Synchronized Measurement of Cloud Cavitating Flow around a 3D Twisted Hydrofoil

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Abstract

Cloud cavitation shedding from sheet cavitation usually can be seen on propellers, rudders and shaft brackets of fast running ships. The unsteady and instable behavior of these cavitation structures generally can produce severe impingement on the neighboring wall, which is one of the main reasons for vibration, noise and erosion induced by cavitation. Therefore, it is significant to know the relation between the cavitation structure and its reduced pressure signals, which can help to recognize the generation mechanism of cavitation impact. In this paper, cavitation behavior, pulse pressure and noise were synchronized measured to illustrate the dynamic characteristics of cavitation structures around a 3D twisted hydrofoil. The pressure fluctuation and noise were recorded under different cavitation numbers, including cases of flow without cavitation and with cavitation at the same incoming velocity. Then cavitation behavior and relevant pressure signals were compared both in time domain and in frequency domain to investigate the relation between the unsteady cavitation structures and the corresponding pressure response.

Keywords: synchronized measurement; cloud cavitating flow

Introduction

Cavitation is a unique phenomenon in liquid due to the local pressure dropping to the saturated vapor pressure. It is a source of vibration, noise and erosion for ships under fast speed. In general, cavitation can be divided into different types according to its appearance, such as bubble cavitation, sheet cavitation, cloud cavitation and vortex cavitation. Among these types, cloud cavitation shedding from sheet cavitation is usually considered to be one of the most harmful one since its evolution can produce strong dynamic pressure. Extensive investigations have been focused on the collapse of a single isolated bubble to illustrate the generation mechanism of violent radiated pressure waves. However, cloud cavitating flow is a complicated process coupled with phase change, vertical structures and micro bubble clusters, the understanding on the dynamic process is still not enough at this moment. Recent study (Cao et al. 2015, Peng et al. 2016) has shown that there exist distinct U-shaped vortex structures in large scale cloud cavitating flows under various flow configurations. And the overall contribution of different cavitation structures to cavitation erosion was evaluated qualitatively using painting method (Cao et al. 2017). To further understand the reason for the test result of paint loss regions, the pressure fluctuations and acoustic signals were recorded simultaneously with cavitation behavior.

Cavitation on spanwise uniform (2D) hydrofoil sections has been investigated extensively (such as Kjeldsen et al. 2000, Arndt et al. 2000, Ganesh et al. 2016). However, the shedding location on this kind of models in spanwise direction is random, which may bring more uncertainty and complexity in the association of instantaneous cavitation structure to corresponding dynamics. Foeth (2008) introduced a 3D twisted hydrofoil that can produce periodic shedding cloud cavitation resulted from sheet cavitation in his work. As a result, we choose to use this kind of configure to estimate the relationship between the cavitation structures and its reduced dynamic signals.

Test facility and experimental setup

Cavitation tests were conducted in the high speed cavitation tunnel (as shown in Figure 1) located in China Ship Scientific Research Center (CSSRC). The test section is composed of 8 perspex window which permits to observe cavitation structures from different sides. The length of test section is 1600mm×225mm×225mm. The maximum flow velocity can reach 25m/s and the background pressure can be adjusted from 5kPa to 500kPa, which allows the cavitation number defined as formula 1 to be easily changed. In addition, this tunnel has a fast degassing system allowing to degass the water in limited time.

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$$\sigma = \frac{p_\infty - p_v}{0.5\rho U^2} \tag{1}$$

The test model used in this test is a NACA16012 3D twisted hydrofoil (as shown in Figure 2) with a chord length of 100mm and a spanwise length of 225mm. It is a symmetric hydrofoil with spanwise varied attack angle and the maximum angle of 11 degree in the middle. The AOA (angle of attack) was set to be 0 degree based on the end of straight part in spanwise. The cavitation structures were observed synchronously by two high speed cameras from the bottom and backside of test section (as shown in Figure 3), which consequently can get both the top view and backside view of cavitation structures around the hydrofoil. Two LED lights provide light for high speed cameras. The images were recorded at a frame rate of 6000 FPS during the experiment. Figure 4 shows the location of pressure transducers and hydrophone. The range of pressure transducers is 300 kPa with an accuracy of 0.3%. In this paper the result of P2 was considered to be more convincible because signals of P1 contain some high frequency electrical noise. The hydrophone used in this test is B&K 8103 installed inside a water filled cylindrical box which is put outside of side window. The sampling rate of transducers was set to be 195652.18Hz. However, it should be noticed that the response frequency of pressure transducers could not reach so high. As a result, in this test the pressure transducers can measure relatively low frequency (within 1000Hz) dynamic signals accurately while the hydrophone can measure signals with both low and high frequency components.

