FINAL REPORT

1 General Information

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Project title: Cavitation Control using Mesoscale Surface Structuring in Marine Engineering and Hydraulic Systems

Name of the applicant: Prof. Bettar O. el Moctar

Official address(es): University of Duisburg-Essen, Bismarckstraße 69, 47057-Duisburg

Name of the co-applicants: -

Name of the cooperation partner: Professor Dimitry Markovich

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2 Summary

We propose a passive cavitation control method to mitigate undesirable effects, such as structural vibration in the context of marine engineering and hydraulic systems. For this aim, we used different mesoscale surface structures, such as scalloped and sawtooth riblet structures, finned and roughness structures to control the cavitating flow around circular cylinders, and hydrofoils. We performed extensive experiments to investigate the effects of wall roughness and riblet structures on the dynamics of cavitation, cavitation instability and turbulence structures in the cross flow around and in the wake of a circular cylinder, and a hydrofoil at different cavitating regimes and various Reynolds numbers. We used high-speed cameras to visualize the cavitation structure and a Particle Image Velocimetry (PIV) method to measure the velocity fields. In addition, we measured the forces acting on the smooth cylinder and on the cylinders with different mesoscale surface structures, and we also performed an acoustic measurement, using a hydrophone located downstream of the cylinders. Finally, we numerically studied the dynamics of the cavitation flow around a benchmark hydrofoil with and without passive control methods and compared our numerical results with our experimental data. Our results showed that the mesoscale surface structures were very efficient in suppressing or mitigating cavitation. The cavitation-induced vibration exciting forces acting on the cylinders and hydrofoils with riblet structures were significantly reduced compared to the cases without cavitation control. Furthermore, a substantial reduction in the cavitation volume and the sound pressure level in the low- and middle-frequency ranges were observed for the hydrofoils with riblet structures. The large-scale cloud cavity on the hydrofoil with scalloped and sawtooth riblets was changed to a small-scale cavity, which modified the cavitation dynamics on the hydrofoil surface and controlled unsteady cloud cavitation.

Zusammenfassung

Im Rahmen dieses Vorhabens wurden Methoden zur passiven Kavitationskontrolle entwickelt, mit dem Ziel, unerwünschte Effekte wie Schwingungen im Zusammenhang mit schiffstechnischen Strukturen und hydraulischen Systemen zu verringern oder zu vermeiden. Zu diesem Zweck wurden verschiedene mesoskalige Oberflächenstrukturen wie Riblet-Strukturen, Rippen- und Rauheitsstrukturen verwendet, um die kavitierende Strömung um kreisförmige Zylinder und Tragflächen zu kontrollieren. Es wurden umfangreiche Experimente durchgeführt, um die Auswirkungen von Wandrauhigkeit und Riblet-Strukturen auf die Kavitationsdynamik, die Kavitationsinstabilität und die Turbulenzstrukturen in der Querströmung um und im Nachlauf eines Kreiszylinders und eines Tragflügels bei verschiedenen Kavitationsregimen und unterschiedlichen Reynoldszahlen zu untersuchen. Es wurden Hochgeschwindigkeitskameras zur Visualisierung der Kavitationsstruktur und eine Particle Image Velocimetry (PIV) Methode zur Messung der Geschwindigkeitsfelder eingesetzt. Darüber hinaus wurden die Kräfte gemessen, die auf den glatten Zylinder und auf die Zylinder mit

unterschiedlichen mesoskaligen Oberflächenstrukturen wirken. Weiterhin wurden der Unterwasserschall mit einem Hydrophon gemessen. Schließlich wurde die Dynamik der kavitierenden Strömung um einen Tragflügel mit und ohne passive Kavitationskontrolle numerisch untersucht. Die numerischen Ergebnisse wurden mit den experimentellen Daten verglichen. Unsere Ergebnisse zeigen, dass die mesoskaligen Oberflächenstrukturen die Kavitation sehr effizient unterdrücken oder abschwächen. Die kavitationsbedingten Schwingungserregerkräfte, die auf die Zylinder und Tragflügel mit Riblet-Strukturen wirken, wurden im Vergleich zu den Fällen ohne Kavitationskontrolle deutlich reduziert. Darüber hinaus wurde bei den Tragflügeln mit Riblet-Strukturen eine erhebliche Verringerung des Kavitationsvolumens und des Schalldruckpegels im niedrigen und mittleren Frequenzbereich festgestellt. Die großflächigen Kavitationswolken konnten durch die Kavitationskontrolle gebrochen werden, wodurch die Kavitationsdynamik auf der Tragflügeloberfläche verändert und die instationäre Wolkenkavitation kontrolliert wurde.

