Experimental investigation of the passive control of unsteady cloud cavitation using miniature vortex generators (MVGs)

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Abstract. The research is aimed at the study of a passive control method to control unsteady cloud cavitation that is characterized by regular shedding of large vapour structures from the solid surface of a cavitating immersible body. The unsteady cloud cavitation is an important subject of research because of its destructive impacts in various industrial applications, including ship propellers and rudders, pumping and hydraulic machinery systems. For this, we placed miniature vortex generators (MVGs) of a cylindrical type on the surface of a benchmark CAV2003 hydrofoil and investigated effects of these MVGs on the spatial structure of unsteady cavitation clouds. We analyzed the temporal and spatial cavity characteristics in comparison with those for the original hydrofoil (without MVGs) by means of high-speed imaging. In addition, we used a hydrophone to register the signal of pressure pulsations in time and thereby derive power spectra of the pressure pulsations. The results showed that the implemented cavitation control method is an effective tool to manage the unsteady behaviour of cloud cavitation and to mitigate the amplitude of pressure pulsations. It was revealed that, with this control approach, the large-scale cavitation clouds appear to be broken and only small-scale cavity structures are shed away from the hydrofoil surface. Moreover, a notable reduction in the cavitation-induced vibrations of the solid surface may be expected.

1. Introduction

Unsteady cloud cavitation and methods of mitigation of this type of cavitation are one of the important subjects in many fields such as marine engineering, ship engineering and turbomachinery. Unsteady partial and unsteady cloud cavitations can be generated by oscillations of cavity structures and leads to undesirable effects such as erosion, vibration and noise, [1] - [3]. The mechanism of formation of the unsteady cloud cavitation were studied by many researchers, [4] - [9]. They have identified that re-entrant jets as the main and primary role for the formation of oscillations of cavity structures. Their results showed that the re-entrant jets can move upstream under the cavity surface and then break the cavity into different pieces when the cavity closure located in the region of adverse pressure. Recently, researchers studied different methods to mitigate and suppress the deleterious effects of the unsteady cloud cavitation.
Delgosha et al. [10] investigated the surface roughness in order to manipulate the cyclic behavior of the cavitation in the sheet cavitating flow regime. Crimi et al. [11] indicated that the effect of sweep angle of a hydrofoil has an influence on the mitigation of the cavitation-induced erosion. They studied the influences of the different sweep angles on the reduction of the erosion area on the surface of the hydrofoil. Danlos et al. [12] performed some experiments to study the effects of surfaces roughness on the venturi profile. They found that the surface roughness can suppress the instabilities of the cloud cavitation shedding in some cavitating flow conditions. Kim et al. [13] studied the effect of an axi-asymmetrical obstacle plate installed upstream of an inducer inlet in order to control the cavitation surge problem. They showed that the axi-asymmetrical method can be an effective method for mitigation of the cavitation surge instabilities. Kamikura et al. [14] studied a suppression technique to control the cavitation instabilities by using asymmetric slits on blades as a passive cavitation control. Their results showed that the cavitation instabilities may be mitigated or suppressed by a certain arrangement of asymmetric slits. Javadi et al. [15] investigated a passive control method around a 2D hydrofoil using cavitation bubble generator mounted on the hydrofoil surface. Their results showed that the cavitation may be controlled with a well-designed cavitating-bubble generator. Kadivar et al. [16] - [17] studied a wedge-type vortex generator to mitigate the unsteady cloud cavitation around a 3D hydrofoil. They showed that wall-pressure peaks and the turbulent velocity fluctuations on the hydrofoil surface can be mitigated using the passive control method.

Researchers performed different studies for the control of cavitation, but so far, there are still not enough studies to control the instabilities and destructive effects of unsteady cloud cavitation in details. In this work, we analyzed the effects of miniature vortex generators (MVGs) on the cavitation characteristics experimentally in comparison with those for the original hydrofoil without MVGs by means of high-speed visualization. In addition, we analyzed the effects of the MVGs on the pressure pulsations in the wake region of the hydrofoil surface using an acoustic measurement.

