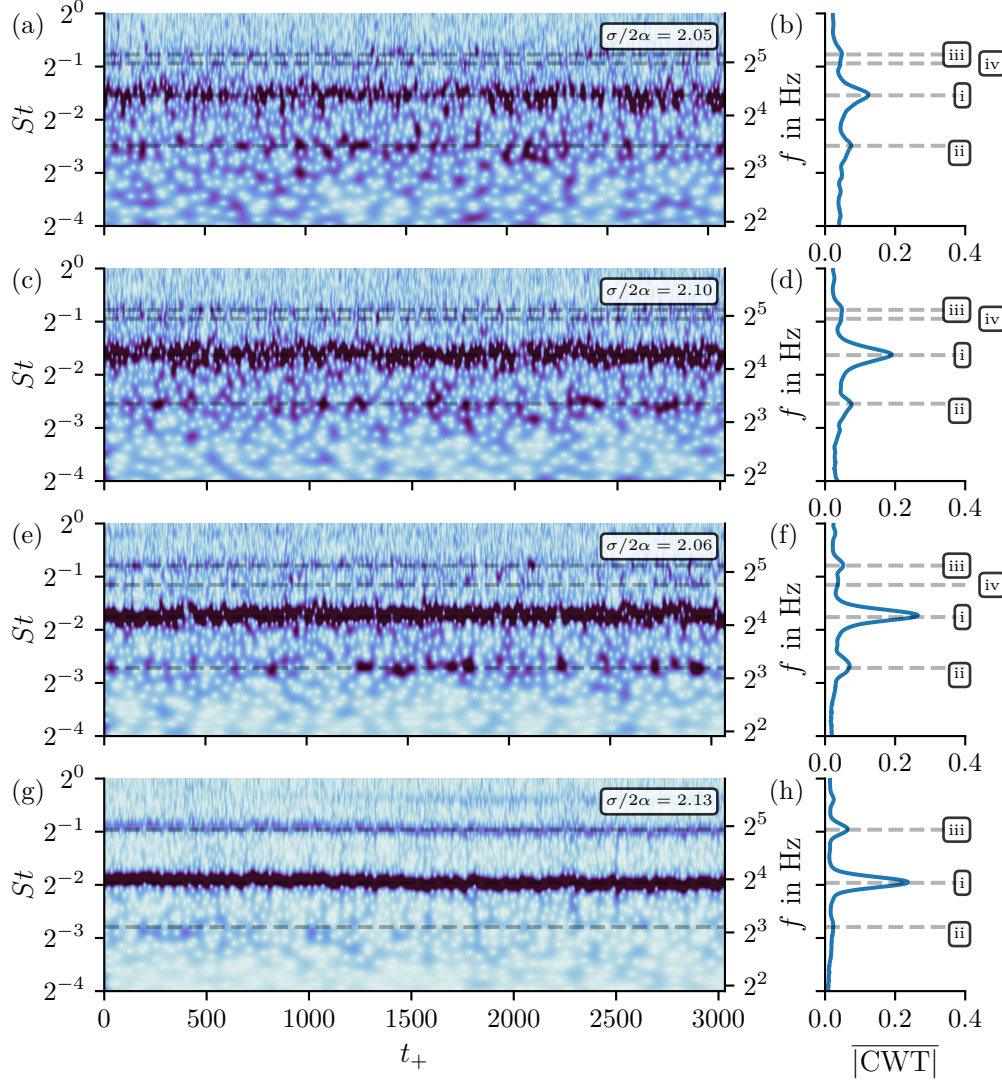


Figure 4.10: (a), (c), (e), (g) show the absolute value of the CWT of the lift coefficient for a cavitation number σ of 1.01, 0.88, 0.76, and 0.50 and an incidence α of 14° , 12° , 10.5° and 6.75° , respectively, for similar $\sigma/2\alpha \approx 2.10$. (b), (d), (f), (h) show the corresponding CWT averaged over the time.

that the data must be recorded for a sufficient duration to capture the long-time-scale intermittency of the modes.

As $\sigma/2\alpha$ is reduced to 1.79 by increasing the incidence to 8° , mode (ii) is no longer evident and does not occur in any time instances in the absolute CWT or in the spectrum of the time-averaged CWT, figure 4.9 (c) and (d), respectively. The shedding becomes highly coherent and unimodal, with a Strouhal number of $St_i = 0.24$. This is because the cavity length reaches the trailing edge of the hydrofoil, see figure 4.2, initiating a

condensation shockwave. The detailed mechanism is discussed in section 5.3. Mode (iii) is evident, and as shown later, it acts as a harmonic of mode (i) with high positive correlation. With further $\sigma/2\alpha$ reduction to 1.01 and a corresponding incidence of 14° , mode (ii) reappears, once again exhibiting intermittent behaviour, figure 4.9 (e) and (f). However, mode (i) is no longer strongly weakened by the presence of mode (ii), as is the case in figure 4.9 (a). For this operation point ($\sigma/2\alpha = 1.01$), the cavity sheet extends far beyond the trailing edge of the hydrofoil, $\hat{a}_+ = 1.39$, and the spanwise cavity extent reaches the tip of the hydrofoil, $\hat{s}_+ = 2.04$. The shedding becomes less coherent with alternating 2D and 3D behaviour. Mode (i) appears weaker when mode (ii) reappears compared to the highly coherent shedding for $\sigma/2\alpha = 1.79$, compare figure 4.9 (c) and (d) to (e) and (f). A still photograph showing the cavitation topology can be seen in figure 4.1 for $\sigma = 0.50$ and $\alpha = 14^\circ$. Due to the growth in maximum cavity length compared to $\sigma/2\alpha = 1.79$, the Strouhal number of fundamental mode (i) decreases from 0.24 to 0.20.

Next, the CWT is compared for the four σ values for approximately the same $\sigma/2\alpha$ of 2.10, see figure 4.10. This corresponds to operation points where mode (i) occurs in conjunction with mode (ii), see figure 4.5. It can be seen that for reduced cavitation number, the shedding becomes increasingly coherent with less intermittency, figure 4.10 (a), (c), (e), and (g). Although mode (ii) still occurs in figure 4.10 (g), it is very weak. However, for similar $\sigma/2\alpha$ values, the spectral content, as indicated by the CWT, is fairly similar.

4.3.2 Ratio of mode frequencies

The peaks and the corresponding frequencies of modes (i) and (iii) in the PSD and the time-averaged CWT are detected and depicted in figure 4.11 (a) and (b), respectively. The squares represent the PSD from the spectrum (figure 4.11 (a)) or the absolute value of the CWT (figure 4.11 (b)) of mode (i) with the frequency f_i , and the triangles represent the frequency ratio of mode (i) and mode (iii), i.e., St_i/St_{iii} . The data from the spectra and the CWT match well, exhibiting the same trend. As discussed above, shockwave mode (i) is stronger with higher coherence for the lower cavitation numbers, 0.76 and 0.50, green and red markers in figure 4.11, whereas re-entrant flow-driven cloud cavitation, mode (iv), occurs for the higher cavitation numbers. This can be concluded from both the PSD and the absolute CWT, figure 4.11.

For these low cavitation numbers, the shedding is more coherent, since the effect of shear cavitation is absent, and thus the 3D behaviour, including shedding at multiple spanwise locations, does not occur. In this case, the frequency ratio St_i/St_{iii} is about 0.5. Thus, mode (iii) appears to contain a stronger harmonic artefact used to reconstruct the signal for non-sinusoidal behaviour. However, this behaviour cannot be conclusively determined from the ratio alone and is further studied through simultaneous high-speed photography and force measurements in chapter 5.

For low $\sigma/2\alpha$, the onset of sheet cavitation is approached, resulting in a less coherent shedding for $\sigma = 0.76$ and 0.50. At this point, the frequency ratio becomes > 0.5 . Increasing σ results in a gradual increase of the frequency ratio as well, with values > 0.5 . This suggests that mode (iii) is not only a harmonic artefact, but rather a physical mode,

4.3 Transient behaviour and correlation between modes

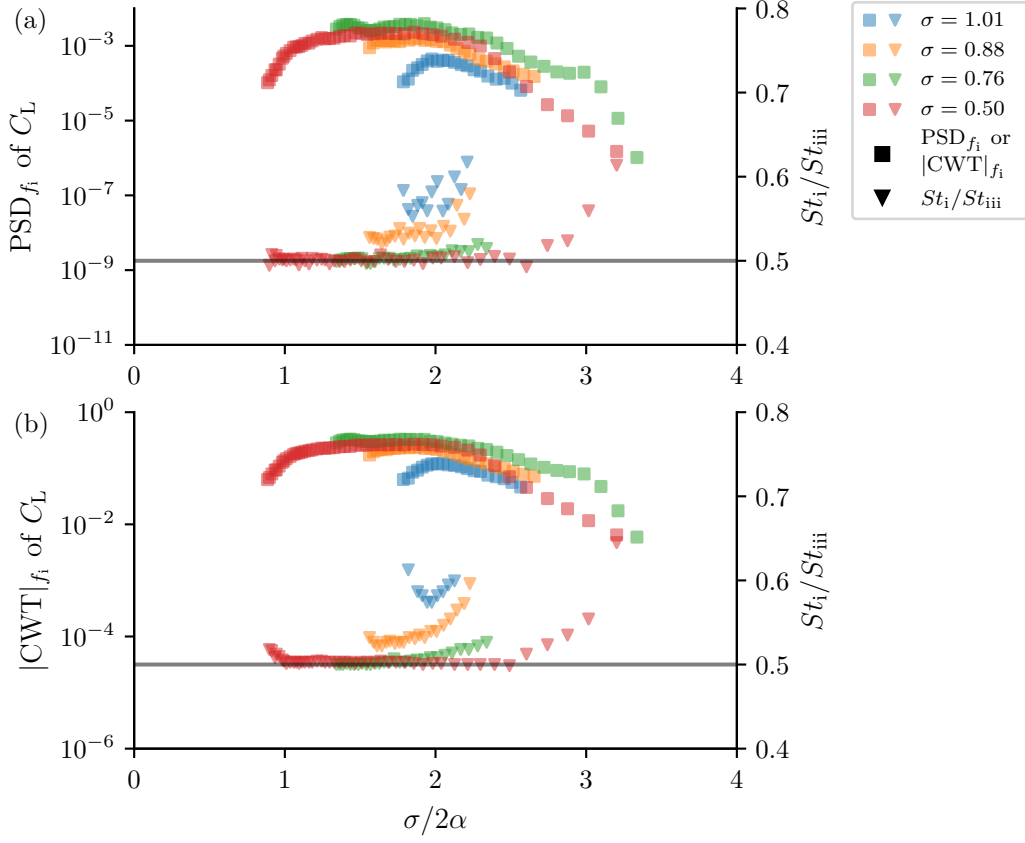


Figure 4.11: (a) PSD of the C_L at frequency St_i and St_i/St_{iii} calculated from the Welch PSD, and (b) CWT coefficient of the C_L at frequency St_i and St_i/St_{iii} calculated from the CWT. It can be seen that the ratio St_i/St_{iii} is getting closer to 0.5 as the cavitation number is reduced. The fact that the ratio St_i/St_{iii} deviates from 0.5 indicates that mode (iii) is not merely a harmonic artefact of mode (i). The data for subfigure (a) are available in the TUdatalib repository (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025c).

as demonstrated in section 5.5. This mode arises from the fact that the shedding becomes more 3D and chaotic at high incidence, where intermittent and local shedding events occur at various locations along the span. As already mentioned, for the low cavitation numbers, 0.76 and 0.50, the energy of mode (i) is high for $St_i/St_{iii} \approx 0.5$, where the content of the harmonic artefact is high.

The same analysis is conducted for mode (i) and mode (ii), figure 4.12. Now, the PSD and the absolute CWT of mode (ii) are plotted as functions of $\sigma/2\alpha$, as well as the frequency ratio St_{ii}/St_i . Mode (ii) is not a subharmonic artefact, since St_{ii}/St_i varies from 0.5 depending on $\sigma/2\alpha$. Venning et al. (2022) observed that the energy of mode (ii) reaches its maximum value for $St_{ii}/St_i = 0.5$, i.e., when mode (ii) becomes a subharmonic of mode (i). The data in the present study do not show this effect as clearly

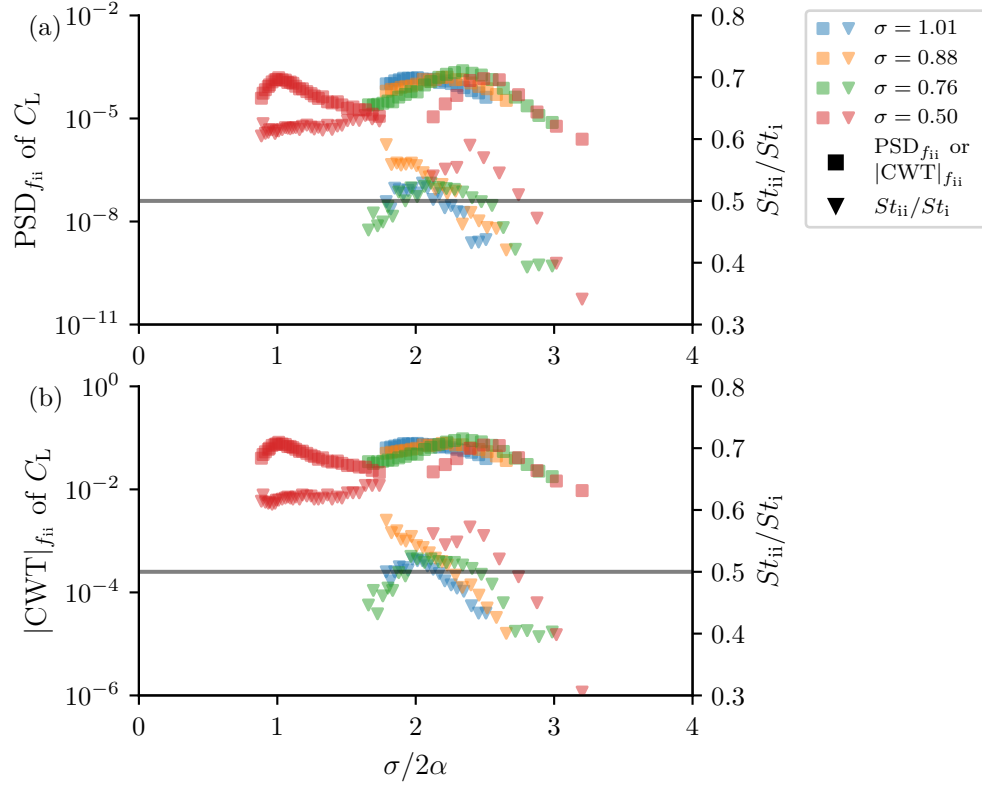


Figure 4.12: (a) PSD of C_L at frequency St_{ii} and St_{ii}/St_i , calculated from the Welch PSD, and (b) CWT coefficient of the C_L at frequency St_{ii} and St_{ii}/St_i , calculated from the CWT. The data for subfigure (a) are available in the TUDatalib repository (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025c).

as in Venning et al. (2022). Figure 4.12 shows that the data across σ exhibit the same trend. As $\sigma/2\alpha$ is reduced, the ratio St_{ii}/St_i initially increases, reaching the subharmonic case ($St_{ii}/St_i = 0.5$). After reaching a maximum, the frequency ratio decreases for all cavitation numbers except $\sigma = 0.88$, for which it stagnates. For $\sigma = 0.50$, mode (ii) vanishes and reappears at $\sigma/2\alpha = 1.74$, with a higher frequency ratio of 0.6. At this point, the spanwise cavity extent reaches the hydrofoil's tip, i.e., $\hat{s}_+ \approx 2$, and the cavity sheet length grows beyond the chord length of the hydrofoil, i.e., $\hat{a}_+ > 1$. Although the cavitation appears less coherent than at higher $\sigma/2\alpha$, the PSD remains of the same order of magnitude.

In summary, the frequency ratios between modes (i) and (ii), and (i) and (iii) indicate that the modes cannot be regarded as purely harmonic artefacts; rather, they also represent distinct physical modes, as the frequency ratios deviate from 0.5. However, a ratio of 0.5 does not necessarily indicate the presence of a harmonic artefact. These modes require a more detailed analysis, as presented in chapter 5.

4.3.3 Correlation between modes

The PCC (Ross, 2014, p. 37) is calculated between the absolute CWT components of mode (i) and modes (ii), (iii), and (iv), see figure 4.13 (a), (b), and (c), respectively. A value of $r > 0$ indicates positive correlation, $r < 0$ indicates negative correlation, and $r = 0$ indicates no correlation. In other words, $r > 0$ means that large (small) values of one variable tend to occur together with large (small) values of the other, $r < 0$ means that large values of one variable tend to occur together with small values of the other, and $r = 0$ means that the variables vary independently of each other.

A notable correlation between modes (i) and (ii) is observed only at $\sigma = 0.50$, while for the other cavitation numbers, the correlation scatters around zero, see figure 4.13 (a). A positive correlation is observed around $\sigma/2\alpha = 3$; however, the PSD of mode (i) for these operation points is low. A negative correlation is observed for $2.1 < \sigma/2\alpha < 2.5$. Mode (i) and (ii) occur exclusively, with the presence of mode (ii) weakening mode (i) as qualitatively observed in the CWT for $\sigma/2\alpha = 2.39$, see figure 4.9 (a). As $\sigma/2\alpha$ is reduced, the negative correlation diminishes, indicating that there is less interaction or coupling between these modes. This can also be inferred from the CWT in figure 4.9 (c). To visualise this behaviour, a colourmap is presented in which the absolute CWT component of mode (i) is plotted against those of mode (ii), (iii) and (iv), see figure 4.14. This is done for a fixed cavitation number of 0.50 and $\sigma/2\alpha = 2.39, 1.79, 1.01$ and 0.94. For $\sigma/2\alpha = 1.79$ mode (ii) vanishes, see figure 4.9 (b).

Inspection of the absolute CWT components of mode (i) and (ii) (first column) shows that their correlation weakens substantially with increasing incidence: the PCC declines from $r = -0.65$ at $\sigma/2\alpha = 2.39$ to $r = -0.05$ at $\sigma/2\alpha = 0.94$. The correlation around zero indicates that there is effectively no relationship between the two modes; section 5.2 will verify this conclusion using the high-speed photographs. It can be concluded that although the spectra appear nearly identical and contain the same modes, their temporal behaviour differs and is governed by different physical mechanisms – underscoring that spectra alone can be misleading.

The correlation between mode (i) and (iii) shows a distinct behaviour for $\sigma = 0.50$, figure 4.13 (b). The correlation remains high throughout the $\sigma/2\alpha$ range and decreases at lower $\sigma/2\alpha$, due to the 3D behaviour of the shedding and less coherence. As coherence gradually decreases, the corresponding reduction in r becomes visible when the absolute CWT of modes (i) and (iii) are plotted against each other, figure 4.14, second column. A positive slope indicates that modes (i) and (iii) arise and decay simultaneously and appear and disappear together, leading to the conclusion that mode (iii) is a harmonic artefact. This indicates that the periodicity of cloud cavitation here is non-sinusoidal and harmonic components are necessary to reconstruct the signal. The maximum value of the correlation occurs at $\sigma/2\alpha \approx 2.3$, where the shedding is highly 2D.

For the cavitation number of 0.76, the correlation increases as $\sigma/2\alpha$ is reduced, reaching a maximum value of $r = 0.74$ at $\sigma/2\alpha = 1.36$. This trend suggests that mode (iii) increasingly behaves as a higher harmonic, rather than as a physical mode. For the two high cavitation numbers, 0.88 and 1.01, the correlation remains low, with an increasing trend as $\sigma/2\alpha$ is reduced. Since mode (i) is highly 3D at high cavitation numbers and

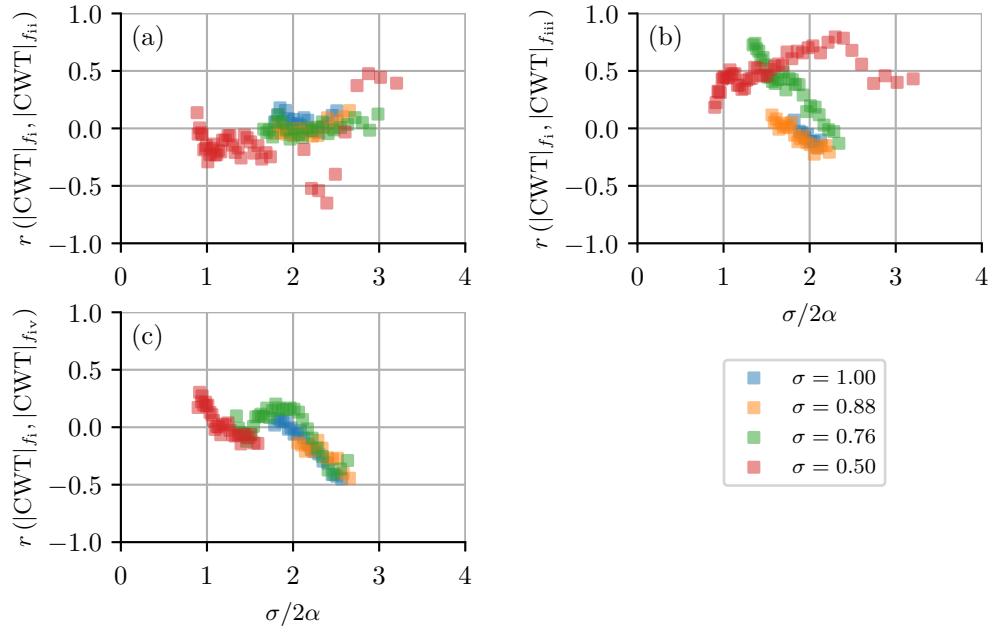


Figure 4.13: PCC between the absolute value of the CWT coefficients, (a) $|CWT|_{f_i}$ and $|CWT|_{f_{ii}}$, (b) $|CWT|_{f_i}$ and $|CWT|_{f_{iii}}$, (c) $|CWT|_{f_i}$ and $|CWT|_{f_{iv}}$.

has low energy, mode (iii) represents physical modes, as confirmed in section 5.5.

The correlation between mode (i) and (iv), figure 4.13 (c), exhibits a negative correlation for high $\sigma/2\alpha$. Mode (iv) is the fundamental shedding for these conditions and the transition to mode (i) appears as $\sigma/2\alpha$ is reduced. Within this transitional regime, mode (i) and (iv) occur exclusively as indicated by the negative correlation. However, as shown in section 5.4, the modes also occur simultaneously.

Although mode (iv) is weak for $\sigma = 0.76$, it follows the same trend with respect to $\sigma/2\alpha$ as for $\sigma = 1.01$ and 0.88 , for sufficiently high $\sigma/2\alpha$. For $\sigma = 0.76$, 0.88 and 1.01 and decreasing $\sigma/2\alpha$, mode (iv) becomes energetically weaker, and its correlation approaches 0. For $\sigma = 0.50$, the correlation increases as $\sigma/2\alpha$ is reduced; There is some evidence that mode (iv) emerges during a mode (i) cycle; however since mode (iv) is too weak, no definitive conclusion can be drawn. This effect becomes evident in figure 4.14, third column.

In summary, the temporal occurrence of modes – exclusive, $r < 0$, simultaneous, $r > 0$, or uncorrelated, $r = 0$ – is ambiguous and varies with $\sigma/2\alpha$. To substantiate these observations beyond the spectral analysis, it is necessary to find evidence in the high-speed photographs, see chapter 5.

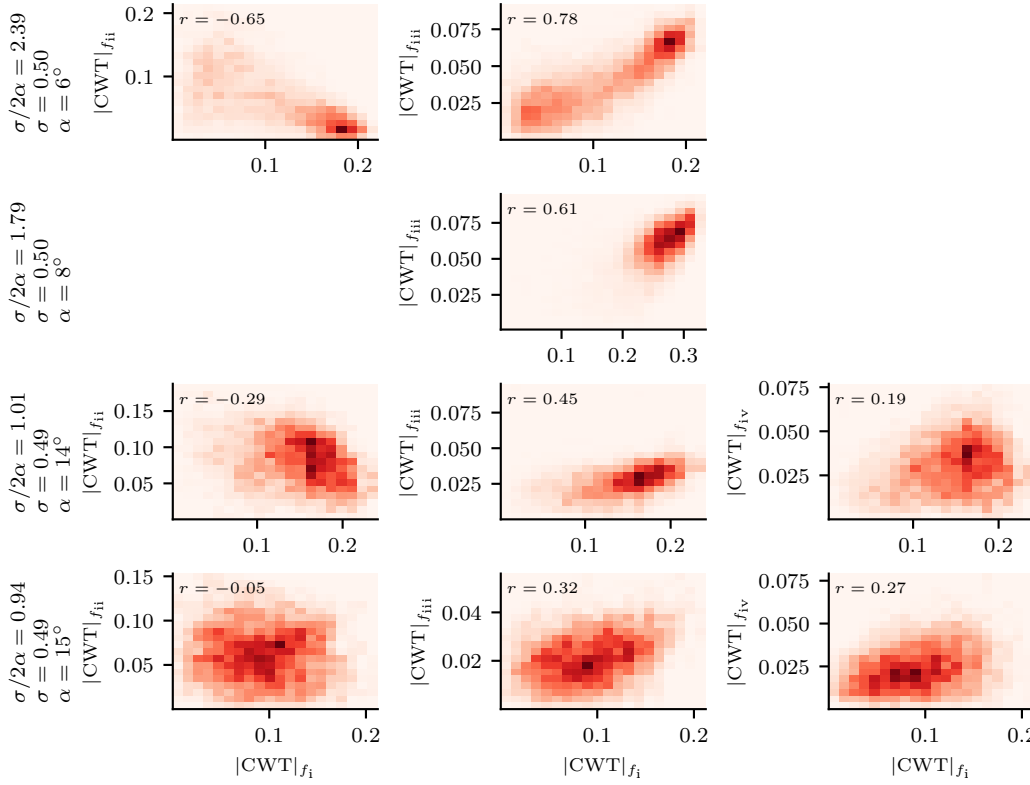


Figure 4.14: The absolute values of the components of the CWT of mode (i) are plotted against those of modes (ii), (iii), and (iv), respectively. The corresponding PCC is provided. Mode (ii) exhibits a strong negative correlation at low incidence, indicating exclusive behaviour, and a weak correlation at high incidence.

4.4 Summary of key findings

The topology and the characteristic lengths of the cavity have been investigated for four cavitation numbers ($\sigma = 0.50, 0.76, 0.88, 1.01$) with varying incidence. The observed cavitation phenomena range from incipient cavitation to shear cavitation and supercavitation at high incidence. High-speed photography and force measurements enable the identification of characteristic lengths and spectral content. As expected, the cavity length in chordwise and spanwise directions increases as the incidence is increased, and the cavitation number is reduced. Spectrograms for each cavitation numbers were generated, obtaining an overview of the modes. Four modes were defined: (i) condensation shockwave-driven cloud shedding; (ii) low-frequency tip mode; (iii) high-frequency physical mode and harmonic artefact; (iv) coupled re-entrant flow and condensation shockwave-driven cloud shedding. The detailed underlying physics of the mechanisms of the modes are described and analysed in the following chapter (chapter 5). The mode frequencies are extracted from the spectra, and the chord-based and cavity velocity-based

Strouhal numbers were computed, with the latter exhibiting better collapse. Data are compared with literature values for the same hydrofoil shape, i.e., NACA 0015, revealing significant scattering. In the literature, shockwave-driven cloud cavitation is associated with a characteristic frequency that is independent of the cavitation number, while re-entrant flow-driven cloud cavitation exhibits a clear dependence on the cavitation number or on $\sigma/2\alpha$. In contrast, this study finds that the frequency or the chord length-based Strouhal number associated with the re-entrant flow-driven cloud cavitation (coupled with a subsequent condensation shockwave) does not depend on $\sigma/2\alpha$. In other words, the maximum cavity length-based Strouhal number is not constant, in contrast to what is reported in the literature. This mechanism is analysed in detail in section 5.1.

To account for the incidence, the parameter $\sigma/2\alpha$ derived for a flat plate (Brennen, 2013, p. 230) is used, rather than plotting solely against the cavitation number. Although this parameter serves as a useful descriptor of the shedding behaviour, it has its limitations: as demonstrated, the cavitation behaviour is highly influenced by the cavitation number. At high cavitation numbers ($\sigma = 0.88, 1.01$) and low incidence, the coupled mechanism of a re-entrant flow and a subsequent condensation shockwave, mode (iv), dominates. At low cavitation numbers ($\sigma = 0.50, 0.76$) condensation shockwaves, mode (i), are the driving mechanism of cloud cavitation, while the re-entrant flow-driven cloud cavitation fully vanishes.

It is observed that for $\sigma = 0.50$, when the cavity length equals the chord length of the hydrofoil, the cavity growth stagnates, as does the shedding frequency (and the chord-based Strouhal number) as the incidence is further reduced. A condensation shockwave is triggered at the hydrofoil trailing edge, being consistent with previous findings by Hatzissawidis, Kuhr, and Pelz (2025). A detailed analysis is presented in section 5.3.

The transient analysis using CWT reveals that the modes can occur both simultaneously and exclusively: At the high cavitation number ($\sigma = 1.01$), the transition from mode (iv) to (i) appears *smoothly* as the incidence is increased. Within the transitional regime of mode (i) and (iv) the modes occur exclusively and simultaneously (the latter will be shown in chapter 5). Mode (i) and (ii) are confined to a specific $\sigma/2\alpha$ -band where they occur exclusively, with the intermittent occurrence of mode (ii) weakening mode (i). Outside this band, mode (i) and (ii) occur simultaneously. Mode (iii) acts as a harmonic artefact at low cavitation numbers and moderate incidence. However, at high cavitation number and incidence, mode (iii) represents the 3D behaviour of cloud cavitation. The occurrence of mode (iii) as a physical mode is supported by the frequency ratio between mode (i) and (iii).