3 Progress Report

Background and objectives of the project

Cavitation negatively affects the performance of pumps, marine propellers and rudders, and other machinery as it is the main factor of erosive wear and mechanical damage of operating elements of the hydraulic equipment, and this can be a source of flow instabilities. In this regard, the development of cavitation control methods has been an urgent problem to improve the design of modern pumping, turbine, propulsion, and steering systems. At present, wall morphology (and the associated physical properties) is admittedly one of the key parameters along with cavitation nuclei concentration, initial turbulence level and its spectral composition, and surface pressure distribution that govern the evolution of hydrodynamic cavitation. Besides, this characteristic is presumably the least studied among other characteristics that affect cavitation inception and its behaviour. Thus, by modifying mesoscale patterns and, consequently, physical properties of the wall, it may become possible to control flow separation, boundary-layer characteristics, and cavitation. The onset and development of hydrodynamic cavitation are influenced by many factors, including the roughness of a body's surface, the amount of air dissolved in a liquid, the initial level of turbulent fluctuations, and the presence of impurities in a liquid flow. By changing any of these parameters, it is possible to partly control cavitation on submerged objects. Today, based on various physical principles, there are a number of passive and active methods to manipulate cavitating flows. The advantage of passive methods over active ones is that there is no need to supply energy to the system, and a desired effect is achieved by modifying the geometry or physicochemical properties of a body surface. The main objective of this project was to develop passive cavitation control methods for different types of cavitation and to mitigate their undesirable effects on hydrofoils. With this end in view, we implemented mesoscale (of the order of or less than a millimetre) regular wall structuring. Various surface textures were produced, using appropriate processing technologies (milling, deformational cutting). We performed extensive experiments to investigate the effects of wall roughness and riblet structures on the dynamics of cavitation, cavitation instability and turbulence structures in the cross flow around and in the wake of a circular cylinder, and a hydrofoil at different cavitating regimes and various Reynolds numbers. We used high-speed cameras to visualize the cavitation structure and a Particle Image Velocimetry (PIV) method to measure the velocity fields. In addition, we measured the forces acting on the smooth cylinder and on the cylinders with different mesoscale surface structures, and we also performed an acoustic measurement using a hydrophone located downstream of the cylinders. Finally, we numerically studied the dynamics of the cavitation flow around a benchmark hydrofoil with and without passive control methods and compared our numerical results with our experimental data.

Results and Discussion

We first studied the effects of the passive control method, using mesoscale riblets to control cavitation induced-erosion caused by bubble collapses near a solid boundary. For this aim, we experimentally investigated the effects of different mesostructured V-shaped riblets on the dynamics of a laser-induced single cavitation bubble at four different wall distances. First, we captured the dynamics of a single cavitation bubble near a flat solid surface, using a high-speed camera. Second, we analysed the dynamics of a single cavitation bubble near the mesostructured riblets at different relative wall distances (γ) and compared these with the bubble collapse dynamics near the unmodified solid surface. The results showed that the bubble collapse dynamics was changed during its collapse and rebound process near the mesostructures riblets. The riblets caused a reduction of the bubble's first and second collapse time near the riblet surface at the relative wall distances $\gamma = 1.4$ compared to the bubble near a flat solid surface. For the bubble near the riblet surface at the relative wall distances $\gamma = 1.8$, the time duration of the first collapse was not significantly changed. However, a reduction of the collapse time for the second bubble collapse was observed. Furthermore, the equivalent bubble radius for the bubble near the riblet structures was mitigated at the relative wall distance $\gamma = 1.8$. For both relative wall distances, a faster damping of the collapse-induced attached cavity near the riblet surface was observed compared to the bubble near the flat boundary. Figure 1 show the collapse dynamics obtained from the experiments for a single cavitation bubble at $\gamma = 1.8$ with and without mesostructured riblets, respectively. Furthermore, it can be seen that the collapse-induced cavity, even after the second collapse, did not attach itself to the riblet surface. This clearly indicates that the effect of the riblet structure suppressed or mitigated the microjet impact on the riblet structure, which can be formed after the collapse near the solid boundary.