2. Methodology
In this work, we studied a passive control method to control destructive effects of an unsteady cloud cavitation such as collapse of the large-cavity structures and pressure pulsations in the wake region of a benchmark hydrofoil. For this aim, we used discrete miniature cylindrical vortex generators (MVGs) and mounted the MVGs in spanwise direction on the suction surface of the hydrofoil. This technique was proposed in our previous numerical work, Kadivar et al. [18]. We used benchmark hydrofoil CAV2003 [19] which mostly used to study the mechanism of the unsteady partial cavitation and unsteady cloud cavitation regimes. The previous numerical studies indicated that the size of the MVGs should be small enough which may not cause the significant reduction in the hydrodynamic efficiency of the hydrofoil, [20]. Fig. 1 shows the hydrofoil with MVGs and a close-up view of MVGs mounted on the suction side of the hydrofoil. The diameter of the CCGs, height of the CCGs and distance between the cylindrical obstacles are 1 mm, 1 mm and 4 mm, respectively. The chord length of the hydrofoil and the location of the CCGs to the leading edge are 100 mm and 36 mm, respectively. More information about this passive control method can be found in [18].
3. Results
The experiments were performed in the cavitation tunnel in Kutateladze Institute of Thermophysics SB RAS. The setup is equipped with two centrifugal pumps, ultrasonic flowmeter and different pressure and temperature sensors. The amount of oxygen dissolved in water was kept to 7 mg/l with fluctuation within ± 0.5 mg/l during the experiments. The water temperature was 30 °C and during the experiments the temperature of the water in the cavitation tunnel was kept constant using a control system. The description of the cavitation tunnel and the measurement techniques can be found in [21]. The high-amplitude pressure pulsations at the wake region of the hydrofoil generated by the collapse of the large-scale cavity were measured using a hydrophone in the test channel sidewall downstream of the hydrofoil. At first, the location of Re-entrant jets on the hydrofoil without cavitation control was found using the high-speed camera. The video cameras are Photron FASTCAM SA5 with the frame rate to 20 kHz. In addition, the pressure pulsations in the wake region of the hydrofoil surface were recorded using an acoustic measurement. The hydroacoustic pressure transducer is a hydrophone Brüel&Kjær Type 8103 with a measurement frequency range from 0.1 Hz to 180 kHz which was flush-mounted into the sidewall of the test section using wax as a sealant. After that, we mounted the MVGs upstream the inception region of the side-entrant jets on the hydrofoil suction surface. Then we studied the effect of MVGs on the dynamics of an unsteady cloud cavitation. Fig. 2 shows the effects of the MVGs on the unsteady cloud cavitation dynamics for the hydrofoils with and without MVGs at Reynolds number $1.4 \times 10^6$ during one typical oscillation cycle.

Figure 1: The 3D view of the hydrofoil CAV2003 with MVGs and close-up view of MVGs mounted on the suction side of the hydrofoil.
Figure 2: Sequence images of the formation of the unsteady cloud cavitation during one typical oscillation cycle for the hydrofoil without and with MVGs. The flow direction is from left to right and the experiments was measured at Reynolds number $1.4 \times 10^6$. The shedding frequencies for the hydrofoil without MVGs and with MVGs are $f = 74$ Hz and $f = 78$ Hz, respectively. The time steps between images for the hydrofoil without MVGs and with MVGs are $\Delta t = 3.3$ ms and $\Delta t = 3.2$ ms, respectively.
Figure 3: Sequence images of the side-view of formation of the unsteady cloud cavitation during one typical oscillation cycle for the hydrofoil without and with MVGs. The flow direction is from left to right and the experiments was measured at Reynolds number $1.4 \times 10^6$. The shedding frequency for the hydrofoil without MVGs and with MVGs are $f = 74$ Hz and $f = 78$ Hz, respectively. The time step between images for the hydrofoil without MVGs and with MVGs are $\Delta t = 1.68$ ms and $\Delta t = 1.6$ ms, respectively.

As the figure 2b and figure 3b show, the shedding of the large-scale cavity structures can be mitigated for the hydrofoil with MVGs compared to the case without MVGs. The cavitating-bubbles which induced by the MVGs may reduce the momentum of the side-entrant jets and middle-entrant jet and theirs motion towards the leading edge of the hydrofoil. In other words, the side-entrant jets have not enough energy to propagate diagonally upstream near the leading edge and pinch off the cavity due to the effects of cavitating-bubbles induced by the MVGs on the cavity structures at the vicinity of the hydrofoil surface.

Fig. 4 shows Fast Fourier Transform (FFT) diagram of the pressure pulsations for the hydrofoil with and without MVGs at the Reynolds number $1.5 \times 10^6$. The results reveal a significant reduction of the amplitude of pressure pulsations for the hydrofoil with MVGs. The results indicate that the amplitude of pressure pulsations were reduced in comparison to the hydrofoil without MVGs.
4. Conclusions
In this work, we studied a passive control method to control unsteady cloud cavitation. We placed miniature vortex generators (MVGs) of a cylindrical type on the surface of a benchmark hydrofoil and studied the effects of the MVGs on the dynamics of the unsteady cavitation clouds. We analyzed the temporal and spatial cavity structures by means of high-speed camera. In addition, we measured the signal of pressure pulsations at the wake region of the hydrofoil. The results revealed that, the large-scale cavitation clouds were mitigated and only small-scale cavity structures are shed away from the hydrofoil surface. Moreover, a notable reduction in the pressure pulsations at the wake region of the hydrofoil was received.