Thus far, the modes, along with their characteristic lengths, frequencies, temporal behaviour, and correlations, have been analysed. In the subsequent chapter 5, the second part of the results, the underlying physics of the modes and the regime transition will be examined.

Chapter 5

Shedding mechanisms and mode transition

Following the identification of the modes together with their spectral content and temporal behaviour in the previous chapter, this chapter explores the physical mechanisms that underlie these modes. To this end, high-speed photography and simultaneous force measurements are used and SPOD is applied, see section 3.3. The content of this chapter is taken and adapted from the following manuscript, which has been submitted to the *Journal of Fluid Mechanics*: Hatzissawidis, Russell, Venning, Pelz, and Brandner (2025b).

As α is increased, a rich variety of cloud cavitation phenomena emerges, including modal interactions and three-dimensionality. First, an overview of the spatial structures of the dominant modes and their corresponding frequencies is provided, before exploring the underlying physics in detail. Four dominant cavitation modes, labelled (i), (ii), (iii), and (iv), were identified in the spectra for four cavitation numbers $\sigma = \{1.01, 0.88, 0.76, 0.50\}$. Modes (i) and (iv) represent the fundamental shedding modes, see chapter 4. Applying SPOD to the high-speed photographs of the run type ‘medium’ enables the characteristic frequencies identified in the C_L spectra to be linked to their corresponding spatial modes. Figure 5.1 presents the absolute value of a representative leading SPOD eigenmode for each mode, (i) to (iv), for the different cavitation numbers. The colourbar is scaled identically for all spatial modes to allow a direct comparison between them. The dominant shedding modes discussed in detail in this study are marked by thicker axis lines.

Mode (i) dominates the shedding at low cavitation numbers 0.50 and 0.76 (figure 4.5 (c) and (d)), while mode (iv) dominates at high cavitation numbers 0.88 and 1.01 (figure 4.5 (a) and (b)). It is evident that the chordwise extent of the cavity associated with mode (i) is larger than that of mode (iv), when they act as fundamental modes. Mode (iv) is further associated with a higher characteristic shedding frequency than mode (i). Given that mode (i) is associated with shockwave-driven cloud cavitation and mode (iv) with re-entrant flow-driven cloud cavitation – as shown later – these differences are to be expected.

Mode (ii) appears only in conjunction with mode (i) (see chapter 4), and exhibits higher energy at the lower cavitation numbers, 0.50 and 0.76. It displays strong intensity at the cavity tip across all cavitation numbers, with the region of high intensity expanding as the cavitation number is reduced, indicating increasingly pronounced cavity tip excursion.

Mode (iii) exhibits high intensity near the same regions as mode (i) at low cavitation numbers, with approximately half the wavelength and twice the frequency – indicating strong harmonic content needed to reconstruct the non-sinusoidal nature of cloud cavitation. These observations align with the spectral analysis in chapter 4, which showed a

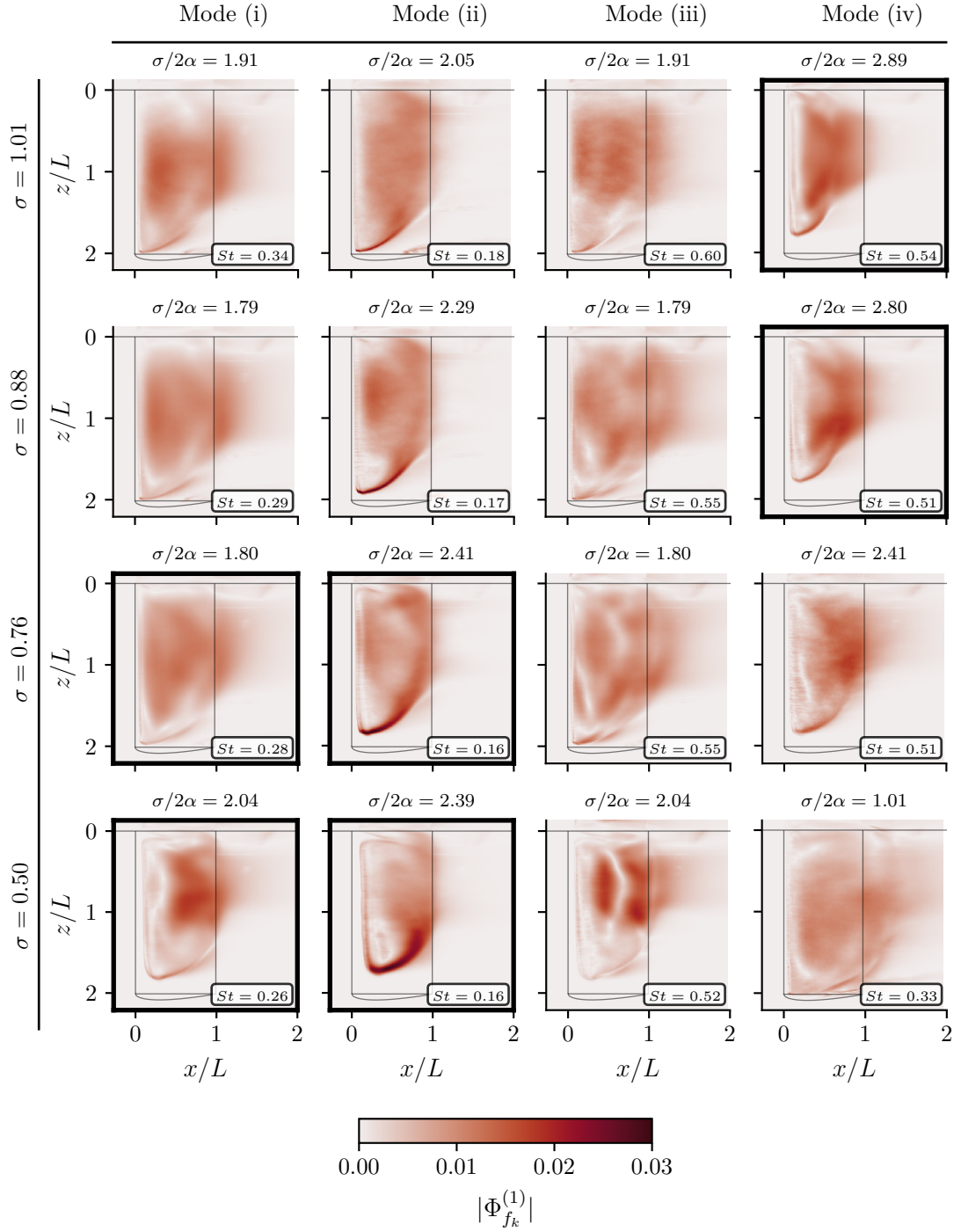


Figure 5.1: Absolute value of the leading eigenmodes $|\Phi_{f_k}^{(1)}|$ at representative operation points throughout the four cavitation numbers for modes (i) to (iv). Dominant shedding modes are marked by thicker axis lines. Modes (i) and (ii) are strong for the lower cavitation numbers $\sigma = 0.50, 0.76$ driven primarily by shockwaves, whereas mode (iv) is strong for the high cavitation numbers $\sigma = 0.88, 1.01$ driven by the re-entrant flow.

Mode	σ	$\sigma/2\alpha$	St	Mechanism
(i)	1.01	1.79 – 2.45	0.33 – 0.41	Fundamental mode driven by condensation shockwave
	0.88	1.56 – 2.46	0.29 – 0.37	
	0.76	1.34 – 2.99	0.24 – 0.45	
	0.50	0.89 – 2.49	0.19 – 0.29	
(ii)	1.01	1.79 – 2.40	0.17 – 0.18	Low-frequency tip mode driven by shockwave
	0.88	1.79 – 2.52	0.17 – 0.18	
	0.76	1.66 – 2.72	0.12 – 0.16	
	0.50	0.89 – 1.55; 2.21 – 2.74	0.12 – 0.15; 0.15 – 0.17	
(iii)	1.01	1.85 – 2.21	0.58 – 0.60	High-frequency harmonic artefact and physical mode
	0.88	1.56 – 2.14	0.55 – 0.60	
	0.76	1.34 – 2.17	0.48 – 0.59	
	0.50	0.93 – 2.74	0.38 – 0.63	
(iv)	1.01	1.82 – 3.32	0.51 – 0.56	Fundamental mode driven by coupled re-entrant flow and condensation shockwave
	0.88	1.97 – 3.16	0.51 – 0.52	
	0.76	1.36 – 2.63	0.38 – 0.51	
	0.50	0.93 – 1.55	0.31 – 0.39	

Table 5.1: Summary of the occurrence of the modes for the four cavitation numbers. The $\sigma/2\alpha$ range and the corresponding St range are given.

strong positive correlation between mode (i) and (iii), especially for $\sigma = 0.50$. However, as the cavitation number is increased, its frequency no longer corresponds to twice of mode (i), and the spatial structure cannot be attributed to a higher harmonic. Rather, it appears as a physical mode.

The modes, their ranges of appearance, and the Strouhal numbers are summarised in table 5.1. The data are taken from the spectrograms of C_L , figure 4.5.

5.1 Coupled re-entrant flow and condensation shockwave

Cloud cavitation driven by a coupled re-entrant flow and condensation shockwave mechanism, denoted as mode (iv), is investigated in this section. First, a phenomenological description is provided; thereafter, the invariance of the shedding frequency with increasing incidence is analysed. This mechanism has been reported for a cavitating sphere, where a high adverse pressure gradient is intrinsic to the geometry (de Graaf et al., 2017). The present study documents a similar mechanism at high incidence for a NACA 0015 hydrofoil.

5.1.1 Phenomenological analysis

The re-entrant flow emerges as the fundamental shedding mechanism for cloud cavitation at high cavitation numbers, 0.88 and 1.01, as $\sigma/2\alpha$ is reduced to 3.16 and 3.32, respectively. As seen in the supplementary movie 3, a re-entrant flow develops due to the combination of sufficient cavity thickness and strong adverse pressure gradient (Callenaere et al., 2001). Having gained enough momentum, it triggers cloud detachment as it reaches the cavity leading edge (Pelz et al., 2017). For completeness, it should be mentioned that at high $\sigma/2\alpha$ above the critical value which defines the transition from sheet to cloud cavitation (Pelz et al., 2017), there is a narrow range in which quasi-steady sheet cavitation is observed. A further increase in $\sigma/2\alpha$ leads to cavitation desinence.

For this mode (iv), the non-dimensionalised cavity sheet length, $\hat{a}_+ := \hat{a}/L$, ranges between 0.62 – 0.89 and 0.62 – 0.92, for $\sigma = 0.88$ and 1.01, respectively. The chord-based Strouhal number, $St := fL/U_\infty$, is 0.51 – 0.56 and 0.51 – 0.52, respectively, showing surprisingly small variation as $\sigma/2\alpha$ is varied.

The re-entrant flow-driven mechanism is analysed in detail for $\sigma = 1.01$ and $\alpha = 10^\circ$ ($\sigma/2\alpha = 2.89$). Figure 5.2 is a stacked figure showing re-entrant flow-driven cloud cavitation; subfigures are temporally aligned and plotted against the non-dimensionalised time t_+ . Figure 5.2 (a) shows the lift and the pitching coefficient, blue and red curves, respectively. The transparent blue and red curves are the unfiltered signals and the solid curves are the filtered. The filter applied is a fourth order digital Butterworth low-pass filter with a cutoff frequency at 80 Hz. The same filter is applied to all subsequent figures that show the same signals (lift and pitching coefficient). Figure 5.2 (b) shows the real part of the CWT of the lift coefficient, allowing a time-frequency analysis (see section 3.2 and appendix C.2 for more information regarding the CWT). Taking a slice of the real part of the CWT at a specific frequency f , the corresponding component of the CWT denoted by CWT_f can be visualised. The CWT component of the frequency corresponding to mode (iv) is extracted as indicated by the pink horizontal line in figure 5.2 (b). The component is plotted in figure 5.2 (c). From the simultaneously recorded high-speed photographs, a space-time diagram is generated in figure 5.2 (d). The vertical slice taken is near the leading edge at $x/L = 0.15$, as indicated by the pictogram on the right-hand side of figure 5.2 (d). The data used for this analysis are from the run type ‘short’ (see table 3.1), ensuring sufficient time resolution.

The shedding at this operation point exhibits strong coherence and unimodal behaviour, as shown in figure 5.2 (a) to (d). The spanwise space-time diagram (figure 5.2 (d)) taken near the leading edge at $x/L = 0.15$ reveals the strong coherence of the mode, however, cycle-to-cycle variations exist. The topology and position of the spatial features resembling ‘gaps’ in the space-time diagram vary from cycle to cycle; however, the variations do not affect the overall period of the shedding cycle. These ‘gaps’ are marked with a red transparent rectangle in figure 5.2 (d) and are shown side by side for multiple cycles in figure 5.3. These features can appear at multiple spanwise locations and may differ in their spanwise extent. At these locations, the re-entrant flow breaks through the cavity sheet, initiating large-scale cloud shedding and condensation of the remaining cavity sheet near the hydrofoil’s leading edge. This mechanism was previously observed by

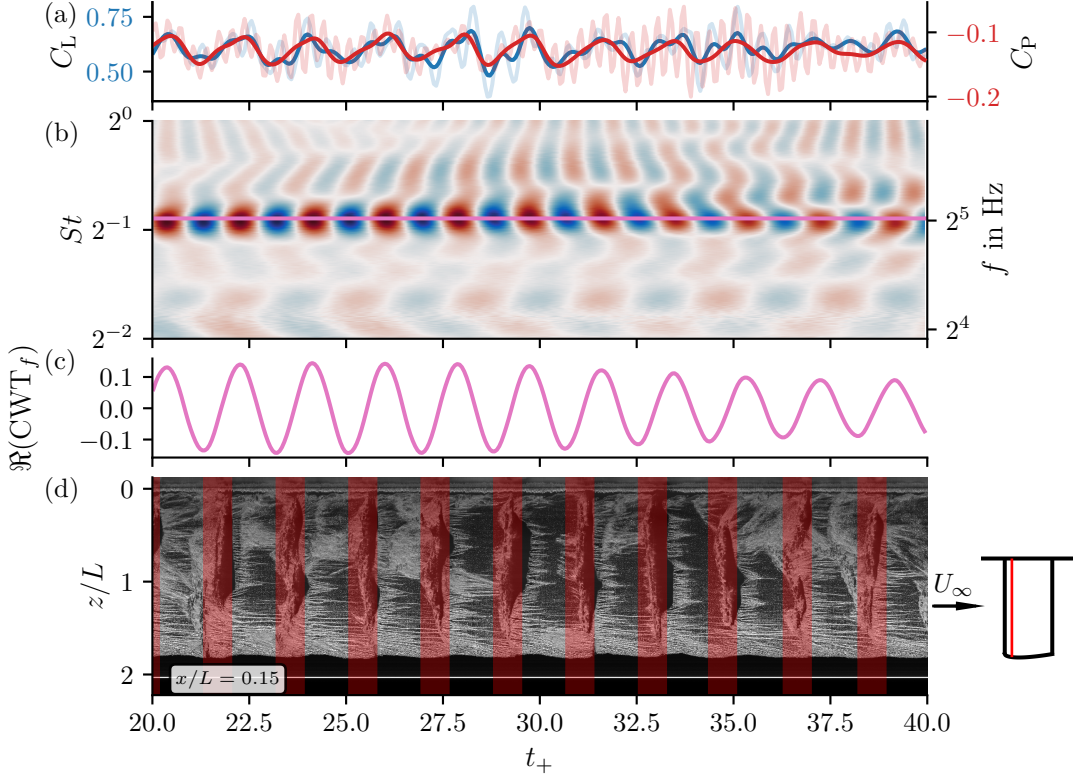


Figure 5.2: Simultaneously recorded data of the (a) lift and pitching coefficient, C_L and C_P , respectively, (b) the real value of the CWT, (c) the CWT of the frequency $f_{iv} = 33$ Hz or $St_{iv} = 0.54$ of the fundamental mode (iv) and (d) the spanwise space-time diagram at $x/L = 0.15$. The high-speed photographs are the short runs corresponding to the higher temporal resolution. The red transparent rectangles in the space-time diagrams are detected through the peaks of the CWT at the fundamental frequency showing the shedding mechanism at the leading edge. Although the fundamental shedding is strongly coherent and 2D, the spatial features at the leading edge vary from cycle to cycle. The re-entrant flow breaks through the sheet downstream of the cavity leading edge and the remaining attached cavity sheet condenses abruptly. This is the coupled re-entrant flow and condensation shockwave mechanism similar to de Graaf et al. (2017). The cavitation number is $\sigma = 1.01$ and the incidence is $\alpha = 10^\circ$ ($\sigma/2\alpha = 2.89$).

de Graaf et al. (2017) about a cavitating sphere where the re-entrant flow experiences a strong adverse pressure gradient. Evidently, the adverse pressure gradient along the NACA 0015 hydrofoil at the present incidence ($\alpha = 10^\circ$) is sufficiently strong to produce a similar effect. The topology of this mechanism is highly 3D, even though the overall shedding process remains largely 2D.

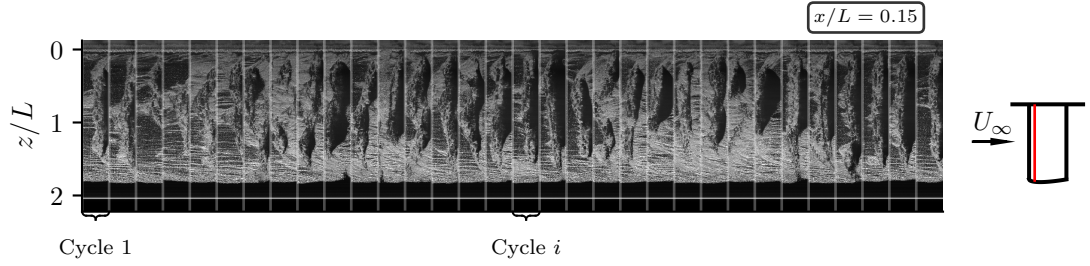


Figure 5.3: Space-time diagrams placed next to each other of the cycles where the re-entrant flow breaks through the cavity sheet initiating a condensation shockwave. These time instances correspond to the transparent red rectangles in figure 5.2. The physical time Δt for each cycle i is 11.4 ms and the non-dimensionalised time Δt_+ is 0.685.

A sequence of high-speed photographs in figure 5.4 shows one representative cycle of mode (iv) and a corresponding movie is provided as supplementary movie 3. During the cavity growth phase, re-nucleation near the hydrofoil’s leading edge can be perceived, while the large-scale cloud from the previous cycle – spanning the full spanwise extent of the cavity – is advected downstream, see figure 5.4 (a). The cavity tip is not fully condensed from the previous cycle and continues to be connected to the cloud. Then, the cavity continues to grow, while the cloud detaches from the sheet and is advected downstream, figure 5.4 (b). By the midpoint of the shedding cycle, a re-entrant flow has already formed during the growth phase, visible beneath the cavity sheet in figure 5.4 (c). Apart from the opaque regions at the cavity tip and root, the cavity sheet remains largely translucent, allowing the re-entrant flow to be clearly visible. The opacity at the tip and the root is caused by condensation shockwaves, see Venning et al. (2022); however, these are relatively weak and do not govern the shedding process. With the ongoing growth of the cavity sheet, the re-entrant flow propagates further upstream leading to perturbations on the cavity surface, which now appear opaque at some locations, figure 5.4 (d). When the re-entrant flow approaches the cavity leading edge, it impinges upon the cavity surface near the root, as annotated in figure 5.4 (e). Multiple ‘gaps’ become visible in the cavity region downstream of the re-entrant flow path. Finally, the cavity ruptures, and a shockwave propagates spanwise from the rupture point, causing the remaining cavity to condense, see figure 5.4 (f) and (g). In this case, where the shockwave is highly energetic, it leads to the condensation of nearly the entire cavity leading edge except for the tip, figure 5.4 (h). The tip of the cavity does not condense, as is evident in figure 5.4 (a) and (h), as well as in the supplementary movie 3. This has also been reported by Smith et al. (2020a) for re-entrant flow-driven cavitation without the subsequent condensation shockwave about a NACA 0009 hydrofoil with a tapered planform. However, in their study, cloud shedding was confined to the mid-span region, while the tip and root part of the cavity remained stable. In contrast, this study shows that the condensation shockwave initiates large-scale cloud shedding over nearly the entire span. This larger spanwise extent is also reflected in the SPOD mode shown in

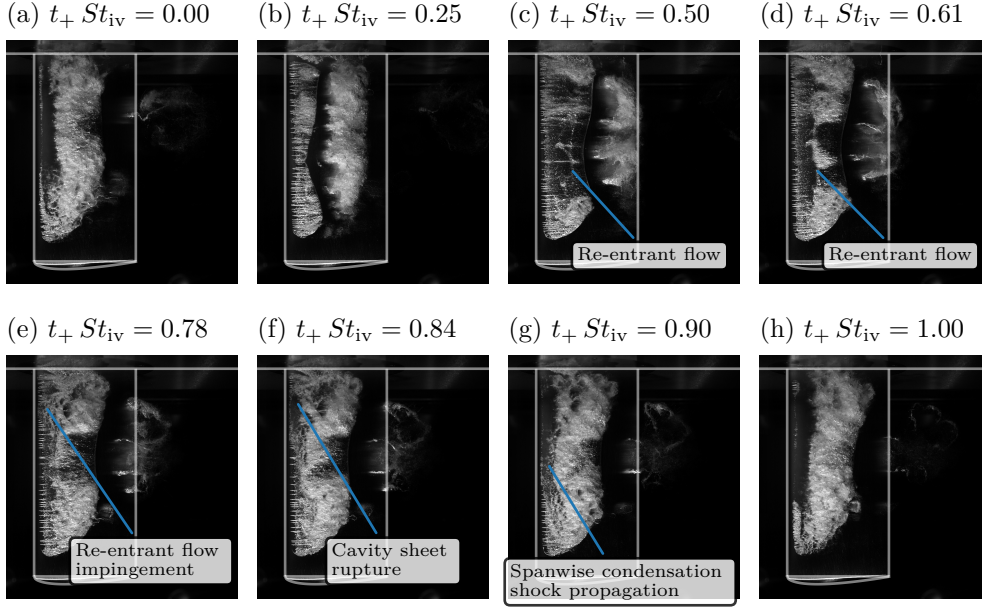


Figure 5.4: Sequence of high-speed photographs showing the coupled re-entrant flow and condensation shockwave mechanism, mode (iv). The dimensionless cycle time instance is given as $t_+ St_{iv}$. (a) The cloud from the previous cycle is shed, and the sheet begins to grow. (b) The sheet grows, and the cloud is shed downstream with the bulk flow. (c) and (d) The re-entrant flow develops before the cavity length reaches its maximum length and flows upstream beneath the cavity sheet. In (d) the cavity sheet reaches its asymptotic maximum length. (e) The re-entrant flow impinges the cavity sheet downstream of the cavity leading edge and (f) leads to its rupture. (g) From this point of rupture, a condensation shock wave propagates in the spanwise direction leading to an (h) extinction of the cavity and the cycle repeats. The cavitation number is 1.01 and the incidence is 10° ($\sigma/2\alpha = 2.89$). A supplementary movie 3 is available.

figure 5.1 for mode (iv) at $\sigma = 1.01$. For this mechanism to occur, a high re-entrant flow momentum driven by a strong adverse pressure gradient is required – conditions not met at the lower incidence of 6° in the study by Smith et al. (2020a), in contrast to the 10° in the present case. An indication of this is that the mechanism appears to weaken at lower incidence, suggesting a strong dependence on the adverse pressure gradient and resulting re-entrant flow momentum.

A detailed chordwise space-time diagram, figure 5.5, at approximately mid-span, $z/L = 0.83$, for the same cycle (figure 5.4) highlights the characteristic features as lines, i.e., sheet growth (blue), re-entrant flow (green), and cloud advection (red). The slope of each line indicates the corresponding velocity, with the flow direction orientated from bottom to top. Vertical lines labelled ‘a’ through ‘h’ mark the time instance corresponding

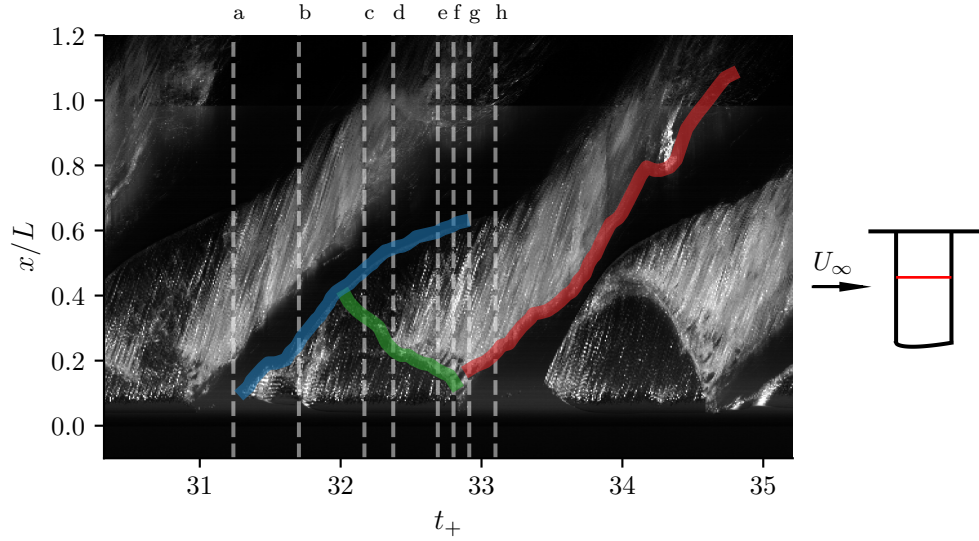


Figure 5.5: Detailed chordwise space-time diagram at $z/L = 0.83$ of the run type ‘short’ indicating the cavity sheet growth (blue), re-entrant flow (green), and detached cloud (red). The cycle is the same as in figure 5.4. The vertical dashed lines correspond to the time instances of the frames in figure 5.4. The physical time is 81.1 ms. A supplementary movie 3 is available.

to the high-speed photographs in figure 5.4. The cavity sheet, indicated by the blue line, grows at a mean velocity of $0.36 U_\infty$, with a coefficient of determination $R^2 = 96.6\%$. Initially, the growth velocity is higher and gradually decreases until the cavity reaches its maximum length at $\hat{a}_+ = 0.65$. During the cavity growth at approximately $t_+ = 32$, a re-entrant flow, indicated by the green line, develops and flows upstream beneath the cavity sheet at a velocity of $-0.32 U_\infty$ ($R^2 = 95.6\%$). At $t_+ = 32.9$, the re-entrant flow impingement upon the cavity sheet occurs. Finally, a cavitation cloud forms and is advected downstream at a velocity of $0.52 U_\infty$ ($R^2 = 98.6\%$), indicated by the red line.

To visualise the impingement of the re-entrant flow, a spanwise space-time diagram at $x/L = 0.1$ near the hydrofoil’s leading edge is presented in figure 5.6. The re-entrant flow impinges the cavity sheet at a spanwise position of $z/L \approx 0.4$ to 0.5 , downstream of the cavity leading edge. At this point, a shockwave arises that condenses the remaining cavity, indicated by the two orange lines, figure 5.6. This condensation shockwave propagates in both directions from the point of origin, towards the hydrofoil’s root and tip with a spanwise velocity of $1.22 U_\infty$ ($R^2 = 99.3\%$) and $3.45 U_\infty$ ($R^2 = 97.3\%$), respectively.

The space-time diagram clearly shows that the cavity sheet at the tip remains connected, indicating that the tip of the cavity stays stable and does not undergo condensation. In contrast, the root of the cavity experiences condensation; however, this does not occur in each cycle. For example, in the subsequent cycle at $t_+ = 34.8$, the cavity sheet remains also connected at the root. This highlights the inherent 3D nature of the shedding mechanism, as well as the cycle-to-cycle variation in shockwave strength and the random

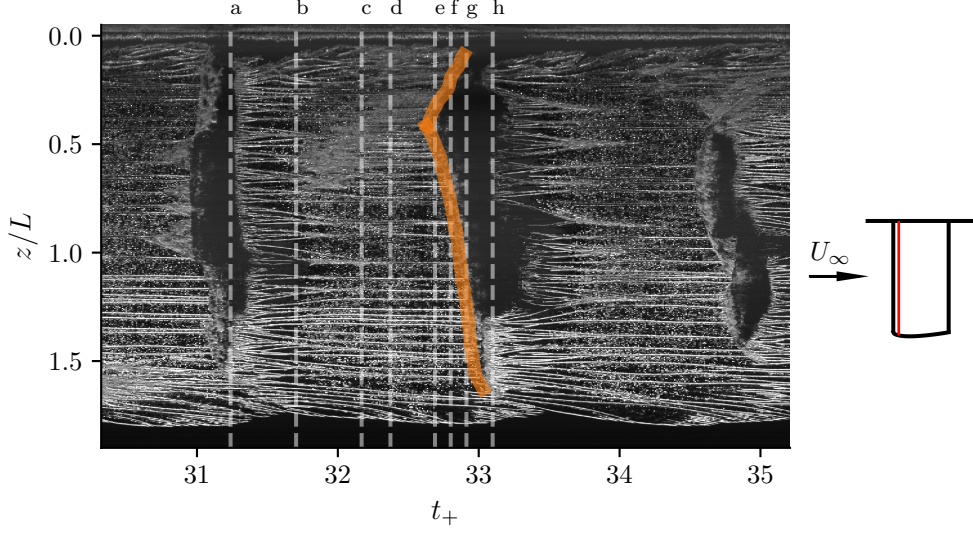


Figure 5.6: Detailed spanwise space-time diagram at $x/L = 0.1$ of the run type ‘short’ indicating the condensation shockwave at the leading edge of the hydrofoil. The cycle is the same as in figure 5.4. The vertical dashed lines correspond to the time instances of the frames in figure 5.4. A supplementary movie 3 is available.

spanwise location of the re-entrant flow impingement.