The results were **published** in our paper entitled “Experimental study of the influence of mesoscale surface structuring on single bubble dynamics” by **Kadivar et al. (2022).**

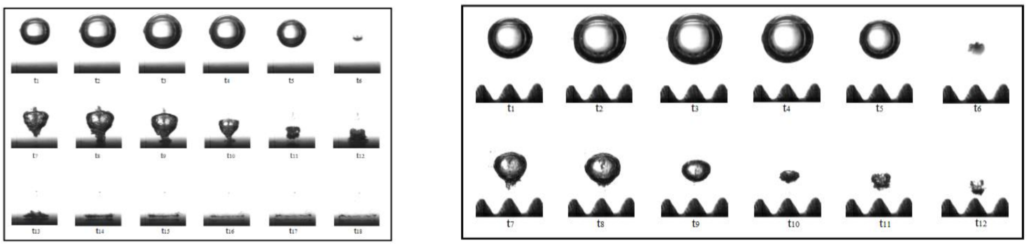

Figure 1: (left) High-speed images of collapse dynamics obtained from our experiments for a single cavitation bubble at γ = 1.8 from the flat solid surface and (right) from the flat solid surface with mesostructured riblets. The time step is 0.05 ms, Kadivar et al. (2022).

Second, we investigated experimentally the effects of cavitation control on the cavitating flow around a circular cylinder, using a mesoscale surface structuring at different cavitation and Reynolds numbers. Two types of scalloped riblets were manufactured on the surface of circular cylinders to control cavitation and cavitation-induced vibration. First, we performed the experiments for a smooth cylinder (without riblets) at different cavitating regimes. Second, we studied the effects of the riblet structures on the cylinders. Two cylinders, one with horizontal riblets and one with vertical riblets (see Fig. 2), were investigated under the same conditions as for the smooth cylinder to analyse the effects of the riblets on controlling the cavitation dynamics behind the cylinder and the associated cavitation-induced vibration exciting forces. The results show that the horizontal riblets reduced the maximum lift force amplitudes significantly, compared to the force amplitudes of a smooth cylinder. Furthermore, the riblets suppressed the tip-vortex cavitation behind the cylinder. Figure 3 reveals that the cavitating vortices shed behind the cylinder with vertical riblets at cavitation numbers σ = 1.5 were significantly mitigated compared to those behind the smooth cylinder. The large-scale vortical cavitation structures behind the cylinder changed into smaller cavity structures. Figure 4 shows the frequency spectrum of the lift force acting on the smooth cylinder and on the cylinders with horizontal and vertical riblets at σ = 1.0. The horizontal riblets reduced the lift force amplitude by about 65%. Figure 5 illustrates that the miniature riblets induced the small vortex structures nearby as the flow interacted with the cylinder, and these small vortices significantly impacted the instabilities that typically formed on the smooth cylinder’s surface. We concluded that both selected horizontal and vertical scalloped riblets showed a positive effect on controlling the cavitating flow around the cylinder at different cavitating regimes and various Reynolds numbers. The horizontal scalloped riblets were more effective in controlling the cavitation-induced vibration exciting forces and shedding frequency in most of the cavitating regimes. However, this passive control method is limited to moderate angles of attack. At a high angle of attack, the flow around the hydrofoil may fully separate. Therefore, such full separated flow can hardly be controlled using a passive control method. More details can be found in our paper by **Kadivar et al. (2024)**.