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6. References
[1] Patella R F, Choffat T, Reboud J L, Archer A 2013 Mass loss simulation in cavitation erosion: Fatigue criterion approach, Wear, 300, pp. 205-215.
[2] Arndt R E A, Song C C S, Kjeldsen M, Keller A 2000 Instability of partial cavitation: A numerical/experimental approach, proceedings of the twenty-third symposium on naval hydrodynamics, Val de Reuil, France.
[3] Leroux J, Coutier-Delgosha O, Astolfi J 2005 A joint experimental and numerical study of mechanisms associated to instability of partial cavitation on two-dimensional hydrofoil, Physics of fluids, 17, pp. 052101-20.
[4] Furness R A, Hutton S P 1975 Experimental and theoretical studies of two-dimensional fixed-type cavities, J. Fluids Eng, 97, 4, pp. 515-521.
[5] Kubota A, Kato H, Yamaguchi H, Maeda M 1989 Unsteady structure measurement of cloud cavitation on a foil section using conditional sampling technique, J.Fluids Eng, 111 (2), pp. 204-210.
[6] Kawamura Y, Kato H, Yamaguchi H, Tanimura M, Tagaya Y 1997 Mechanism and control of cloud cavitation, J. Fluids Eng, 119, pp. 788-794.
[7] Callenaere M, Franc J P, Michel J, Riondet M 2001 The cavitation instability induced by the development of a reentrant jet, J. Fluid Mech, 444, pp. 229-250.
[8] Saito Y, Nakamori I, Ikohagi T 2003 Numerical analysis of unsteady vaporous cavitating flow around a hydrofoil, in: Proceedings of the Fifth International Symposium on Cavitation, Osaka, Japan.

[9] Pelz P F, Keil T, Ludwig G 2014 On the kinematics of sheet and cloud cavitation and related erosion, Advanced experimental and numerical techniques for cavitation erosion prediction, the series Fluid Mechanics and Its Applications 106, pp. 221-237.

[10] Coutier-Delgosha O, Devillers J, Leriche M, Pichon T 2005 Effect of wall roughness on the dynamics of unsteady cavitation, ASME. J. Fluids Eng, 127 (4), pp. 726-733.

[11] Crimi P 1970 Experimental study of the effects of sweep on hydrofoil loading and cavitation (Sweep angle relationship to cavitation inception on hydrofoils and to hydrofoil performance deterioration due to cavitation), Journal of Hydronautics, 4 (1), pp. 3-9.

[12] Danlos A, Mehal J, Ravelet F, Coutier-Delgosha O, Bakir F 2014 Study of the cavitating instability on a grooved venturi profile, ASME. J. Fluids Eng, 136 (10), 101302-101302-10.

[13] Kim J H, Ishzaka K, Watanabe S, Furukawa K 2010 Cavitation Surge Suppression of Pump Inducer with Axi-asymmetrical Inlet Plate, International Journal of Fluid Machinery and Systems, 3 (1), pp. 50-57.

[14] Kamikura Y, Kobayashi H, Kawasaki S, Iga Y 2018 Three dimensional numerical analysis of inducer about suppression of cavitation instabilities by asymmetric slits on blades, IAHR Symposium, Kyoto, Japan.

[15] Javadi Kh, Dorostkar M M, Katal A 2017 Cavitation Passive Control on Immersed Bodies, J. Marine Sci. Appl, 16 (1), pp. 33-41.

[16] Kadivar E, Javadi Kh 2017 Effect of Cavitating-bubble Generators on the Dynamics of Unsteady Cloud Cavitation, The 19th Marine Industries Conference, Kish, Iran.

[17] Kadivar E, el Moctar O 2018 Investigation of cloud cavitation passive control method for hydrofoils using Cavitating-bubble Generators (CGs), in: Proceedings of the 10th International Symposium on Cavitation, Baltimore, USA.

[18] Kadivar E, el Moctar O, Javadi Kh 2019 Stabilization of cloud cavitation instabilities using Cylindrical Cavitating-bubble Generators (CCGs), International Journal of Multiphase Flow 115, pp. 108-125.

[19] Franc J P, Schnerr G H 2003 Workshop on physical models and CFD tools for computation of cavitating flows, Call for participation in present workshop, CAV2003, Osaka, Japan.

[20] Kadivar E, el Moctar O, Javadi Kh 2018 Investigation of the effect of cavitation passive control on the dynamics of unsteady cloud cavitation, Appl. Math. Model, 64, pp. 333-356.

[21] Timoshevskiy M V, Zapryagaev I I, Pervunin K S, Mal'tsev L I, Markovich D M, Hanjalic K 2018 Manipulating cavitation by a wall jet: Experiments on a 2D hydrofoil, International Journal of Multiphase Flow, 99, pp. 312-328.