These findings motivate a critical re-examination of the re-entrant flow mechanism underlying cloud cavitation about hydrofoils, particularly at high incidence where the adverse pressure gradient is strong. The study by Pelz et al. (2017) is extended by the observation that the re-entrant flow does not need to reach the cavity leading edge to trigger cloud shedding; rather it must meet the necessary condition to interact with and impinge upon the cavity sheet. Consequently, the cavity sheet thickness becomes a critical factor – if it is sufficiently thick at any chordwise location, there is no interaction between the re-entrant flow and the cavity sheet, see Callenaere et al. (2001).

5.1.2 Invariance of the shedding frequency

As observed in chapter 4, mode (iv) – driven by the coupled mechanism discussed above – exhibits only a weak variation in frequency with varying α . This result was unexpected, as it is generally accepted that as the cavity grows to maximum length, the re-entrant flow must travel a larger distance upstream to reach the cavity leading edge and trigger the shedding, leading to a decrease in shedding frequency. In other words, the decrease in shedding frequency, f , is compensated by the increase in the maximum cavity sheet length, $\hat{a}$, resulting in a constant cavity length-based Strouhal number (equation (2.3)). As shown in a comprehensive comparison presented in section 2.2.2, most studies in the literature investigate cavitation dynamics with varying σ at fixed α . In these studies, the characteristic shedding frequency or the chord-based Strouhal number of re-entrant

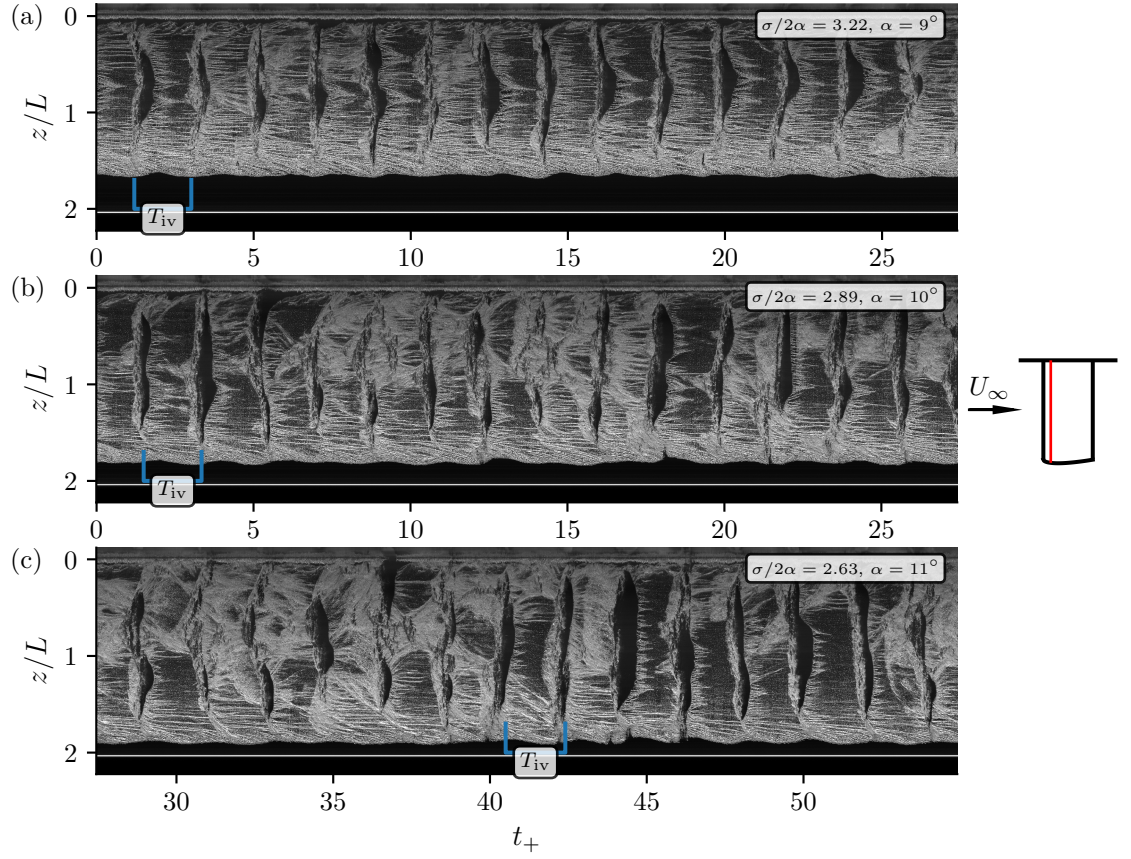


Figure 5.7: Spanwise space-time diagrams at chordwise position $x/L = 0.15$ for $\sigma = 1.01$ and (a) $\alpha = 9^\circ$, (b) $\alpha = 10^\circ$, (c) $\alpha = 11^\circ$ or (a) $\sigma/2\alpha = 3.22$, (b) $\sigma/2\alpha = 2.89$, (c) $\sigma/2\alpha = 2.63$. The corresponding chord-based and cavity length-based Strouhal numbers of mode (iv) are (a) $St_{iv} = 0.55$, $\hat{St}_{iv} = 0.34$, (b) $St_{iv} = 0.54$, $\hat{St}_{iv} = 0.37$, and (c) $St_{iv} = 0.53$, $\hat{St}_{iv} = 0.39$, respectively. The cloud shedding frequency of mode (iv) or the chord-based Strouhal number is incidence-invariant for small enough values of $\sigma/2\alpha$, whereas the cavity length-based Strouhal number decreases with $\sigma/2\alpha$. The physical time is 454.54 ms. A supplementary movie 4 is available.

flow-driven cloud cavitation exhibits a strong dependence on σ . The cavity length-based Strouhal number is commonly reported to be approximately constant, ranging between 0.2 and 0.4, across various geometries – including hydrofoils, convergent-divergent nozzles, and backward facing steps – as well as under different operation conditions (Kawanami et al., 1997; Stutz & Reboud, 1997; Pham et al., 1999; Callenaere et al., 2001; Arndt, 2012; Jahangir et al., 2018; Hatzissawidis, Kuhr, & Pelz, 2025). In contrast, by varying the incidence, a different behaviour is observed.

Varying α at fixed σ does not significantly change the characteristic shedding frequency

as well as the shedding topology, evident in the spanwise space-time diagrams for $\alpha = 9^\circ$, 10° , and 11° in figure 5.7 (a), (b), and (c), respectively. A supplementary movie 4 is provided. For an appropriate comparison, the duration time for all space-time diagrams is the same, and the period T_{iv} of one cycle is annotated in each diagram. Further, the space-time diagrams reveal an increasing spanwise extent $\hat{s}$ of the cavity as the incidence is increased. The non-dimensionalised spanwise cavity extent, $\hat{s}_+ := \hat{s}/L$, is 1.68, 1.81, and 1.90, for $\alpha = 9^\circ$, 10° and 11° , respectively.

A corresponding chordwise space-time diagram at a spanwise position of $z/L = 0.72$ shows the increase in maximum sheet length as α is increased, see figure 5.8. The blue dashed line represents the maximum cavity sheet length, being 0.62, 0.65, and 0.68, respectively. It is worth noting that the re-entrant flow is inherently 3D, and is not always directed chordwise; rather, it exhibits spanwise variations in its propagation. Furthermore, the maximum chordwise extent of the cavity sheet does not occur at the same spanwise position during each cycle. Additionally, due to randomly distributed perturbation on the cavity surface that render it opaque, the re-entrant flow is not always visible in a chordwise space-time diagram, see also supplementary movie 4. These factors complicate the interpretation of the chordwise space-time diagram.

The chord-based (St), cavity length-based ($\hat{St}$), and cavity velocity-based Strouhal number ($St^* := fL/U_\infty\sqrt{1+\sigma}$), along with the maximum cavity length, are presented as a function of $\sigma/2\alpha$ (figure 5.9). The high cavitation numbers, 0.88 and 1.01, are chosen as re-entrant flow-driven cloud cavitation appears as the fundamental mode. It is evident that the frequency does not decrease proportionally to the increase in cavity length. The commonly held assumption – that the re-entrant flow must travel a longer upstream distance and must cause a decrease in frequency – does not hold in the present study with varying incidence. If this assumption were true, it would imply that the re-entrant flow velocity remains constant. Since the frequency or the chord-based Strouhal number remains constant, it follows that either the cavity sheet expands more rapidly or the re-entrant flow velocity increases. Given that the cavitation number remains constant, the theoretical velocity of the re-entrant flow, $U_\infty\sqrt{1+\sigma}$, as predicted by irrotational flow theory, stays the same. As a result, the cavity velocity-based Strouhal number follows the same trend as the chord-based Strouhal number.

However, the flow does not behave according to irrotational flow theory; the invariance of the re-entrant flow frequency is instead attributed to an increase in the re-entrant flow velocity as detailed in the following. The cavity-length based Strouhal number, $\hat{St}$, increases as $\sigma/2\alpha$ is decreased or α is increased, see figure 5.9. From the dimensional analysis derived by Hatzissawidis, Kuhr, and Pelz (2025), $\hat{St}$ depends solely on the model shape, which is a function of the geometry (here NACA 0015) and the incidence, as it influences the pressure distribution (see the dimensional analysis in section 2.2.1). Thus, the shape can be expressed as $\text{shape} := \{\text{NACA 0015}, \alpha\}$. The pressure distribution along the hydrofoil is fully considered by the shape (Pelz et al., 2017; Hatzissawidis, Kuhr, & Pelz, 2025). Since α is increased, this results in a stronger adverse pressure gradient, which in turn increases the momentum and velocity of the re-entrant flow. This counteracts the effect of the increasing maximum cavity length. Otherwise, this would lead to a decrease in frequency and $\hat{St}$ would be constant as initially expected. Since $\hat{St}$

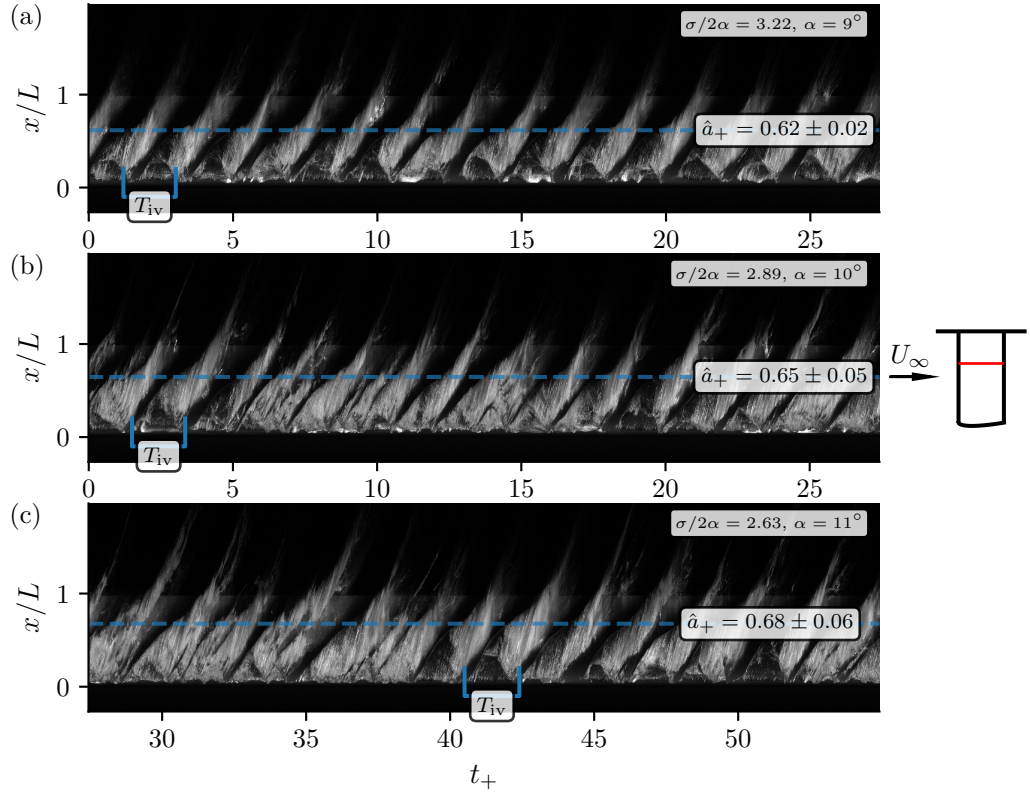


Figure 5.8: Chordwise space-time diagrams at spanwise position $z/L = 0.72$. The conditions are the same as in figure 5.7. The blue horizontal dashed line denotes the maximum cavity length. A supplementary movie 4 is available.

increases as α is increased (or $\sigma/2\alpha$ is decreased) (figure 5.9), the re-entrant flow velocity is increased.

This effect becomes evident for both cavitation numbers, 0.88 and 1.01, showing good agreement (figure 5.9). At $\sigma = 1.01$ and $\sigma/2\alpha = 3.63$, the frequency deviates from the trend showing a much higher value. However, this operation point exhibits sheet cavitation with small-scale vortices as well as strong interaction between the re-entrant flow and the thin cavity sheet.

In summary, the incidence modifies the pressure distribution, which in turn affects the re-entrant flow velocity. As the incidence is increased, the maximum cavity sheet length increases and, simultaneously, the re-entrant flow velocity increases, and vice versa. This coupling leads to an invariant shedding frequency. Until now, this effect has not been reported in the literature, because most studies vary the cavitation number, rather than the incidence. When the cavitation number is decreased, the maximum sheet length increases and closes further downstream where the adverse pressure gradient is weaker. Thus, the re-entrant flow has less momentum, which reduces its velocity. The combined effect of the larger cavity length and the reduced adverse pressure gradient then enhances

5.1 Coupled re-entrant flow and condensation shockwave

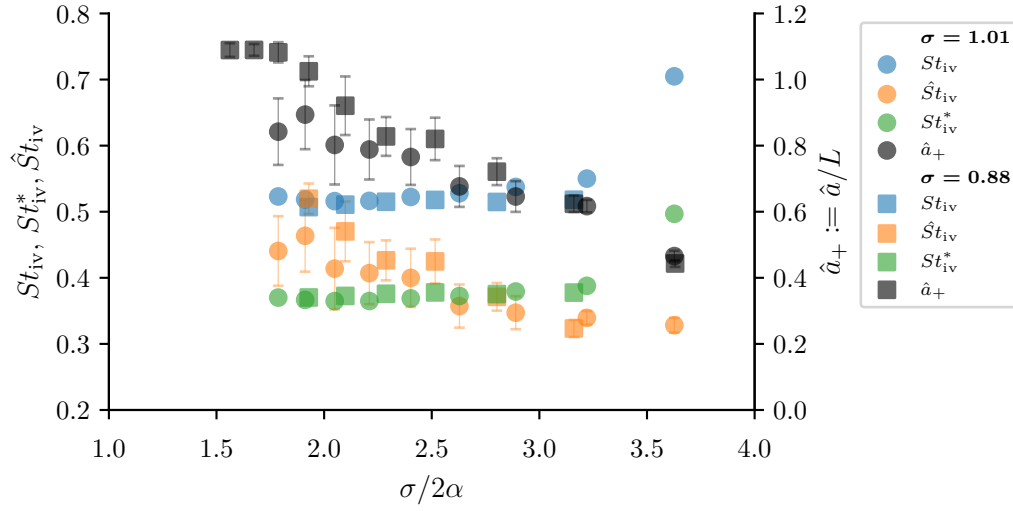


Figure 5.9: Chord-based (blue), cavity length-based (orange), and cavity velocity-based (green) Strouhal number of mode (iv), together with the sheet length (black) for the two cavitation numbers of 0.88 and 1.01 over $\sigma/2\alpha$. The chord-based Strouhal number and the cavity velocity-based Strouhal number are incidence-invariant, whereas the cavity length-based Strouhal number increases as $\sigma/2\alpha$ is reduced.

the decrease in shedding frequency.

5.2 Fundamental shockwave-driven mode and tip shedding mode

Decreasing σ from 1.01 to 0.50, re-entrant flow-driven cloud cavitation no longer appears as a fundamental mode; rather, condensation shockwaves dominate the shedding process. Mode (i) appears in conjunction with a low-frequency mode (ii) as observed by Venning et al. (2022) for the same geometry but larger chord. This aforementioned study is extended by examining numerous operation points where mode (i) and (ii) occur, focusing on two cases for $\sigma = 0.50$ at $\alpha = 6^\circ$ and 14° . As demonstrated in section 4.3.3, mode (ii) exhibits either high negative correlation or weak correlation with mode (i), which is investigated further here by selecting two operation points where each behaviour is observed.

The SPOD modes, calculated from the high-speed photographs of run type ‘medium’, are presented as intensity maps (absolute values) and corresponding phase maps. They reveal the regions of high energy of a specific mode along with the associated relative phase shift, figure 5.10. A supplementary movie 5 of the run type ‘short’ is available. Mode (i), the fundamental shedding mode driven by condensation shockwaves, exhibits a high activity at mid-span of the cavity for $\alpha = 6^\circ$ and 8° . At the higher incidence of 14° , the intensity is more spread, showing a more homogeneous intensity distribution. This observation is due to shedding spanning the whole cavity including condensation of the cavity’s root, whereas in the other two cases, the activity of the shedding is focused at the mid-span of the cavity. The phase of mode (i) at $\alpha = 6^\circ$ and 8° shows that the cavity at mid-span is at about $\pi/2$ and the regions above and below exhibit a phase of π . This indicates that the cavity at mid-span is out of phase with these two regions. As shown later, this occurs due to tip and root shockwaves. In contrast, mode (i) at $\alpha = 14^\circ$ exhibits a more 2D behaviour, suggesting that the entire cavity sheet condenses in-phase across all spanwise positions, see supplementary movie 5.

As shown in chapter 4, mode (ii) occurs in conjunction with mode (i) as $\sigma/2\alpha$ is reduced, (see figure 5.10, $\alpha = 6^\circ$). However, as $\sigma/2\alpha$ is further reduced, the maximum cavity length equals to the chord of the hydrofoil and mode (ii) diminishes. This occurs for an incidence of 8° , see figure 5.10, and is examined later in section 5.3. A further reduction in $\sigma/2\alpha$ leads to a maximum cavity length beyond the hydrofoil’s trailing edge, and mode (ii) recurs (see figure 5.10, $\alpha = 14^\circ$).

At both lower and higher incidences, mode (ii) is present and exhibits a higher intensity at the tip, which is evident for 6° and 14° , see figure 5.10. At $\alpha = 14^\circ$, mode (ii) is confined to a narrower region at the cavity tip and extends beyond the trailing edge. Although the two modes exhibit similar topology, the transient behaviour differs, as shown in section 4.3. At 6° , a high negative correlation with mode (i) is observed ($r = -0.65$), whereas at 14° a weak correlation is evident ($r = -0.29$). In other words, for the former case, the appearance of mode (ii) diminishes mode (i) and vice versa, while for the latter, both modes occur without essentially influencing each other.

Mode (iii) is predominantly a harmonic artefact, although there is evidence of physical content, which is consistent with Venning et al. (2022). The harmonic nature is indicated

5.2 Fundamental shockwave-driven mode and tip shedding mode

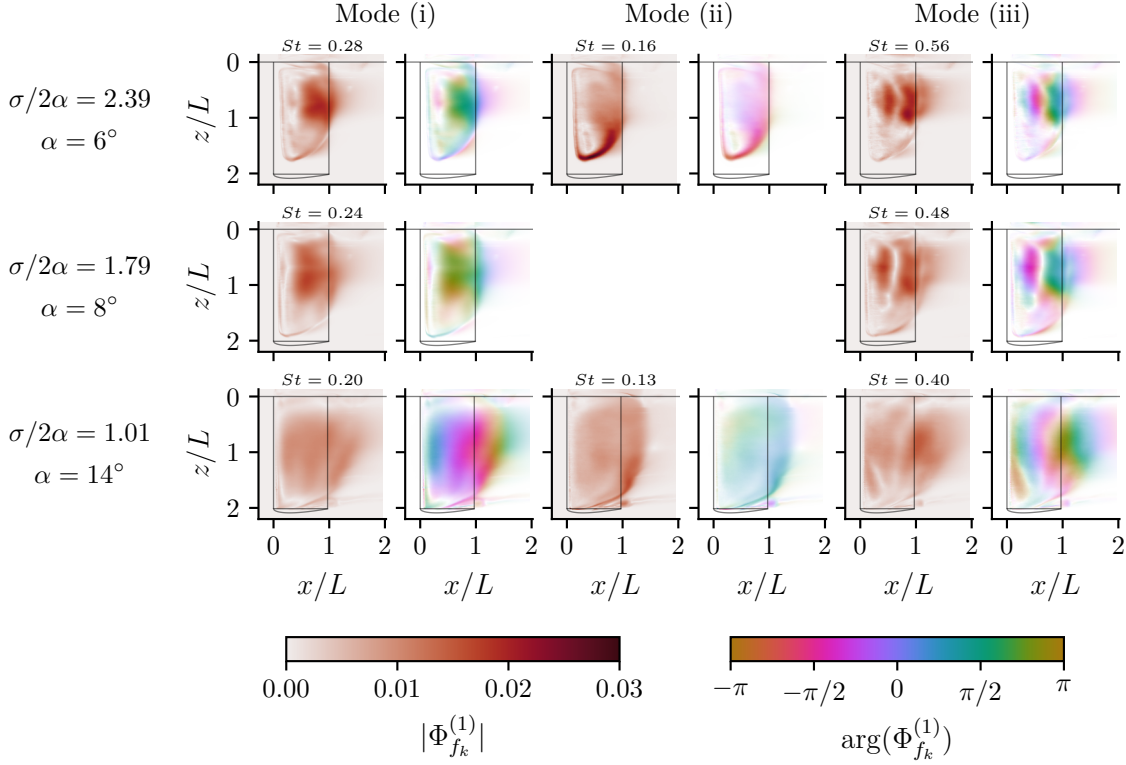


Figure 5.10: Leading SPOD eigenmodes of mode (i), (ii), and (iii) presented as absolute values and phase for $\sigma = 0.50$ and $\alpha = 6^\circ$, 8° and 14° or $\sigma/2\alpha = 2.39$, 1.79 , and 1.01 . The phase maps are scaled by the absolute values to emphasise the important regions for a specific mode. The scale of the absolute values are normalised to allow a fair comparison between the operation points. A supplementary movie 5 is available.

by the frequency, which is twice that of the fundamental mode (i), and by the wavelength, which is half, see also Hatzissawidis, Sieber, Oberleithner, and Pelz (2025). As shown later in section 2.1.3, mode (iii) also contains a physical part for higher cavitation numbers despite its harmonic artefact.

Due to the short recording duration of the run type ‘short’, mode (ii) is not captured in figure 5.11. However, the high time resolution allows for a detailed analysis of the underlying physics of mode (i) for a cavitation number of 0.50 and an incidence of 6° ($\sigma/2\alpha = 2.39$). From the stacked figure of simultaneous captured data, the coherent nature of mode (i) becomes evident. The slice for the space-time diagram is placed where the intensity of mode (i) is high, see figure 5.10. As the SPOD modes reveal (figure 5.10), the shedding is concentrated at cavity mid-span, which becomes also evident in the spanwise space-time diagram, see figure 5.11 (e). The spanwise space-time diagram near the cavity leading edge (figure 5.11 (d)) shows that the cavity sheet is not fully condensed at the end of the cycle, as it appears to be connected. Particularly at the cavity tip, the

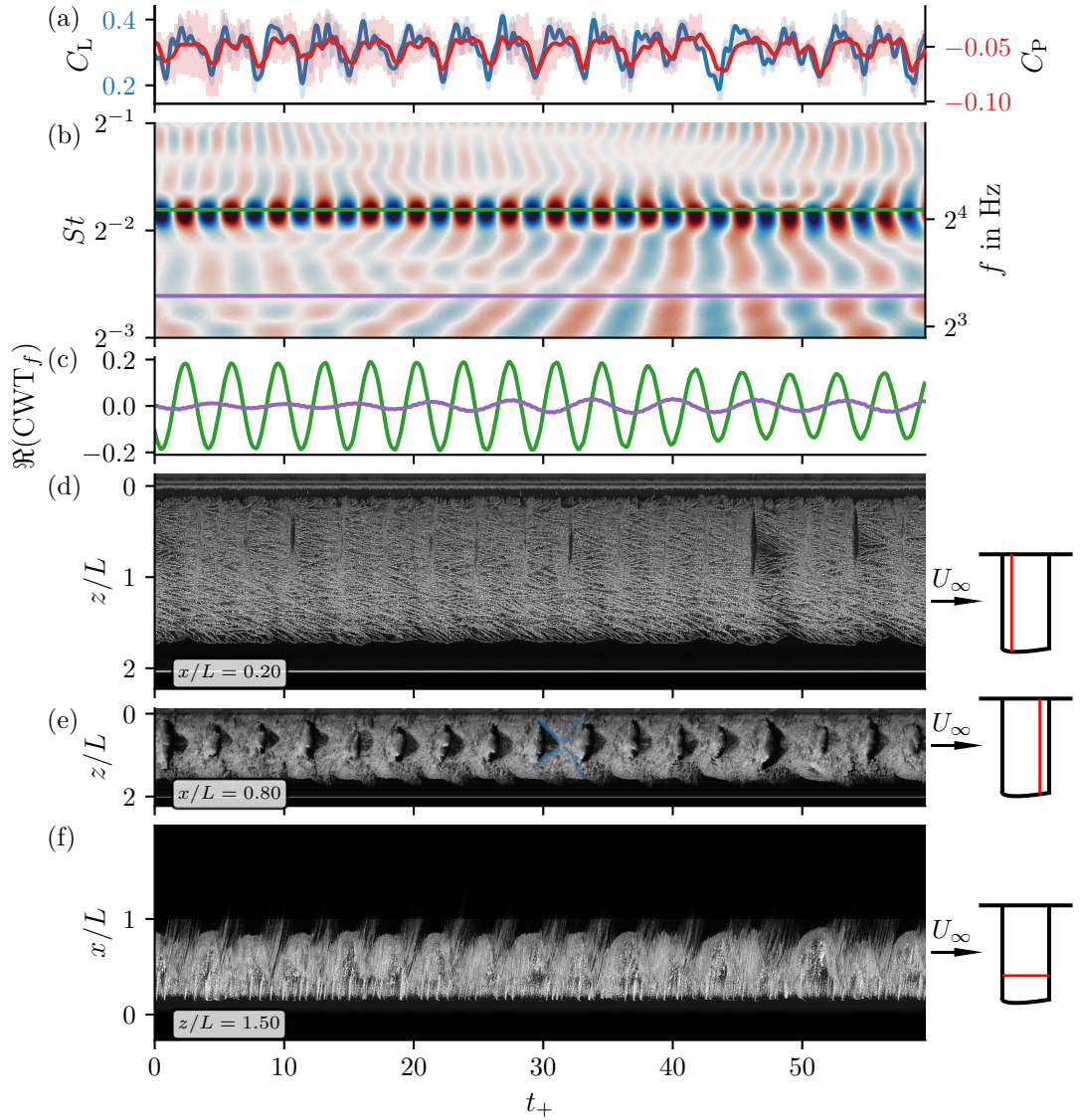


Figure 5.11: Simultaneously captured data showing the (a) lift coefficient (C_L , blue line) and pitching coefficient (C_P , red line), (b) the real part of the CWT of C_L , (c) the CWT component at f_i (green line) and f_{ii} (purple line), and (d-f) space-time diagram from the high-speed photography from run type ‘short’. (d) and (e) are spanwise space-time diagrams at $x/L = 0.20$ and $x/L = 0.80$, respectively, and (f) is a chordwise slice towards the tip at $z/L = 1.50$. The operation point is $\sigma = 0.50$, $\alpha = 6^\circ$ ($\sigma/2\alpha = 2.39$). The physical time is 1000 ms.

spanwise-moving cells, resembling branches, are continuously connected throughout the whole time, see figure 5.11 (d) at about $1.1 < z/L < 1.5$. This is further evident in the

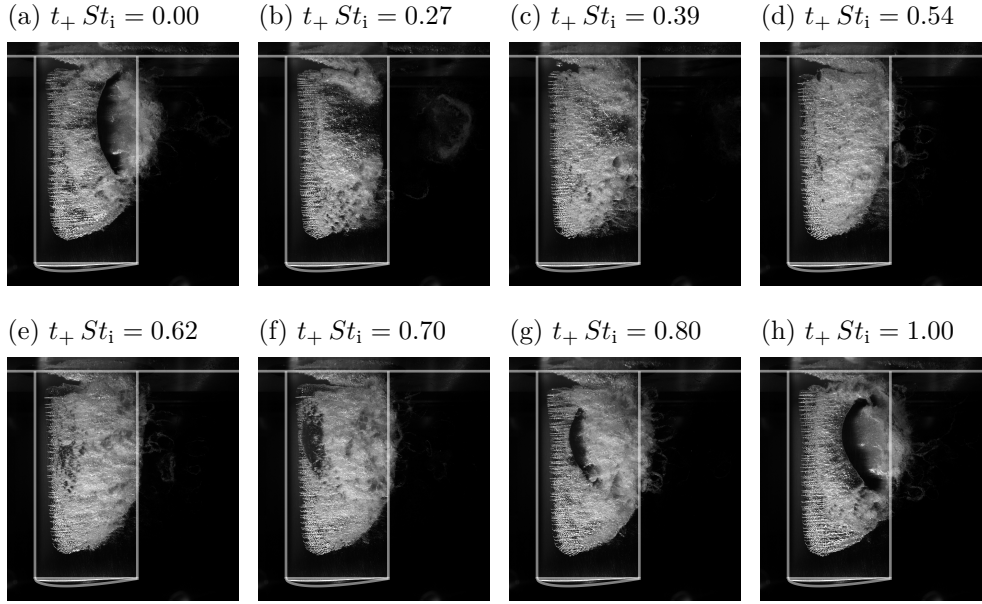


Figure 5.12: Sequence of high-speed photographs showing the condensation shockwave mechanism, mode (i). The dimensionless cycle time instance is given as $t_+ St_i$. (a) The cavity sheet is growing with the cloud from the previous cycle still being visible, (b) the oblique shockwaves from the cavity root and the tip are visible and growing towards the mid point of the cavity. The cavity sheet appears frothy behind the shockwaves. (c) The cavity sheet length reaches the trailing edge of the hydrofoil and a shockwave is initiated, (d) travelling upstream. (e), (f) The shockwave reaches the leading edge of the cavity, resulting in large-scale cloud shedding. (g), (h) The cavity starts to regrow and the cycle repeats. The cavitation number is 0.50 and the incidence is 6° ($\sigma/2\alpha = 2.39$).

supplementary movie 5.