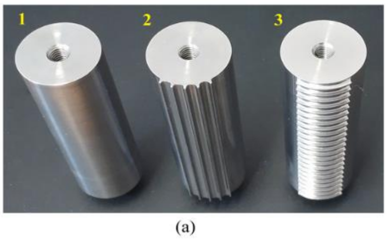

Figure 2: Side views of the smooth cylinder, the cylinder with vertical scalloped riblets, and the cylinder with horizontal scalloped riblets.

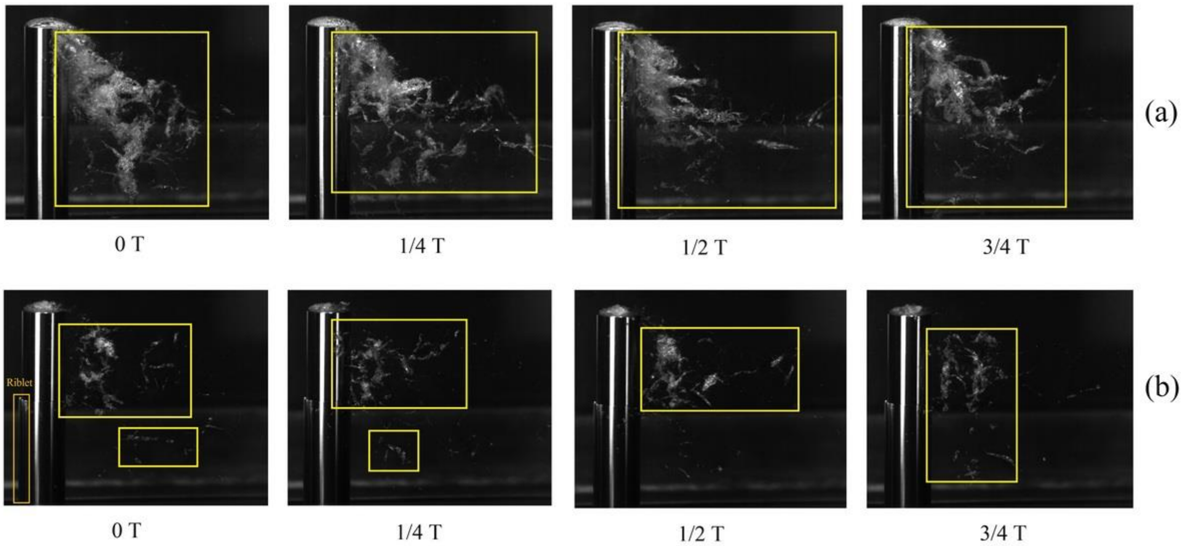

Figure 3: (a) Cavity structures behind the smooth circular cylinder at σ = 1.5, (b) cavity structures behind the circular cylinder with vertical riblets at σ = 1.5. The orange rectangle on the cylinder (left part of the image) indicates the position of the riblets. The flow is from left to right, and the Reynolds number is Re = 1.5e5 (Lin et al., 2024).