Although mode (ii) is not clearly visible in figure 5.11, a weakening of mode (i) can be observed at $t_+ > 40$, as seen in the CWT components in figure 5.11 (c). This effect is also evident in the chordwise space-time diagram, figure 5.11 (f), at $40 < t_+ < 50$, showing a slightly increased activity of mode (ii). Mode (ii) will be analysed later for the run type ‘medium’, where time instances with high intensity occur.

The blue ‘cross’ annotations in figure 5.11 (e) represent the paths of the tip and root condensation shockwaves. For mode (i) to occur, this ‘cross’ has to be present, indicating the synchronisation of the two condensation shockwaves at the tip and the root. As shown later, this ‘cross’ is absent during high mode (ii) activity, suggesting that these condensation shockwaves influence the appearance of mode (i).

The physics of mode (i) are analysed in detail for the single shedding cycle annotated in figure 5.11 (e). A sequence of high-speed photographs in figure 5.12 shows the

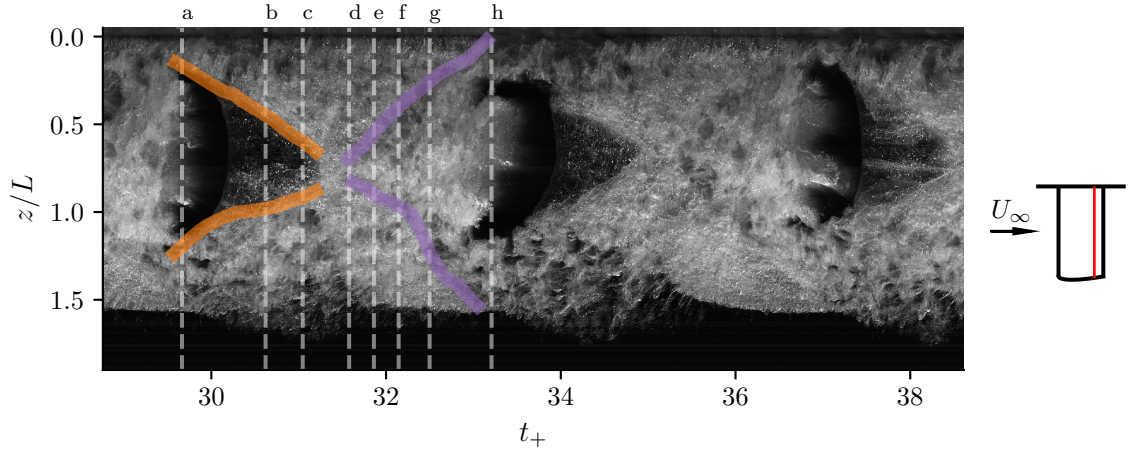


Figure 5.13: Detailed spanwise space-time diagram at $x/L = 0.80$ of the run type ‘short’. The cycle is the same as in figure 5.12. The vertical dashed lines correspond to the time instances of the frames in figure 5.12. The ‘cross’-shape of the root and tip shockwave is evident for the mode (i) shockwave-driven shedding. The orange path traces the condensation during the cavity growth phase, and the purple path traces the condensation during the cavity condensation phase. For mode (ii) shedding, where mode (i) is suppressed, this ‘cross’-shape is no longer visible. The cavitation number is 0.50 and the incidence is 6° ($\sigma/2\alpha = 2.39$). The physical time is 165.61 ms. A supplementary movie 6 is available.

condensation mechanisms of mode (i). The cavity sheet grows and exhibits a crescent shape, as also observed by Venning et al. (2022), figure 5.12 (a). The cloud from the previous cycle is still visible. A re-entrant flow develops during the growth phase and becomes visible beneath the sheet; However, it remains stable throughout the cycle and does not drive the shedding mechanism, figure 5.12 (a) and (b). The tip and root condensation shockwaves are also visible, figure 5.12 (b) and (c). The shedding is initiated as the cavity reaches the hydrofoil’s trailing edge, figure 5.12 (c), consistent with previous findings (Hatzissawidis, Kuhr, & Pelz, 2025). The shockwave is propagating upstream, see figure 5.12 (d), and reaches the leading edge of the cavity, figure 5.12 (e). A large-scale cloud is formed and advected downstream, see figure 5.12 (f) and (g), and the cycle repeats, figure 5.12 (h). The tip of the cavity is not condensed and remains stable during mode (i) activity. The oblique condensation shockwaves at the root and the tip are not solely responsible for the shedding, however, as mentioned above, the ‘cross’ shape formed by the shockwaves is important for mode (i).

The ‘cross’-shaped structure formed by the tip and root condensation shockwaves is presented in the spanwise space-time diagram in figure 5.13 for the same cycle. The subsequent cycle is also presented and exhibits the same structure. The orange path traces the condensation during the cavity growth phase, while the purple path traces

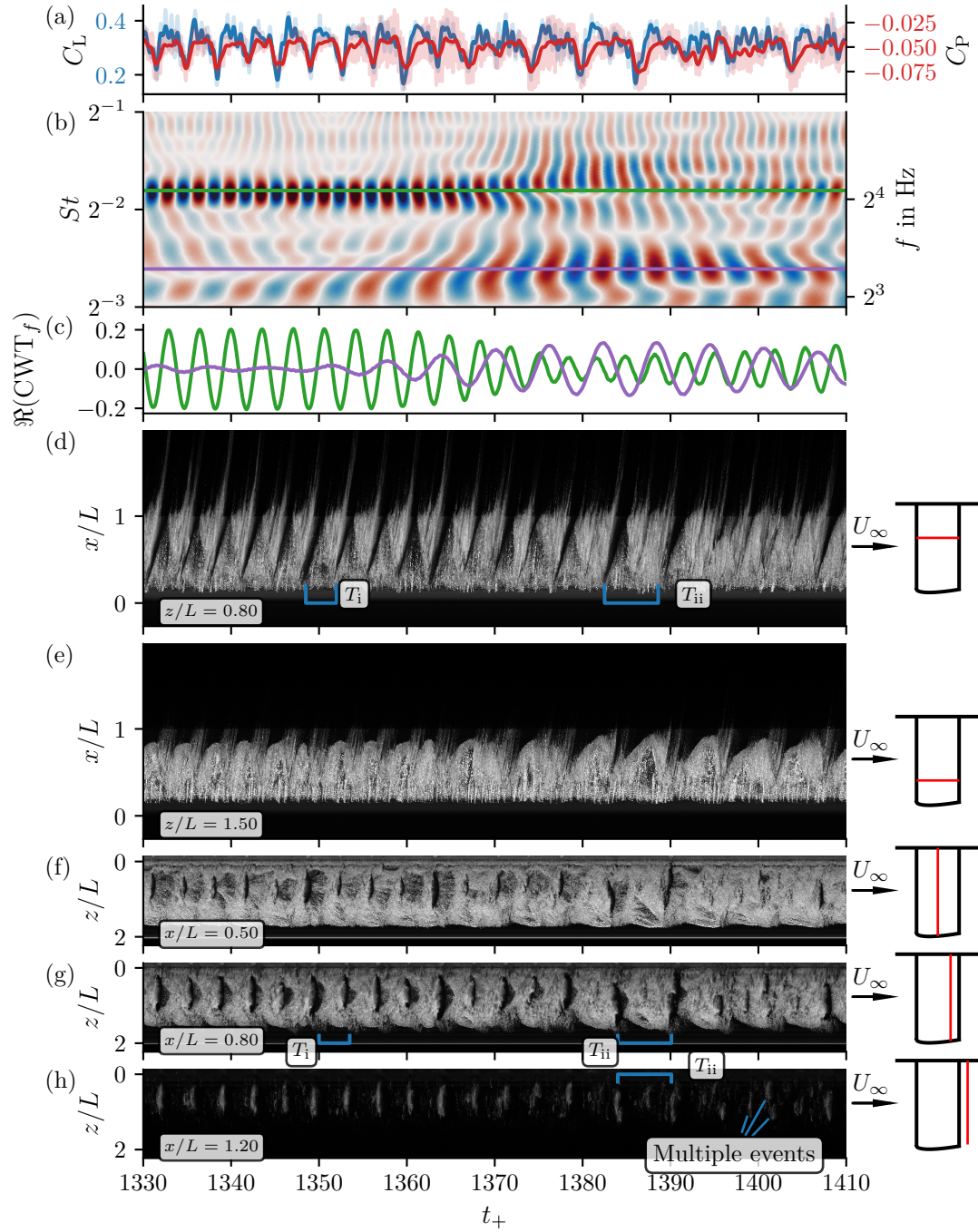


Figure 5.14: The intermittent behaviour of mode (i) and mode (ii) is shown for $\sigma = 0.50$, $\alpha = 6^\circ$ ($\sigma/2\alpha = 2.39$). Simultaneous time series of the (a) lift (C_L) and pitching coefficient (C_P), the (b) real part of the CWT of C_L , and (c) mode (i) ($St_i = 0.29$) and mode (ii) ($St_{ii} = 0.16$) CWT components in green and purple, respectively, together with the space-time diagrams for the ‘medium’ run type: (d) chordwise at $z/L = 0.80$, (e) chordwise at $z/L = 1.50$, (f) spanwise at $x/L = 0.50$, (g) spanwise at $x/L = 0.80$, (h) spanwise at $x/L = 1.20$ (Continued on the following page).

Figure 5.14: (continued) The transition from mode (i) to mode (ii) is evident in the CWT, (b) and (c), and occurs between $t_+ = 1360$ and 1370 . The transition is also evident in the space-time diagrams. For dominant mode (i) the shedding is highly coherent, whereas for dominant mode (ii), mode (i) is diminished and multiple shedding events along the span can be seen, e.g. $t_+ = 1400$. A supplementary movie 7 is available.

the condensation during the cavity condensation phase after the shockwave is initiated at the trailing edge of the hydrofoil. A supplementary movie 6, with the annotations in the same colours, is provided. These two condensation shockwaves at the tip and the root are synchronised for high mode (i) activity. They form during the growth phase and propagate slowly upstream to the cavity midpoint. Once the main shockwave is triggered at the hydrofoil's trailing edge and propagates upstream in the chordwise direction, the cavity at mid-span is condensed. The tip and root shockwave, however, continue to propagate until the next cycle begins. At that point, the tip and root shockwaves form again. When this process falls out of synchronisation, the tip shockwave perturbs mode (i), and mode (ii) becomes dominant.

The transition from mode (i) to mode (ii) is visualised through the high-speed photographs of the run type 'medium', since there was enough time for mode (ii) to appear, as the characteristic time scale for mode (ii) appearance and disappearance is of the order of magnitude of seconds. A supplementary movie 7 is available. Simultaneous captured force data, C_L and C_P , the CWT of C_L , as well as the CWT components at f_i and f_{ii} are presented together with space-time diagrams of the high-speed photography, figure 5.14. The transition occurs from $t_+ = 1360$ to 1380 , which becomes evident in the CWT of the C_L , figure 5.14 (b) and (c). The corresponding Strouhal number for mode (i) and mode (ii) are $St_i = 0.29$ and $St_{ii} = 0.16$, respectively. A strong correspondence to the force time series and the CWT results can be revealed from the space-time diagrams, figure 5.14 (d) to (h). The periods T_i and T_{ii} corresponding to mode (i) and (ii), respectively, are annotated in figure 5.14 (d), (g), and (h). As mode (i) is dominant, the shedding appears highly coherent, with the 'cross'-shaped features becoming evident in the spanwise space-time diagram in figure 5.14 (g) for $t_+ < 1360$. As mode (ii) appears at $t_+ > 1380$, mode (i) diminishes. This intermittent behaviour is shown through the correlation coefficient in section 4.3.3. The 'cross'-shaped feature is no longer detectable, and the shedding is less coherent, with full span shedding events at e.g. at $t_+ = 1390$, or events where smaller clouds at different spanwise locations are shed, and the full span shedding is interrupted, e.g. at $t_+ = 1400$, see figure 5.14 (g) and (h). Hence, during mode (ii) activity, mode (i) is diminished, and the tip and root shockwaves are out of phase.

As mode (ii) appears, the main cycle exhibits strong cavity tip excursion, which is clearly visible in the spanwise space-time diagrams at two different locations figure 5.14 (f) and (g). The cavity tip is oscillating stronger compared to time instances where mode (i) is dominant. Strong tip excursion is evident when mode (ii) is dominant, whereas little

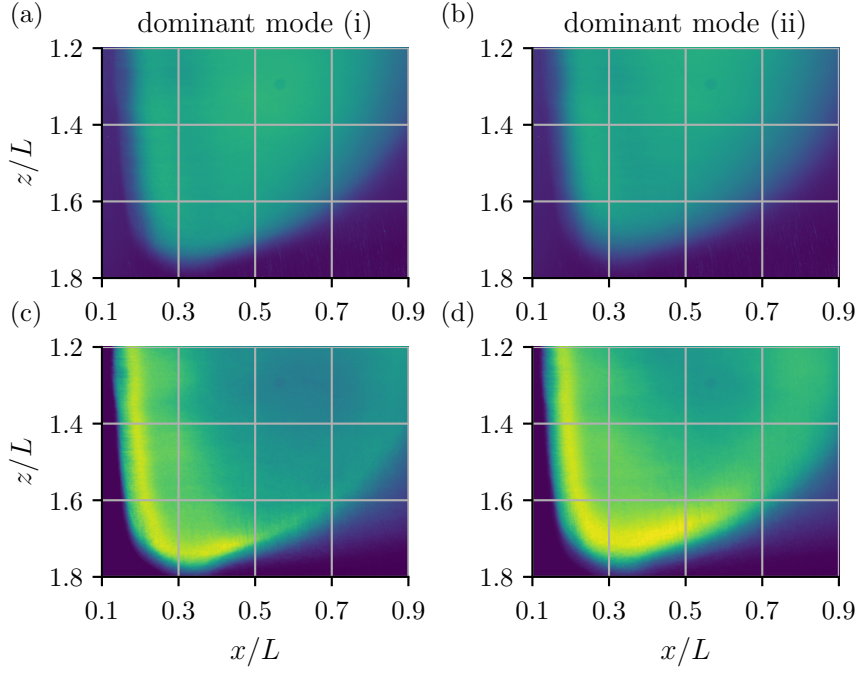


Figure 5.15: Temporal mean (a), (b) and standard deviation (c), (d) of the high-speed photographs near the cavity tip for dominant mode (i), (a), (c), and dominant mode (ii), (b), (d) over 50 cycles. The frames were discriminated to be either mode (i) dominant or mode (ii) dominant or indeterminate (not included) comparing the absolute values of mode (i) and (ii) of the CWT components. The operation point is $\sigma = 0.50$, $\alpha = 6^\circ$ ($\sigma/2\alpha = 2.39$).

tip excursion is evident when mode (i) is dominant. This is supported by the SPOD results, see figure 5.10, mode (ii) at $\sigma/2\alpha = 2.39$. The strong intensity at the cavity tip is due to the difference in pixel intensity, where the cavity sheet at the tip appears bright and the hydrofoil surface dark. Despite mode (ii) exhibiting strong cycle-to-cycle variation, the tip excursion is present across each cycle. This is also visualised in the supplementary movie 7, where the mean cavity tip location is annotated in orange. The condensation of the cavity tip occurs due to a tip shockwave, e.g. $t_+ = 1388$ in the chordwise space-time diagram, figure 5.14 (e). Shockwaves are not solely propagating chordwise, rather they propagate in spanwise direction towards the tip and the root which becomes evident in the spanwise space-time diagram figure 5.14 (f) at $t_+ = 1388$ and from 1390 to 1410, respectively. The chaotic occurrence of shockwaves at mode (ii) activity becomes clear in the supplementary movie 7. However, the tip shockwave seems to occur regularly, leading to the high intensity for mode (ii) at the tip.

To further substantiate the presence of tip excursion during mode (ii) activity, the temporal mean and standard deviation of the high-speed photographs near the cavity tip are computed separately for frames classified as mode (i) dominant and mode (ii)

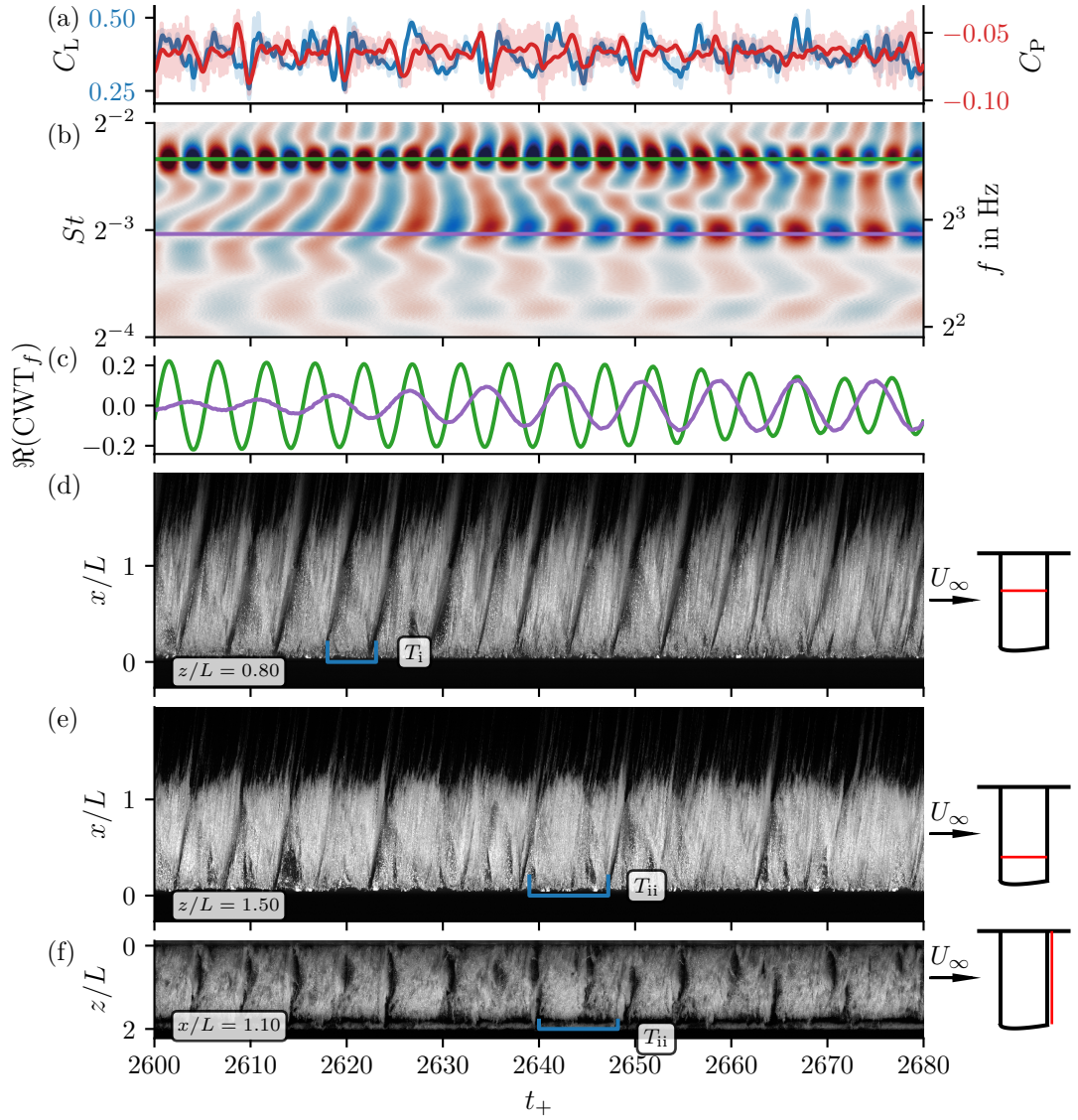


Figure 5.16: The occurrence of mode (i) and mode (ii) with weak correlation is shown for $\sigma = 0.50$, $\alpha = 14^\circ$ ($\sigma/2\alpha = 1.01$). Simultaneous time series of the (a) lift (C_L) and pitching coefficient (C_P), the (b) real part of the CWT of C_L , and (c) mode (i) ($St_i = 0.20$) and mode (ii) ($St_{ii} = 0.12$) CWT components in green and purple, respectively, together with the space-time diagrams for the ‘medium’ run type: (d) chordwise at $z/L = 0.80$, (e) chordwise at $z/L = 1.50$, (f) spanwise at $x/L = 1.10$. A supplementary movie 8 is available.

dominant over 50 cycles. The classification is based on the comparison of the absolute values of the CWT components of C_L for mode (i) and mode (ii). The results are shown

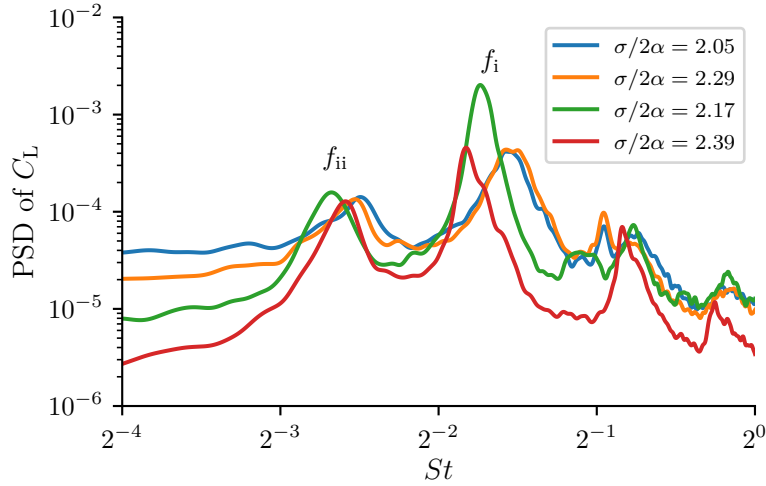


Figure 5.17: PSD of C_L for operation points where mode (i) and mode (ii) occurs for similar $\sigma/2\alpha$ across the four cavitation numbers. The operation points are $\sigma = 1.00$, $\alpha = 14^\circ$ (blue line), 0.88 , 11° (orange line), 0.76 , 10° (green line), and 0.50 , 6° (red line). The corresponding space-time diagrams are presented in figure 5.18.

in figure 5.15. For mode (ii) dominant frames, the area of high standard deviation near the tip is larger, indicating pronounced motion, whereas for mode (i) dominant frames, the standard deviation is restricted to a narrower portion of the tip. This quantitative analysis confirms that the cavity tip excursion is a distinguishing feature of mode (ii) activity. These results match the SPOD modes, see figure 5.10, where the cavity tip excursion is pronounced for mode (ii).

The same stacked figure is presented for the operation point $\sigma = 0.50$ and $\alpha = 14^\circ$, where mode (i) and mode (ii) are also present, see figure 5.16. However, no such high correlation was found between mode (i) and mode (ii), with a correlation coefficient of $r = -0.29$, see section 4.3.3. For this operation point, the cavity sheet extends beyond the trailing edge of the hydrofoil and the spanwise extent has reached the span of the hydrofoil. The SPOD results reveal that mode (ii) is concentrated at the cavity tip, as for $\alpha = 6^\circ$, see figure 5.10. The intensity of mode (i) is uniformly distributed, without distinct zones of concentrated energy. In contrast, for $\alpha = 6^\circ$, the intensity exhibits localised concentration, see figure 5.10. Mode (i) is driven by a condensation shockwave, as it is for $\alpha = 6^\circ$. For dominant mode (i), the condensation shockwave forms when the cavity sheet reaches its maximum extent beyond the hydrofoil's trailing edge, $\hat{a}_+ = 1.39$, leading to the condensation of the cavity sheet and cloud shedding, see figure 5.16 (d) and supplementary movie 8. A tip and a root shockwave is also evident; however, it is not as clear as for $\alpha = 6^\circ$. When mode (ii) occurs at about $t_+ = 2640$, a tip shockwave condensates the cavity tip, see figure 5.16 (e) between $2645 < t_+ < 2648$. The 2D behaviour of the shedding is disturbed, figure 5.16 (f), and clouds are shed from top and bottom spanwise locations. Compared to $\alpha = 6^\circ$, mode (i) is not strongly affected when

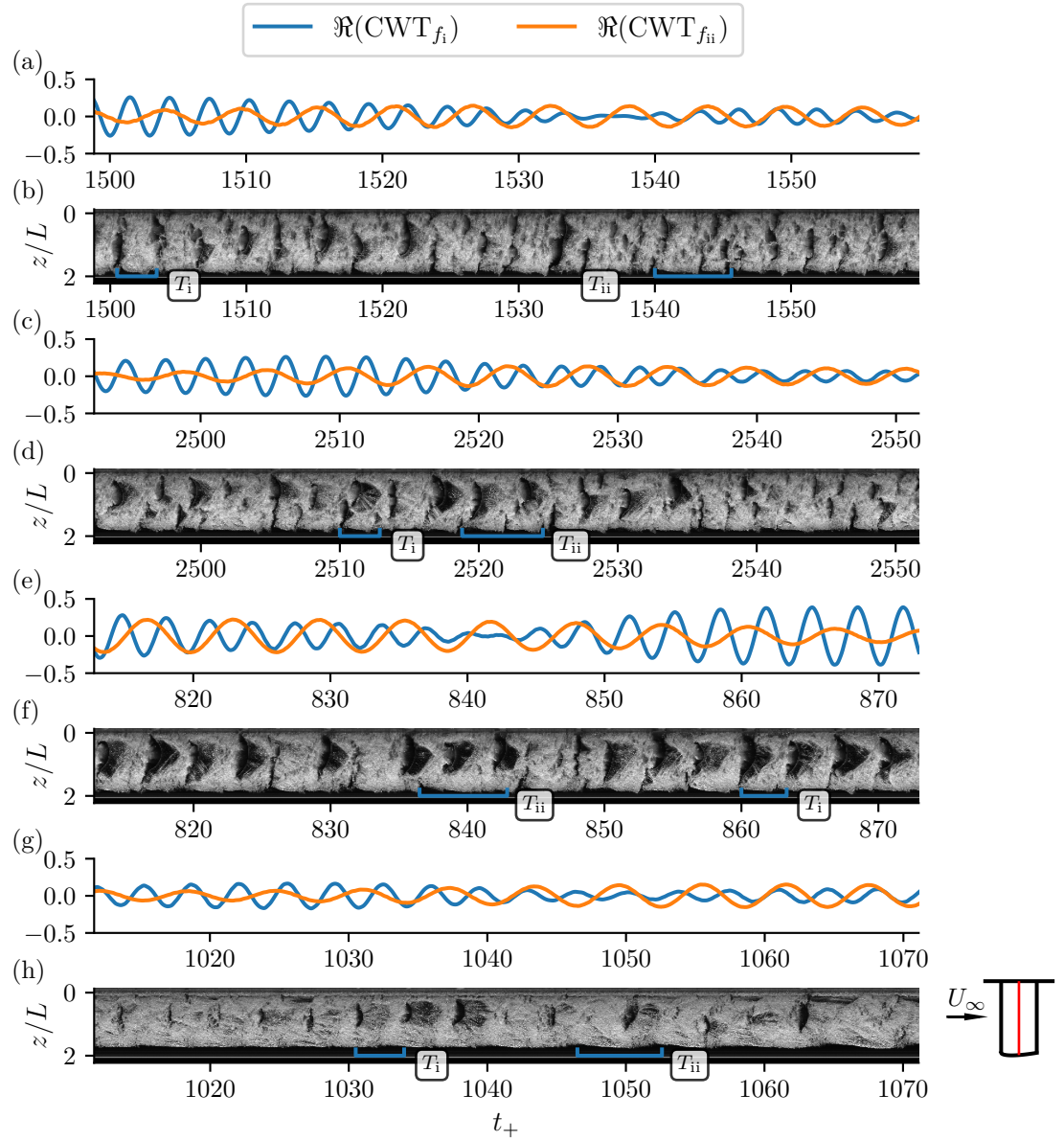


Figure 5.18: Comparison of spanwise space-time diagrams at $x/L = 0.5$ (b,d,f,h) and the CWT components at f_i and f_{ii} (a,c,e,g) for the transition between mode (i) and mode (ii) across the four cavitation numbers, $\sigma = 1.00, 0.88, 0.76, 0.50$, for incidences $\alpha = 14^\circ, 11^\circ, 10^\circ, 6^\circ$ or $\sigma/2\alpha = 2.04, 2.28, 2.17, 2.39$. A supplementary movie 9 is available.

mode (ii) appears, which is confirmed by the larger correlation coefficient.

Comparing the PSD of C_L of operation points where mode (i) and mode (ii) are dominant across the four cavitation numbers reveals a similar trend, figure 5.17. The

corresponding spanwise space-time diagrams are presented in figure 5.18, together with the CWT components at f_i and f_{ii} . Vertical cuts are taken at $x/L = 0.5$ and the maximum sheet lengths are between 0.8 and 1. The amplitude of mode (i) for $\sigma = 0.76$ (green line) is about one order of magnitude larger than for the other operation points, figure 5.17. This becomes evident in the space-time diagram, figure 5.18 (f), for $t_+ > 850$, where the shedding extends coherently across the entire spanwise direction of the cavity sheet. The corresponding CWT component at f_i likewise exhibits a pronounced amplitude in this time range, figure 5.18 (e). The correlation coefficient between the absolute value of the CWT component at f_i and f_{ii} is approximately 0, see section 4.3.3, compared to the negative high correlation for $\sigma = 0.50$ – As discussed above, the shedding for $\sigma = 0.50$ remains also coherent, with mode (ii) exerting a pronounced influence on mode (i), figure 5.18 (g) and (h). Although mode (i) and mode (ii) are clearly discernible in the PSD for the two high cavitation numbers, 0.88 and 1.01, their spatial structures are less apparent in the space-time diagrams, figure 5.18 (b) and (d), as the shedding develops an increasingly 3D character, with multiple spanwise shedding events. Moreover, the peaks at f_i for the high cavitation numbers, 0.88 and 1.01, appear brighter, reflecting cycle-to-cycle frequency variations and less coherence, whereas at the lower cavitation numbers, 0.50 and 0.76, mode (i) is characterised by a distinctly narrower peak, see figure 5.17. A supplementary movie 9 comparing all four operation points is available.

In summary, while the PSD and the SPOD appear similar, the space-time diagrams reveal the underlying 3D behaviour and highlight the differences across the cavitation numbers. A detailed discussion of the 3D behaviour and their coherence is provided later.

5.3 Condensation shock initiation at the trailing edge

Shockwave-driven mode (i) is the fundamental shedding for a cavitation number of 0.50 for all incidences investigated. As discussed above, tip shedding mode (ii) is diminished for $1.55 \lesssim \sigma/2\alpha \lesssim 2.21$, see table 5.1 and figure 5.19. Under this condition, the shedding becomes unimodal, with mode (i) as well as its harmonic mode (iii) alone persisting, characterised by well-defined coherent shedding. The PSD peaks of C_L at mode (i) frequency f_i and the SPOD variance at that frequency exhibit the same trend. The SPOD variance is calculated according to equation (3.18), describing the ‘energy’ content of a specific mode relative to the total ‘energy’. The PSD of mode (i) reaches a maximum as mode (ii) diminishes, and slightly decreases once mode (ii) re-emerges as $\sigma/2\alpha$ is lowered, figure 5.19. For low $\sigma/2\alpha \lesssim 1.1$ or high incidence, the energy content of mode (i) and (ii) decreases due to the transition to supercavitation.

The question arises as to what causes the disappearance of mode (ii). For a cavitation number of 0.50, when the maximum cavity sheet length, $\hat{a}_+$, reaches the trailing edge of the hydrofoil, mode (ii) vanishes and the chord-based Strouhal number remains approximately constant at $St \approx 0.25$, see figure 5.20. This ‘lock-in’ effect occurs due to the triggering of a shockwave when the growing sheet ‘hits’ the trailing edge of the hydrofoil, $\hat{a}_+ \approx 1$. A similar effect was recently reported by Hatzissawidis, Kuhr, and Pelz (2025), where this condition marks the transition from re-entrant flow to shockwave-driven cloud cavitation. In this study, however, this condition does not coincide with such a transition, highlighting the different behaviour observed when varying the incidence (present study) and the cavitation number (Hatzissawidis, Kuhr, & Pelz, 2025).

For comparison, the data for cavitation number of 0.75 are also plotted in the same figure. A stagnation of the sheet growth and Strouhal number is visible, although the effect is less pronounced than for $\sigma = 0.50$.

The ‘lock-in’ effect where the condensation shockwave is triggered at the hydrofoil trailing edge accompanied by a stagnation in the maximum cavity sheet length and in the shedding frequency is visualised in figure 5.21. The stacked figure 5.21 shows the C_L , C_P , the CWT of C_L , and the space-time diagrams for $\sigma = 0.50$, $\alpha = 8^\circ$ ($\sigma/2\alpha = 1.79$). The unimodality and the strong coherence of mode (i) becomes evident. At this operation point, mode (ii) is absent and the shedding of clouds is driven by strong shockwaves (figure 5.21 (d) and (e)). The cavity trailing edge assumes a crescent shape during its growth. Once it reaches the trailing edge of the hydrofoil, a shockwave is initiated and propagates upstream, causing partial condensation of the sheet and the subsequent shedding of a large-scale cloud. The cycle then repeats. As observed by Venning et al. (2022), a re-entrant flow forms during the growth phase, however, it stagnates and does not dictate the shedding. A supplementary movie 10 showing the triggered shockwave at the hydrofoils trailing edge is available.

The horizontal blue line in figure 5.21 (e) marks the trailing edge of the hydrofoil and the shockwave is an oblique line starting at the trailing edge and propagating upstream (negative x -direction). The trailing edge of the cavity evolves from a crescent-like shape to a more convex, bulged form. Since the cavity apex does not reach the hydrofoil trailing edge at the same spanwise location in each cycle, the spanwise shockwave initiation point

5.3 Condensation shock initiation at the trailing edge

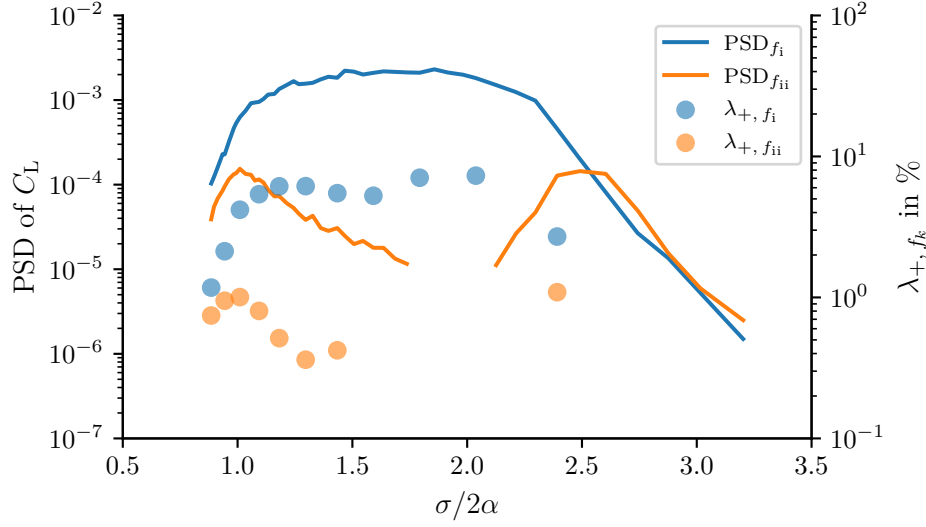


Figure 5.19: The peak of the PSD of C_L (lines) and the relative SPOD variance (dots) for mode (i) (blue) and mode (ii) (orange) as it varies with $\sigma/2\alpha$. The SPOD variance is calculated from the high-speed photographs of the run type ‘medium’, the PSD from the data of the run type ‘long’. Mode (ii) diminishes for $1.55 \lesssim \sigma/2\alpha \lesssim 2.21$ with mode (i) reaching its energy peak.

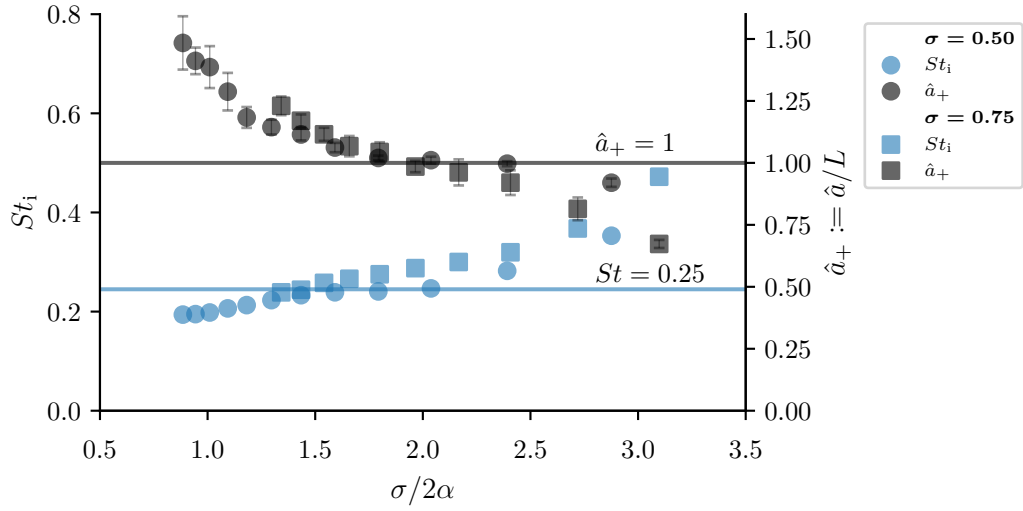


Figure 5.20: Chord-based Strouhal number (blue dots) and maximum cavity sheet length (black dots) for $\sigma = 0.50$ (circles) and $\sigma = 0.75$ (squares) as it varies with $\sigma/2\alpha$. When the maximum cavity sheet length reaches the trailing edge of the hydrofoil, $\hat{a}_+ \approx 1$, a ‘lock-in’ effect is observed, characterised by an approximately constant Strouhal number.

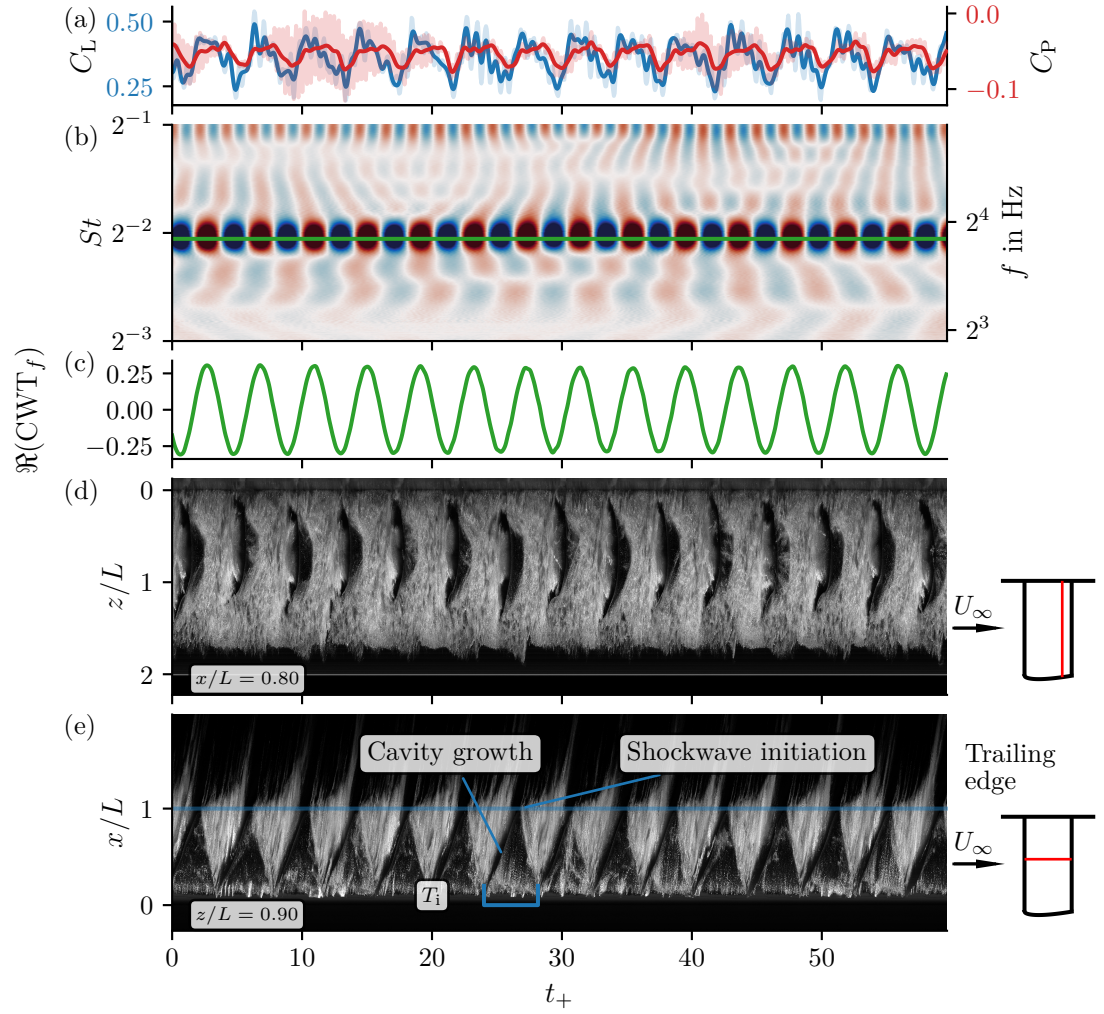


Figure 5.21: Unimodal shedding of shockwave-driven cloud cavitation, mode (i). A shockwave is triggered when the maximum cavity sheet length reaches the trailing edge of the hydrofoil, $\hat{a}_+ \approx 1$. Simultaneously captured (a) C_L and C_P , (b) real part of the CWT of C_L , (c) its f_i component, and space-time diagrams, (d) spanwise at $x/L = 0.80$, and (e) chordwise at $z/L = 0.90$. The operation point is $\sigma = 0.50$, $\alpha = 8^\circ$ or $\sigma/2\alpha = 1.79$. A supplementary movie 10 is available.

varies accordingly. This can be seen at $t_+ = 5$ where the initiation does not seem to coincide with the time instance when the cavity reaches the hydrofoil trailing edge. This variation seems to be strongly influenced by the previous cycle.

Possible explanations for why a shockwave is triggered once the cavity sheet reaches the trailing edge include a discontinuity in the pressure distribution (Hatzissawidis, Kuhr, & Pelz, 2025) or the interaction with the flow originating from the pressure side. This

5.3 Condensation shock initiation at the trailing edge

condition is not strictly necessary, since shockwaves are also observed for cavities that do not extend to the trailing edge of the hydrofoil. However, the trailing edge acts as the trigger for shockwave initiation, leading to stagnation of the sheet growth at $\hat{a}_+ \approx 1$ and a corresponding stagnation of the Strouhal number, figure 5.20. When the pressure on the suction side of the hydrofoil is sufficiently reduced due to an increase in incidence, the cavity sheet extends beyond the hydrofoil's trailing edge. Since only the projected cavity length can be determined from the high-speed photography, it is possible that the attached sheet does not actually reach the trailing edge; in this case, even for $\hat{a}_+ > 1$, the trailing edge may still act as the trigger. However, this requires further verification.

In conclusion, a strong shockwave is triggered at the hydrofoil's trailing edge in each cycle, leading to strongly coherent shedding. The out-of-phase interaction of tip and root shockwaves (see section 5.2) cannot establish itself and is suppressed, which would otherwise lead to mode (ii) development.

5.4 Transition from re-entrant flow to condensation shockwave

For $\sigma = 1.01$, mode (i) is dominant at high incidence α (or low $\sigma/2\alpha$), while mode (iv) is dominant at low α (or high $\sigma/2\alpha$) as described in section 4.2. The transition between these modes is *smooth*. The peak of the PSD of C_L and the relative SPOD variance from high-speed photography is presented in figure 5.22 for σ of 1.01. At this cavitation number, both fundamental modes, i.e., (i) and (iv), are observed as $\sigma/2\alpha$ is varied.

As $\sigma/2\alpha$ is lowered, re-entrant flow-driven cloud cavitation (iv) occurs, and its PSD increases until reaching a peak at $\sigma/2\alpha = 2.82$. Subsequently, mode (iv) begins to decline, while mode (i) emerges at $\sigma/2\alpha = 2.57$. Alongside mode (i), tip mode (ii) also emerges. Mode (i) reaches its peak at $\sigma/2\alpha = 1.98$. The peak PSD of mode (i) is one order of magnitude lower than that of mode (iv). Since mode (i) arises at high incidence and high cavitation number, the transition to shear cavitation affects the shockwave-driven cloud cavitation regime.

Figure 5.23 shows the SPOD maps for three operation points, showing pure mode (iv) ($\alpha = 10^\circ$, $\sigma/2\alpha = 2.89$), modes (i) and (ii) ($\alpha = 14^\circ$, $\sigma/2\alpha = 2.05$), and the transition in between ($\alpha = 12^\circ$, $\sigma/2\alpha = 2.40$). In the transition region, the correlation coefficient between modes (i) and (iv) is -0.31 , indicating moderate exclusivity of the two fundamental modes. However, the SPOD results reveal that mode (i) and (iv) are spatially separated (see figure 5.23, middle row) with mode (i) being dominant on the upper part of the hydrofoil and mode (iv) on the lower part. The phase maps for mode (i) and (iv) exhibit a spatially constant phase in the spanwise direction where the intensity is high, indicating that the shedding described by the leading eigenmode appears 2D, see figure 5.23. While statistically the modes should also exhibit exclusive occurrence, this spatial separation from the SPOD analysis allows for identification of the simultaneous occurrence of the modes from the space-time diagram (figure 5.24). Between $t_+ = 10$ and 20 mode (i) and mode (iv) can each be observed, with mode (i) at the upper part of the hydrofoil and mode (iv) at the lower. The modes occur simultaneously in these time instances. However, between $t_+ = 40$ and 56 only mode (iv) is present, showing that the modes also occur exclusively.

The presence of both re-entrant flow-driven and shockwave-driven modes was also confirmed by Smith et al. (2020a) and Hatzissawidis, Kuhr, and Pelz (2025). As $\sigma/2\alpha$ is reduced or α is increased, shockwaves progressively dominate and establish the fundamental shedding mechanism, while the re-entrant flow becomes less significant. This behaviour can be interpreted in probabilistic terms, analogous to the approach of Bhatt et al. (2023) as σ is decreased.

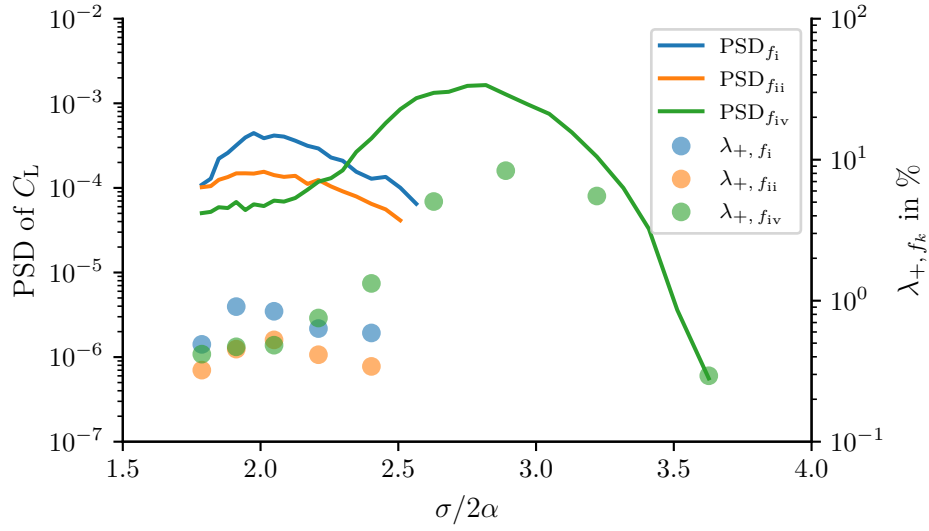


Figure 5.22: The peak of the PSD of C_L (lines) and the relative SPOD variance (dots) for mode (i) (blue), (ii) (orange) and (iv) (green) as it varies with $\sigma/2\alpha$. The transition of the fundamental shedding from mode (iv) to mode (i) occurs smoothly as α is increased or $\sigma/2\alpha$ is lowered. The cavitation number is $\sigma = 1.01$.

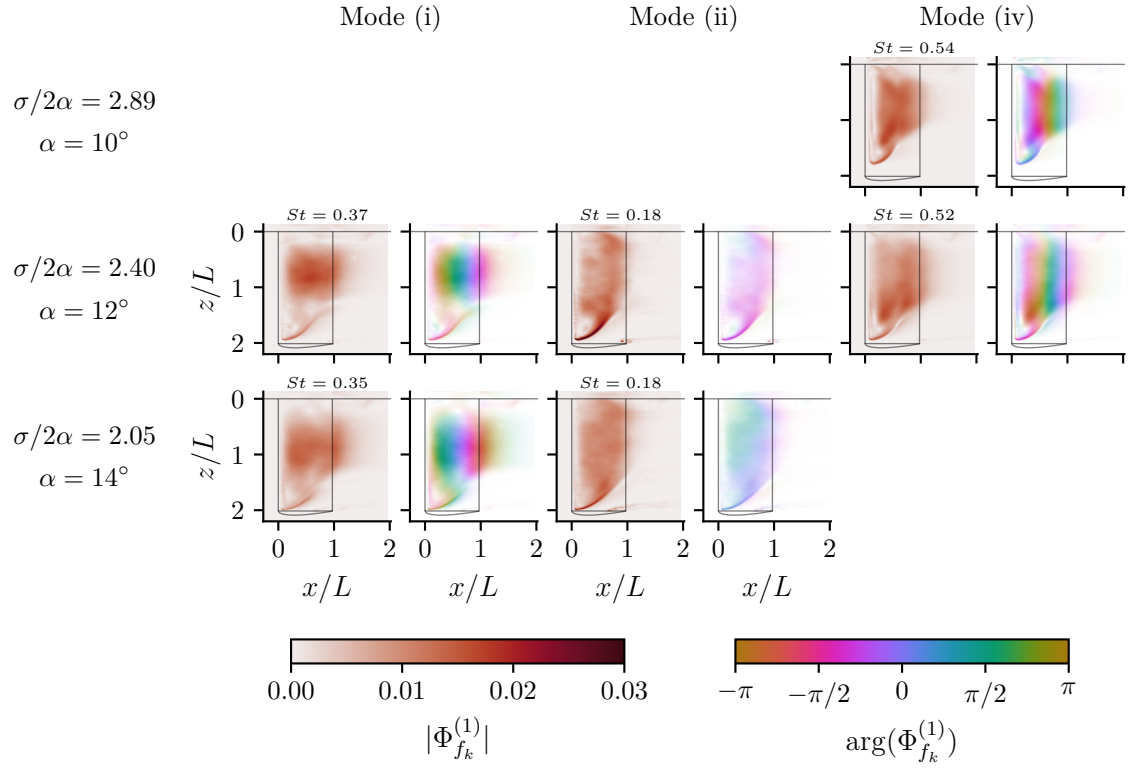


Figure 5.23: Leading SPOD eigenmodes for $\sigma = 1.01$ and $\alpha = 10^\circ, 12^\circ, 14^\circ$ or $\sigma/2\alpha = 2.89, 2.40, 2.05$, showing the transition from re-entrant flow-driven cloud cavitation, mode (iv), to condensation shockwave-driven cloud cavitation, mode (i).

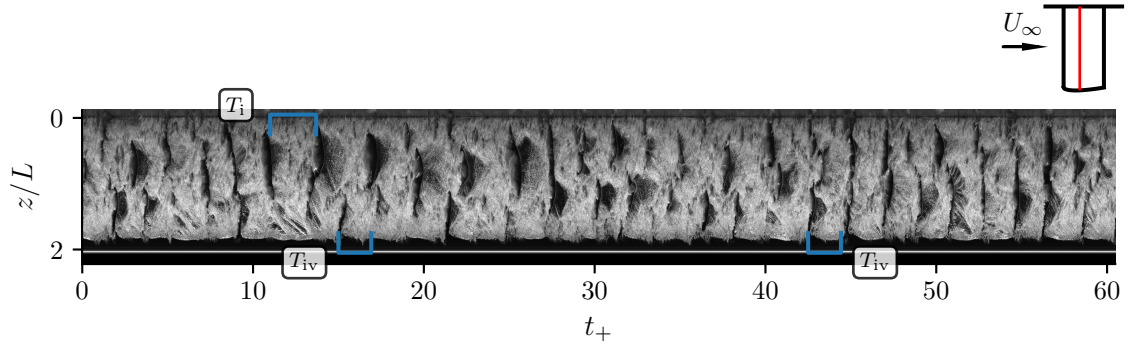


Figure 5.24: Spanwise space-time diagram at $x/L = 0.40$. The transitional operation point marks the regime between mode (i) and mode (iv), where both modes occur either simultaneously or exclusively. The operation point is $\sigma = 1.01$ and $\alpha = 12^\circ$ or $\sigma/2\alpha = 2.40$.

5.5 Top-bottom cloud shedding

In the previous chapter, 3D cavitation behaviour in the transitional regime was observed. At high incidence, the cavitation behaviour likewise become 3D, transitioning from well-defined 2D shedding to 3D behaviour with top-bottom cloud shedding at high incidence. In this section, this 3D cavitation behaviour is analysed at a cavitation number of 1.01. The two leading eigenmodes for each shedding frequency are presented in figure 5.25. In each case, the leading eigenmode is vertically symmetric regarding the SPOD phase, while the second eigenmode is asymmetric. This allows the use of the relative variance of the leading eigenmode to serve as an indicator of the degree of three-dimensionality in the shedding. As shown in figure 5.26, the variance of the second eigenmode of mode (iv) varies with $\sigma/2\alpha$ – as well as higher order eigenmodes not shown here – and becomes increasingly significant at low and high $\sigma/2\alpha$ with a minimum at $\sigma/2\alpha = 2.89$. For 3D shedding, the leading eigenmode is not sufficient to capture the dynamics of these operation points, and higher-order modes have to be considered.

The SPOD spatial modes illustrate how the mode shapes evolve with increasing incidence, figure 5.25. For $\sigma/2\alpha = 2.89$ (at $\alpha = 10^\circ$), the relative variance (see equation (3.18)) of the leading eigenmode is 99%, indicating that mode (iv) can be represented solely by the leading eigenmode ($i = 1$), without contributions from higher-order eigenmodes. As demonstrated in section 5.1, the shedding of mode (iv) is globally 2D. The phase distribution of the leading eigenmode is uniform along a large portion of the span, confirming the predominantly 2D behaviour of this operation point. The second eigenmode ($i = 2$) contains only 1% of the energy and is therefore not considered further. The variance of higher-order eigenmodes is presented in figure 5.27 (a), showing that the variance of the leading eigenmode of mode (iv) is at least two orders of magnitude larger than that of its higher-order eigenmodes. The corresponding spectrum exhibits a single dominant peak at f_{iv} , while contributions from higher-order eigenmodes remain negligible, figure 5.27 (b). The spanwise space-time diagram shows the well-defined periodicity with high coherent cloud shedding with its 2D behaviour, figure 5.28 (a).

Decreasing $\sigma/2\alpha$ to 1.91 or increasing the incidence to 15° , the fundamental shedding transitions from mode (iv) to mode (i). Now, the leading eigenmode of mode (i) contains only 79% of the energy at frequency f_i and the second eigenmode contains 7%, which is one order of magnitude lower. Further, mode (iii) is not merely a harmonic artefact but a physical mode, as evidenced in the space-time diagram, figure 5.28 (b) around $t_+ = 5$ at the upper part of the hydrofoil. At this operation point ($\sigma/2\alpha = 1.91$), this behaviour is captured by the second eigenmode, which would remain undetected if higher-order modes were neglected. Simultaneously, on the bottom part of the hydrofoil, mode (i) is active, represented by the second eigenmode of mode (i). From about $t_+ = 10$ to 20, mode (i) seems to occur exclusively, extending over the full span without top-bottom shedding, represented by the leading eigenmode. Between $t_+ = 30$ to 33, mode (iv) is still discernible; however, the shedding becomes less coherent and spatial structures cannot be clearly distinguished. As the cavitation behaviour becomes increasingly 3D, the variances of the eigenmodes exhibit a different picture than in the 2D case (figure 5.27 (a,b)). Higher-order eigenmodes are only one order of magnitude lower (figure 5.27 (c,d)), and

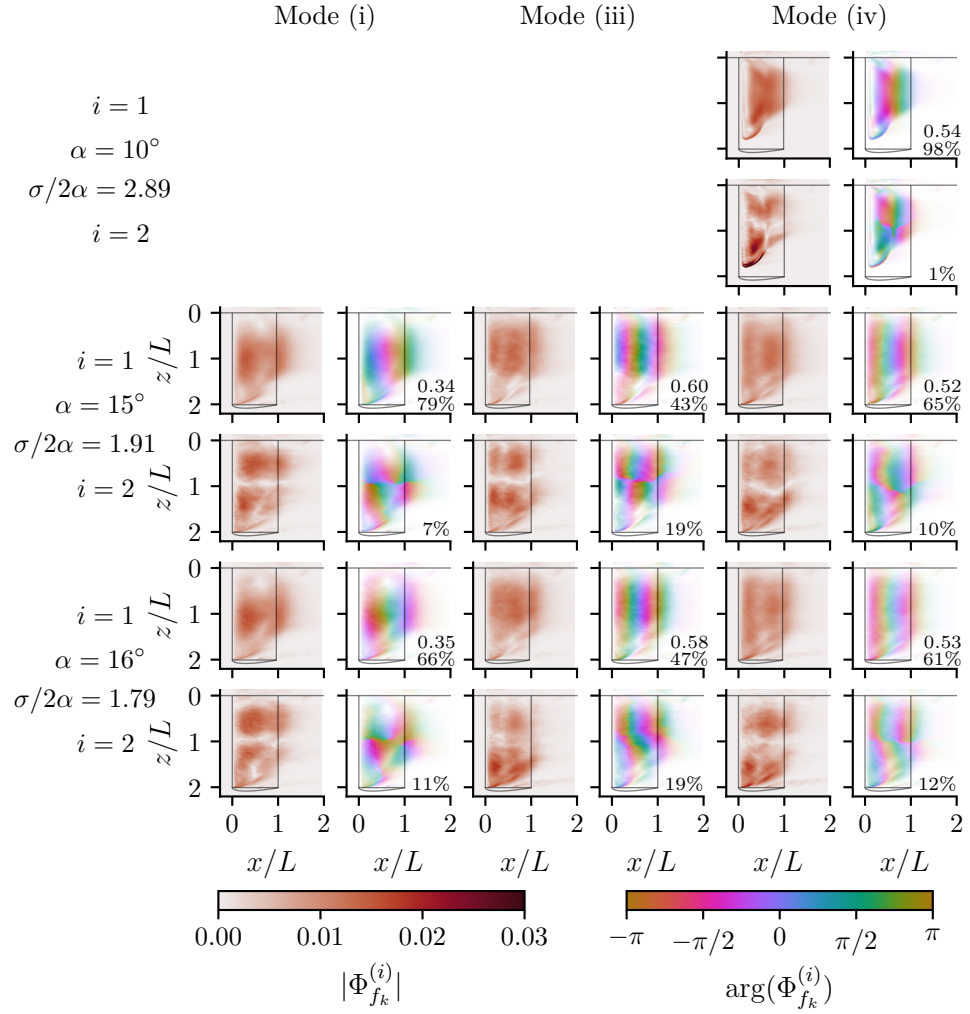


Figure 5.25: Leading and second SPOD eigenmodes ($i = 1$ and 2 , respectively) for mode (i), (iii), and (iv). The chord-based Strouhal number as well as the relative energy content, $\lambda_{+,f_k}^{(i)}$, are given on the bottom right of the phase map. Three operation points were chosen, where the shedding transition from 2D to 3D shedding. The shedding is highly coherent and 2D for $\alpha = 10^\circ$. As the incidence is increased to $\alpha = 15^\circ$ and 16° , the cavitation behaviour exhibits 3D shedding. The cavitation number is 1.01.

are important to describe the cavitation behaviour.