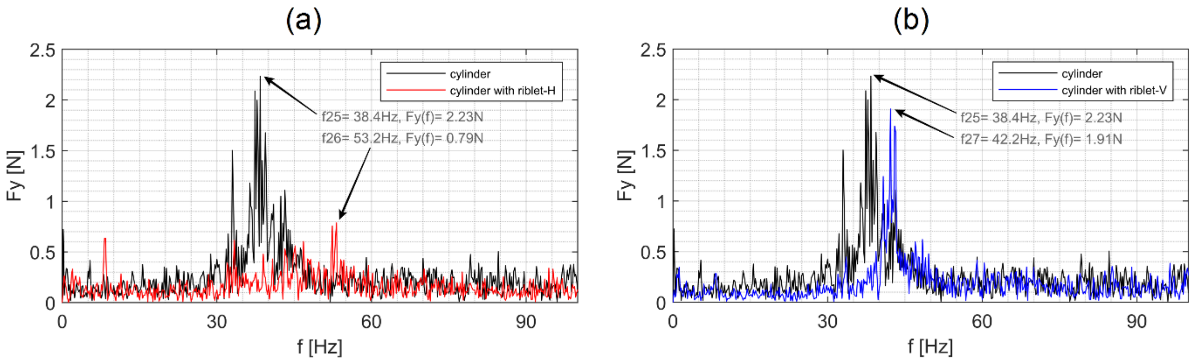

Figure 4: (a) Frequency spectrum of the lift force for the smooth cylinder and for the cylinder with horizontal riblets, (b) frequency distributions of the lift force for the smooth circular cylinder and for the cylinder with vertical riblets. The cavitation Reynolds number are σ = 1.0 and Re = 1.5e5, respectively (Lin et al., 2024).

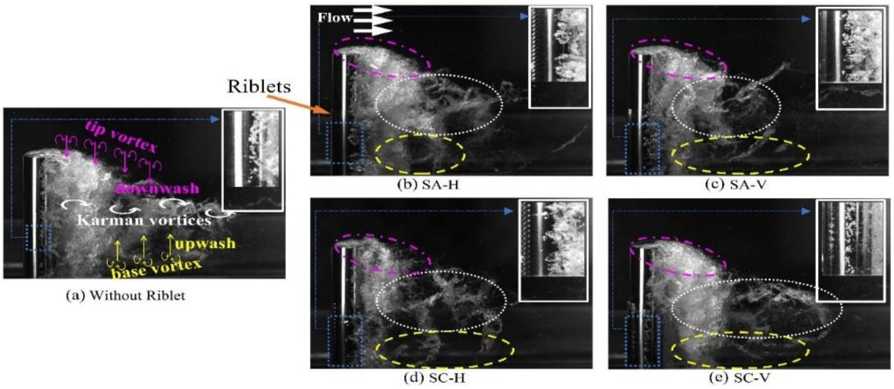

Figure 5: Cavitation patterns behind the smooth cylinder (a), behind the cylinder with horizontal sawtooth riblets SA-H (b), behind the cylinder with vertical sawtooth riblets SA-V (c), behind the cylinder with horizontal scalloped riblets SC-H (d), and behind the cylinder with vertical scalloped riblets SC-V (e) (Kadivar e t al., 2024).

In addition to our experimental investigations, we performed with Markovich's group an experimental study of the effect of wall roughness/wettability on the occurrence of cavitation and turbulence structures in the cross flow around and in the wake of a circular cylinder at two characteristic regimes. Three bodies with different wall morphologies were tested, namely, a smooth body (reference), a body with micro-scale irregularities (rough), and a body with a large-scale (of the order of a millimetre) regular texture (finned). High-speed visualization was employed to observe cavitation structures, and Particle Image Velocimetry (PIV) was used to measure the velocity fields along with the method of quantification of the probability of vapor phase occurrence. For this aim, the conducted in-depth analysis of the data and the measured turbulence characteristics of the flow, including the higher-order moments of turbulent fluctuations (i.e., the coefficients of skewness and excess) and the time-averaged vapor content around and in the wake of each of the cylinders in the two typical regimes of the cavitating flow, allowed us to conclude the following: a) Elevated surface roughness led to significant cavitation suppression. For the considered wall morphologies, the small-scale irregularities led to the more pronounced effect, indicating the high efficiency of this passive control method. b) Both types of roughness noticeably affect the turbulence structure of the wake flow, including its mean velocity, its dispersion, and the higher-order moments of turbulent fluctuations. A change in the flow regime for the rough and finned cylinders has almost no effect on the amplitude of the higher-order moments, regardless of the roughness scale, compared to that of the smooth cylinder. c) Regardless of the type of surface morphology, the influence of roughness on the formation of large-scale vortices and their characteristics was weakened. However, it made local flow conditions highly unsteady. The larger-scale of irregularities led to a more chaotic process. As seen in Fig. 9, the spatial distributions of the time-averaged flow velocity are different downstream of the smooth and rough cylinders, even for the streamwise mean velocity in the main part of the turbulent wake. The results were **published** in our paper entitled “Cavitation suppression and transformation of turbulence structure in the cross flow around a circular cylinder: Surface morphology and wettability effects” by **Nichik et al. (2024)**.