Decreasing $\sigma/2\alpha$ further to 1.79 exhibits the same effect; the cavitation becomes less coherent (figure 5.28 (c)), and higher-order eigenmodes are needed to capture its dynamics. At this operation point, it is harder to assign the spatial structures to a specific mode, since the shedding becomes chaotic due to the onset of shear cavitation. However, the fundamental mode (i) is evident in the space-time diagram, see figure 5.28 (c) at

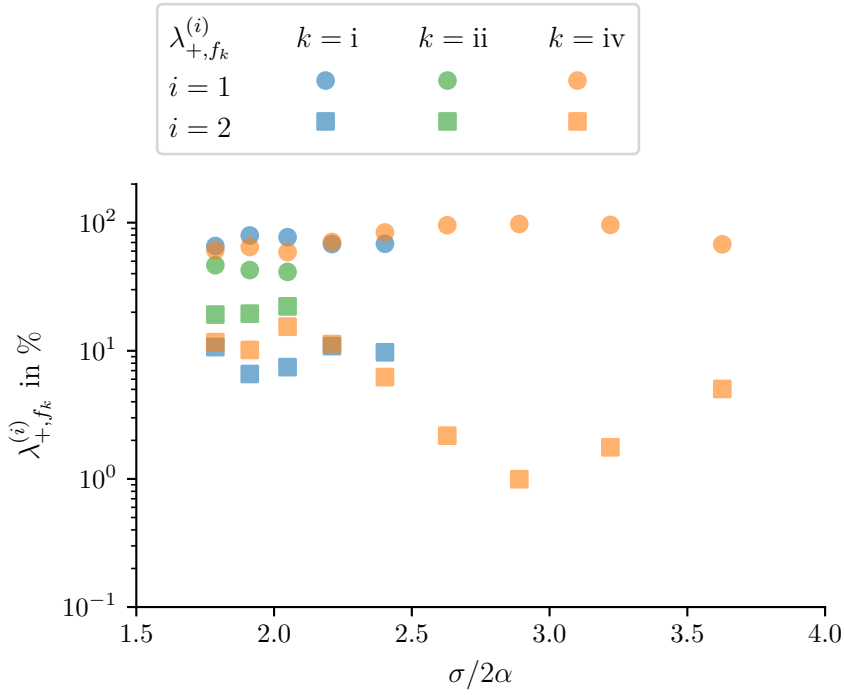


Figure 5.26: Relative variance of modes (i), (iii), and (iv) (blue, green, and orange dots), of the leading SPOD eigenmode ($i = 1$, circles) and the second eigenmode ($i = 2$, squares) as they vary with $\sigma/2\alpha$.

$t_+ = 6$. Mode (iv) at $t_+ = 8$ and mode (iii) at $t_+ = 22.5$ are also visible in the space-time diagram, both in the bottom part of the cavity. Again, these spatial structures are captured by the second-order SPOD eigenmodes, see figure 5.25. It should be mentioned that a superposition of different modes can also be necessary to capture the flow field or a specific spatial structure. Thus, the spatial modes cannot be solely considered in isolation; instead, appropriate combinations of modes must be taken into account to capture the physics.

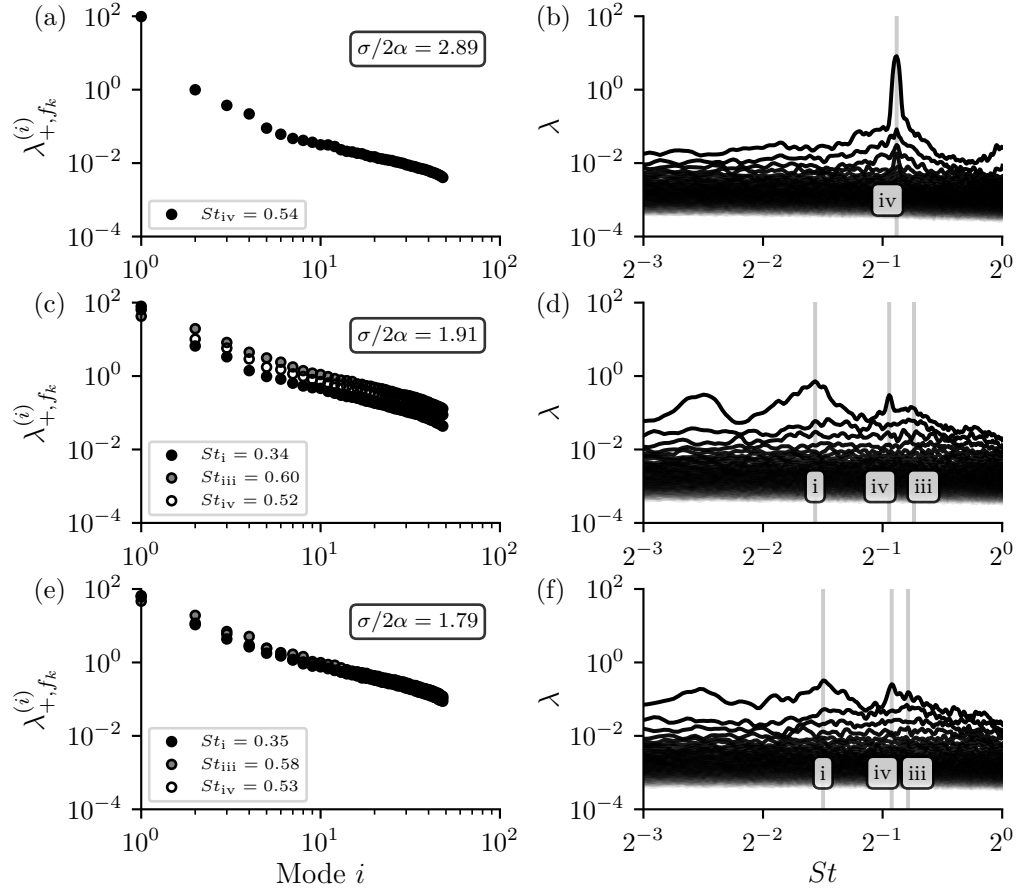


Figure 5.27: Relative mode variance as a function of eigenmode i (a,c,e) for the dominant shedding modes and the corresponding spectrum, where the eigenvalues are presented as a function of the Strouhal number (b,d,f). The three operation points are the same as in figure 5.25.

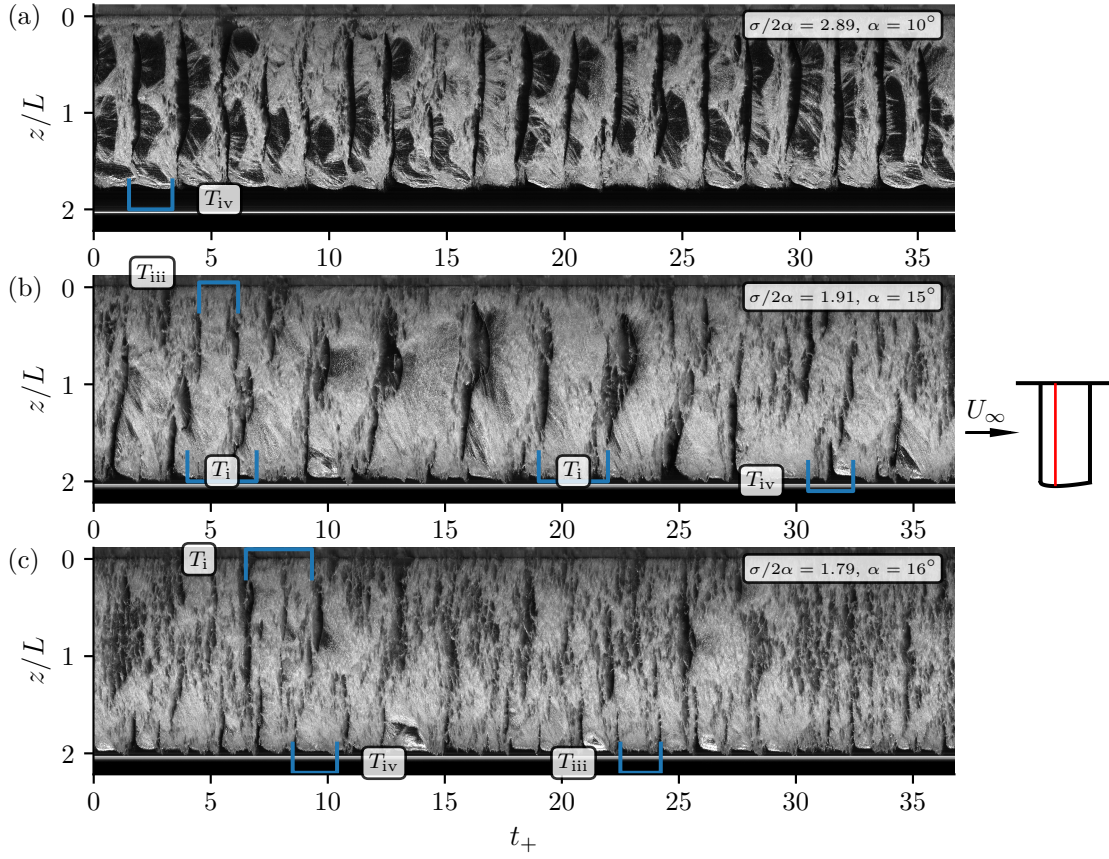


Figure 5.28: Spanwise space-time diagrams at $x/L = 0.3$ visualising the transition from 2D to 3D shedding. The three operation points are the same as in figure 5.25 and figure 5.27.

5.6 Summary of key findings

The underlying physical mechanisms of the modes (i) to (iv), identified in chapter 4, are investigated for four cavitation numbers ($\sigma = 0.50, 0.76, 0.88, 1.01$) with varying incidence. The four modes are associated with the following mechanisms: (i) fundamental mode where a re-entrant flow develops and stagnates and a condensation shockwave drives the cloud shedding, more pronounced at low cavitation numbers; (ii) intermittent low-frequency mode describing cavity tip excursion, occurring only in conjunction with mode (i) when the tip and root shockwave are out of phase; (iii) harmonic artefact and physical mode for high incidence when the shedding becomes 3D; (iv) fundamental mode driven by a coupled re-entrant flow and condensation shockwave mechanism at high cavitation numbers.

SPOD successfully decomposes the flow field from the high-speed photographs, i.e., pixel greyscale values, and identifies the spatial, coherent structures of each mode. These mode shapes guide the placement of horizontal or vertical ‘cuts’ for constructing space-time diagrams. The resulting space-time representation is an effective diagnostic tool to visualise the underlying physical mechanisms; in such diagrams, the slope of a feature corresponds to its propagation velocity.

Mode (iv) is identified as a coupled re-entrant flow and condensation shockwave mechanism: the re-entrant flow ruptures the cavity sheet near the leading edge, and the remaining sheet subsequently collapses under a condensation shockwave. In the literature, the maximum cavity length-based Strouhal number is often reported to be approximately constant for re-entrant flow-dominated cloud cavitation for a fixed shape. In the present study, this does not hold because the incidence – and thus the shape – varies: the maximum cavity length-based Strouhal number increases as the incidence increases (equivalently, $\sigma/2\alpha$ decreases).

Mode (i) corresponds to classical condensation shockwave-driven cloud shedding. A shockwave is initiated at the cavity trailing edge and propagates upstream, condensing the sheet cavity. Under specific conditions, the shockwave is triggered when the maximum cavity length reaches the hydrofoil trailing edge. This ‘lock-in’ effect produces a plateau in both shedding frequency and maximum cavity length, indicating a stagnation of their variation.

Mode (ii) describes cavity tip excursion and appears only in conjunction with mode (i). In the space-time diagram, during mode (i) shedding, two shockwaves – one emanating from the root and one from the tip – form a ‘cross’-shaped pattern when they meet. When the two shockwaves are out-of-phase and do not intersect, the tip oscillation mode (ii) emerges and the energy of mode (i) is reduced. Mode (ii) vanishes with increasing incidence once the trailing edge-triggered shockwave reaches its maximum energy, and reappears at higher incidence.

The transition from mode (iv) to mode (i) at high cavitation number, $\sigma = 1.01$, with increasing incidence occurs smoothly. Within a finite range of $\sigma/2\alpha$, the two modes occur exclusively and simultaneously, defining a transitional regime. As the incidence is reduced, shockwaves increasingly dominate.

The top-bottom shedding, associated with the 3D character of cloud cavitation, arises

5.6 *Summary of key findings*

at high cavitation numbers and with increasing incidence. In this regime, cloud shedding becomes less coherent and more difficult to interpret. However, SPOD can decompose the dynamics by considering higher-order eigenmodes, rather than relying on the leading eigenmode as in predominantly 2D shedding.

Chapter 6

Conclusion

This chapter presents the conclusion of the study, beginning with a restatement of its aims. A summary of the main results is provided, along the answers to the research questions, RQ1 – RQ5, introduced in section 1.2 of the introduction. The practical implications of these results for real-world applications are discussed. Additionally, the limitations of the study are addressed, and recommendations for future research are presented. Finally, some concluding thoughts are offered.

Parts of this chapter are adapted from the following manuscripts, which have been submitted to the *Journal of Fluid Mechanics*: Hatzissawidis, Russell, Venning, Pelz, and Brandner (2025a, 2025b).

6.1 Restating the aims of the study and approach

This study arises from the current gap in data on cloud cavitation dynamics with varying incidence and the need for a detailed investigation into the physical mechanisms underlying the observed modes. While numerous studies have explored cavitation dynamics with varying cavitation numbers, the incidence is typically maintained constant. Two fundamental shedding mechanisms are well-established in the literature: re-entrant flow and condensation shockwave. However, the detailed physics of these mechanisms, especially their variation with incidence, have not been thoroughly investigated and remain of significant technical relevance.

The overarching aim is to understand the above-mentioned driving mechanisms of cloud cavitation with varying incidence. The following subordinate, specific aims were outlined as research gaps in section 2.5.2:

- Investigate if the condensation shockwave is triggered at the trailing edge of the hydrofoil (see RQ1)
- Examine the behaviour of the characteristic frequencies of the modes as the incidence is varied (see RQ2)
- Assess how general the parameter $\sigma/2\alpha$ is in describing cloud cavitation dynamics (see RQ3)
- Investigate the physics of the re-entrant flow-driven cloud cavitation with increasing incidence (see RQ4)

- Explore the transient behaviour, 3D behaviour, and multimodality, especially in the transitional regime, and evaluate how SPOD can identify these phenomena (see RQ5)

To address these aims and clarify the underlying physics, experiments were conducted on a NACA 0015 hydrofoil, a widely recognised benchmark geometry in cavitation research at four cavitation numbers ($\sigma = 1.01, 0.88, 0.76, 0.50$) and small incidence increments $\Delta\alpha$ of 0.25° . High-speed photography, coupled with simultaneous unsteady force measurements, enables the identification of characteristic lengths and frequencies.

To conduct a transient analysis, CWT was applied for the lift coefficient to identify the spectrum over time, revealing the transient behaviour of each mode. Further, the PCCs of the CWT components at the specific mode frequencies were used to investigate their occurrence, determining whether they appear simultaneously or exclusively. SPOD was successfully applied for the identification of coherent structures as mode maps from high-speed photographs, revealing the regions of high intensity for each mode. The SPOD results serve as a guide for setting the vertical and horizontal ‘cuts’ through the high-speed photographs for the generation of the space-time diagrams.

6.2 Summary of the main results and answers to the research questions

The physical shedding mechanisms underlying cloud cavitation about a hydrofoil over a range of incidences and four cavitation numbers ($\sigma = 1.01, 0.88, 0.76, 0.50$) have been investigated, spanning regimes from cavitation inception to the onset of supercavitation. After identifying the four modes, (i)-(iv), in chapter 4 and analysing their cavity topology, spectral content, and transient dynamics, a detailed analysis of the physical mechanisms driving the cloud shedding was conducted in chapter 5.

The four modes were identified and their associated shedding mechanisms were described as follows: (i) fundamental mode characterised by a developing and stagnating re-entrant flow and a condensation shockwave as primary shedding mechanism; (ii) low-frequency mode describing the excursion of the cavity tip; (iii) harmonic mode of fundamental mode (i) which can be either a harmonic artefact of the DFT or a physical mode; (iv) second fundamental mode featuring coupled re-entrant flow and subsequent shockwave propagation near the cavity leading edge that condenses the remaining cavity sheet. The two fundamental shedding modes, (i) and (iv), dominate at low cavitation numbers (0.50 and 0.76) and at high cavitation numbers (0.88 and 1.01), respectively.

First, the main results of the spectral analysis from chapter 4 are summarised, addressing the research questions RQ2, RQ3, and the first part of RQ5.

The parameter $\sigma/2\alpha$, derived from flat plate theory, compensates for the effect of incidence on the pressure distribution along the hydrofoil. It was tested by assessing how similar the cavitation topologies are in still photographs at similar values of $\sigma/2\alpha$. To assess its relevance, the characteristic lengths (i.e. cavity length and spanwise extent) obtained from the high-speed photography as well as the mean and standard deviations

6.2 Summary of the main results and answers to the research questions

of the lift coefficient were plotted as functions of $\sigma/2\alpha$. Spectrograms were generated as a useful overview, showing the chord-based Strouhal number and frequency over $\sigma/2\alpha$. These comparisons show good agreement, indicating that the linear theory remains sufficiently valid.

The peaks in the PSD of the spectrograms of each mode were identified and plotted in one figure, summarising the four spectrograms. The cavity velocity-based Strouhal numbers associated with each mode were calculated, and plotted against the parameter $\sigma/2\alpha$. Using the cavity velocity-based Strouhal number results in better data collapse than the chord-based Strouhal number. The data are densely clustered in four regions for each mode (i) to (iv) across the cavitation numbers investigated. This also becomes evident when examining the PSD of the lift coefficient at identical values of $\sigma/2\alpha$. However, at the two high cavitation numbers and moderate incidence, re-entrant flow dominates, whereas at lower cavitation numbers, the re-entrant flow-driven cloud cavitation (iv) diminishes with shockwaves (i) being the dominant shedding mechanism. Hence, the $\sigma/2\alpha$ is a useful descriptor of the shedding behaviour, albeit within limits based on the dominant shedding mechanism associated with the cavitation number.

The transient analysis using CWT reveals that the modes occur both exclusively and simultaneously over time. The transition from re-entrant flow to condensation shockwave-driven cloud cavitation – from mode (iv) to mode (i) – occurs smoothly, with the two modes appear to occur exclusively and simultaneously. The exclusive behaviour of the modes is supported by the PCC between the CWT of their frequency components, exhibiting a maximum negative value of about -0.5 . From the space-time diagram, it can be seen that modes (i) and (iv) also occur simultaneously, with shedding locations at the tip and the root part of the cavity. As the parameter $\sigma/2\alpha$ decreases and the cavitation regime shifts towards shockwave-driven cloud cavitation, the correlation weakens, approaching values close to zero.

For a band centred about $\sigma/2\alpha = 2.39$ for $\sigma = 0.50$, the fundamental mode (i) and tip mode (ii) occur exclusively, or the presence of mode (ii) attenuates mode (i), confirming the observations made by Venning et al. (2022). For $\sigma = 0.50$, when the maximum cavity length approaches the trailing edge of the hydrofoil with increasing incidence, a condensation shockwave is initiated (Hatzissawidis, Kuhr, & Pelz, 2025). At this point, mode (ii) is suppressed, and the cloud shedding becomes predominantly unimodal. The cavity length and the cloud shedding frequency remain approximately constant, exhibiting a plateau. When the cavity length increases beyond the hydrofoil's trailing edge, mode (ii) re-emerges, and the spanwise extent approaches the hydrofoil's tip.

Mode (iii) appears to be a harmonic artefact at low cavitation numbers. However, as the cavitation number increases, mode (i) shifts to higher incidences, promoting three-dimensionality and irregular shedding. As a result, mode (iii) contains physical components in addition to harmonic artefacts. This interpretation is supported by the frequency ratio between modes (i) and (iii) for higher cavitation numbers. The frequency ratio deviates from the exact value of 0.5, which would be expected if mode (iii) were a purely harmonic component of mode (i). Additional evidence is provided by PCC, which indicates stronger correlation between the modes at low cavitation numbers.

The conclusions of the second part of the results from chapter 5, where the shedding

modes and their underlying physics were described and analysed in detail are presented below. The research questions addressed are RQ1, RQ4, and the second part of RQ5.

Mode (iv) describes a coupled mechanism in which the re-entrant flow ruptures the cavity sheet at random locations near, but downstream of, the cavity's leading edge, initiating a shockwave that subsequently condenses the remaining cavity. This mechanism is dominant at the higher cavitation numbers (0.88 and 1.01) and the typical Strouhal numbers are $0.51 - 0.52$ and $0.51 - 0.56$, respectively. The corresponding non-dimensionalised maximum cavity sheet lengths are $0.62 - 0.92$ and $0.62 - 0.89$, respectively, i.e., both remain lower than unity. A similar phenomenon is observed for cloud cavitation about a sphere (de Graaf et al., 2017; Brandner et al., 2022). This process exhibits strong 3D features, while the shedding remains predominantly 2D and unimodal. Furthermore, the chord-based Strouhal number of this mode remains invariant with increasing incidence – and consequently increasing cavity length – suggesting that the characteristic velocity of the re-entrant flow must increase accordingly. In contrast, the cavity length-based Strouhal number decreases with increasing $\sigma/2\alpha$. While previous studies typically report this Strouhal number to be approximately constant and between 0.25 and 0.4, our results support the hypothesis that it varies as a function of cavity shape, and thus, in our case, with incidence, see also Hatzissawidis, Kuhr, and Pelz (2025).

Increasing the incidence for constant cavitation number ($\sigma = 1.01$) or lowering $\sigma/2\alpha$ the transition from mode (iv) to (i) occurs. A distinct range of $\sigma/2\alpha$ is identified in which the two modes occur exclusively and simultaneously. This indicates that the transition occurs gradually over a range, with the probability of condensation shockwaves and re-entrant flow varying – shockwaves becoming more probable at lower values of $\sigma/2\alpha$, as was reported by Bhatt et al. (2023) recently. This is confirmed by the PSD of the lift coefficient and the SPOD variances of the leading mode over $\sigma/2\alpha$.

The temporal transition from mode (i) to mode (ii) is analysed for $\sigma = 0.50$ and $\alpha = 6^\circ$ using the CWT and space-time diagrams, revealing that cloud shedding under dominant mode (i) is relatively coherent, with a crescent-shaped cavity trailing edge. In contrast, when mode (ii) dominates, the shedding either spans a larger portion of the span or consists of smaller, spanwise-localised clouds, accompanied by a straighter shape of the cavity trailing edge. Two oblique shockwaves develop at the root and the tip of the cavity during growth phase and meet at the hydrofoil's trailing edge, where a condensation shockwave is triggered – characteristic of mode (i). In this case, the shockwaves form a 'cross'-shape within the spanwise space-time diagram. If the two shockwaves do not meet and are out of phase, the shedding is interrupted for this cycle, resulting in mode (ii). Mode (ii) exhibits high intensity at the tip region of the cavity, as supported by the SPOD spatial mode and the standard deviation computed from time instances in which either mode (i) or mode (ii) is dominant. With increasing incidence – from 7° to 10° or from $\sigma/2\alpha = 2.38$ to 1.43 – mode (ii) vanishes, and the shedding becomes highly coherent, exhibiting a crescent-shaped trailing edge. This regime corresponds to the condition where the non-dimensionalised cavity sheet length reaches unity and the condensation shockwave is triggered at the trailing edge of the hydrofoil. The shedding frequency remains constant within this regime. This phenomenon is referred to as the 'lock-in' effect,

in which the stagnation of the sheet length is accompanied by a plateau in frequency. Beyond this range – i.e. for lower $\sigma/2\alpha$ corresponding to higher incidence and sufficiently long cavity lengths – mode (ii) re-emerges, and the spanwise extent approaches the hydrofoil’s tip. SPOD reveals a high intensity of mode (ii) at the tip, this time located in the detached cavity segment downstream of the hydrofoil trailing edge. At this point, mode (i) is not strongly affected by mode (ii), unlike at higher values of $\sigma/2\alpha$. However, for similar values of $\sigma/2\alpha$ at higher incidence, mode (i) and (ii) appears similar in the spectrum. With higher cavitation numbers, this mechanism weakens due to the onset of shear cavitation at high incidence.

The 3D behaviour of cloud cavitation at high incidence and cavitation number is identified through the SPOD. Cloud cavitation becomes less coherent, making it difficult to isolate and analyse the underlying mechanisms. This three-dimensionality is characterised by chaotic and intermittent shedding across various spanwise locations. The SPOD results confirm this behaviour by showing a reduction in the relative variance of the leading eigenmodes – indicating that it is no longer sufficient to capture the cavitation dynamics by its own and that higher-order eigenmodes must be considered to fully describe the flow. This is confirmed by space-time diagrams that reveal the time intervals during which the modes occur.

6.3 Practical implications of the results

Although the experiments are generic – acknowledging that flows in pumps and marine propellers are considerably more complex – the results constitute a first step towards understanding cloud cavitation dynamics with varying incidence. Studies of this kind remain scarce, and, to the best of the author’s knowledge, systematic investigations of incidence effects on cloud cavitation have not been reported. Varying the incidence is directly relevant to off-design operation conditions, which are commonplace in pump and marine applications.

Direct transfer from hydrofoil experiments to pump impellers by simply matching operation points is challenging, as shown by Caba (2022) in his Master’s thesis. A more robust pathway is regime classification: using machine learning, operation points from both pumps and hydrofoils can be assigned to physical shedding regimes, as demonstrated by Krimm (2023) in a subsequent Master’s thesis. Beyond classification, the present results provide data for calibrating and validating numerical models, thereby improving the predictive capability of cavitation simulations. With suitable material or data-driven erosion models embedded in the numerics, cavitation erosion can also be predicted.

The insights gained enable cavitation control – either by direct surface structures or by adapting the operation conditions. Depending on application requirements, optimisation targets may include reducing efficiency losses under environmental constraints or mitigating force oscillations to avoid harmful vibrations. In addition, the results offer a basis for deriving design guidelines for pump and ship industries aimed at avoiding unfavourable cavitation regimes under off-design operation.

In summary, despite the academic, generic character of the experiments, the findings

are practically relevant: they advance understanding of cloud cavitation dynamics with varying incidence and provide actionable input data for modelling, control, optimisation, and design in real-world applications.

6.4 Limitations and recommendations for future research

From the result of this study, several interesting questions arise for future research. Experiments are the alpha and omega of science; however, future work should incorporate numerical simulations that offer deeper insights into the underlying mechanisms through high-resolution spatial and temporal data. These simulations can support the findings of this study and enable further analysis by providing velocity fields.

To deepen the understanding of the mechanisms, higher spatial and temporal resolution is required, as shockwave phenomena occur on shorter time scales and are more spatially localised. Further, since modal interactions evolve on longer time scales than the shedding period, data must be captured at high temporal resolution over longer recording times. In other words, more temporal resolution is necessary for extended recording periods.

A question for future work concerns the transferability of these experiments to other geometries with different adverse pressure gradients and the extent to which the resulting behaviour of cloud cavitation changes.

In conclusion, while this study provides valuable insights, further advancements in both experimental techniques and numerical simulations are necessary to fully explore and characterise the complex dynamics of cloud cavitation with varying incidence.

6.5 Final thoughts

This thesis demonstrates that cloud cavitation is far from 2D; furthermore, it exhibits transient, multimodal, and chaotic behaviour, with several interacting phenomena that change significantly depending on the cavitation number and the incidence. The incidence has a strong influence on the cavitation dynamics, together with the cavitation number, and the parameters cannot be investigated separately – An aspect that has not been explored in such depth until now. Moreover, the cavitation dynamics depend sensitively on the test model (shape and scale) and on facility-specific characteristics of each cavitation tunnel, as reflected in the considerable scatter in the data and various shedding mechanisms reported.

When considering real-world applications, the complexity increases significantly due to the 3D inflow and rotating geometries such as propellers and impellers. These fundamental, generic experiments aim to both isolate the driving mechanisms – such as re-entrant flow and condensation shockwaves – and to make a step into the 3D behaviour observed in real-world applications.

This research has not only deepened my understanding of complex flow phenomena, but has also broadened my perspective on the methods used to break down such intricate phenomena, analysing large datasets by segmenting them into smaller manageable parts.

Keeping real-world applications in mind, I hope that this study serves as a foundation for further research in the field.

Throughout this journey, one key lesson has resonated with me: when you set out to answer research questions about cavitation, you often end up with even more questions. This realisation has left a deep impression on me.

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Appendix A

Uncertainty analysis

The uncertainty analysis throughout the study follows the Guide to the Expression of Uncertainty in Measurement (GUM) (International Organization for Standardization, 2008) and is implemented using the Python package uncertainties by Lebigot (2025).

The sources of uncertainty may be grouped into ‘stochastic uncertainty’, ‘incertitude’, and ‘ignorance’ (Pelz et al., 2021). Within the GUM, uncertainty is evaluated as ‘Type A’ – which includes the statistical analysis (corresponding to ‘stochastic uncertainty’) – and ‘Type B’ – based on other information such as sensor specifications, calibration, etc. (corresponding to ‘incertitude’). ‘Ignorance’ – or the lack of knowledge – is the uncertainty not considered.

The following briefly outlines the uncertainty calculation procedure in accordance with the GUM; for detailed information and guidance, see International Organization for Standardization (2008). First, ‘Type A’ and ‘Type B’ uncertainties are evaluated.

Considering a random variable q , where n independent observations q_i are captured. The mean and variance of q are estimated from the n independent observations as

$$\bar{q} = \frac{1}{n} \sum_{i=1}^n q_i, \quad (\text{A.1})$$

$$s^2(q_i) = \frac{1}{n-1} \sum_{j=1}^n (q_j - \bar{q})^2, \quad (\text{A.2})$$

respectively. The ‘experimental standard deviation’ represents the ‘variability of the observed values’ q_i . An estimation of the ‘variance of the mean’ can be calculated by

$$s^2(\bar{q}) = \frac{s^2(q_i)}{n}. \quad (\text{A.3})$$

Considering any input quantity X_i with n individual observations $X_{i,k}$, and its input estimate $x_i = \bar{X}_i$, where $\bar{X}_i$ is the ‘arithmetic mean of the individual observations’, the ‘Type A standard uncertainty’ $u_A(x_i)$ can be calculated from equation (A.3):

$$u_A(x_i) = s(\bar{X}_i) = \frac{s(X_{i,k})}{\sqrt{n}}. \quad (\text{A.4})$$

As noted earlier, ‘Type B’ uncertainty is not obtained from repeated observations; instead, it is evaluated from other information such as instrument specifications and

Appendix A Uncertainty analysis

calibration certificates. If the distribution is not specified, it can be assumed that each value is equally likely (International Organization for Standardization, 2008). Thus, a rectangular distribution for the input quantity X_i within the interval a_- and a_+ (lower and upper bound) can be adopted (International Organization for Standardization, 2008). For $2a := a_+ - a_-$, the ‘Type B standard uncertainty’ equals

$$u_B(x_i) = \frac{a}{\sqrt{3}}. \quad (\text{A.5})$$

After determining the ‘Type A’ and ‘Type B’ uncertainties, the ‘combined uncertainty’ $u_c(y)$ of the output estimate or ‘measurement result’

$$y = f(x_1, x_2, \dots, x_N), \quad (\text{A.6})$$

which is calculated from N input estimates x_i using the function f , can be calculated as

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i), \quad (\text{A.7})$$

assuming uncorrelated input quantities. $u(x_i)$ denotes the standard uncertainty of each input, either from a ‘Type A’ or ‘Type B’ evaluation. $\theta_i = \partial f / \partial x_i$ is known as ‘sensitivity coefficient’.

Finally, the ‘expanded uncertainty’ Δy is the combined uncertainty multiplied by a coverage factor k (International Organization for Standardization, 2008):

$$\Delta y = k u_c(y). \quad (\text{A.8})$$

In this study, k is set to 2. According to the GUM, this value corresponds to a 95 % confidence interval for a normal distribution.

The measurement result can now be written as $Y = y \pm \Delta y$, with the measurand defined as

$$Y = f(X_1, X_2, \dots, X_N). \quad (\text{A.9})$$

As a representative case, used to provide insight into the resulting uncertainty values, the uncertainty analysis is presented for $\sigma = 0.50$ and $\alpha = 6^\circ$. The uncertainties for the other operation points are of comparable magnitude and are therefore not shown. The uncertainty analysis is presented as a bar chart (figure A.1 (a) to (f)) and tables (tables A.1 to A.6), for the free-stream velocity U_∞ , Reynolds number Re , cavitation number σ , lift coefficient C_L , drag coefficient C_D , and pitching coefficient C_P , respectively. The table provides the input quantity X_i , arithmetic mean of the individual observations $\bar{X}_i$, the derivative of the output quantity with respect to the input quantities or sensitivity coefficients θ_i , the combined uncertainty of the input estimate $u_c(x_i)$, the product of the sensitivity coefficient and the combined uncertainty, which is the resulting uncertainty contribution from the input estimate to the uncertainty of the output estimate, and its percentage. The contributions of the input estimates to the resulting uncertainty of the output estimate are presented as a bar chart in figure A.1 (a) to (f).

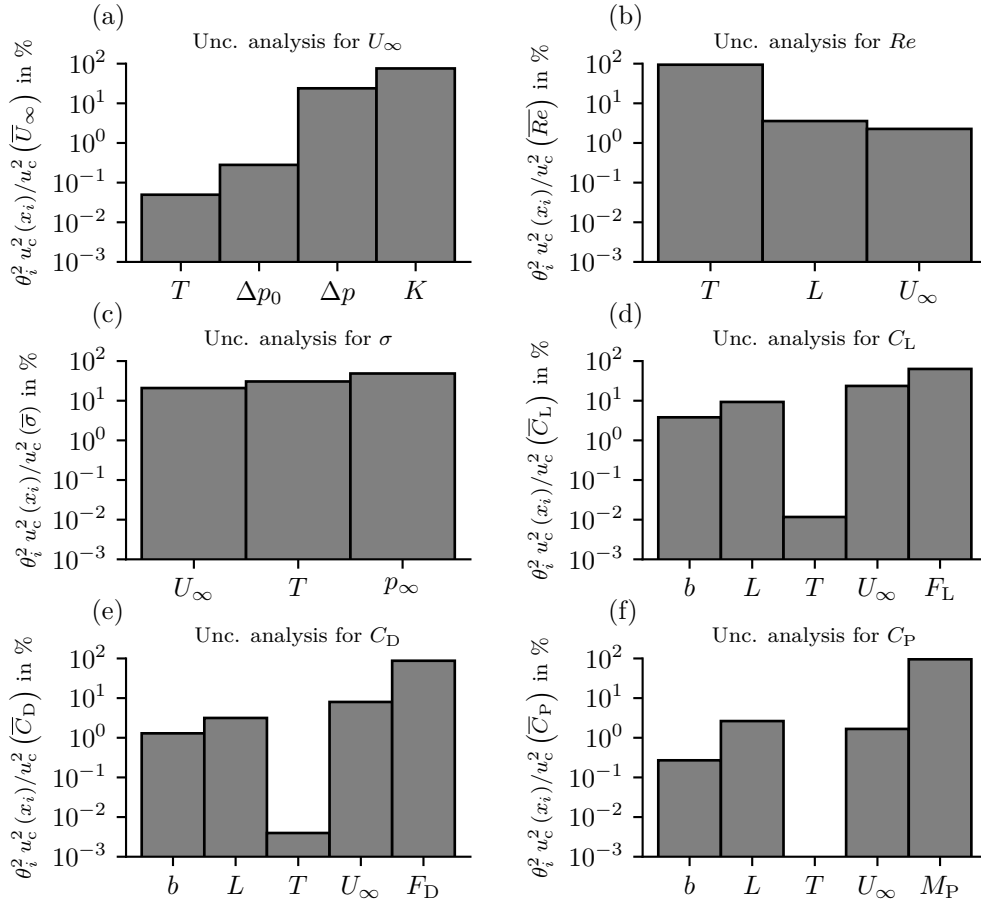


Figure A.1: The contributions of the uncertainty from the input estimates x_i to the combined uncertainty of the output estimate y as a bar chart for the (a) free-stream velocity U_∞ , (b) Reynolds number Re , (c) cavitation number σ , (d) lift coefficient C_L , (e) drag coefficient C_D , (f) pitching coefficient C_P .

The free-stream velocity and its corresponding uncertainty are calculated using equation (3.2). The input quantities X_i are the temperature T to calculate the density ϱ according to equation (D.1), the differential pressure Δp between the cross-sectional areas, see figure 3.3, the offset of the differential pressure Δp_0 at $U_\infty = 0$, which is subtracted from Δp , and the contraction coefficient K between the cross-sectional areas, see table A.1. The resulting expanded uncertainty is 0.23 % of the average value, with Δp and K contributing $> 99\%$ to the resulting uncertainty of $\overline{U}_\infty$. On the other hand, the contribution of the temperature to the expanded uncertainty through ν , p_v , and ϱ (see appendix D) is larger in the case of Re and σ , see figure A.1 (b) and (c), and tables A.2 and A.3.

The uncertainty analysis of the forces of the six-component force balance is presented in figure A.2 (a) to (c) for F_L , F_D , and M_P , respectively, and in figure A.3 (a) to (c)

Appendix A Uncertainty analysis

for C_L , C_D , and C_P , respectively. The calculation of the uncertainties is based on the data provided by Butler et al. (2021) for the same force balance, where the ‘Type B’ uncertainty consists of the uncertainty in the calibration masses (0.1 %), the arm length (0.03 %), the drift (0.17 %), and the calibration residuals, see Butler et al. (2021). The uncertainties are presented as a function of the incidence. Relative uncertainties are high for small incidences, since the absolute forces are low. As the incidence is decreased, forces and coefficients, as well as the corresponding uncertainties, converge for all cavitation numbers. An exception is the drag force and its coefficient: their very low values make them sensitive to small measurement offsets, and a comparable convergence is not observed. However, the discrepancies remain modest in the order of 1 % to 2 %.

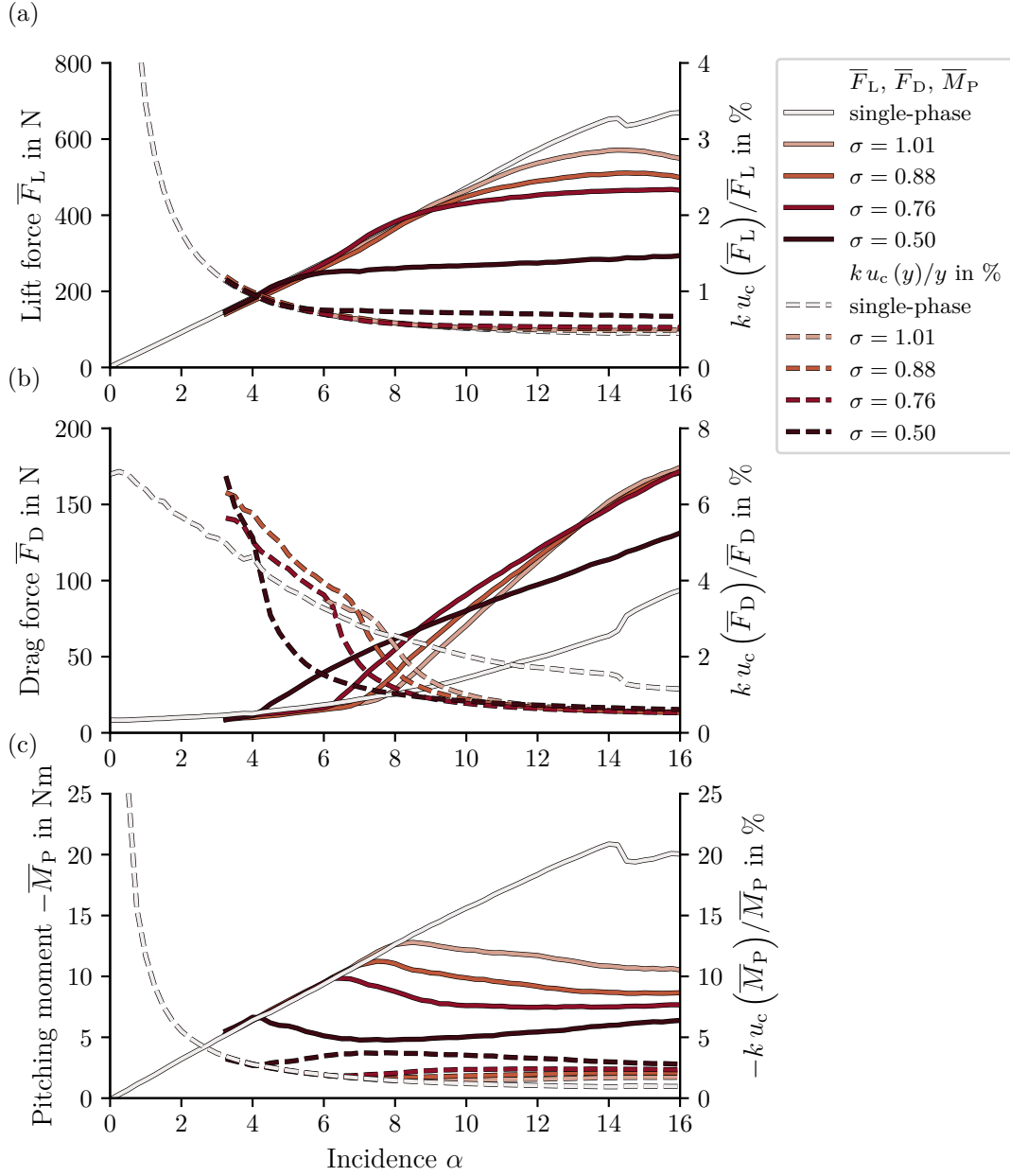


Figure A.2: Uncertainty analysis for the force balance of the (a) lift force, (b) drag force, and (c) pitching moment. The expanded uncertainty is plotted as a function of the incidence α as a percentage of the output estimate, $k u_c(y)/y$ for the four different cavitation numbers and the single-phase flow. The output estimates are also plotted. The expanded uncertainty reaches high values for low incidence due to the low forces acting on the hydrofoil.

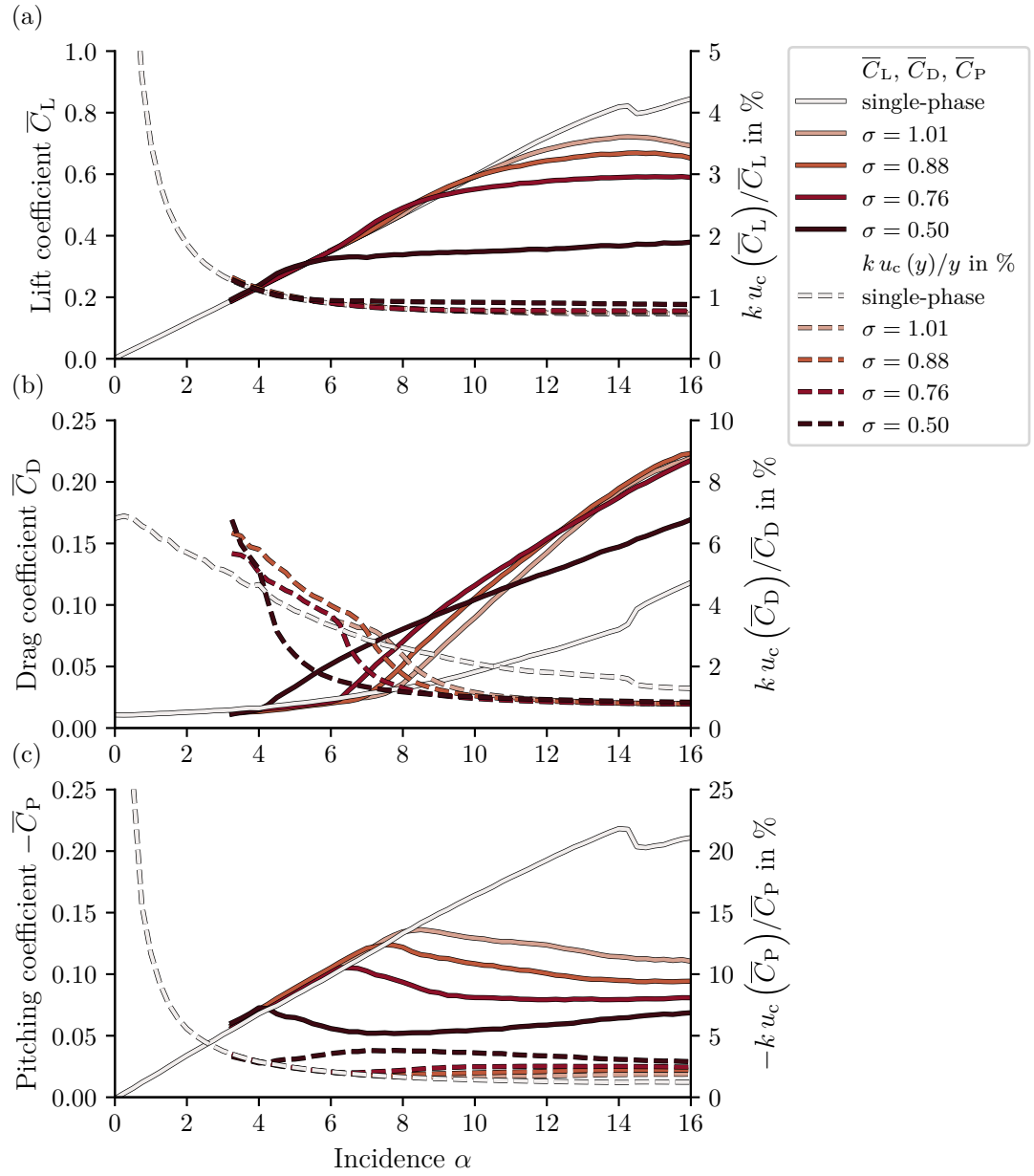


Figure A.3: Uncertainty analysis for the force balance as in figure A.2, now shown for (a) lift, (b) drag, and (c) pitching coefficient.

Table A.1: Uncertainty quantification for free-stream velocity (U_∞) broken down into the portion of the uncertainty of each input quantity X_i . The table provides the input estimates, sensitivity coefficients, the combined uncertainty of each input estimate, the ratios of the resulting combined uncertainties, the output estimate, and its expanded uncertainty. The coverage factor k is 2. The incidence is $\alpha = 6^\circ$ and the cavitation number $\sigma = 0.50$.

X_i	$\bar{X}_i$	$\theta_i = \partial U_\infty / \partial x_i$	$u_c(x_i)$	$\theta_i u_c(x_i)$	$\theta_i^2 u_c^2(x_i) / u_c^2(\bar{U}_\infty)$
T in $^\circ\text{C}$	17.33	6.33×10^{-4}	2.89×10^{-1}	1.83×10^{-4}	0.05 %
Δp_0 in Pa	-10.94	-1.40×10^{-4}	3.10×10^0	-4.34×10^{-4}	0.28 %
Δp in Pa	25452.98	1.40×10^{-4}	2.86×10^1	4.01×10^{-3}	23.90 %
K	1	3.57×10^0	2.00×10^{-3}	7.14×10^{-3}	75.77 %
$\bar{U}_\infty$					7.14 m s $^{-1}$
$k u_c(\bar{U}_\infty)$					0.02 m s $^{-1}$
% $\bar{U}_\infty$					0.23 %

Table A.2: Uncertainty quantification for Reynolds number (Re) broken down into the portion of the uncertainty of each input quantity X_i . See caption of table A.1 for more details.

X_i	$\bar{X}_i$	$\theta_i = \partial Re / \partial x_i$	$u_c(x_i)$	$\theta_i u_c(x_i)$	$\theta_i^2 u_c^2(x_i) / u_c^2(\bar{Re})$
T in $^\circ\text{C}$	17.33	2.06×10^4	2.89×10^{-1}	5.93×10^3	94.16 %
L in m	0.12	6.67×10^6	1.73×10^{-4}	1.16×10^3	3.57 %
U_∞ in m s $^{-1}$	7.14	1.12×10^5	8.20×10^{-3}	9.20×10^2	2.26 %
$\bar{Re}$					8.01×10^5
$k u_c(\bar{Re})$					1.22×10^4
% $\bar{Re}$					1.53 %

Table A.3: Uncertainty quantification for cavitation number (σ) broken down into the portion of the uncertainty of each input quantity X_i . See caption of table A.1 for more details.

X_i	$\bar{X}_i$	$\theta_i = \partial \sigma / \partial x_i$	$u_c(x_i)$	$\theta_i u_c(x_i)$	$\theta_i^2 u_c^2(x_i) / u_c^2(\bar{\sigma})$
U_∞ in m s $^{-1}$	7.14	-1.40×10^{-1}	8.20×10^{-3}	-1.15×10^{-3}	20.88 %
T in $^\circ\text{C}$	17.33	-4.82×10^{-3}	2.89×10^{-1}	-1.39×10^{-3}	30.55 %
p_∞ in Pa	14733.66	3.93×10^{-5}	4.47×10^1	1.76×10^{-3}	48.57 %
$\bar{\sigma}$					0.50
$k u_c(\bar{\sigma})$					0.01
% $\bar{\sigma}$					1.01 %

Appendix A Uncertainty analysis

Table A.4: Uncertainty quantification for lift coefficient (C_L) broken down into the portion of the uncertainty of each input quantity X_i . See caption of table A.1 for more details.

X_i	$\bar{X}_i$	$\theta_i = \partial C_L / \partial x_i$	$u_c(x_i)$	$\theta_i u_c(x_i)$	$\theta_i^2 u_c^2(x_i) / u_c^2(\bar{C}_L)$
b in m	0.25	-1.31×10^0	2.31×10^{-4}	-3.02×10^{-4}	3.81 %
L in m	0.12	-2.72×10^0	1.73×10^{-4}	-4.71×10^{-4}	9.31 %
T in °C	17.33	5.78×10^{-5}	2.89×10^{-1}	1.67×10^{-5}	0.01 %
U_∞ in m s $^{-1}$	7.14	-9.14×10^{-2}	8.20×10^{-3}	-7.50×10^{-4}	23.59 %
F_L in N	249.42	1.31×10^{-3}	9.39×10^{-1}	1.23×10^{-3}	63.28 %
$\bar{C}_L$					0.33
$k u_c(\bar{C}_L)$					0.0031
% $\bar{C}_L$					0.95 %

Table A.5: Uncertainty quantification for drag coefficient (C_D) broken down into the portion of the uncertainty of each input quantity X_i . See caption of table A.1 for more details.

X_i	$\bar{X}_i$	$\theta_i = \partial C_D / \partial x_i$	$u_c(x_i)$	$\theta_i u_c(x_i)$	$\theta_i^2 u_c^2(x_i) / u_c^2(\bar{C}_D)$
b in m	0.25	-2.07×10^{-1}	2.31×10^{-4}	-4.79×10^{-5}	1.29 %
L in m	0.12	-4.32×10^{-1}	1.73×10^{-4}	-7.48×10^{-5}	3.16 %
T in °C	17.33	9.18×10^{-6}	2.89×10^{-1}	2.65×10^{-6}	0.00 %
U_∞ in m s $^{-1}$	7.14	-1.45×10^{-2}	8.20×10^{-3}	-1.19×10^{-4}	8.00 %
F_D in N	39.58	1.31×10^{-3}	3.01×10^{-1}	3.94×10^{-4}	87.54 %
$\bar{C}_D$					0.052
$k u_c(\bar{C}_D)$					0.00084
% $\bar{C}_D$					1.62 %

Table A.6: Uncertainty quantification for pitching coefficient (C_P) broken down into the portion of the uncertainty of each input quantity X_i . See caption of table A.1 for more details.

X_i	$\bar{X}_i$	$\theta_i = \partial C_P / \partial x_i$	$u_c(x_i)$	$\theta_i u_c(x_i)$	$\theta_i^2 u_c^2(x_i) / u_c^2(\bar{C}_P)$
b in m	0.25	2.23×10^{-1}	2.31×10^{-4}	5.15×10^{-5}	0.27 %
L in m	0.12	9.30×10^{-1}	1.73×10^{-4}	1.61×10^{-4}	2.64 %
T in °C	17.33	-9.89×10^{-6}	2.89×10^{-1}	-2.85×10^{-6}	0.00 %
U_∞ in m s $^{-1}$	7.14	1.56×10^{-2}	8.20×10^{-3}	1.28×10^{-4}	1.67 %
M_P in N m	-5.12	1.09×10^{-2}	8.88×10^{-2}	9.69×10^{-4}	95.42 %
$\bar{C}_P$					-0.056
$k u_c(\bar{C}_P)$					0.00198
% $\bar{C}_P$					3.56 %

Appendix B

Scientific method and research data management

The workflow used in this study, which includes the scientific method in conjunction with a comprehensive RDM framework, is presented here. It is illustrated in the schematic shown in figure B.1; its design was inspired by the framework proposed by Maric et al. (2022).

The scientific method applied in this thesis involves identifying the problem, building on the existing literature, utilising methods and data while ensuring their validity, conducting experiments, seeking evidence, and drawing conclusions (Armstrong & Green, 2022, p. 11). The scientific method is often traced back to Galileo Galilei, who is considered one of the pioneers of this approach.

The workflow is divided into three main parts: (I) data acquisition, (II) data analysis, (III) publication, see figure B.1. This process is initiated by the researcher, who makes observations – based on the literature, via a systematic literature review, or through preliminary studies – and derives a research question from these insights. In this study, unexpected cavitation dynamics about a NACA 0015 hydrofoil were observed as the incidence was varied, leading to the formulation of the research questions RQ1 to RQ5.

First, the (I) data acquisition is conducted. With the research question in mind, the main experimental work is conducted by first designing the experiments and then performing them at the CRL. At this point, it is crucial to capture metadata. Because the data exist in different formats, each operation point – defined by its Reynolds number, cavitation number, and incidence – is assigned a unique label so that all data can be reliably linked to one another.

The experiments were carried out for four cavitation numbers and the single-phase flow case at high cavitation number, each investigated over a range of incidences. The unique label has the form `setXXXX_alphaYYYY`. Here, `setXXXX` denotes the set number which corresponds to a cavitation number and `alphaYYYY` is the incidence in degrees. `set0056` corresponds to $\sigma = 1$, `set0071` to $\sigma = 0.5$, `set0073` to $\sigma = 0.75$, `set0077` to $\sigma = 0.88$, and `set0072` to the single-phase condition. For example, `set0056_alpha0625` is at a cavitation number of 1 and an incidence of 6.25° .

Next, the files generated during ‘short’, ‘medium’, and ‘long’ run types (see section 3.1.3) are described, which constitute the main experiments of this study. The data from the cavitation tunnel, including the measurements from the six-component force balance, are stored in a MAT file or hierarchical data format (HDF) (The HDF Group, 2025) file

Appendix B Scientific method and research data management

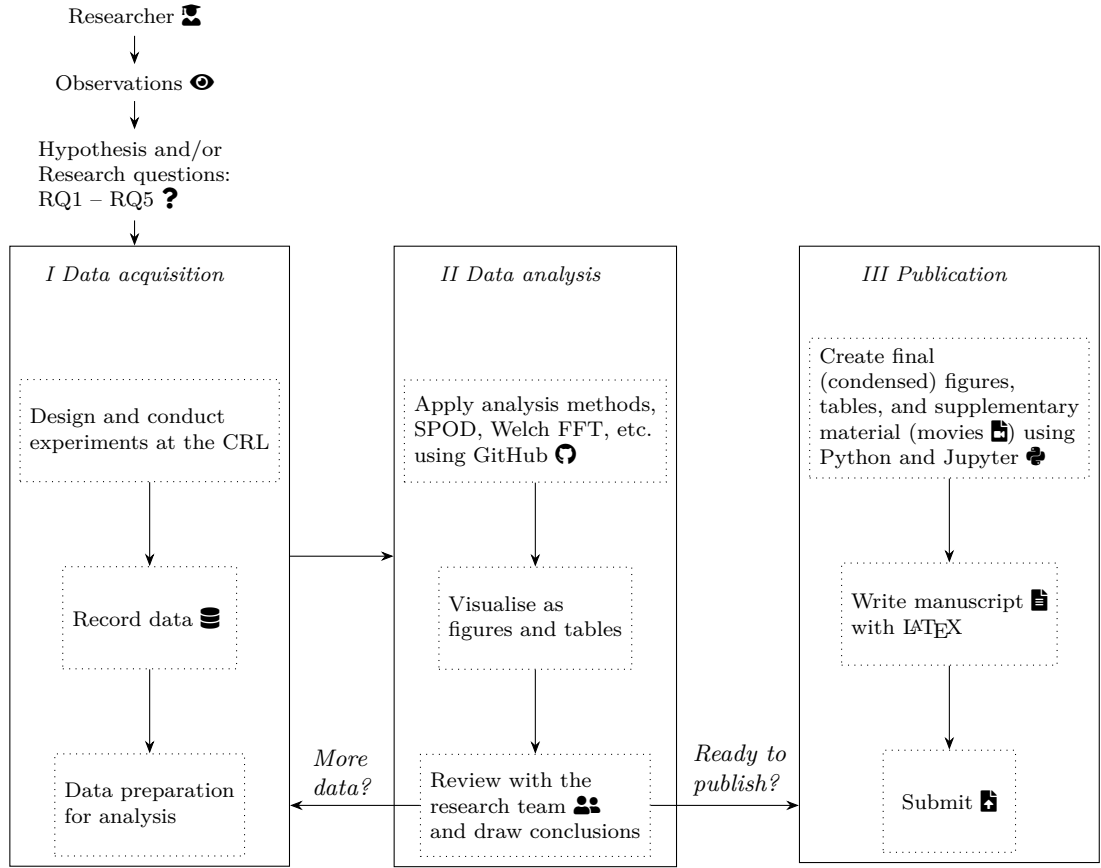


Figure B.1: Schematic of the workflow used in this study, combining the scientific method and the research data management practices. The workflow is divided in three parts: (I) data acquisition, (II) data analysis, (III) publication. The design of the workflow is inspired by Maric et al. (2022).

and can be accessed through the `h5py` package (Collette, 2013) in Python. During the ‘long’ run type, two high-speed photography datasets (‘short’ and ‘medium’) are acquired, and the trigger signal is recorded within the tunnel data. Using the trigger signal, the high-speed photographs can be temporally aligned and linked to the tunnel data. The high-speed photographs receive the same unique label as the corresponding MAT file and are stored as CINE files used by the Phantom high-speed camera, which include all relevant metadata as frame rate, exposure time, etc. The CINE files are used for visual analysis of the high-speed photographs using the PCC software by Vision Research (Phantom, 2025).