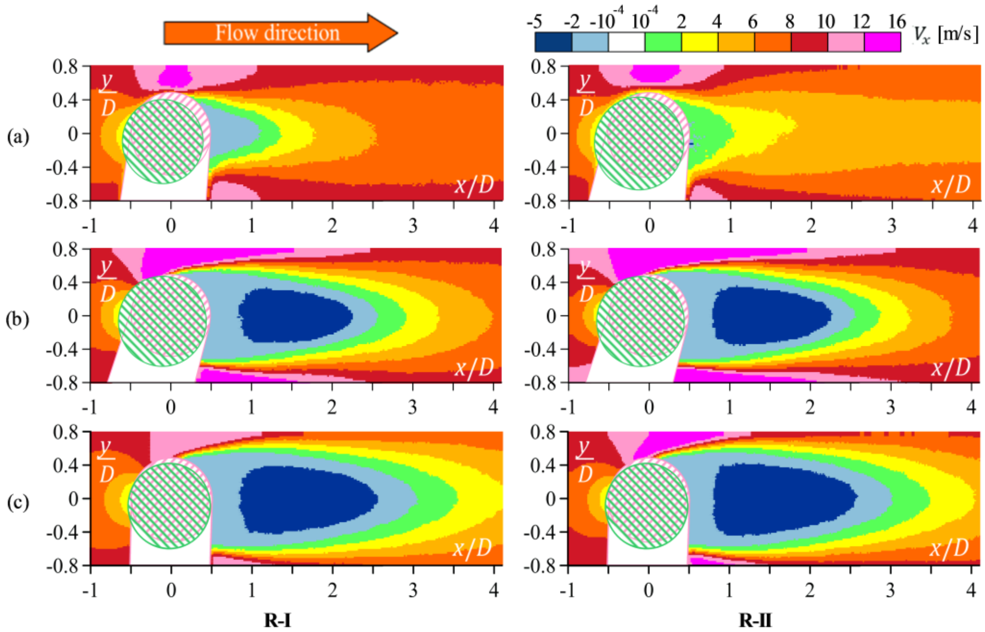

Figure 6: Spatial distributions of the streamwise component of the mean flow velocity around and in the wake of the (a) smooth, (b) rough, and (c) finned cylinder in two different flow regimes (Nichik et al., 2024).

We studied the effects of passive cavitation control, using mesoscale surface structuring on a benchmark hydrofoil, see Fig.7 (left). We used two different riblets, known as scalloped and sawtooth riblets. The results showed a substantial reduction in the cavitation volume and the associated sound pressure level (SPL) within the low- and middle-frequency ranges for the hydrofoil with riblet structures, see Fig. 7(right). Furthermore, the scalloped and sawtooth riblets led to the generation of small-scale vortices, which modified the cavitation dynamics on the hydrofoil surfaces. The proposed riblets (especially the scalloped riblets) were shown to be a practical passive method to control cloud and partial cavitation for different industrial applications. Figure 11 reveals the cavitation dynamics on the smooth hydrofoil, on the hydrofoil with scalloped riblets, and on the hydrofoil with sawtooth riblets. The results show a reduction of the cavity structure on the hydrofoils with scalloped and sawtooth riblets. In addition, the large scale of the cloud cavitation was suppressed on both the hydrofoils with riblets. Furthermore, we performed numerical simulations of the cavitation flow around the unmodified hydrofoil and the hydrofoil with scalloped riblets. The results show a significant reduction of the pressure pulsation amplitude on the hydrofoil with the scalloped riblets. We published the results in our paper entitled “Experimental investigation of partial and cloud cavitation control on a hydrofoil using bio-inspired riblets” by Lin et al. (2024).

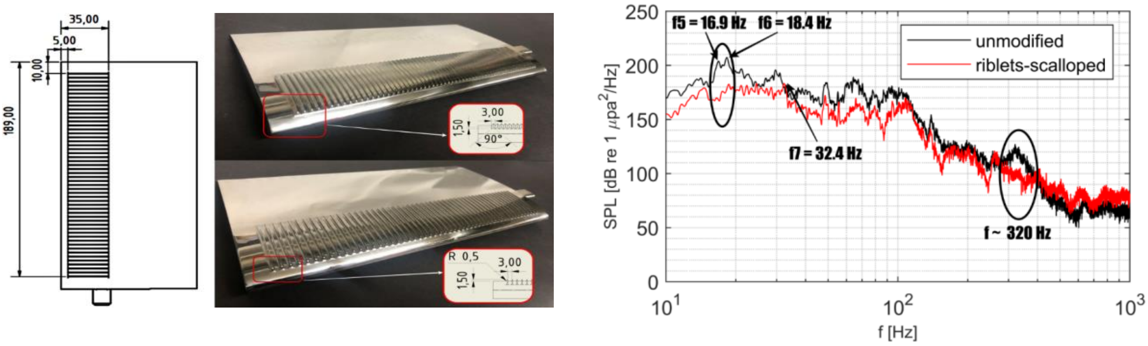

Figure 7: (left) Photo of the hydrofoils with scalloped and sawtooth riblets and (right) acoustic pressure level (SPL) vs. frequency of the cavitating flow on the smooth (unmodified) hydrofoil and on the hydrofoil with scalloped riblets for σ = 1.6 and Re = 1.5e6 (Lin et al., 2024).

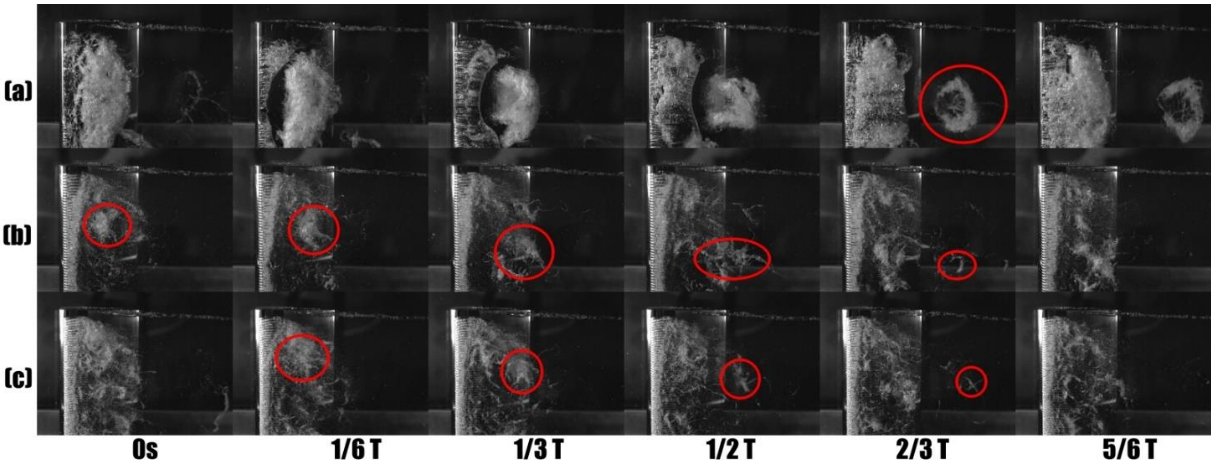

Figure 8: For σ = 1.6, Re = 1.5 ×106, and T = 66 ms, successive cavity structures obtained over one period of the cavitation cloud oscillating on the smooth hydrofoil (a), on the hydrofoil with scalloped riblets (b), and on the hydrofoil with sawtooth riblets (c) (Lin et al., 2024).

Figure 9 shows comparative cavity structures obtained from experimental data and numerical simulations over one period of the cavitation cloud oscillating on the hydrofoil with scalloped riblets. As seen, a favourable agreement of the numerical results of the cavitation dynamics around the hydrofoil with riblets with the experimental data was received. The results will be published in a paper currently under preparation (Dawoodian et al. (2025).