After recording the data, preparation is required to make them accessible and manageable for subsequent analysis, see figure B.1 (I). The raw voltage signals from the tunnel are converted into the required physical quantities, such as the cavitation number, Reynolds number, and force and moment coefficients, among others. The data are then

organised into a pandas DataFrame (McKinney, 2010), with each operation point indexed by the corresponding label mentioned above, allowing for direct access.

The high-speed photographs, stored as CINE files, are converted to HDF5 files in a lossless manner, retaining all necessary metadata. This data format offers numerous advantages, including easier and faster access, among others (see The HDF Group, 2025). Given the large size of the high-speed photographs, which reaches up to 400 gigabytes, HDF5 enables access to only the specific portions of data required.

Following the (I) data acquisition, the next step is (II) data analysis, see figure B.1. Initially, an uncertainty analysis of the data is performed, as detailed in figure B.1, and the corresponding values are incorporated into the pandas DataFrame. Parts of the DataFrame are made available through TUDatalib (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025c).

The data analysis techniques employed in this study include Welch’s method to estimate the PSD, the CWT for time-frequency analysis, and the SPOD by Towne et al. (2018) to identify coherent structures in the high-speed photographs. The PSDs are stored in CSV files, accompanied by all relevant metadata, and can be accessed via TUDatalib (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025c). Given the larger file sizes of the CWT and SPOD results and the need to access portions of the dataset, these are stored in HDF5 files. These data are securely stored at the Chair of Fluid Systems, Technische Universität Darmstadt, and can be accessed upon reasonable request. The paths to the SPOD, CWT, or PSDs files are stored within the pandas DataFrame, allowing direct access for efficient data handling.

The analysis software is managed using GitLab, and the analysis is conducted in Jupyter Notebooks (Kluyver et al., 2016). The resulting tables and figures are reviewed and discussed with the research team. Based on the outcomes, additional data may be collected. Once the results can address the research questions, the writing process is initiated, see (III) publication in figure B.1.

The (III) publication phase involves generating the final figures and tables by exporting them from the Jupyter Notebook, writing the manuscript, and ultimately submitting the work. Throughout this process, GitHub is also utilised for version control.

Despite the publication of parts of the data (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025c), the supplementary movies provided in the study are also available in the TUDatalib repository (Hatzissawidis, Russell, Venning, Pelz, & Brandner, 2025d), along with all the necessary metadata, provided as JSON files.

Appendix C

Spectral analysis tools

In the following, the effects of the parameter on the results of the Welch's method and the CWT are shown and discussed.

C.1 Parameter study for Welch's method

The zero-padding is essential for smoothing the signal and enabling a more precise identification of the peaks in the PSD (Venning, 2016). The effect of zero-padding is shown in figure C.1 for the case without zero-padding (grey line) and with zero-padding with a factor of ten times the original signal length (black line). With no zero-padding and a window size of 2048, the width of a frequency bin is $\Delta f \approx 0.49$ Hz, whereas applying zero-padding yields a finer frequency resolution of $\Delta f \approx 0.049$ Hz. It should be noted that zero-padding does not truly increase the spectral resolution; however, it allows for more precise identification of the peaks. Zero-padding was applied throughout this study wherever Welch's method was used to compute the PSD.

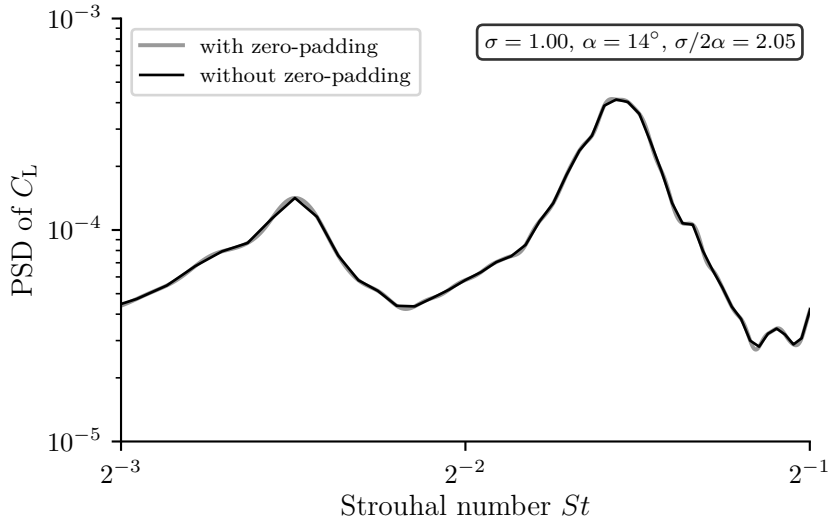


Figure C.1: The effect of zero-padding on the PSD of the lift coefficient for $\sigma = 1.00$, $\alpha = 14^\circ$ ($\sigma/2\alpha = 2.05$). A zero-padding factor of ten times the original signal length was applied. The window size is 2048 with an overlap of 50 %.

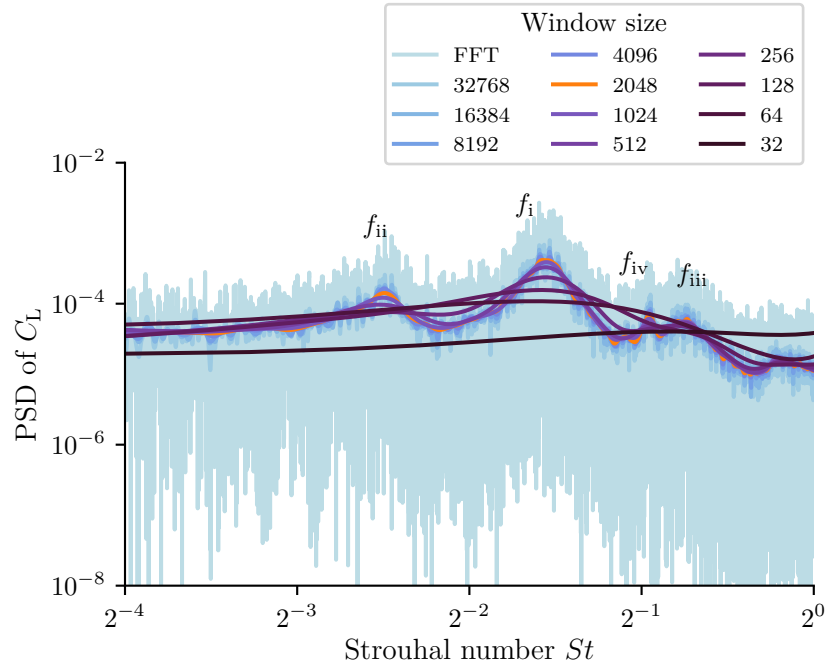


Figure C.2: The effect of the window size on the PSD of the lift coefficient for $\sigma = 1$, $\alpha = 14^\circ$ ($\sigma/2\alpha = 2.05$), from a maximum window size corresponding to the FFT to a small window size (32). Increasing the window size leads to a finer frequency resolution at the expense of increasing noise. The overlap between the windows is 50 %. In this study a window size of 2048 was chosen (orange curve).

The selection of the window size for Welch's method represents a trade-off between spectral resolution and noise reduction. Figure C.2 illustrates the effect of the window on the spectrum at an operation point where all four modes, (i) to (iv), are present. A fast Fourier transform (FFT) using the full signal length as the window size produces a noisy spectrum, as shown in figure C.2, whereas an excessively small window size of 32 yields unusable results. In this study, a window size of 2048 (orange line) with an overlap of 50 % was selected, as it provides sufficient resolution to distinguish all four modes.

C.2 Parameter study for the continuous wavelet transform

The CWT was performed using the Python package PyWavelets by Lee et al. (2019). A complex Morlet wavelet was used. The centre frequency f_c was fixed at 1 Hz. Figure C.3 shows the real (blue line) and imaginary parts (orange line) of the complex Morlet wavelet (mother wavelet) as the bandwidth BW is increased. For larger bandwidths, the wavelet contain more cycles and become wider, resulting in improved frequency resolution at the expense of time localisation. The CWT is applied to the lift coefficient and its absolute

C.2 Parameter study for the continuous wavelet transform

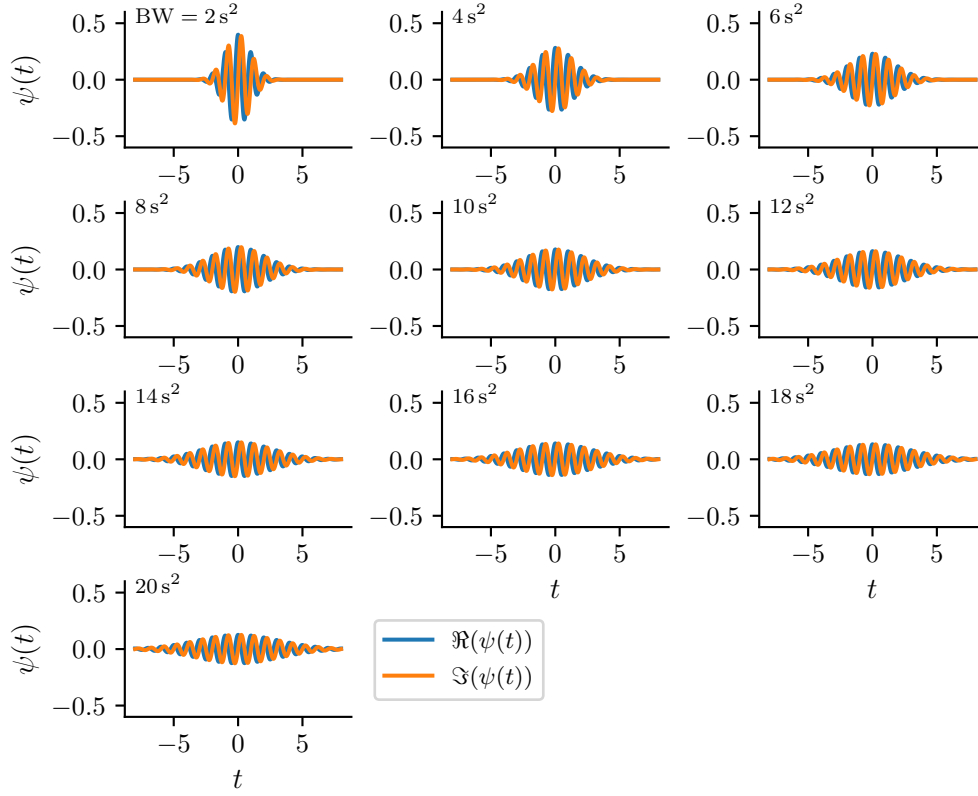


Figure C.3: Real and imaginary part of the complex Morlet wavelet ψ as the bandwidth BW is increased for a constant centre frequency f_c of 1 Hz. In this study a bandwidth BW of 14 s^2 was chosen.

value is averaged in time, see figure C.4. Analogous to Welch's method, see appendix C.1, the objective is to separate the four modes; this is achieved by choosing a bandwidth of 14 s^2 (orange curve in figure C.4). As shown in the results in section 4.3, this bandwidth is sufficient to both resolve the frequencies and localise the modes in time.

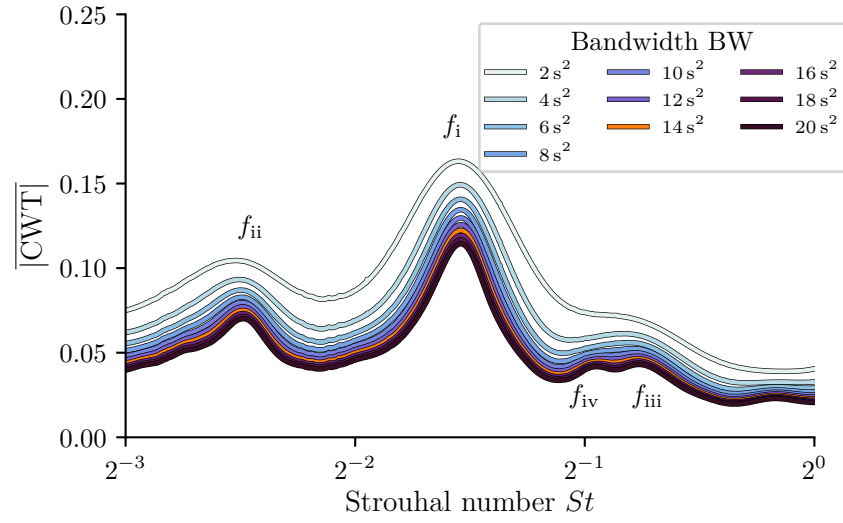


Figure C.4: The effect of the bandwidth BW on the time-averaged absolute value of the CWT, denoted as $|\overline{CWT}|$. Increasing the bandwidth leads to higher frequency resolution at the expense of the time localisation, see section 3.2. The centre frequency f_c is 1 Hz. In this study, $BW = 14 \text{ s}^2$ was set (orange curve). The operation point is $\sigma = 1.00$, $\alpha = 14^\circ$ ($\sigma/2\alpha = 2.05$).

Appendix D

Fluid properties

The water temperature within the tunnel is measured, see section 3.1.1, and the relevant temperature-dependent fluid properties are calculated with the following polynomials by Brandner (2013): density

$$\varrho(T) = -0.00485786 T^2 - 0.00853297 T + 1000.292407; \quad (\text{D.1})$$

kinematic viscosity

$$\nu(T) = (-0.96666667 \times 10^{-5} T^3 + 0.11378571 \times 10^{-2} T^2 - 0.58197619 \times 10^{-1} T + 1.7873714) \times 10^{-6}; \quad (\text{D.2})$$

saturated vapour pressure

$$\begin{aligned} p_v(T) = & 0.61009558 \times 10^{-3} T^4 + 0.11238356 \times 10^{-1} T^3 + \\ & 0.17754990 \times 10^1 T^2 + 0.40688815 \times 10^2 T + \\ & 0.62537637 \times 10^3. \end{aligned} \quad (\text{D.3})$$

The polynomials are derived using data by Warneck and Williams (2012, pp. 272–274). As the fluid properties vary with temperature, their temperature dependence must be considered. The fluid properties are necessary to calculate the Reynolds number Re and the cavitation number σ , which define the operation point, as well as other quantities such as the free-stream velocity U_∞ or the force and moment coefficients, see sections 3.1.1 and 3.1.2.

The polynomials for calculating the density ϱ , kinematic viscosity ν , and saturated vapour pressure p_v , equations (D.1) to (D.3) depending on the temperature, are plotted together with the data points taken from Warneck and Williams (2012, pp. 272–274) in figure D.1 (a), (b), and (c), respectively.

The temperature during the experiments ranges from 16.5 °C to 17.6 °C. Within this interval – computed from equations (D.1) to (D.3) – the density ϱ ranges from 998.83 kg m⁻³ to 998.63 kg m⁻³, the kinematic viscosity ν from 1.09×10^{-6} m² s⁻¹ to 1.06×10^{-6} m² s⁻¹, and the saturated vapour pressure p_v from 1874.14 Pa to 2013.47 Pa.

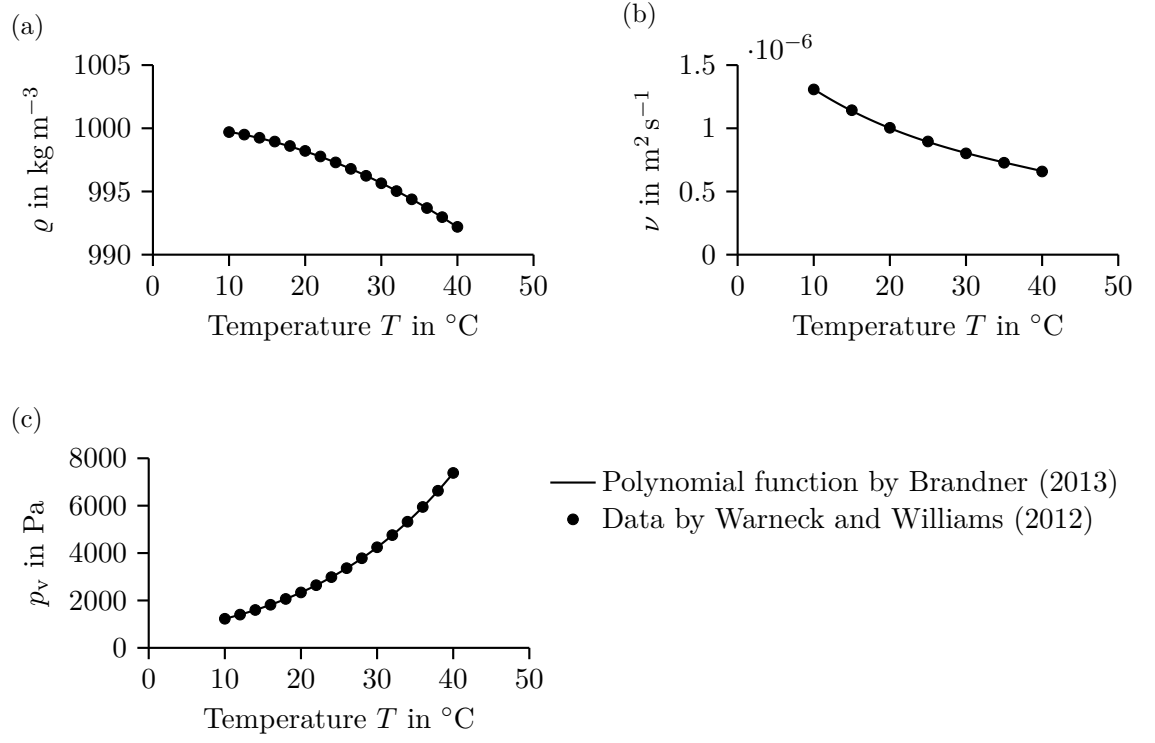


Figure D.1: The dependence of the fluid properties, (a) density ρ , (b) kinematic viscosity ν , and (c) saturated vapour pressure p_v , on the temperature T . The data points are taken from Warneck and Williams (2012, pp. 272–274) and the polynomials from Brandner (2013).

Appendix E

Additional figures

E.1 Inter-study comparison for chord-based Strouhal numbers

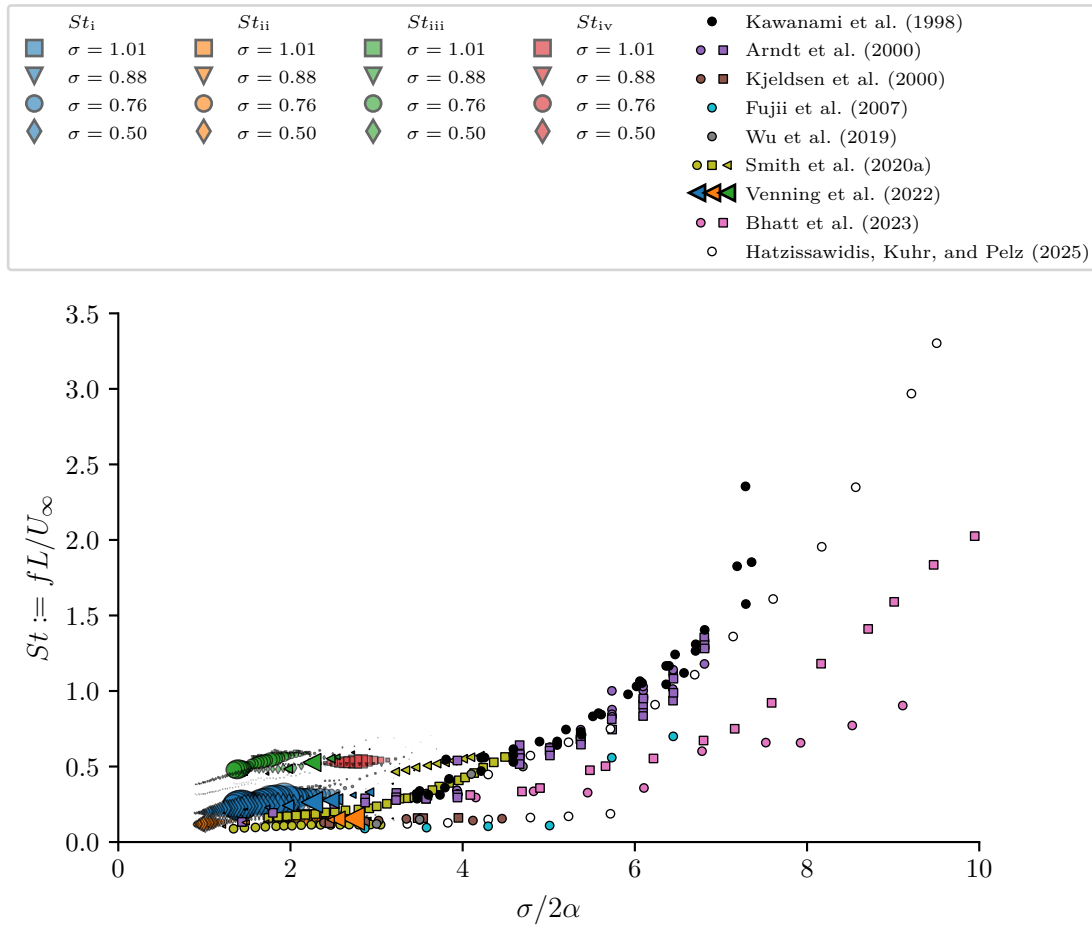


Figure E.1: Comparison of studies on a NACA 0015 hydrofoil with the present work regarding the chord-based Strouhal number St over $\sigma/2\alpha$. See figure 4.7 for a detailed description.

E.2 Spectrograms of the lift coefficients over the incidence

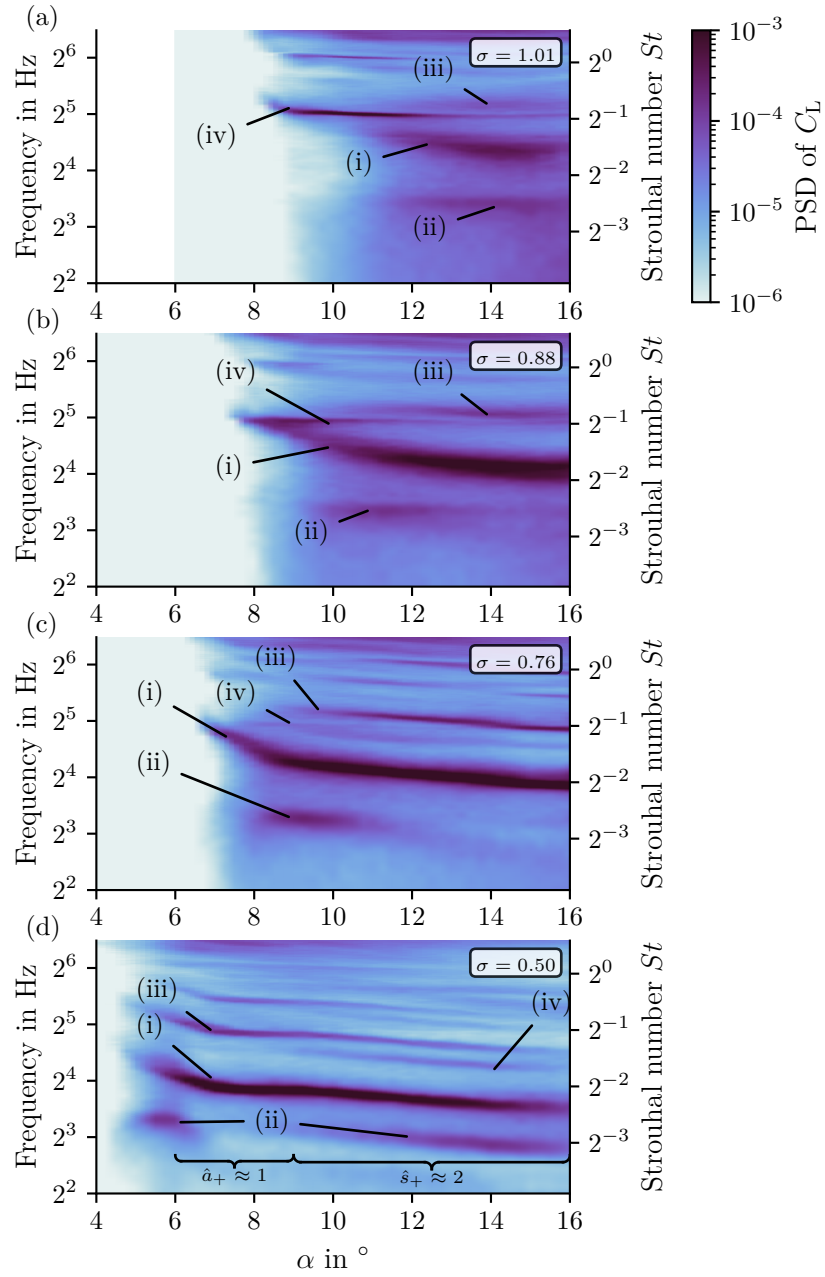


Figure E.2: Spectrograms of the PSD of the lift coefficient C_L showing the frequency and the Strouhal number over α for constant cavitation numbers $\sigma = 1.01, 0.88, 0.76, 0.50$, (a), (b), (c), (d), respectively, at constant Reynolds number of $Re = 8 \times 10^5$.

E.3 Power spectral density for the same $\sigma/2\alpha$

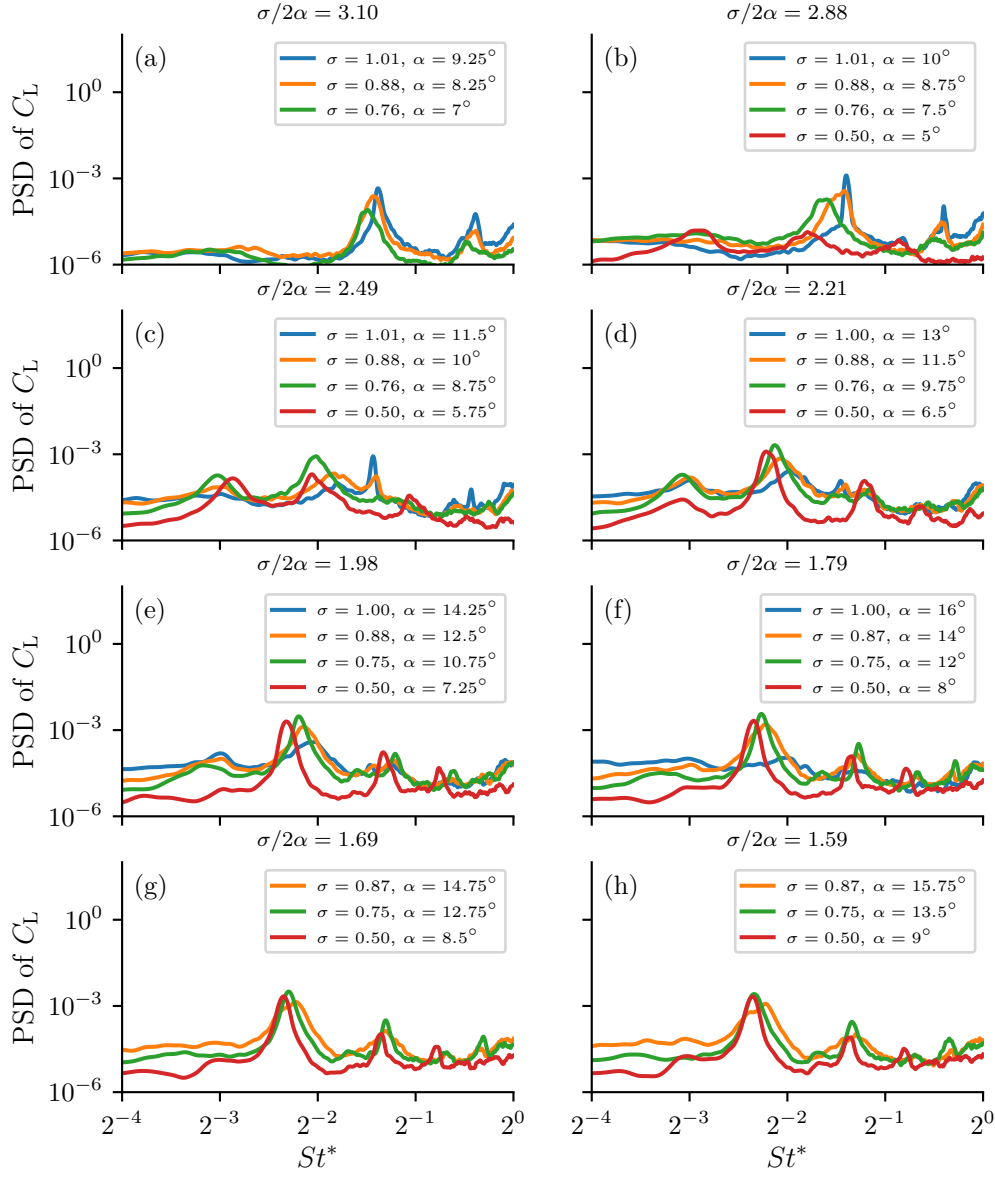


Figure E.3: Similarity of the PSD over the cavity-velocity based Strouhal number St^* for fixed $\sigma/2\alpha$ across the four cavitation numbers.