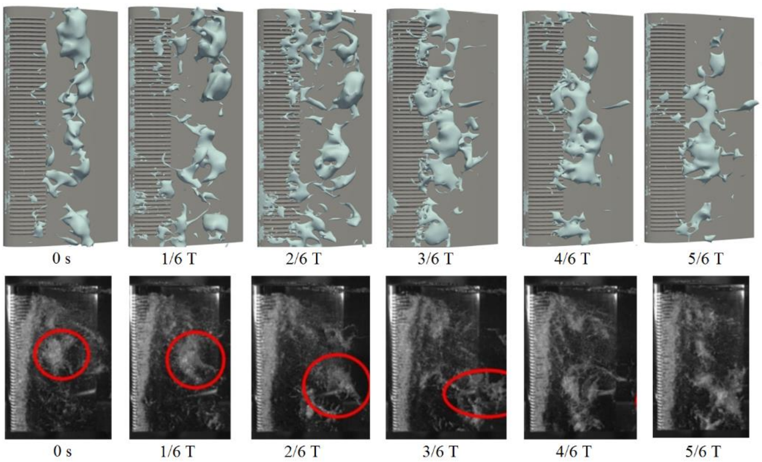

Figure 9: Comparative cavity structures obtained from experimental data and numerical simulations over one period of the cavitation cloud on the hydrofoil with scalloped riblets in the cavitating regime at σ = 1.4. Paper under preparation (Dawoodian et al., 2025).

4 Published Project Results

4.1 Publications with scientific quality assurance

M.Y. Nichik, B.B. Ilyushin, E. Kadivar, O. el Moctar, K.S. Pervunin, Cavitation suppression and transformation of turbulence structure in the cross flow around a circular cylinder: Surface morphology and wettability effects. Ultrasonics Sonochemistry, Volume 106, pp. 106875, 2024. https://doi.org/10.1016/j.ultsonch.2024.106875

Y. Lin, E. Kadivar, O. el Moctar, T.E. Schellin, Experimental investigation of partial and cloud cavitation control on a hydrofoil using bio-inspired riblets, Physics of Fluids, Volume 36, pp. 053338, 2024. https://doi.org/10.1063/5.0207688

E. Kadivar, O. el Moctar, H.J. Sagar, Experimental study of the influence of mesoscale surface structuring on single bubble dynamics. Ocean Engineering, Volume 260, pp. 111892, 2022. https://doi.org/10.1016/j.oceaneng.2022.111892

E. Kadivar, Y. Lin, O. el Moctar, Experimental investigation of the effects of cavitation control on the dynamics of cavitating flows around a circular cylinder. Ocean Engineering, Volume 286, pp. 115634, 2023. https://doi.org/10.1016/j.oceaneng.2023.115634

Y. Lin, E. Kadivar, O. el Moctar, Experimental Study of the Cavitation Effects on Hydrodynamic Behavior of a Circular Cylinder at Different Cavitation Regimes, Fluids, Volume 8, pp. 162, 2023. https://doi.org/10.3390/fluids8060162

E. Kadivar, M. Dawoodian, Y. Lin, O. el Moctar, Experiments on Cavitation Control around a Cylinder Using Biomimetic Riblets, Journal of Marine Science and Engineering, Volume 12, pp. 293, 2024. https://doi.org/10.3390/jmse12020293

4.2 Other publications and published results

P. Kumar, E. Kadivar, O. el Moctar, Experiments on Cavitation Control around a Cylinder Using Biomimetic Riblets, *Applied Ocean Research*, submitted, 2024.

P. Kumar, E. Kadivar, O. el Moctar, Cavitation control by using bio-inspired riblets on hydrofoil through cavitation dynamics analysis using proper orthogonal decomposition, *International Journal of Multiphase Flow*, submitted, 2024.

M. Dawoodian, E. Kadivar, A. Peters, O. el Moctar, Numerical study of cavitation control on a hydrofoil using mesoscale riblet structures, *Applied Ocean Research*, under preparation, 2025.

The results of the project were presented at several international conferences (e.g., CAV2024, SNH, etc.)

4.3 Patents (applied for and granted)

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