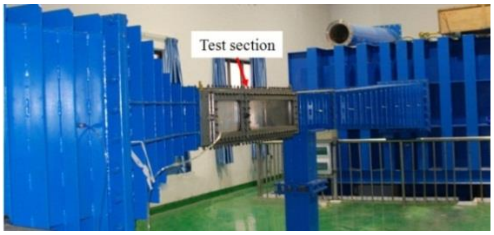

Figure 1 The high speed cavitation tunnel in CSSRC.

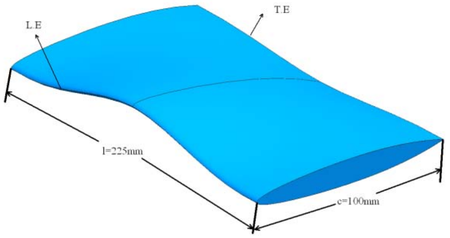

Figure 2 A sketch of NACA16012 3D twisted hydrofoil.

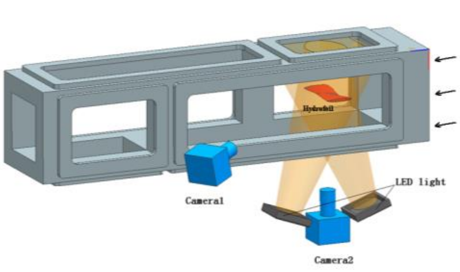

Figure 3 Setup of high speed cameras and lights.

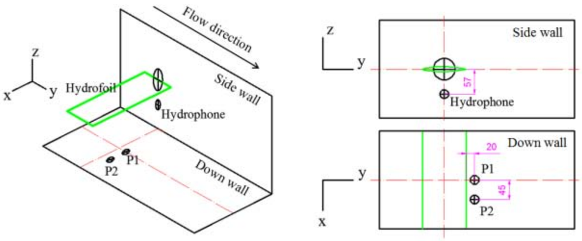

Figure 4 Location of pressure transducer and hydrophone.

Results and discussion

A serious of cases with different cavitation numbers were conducted during the experiment. The incoming flow velocity was set to be 7m/s and the AOA was set to be 0 degree which allows the maximum angle in the middle to be 11 degree. In this paper, we give the results of cavitation behavior only under the condition of $\sigma = 1.0$. Pressure and acoustic spectrum of different cavitation numbers under the condition 7m/s were given for all test conditions. The signal spectrums were expressed in SPL (Sound Pressure Level) and were averaged using 10 group data at the same condition.

The evolution of cavitation behavior

The evolution of cavitation behavior was observed by high speed cameras. The results show that the shedding process of large scale cloud cavitation around the 3D twisted hydrofoil is qusi-periodic. Figure 5 shows the behavior in a classical period and Figure 6 is the corresponding processed noise and pressure signals. The interval between two images is 2.83 ms (17 frames taken with frame rate 6000FPS). In this paper the beginning of a shedding cycle is considered to be the incident when sheet cavity reaches the maximum length (Shown as T1). At this moment, re-entrant flows beneath the sheet reach the leading edge of the hydrofoil and then impinge on the surface of sheet cavity. Thus results in the primary shedding that almost the whole part of cavity was detached from the leading edge (Shown as T2). Then the shed part moved downward and ultimately developed into a U-shaped vortex structure (Shown as T10). Simultaneously a reborn sheet grew up from the leading edge (Shown as T3). During the sheet growing process (From T4 to T6), re-entrant flow continually formed at the two side rear part of the new sheet and induced the local shedding or secondary shedding (Shown as T6). When the reborn cavity approached to the maximum length, re-entrant flow at both side of the rear part moved forward to the center of hydrofoil and gathered together in the spanwise symmetric plane. That's the typical behavior of large scale cloud cavitating flow around a twisted hydrofoil. It can't be denied that the cavitation structure doesn't evolve exactly the same in different cycles, but in most cases it develops in this way or tend to be in this way. The Strouhal number of the main shedding expressed with maximum sheet length is 0.23.

Cao et al. 2017 showed that the unsteady rear part of sheet cavitation is the most erosive structure, and the route where the U-shaped vortex structure evolved from cavitation cloud passes can also be erosion risk region. It can be seen from Figure 6 that the maximum pressure peak in a cycle is around T3, when the cavitation cloud was just formed from the breakup of sheet cavity. It can be interpreted that the generation process of cloud cavitation from sheet cavity could produce relatively high magnitude pressure fluctuation, which was mainly due to the change of cavitation volume. This provides a proof for why the most erosive region was there. From the noise signal showed in Figure 6, it can be seen that there exists some high magnitude pulse signals in time domain which could not be seen from the pressure signals. Considering the response frequency of transducers, it can be deduced that the pulse signal is produced in limited short time. The HSV results (Figure 7, sequential images taken at 6000FPS, between T7 and T8) showed that this pulse in noise signal might be related to the collapse and rebound behavior of part of cloud structure. The data in Figure 6 was normalized with half of the difference between the maximum and minimum value.

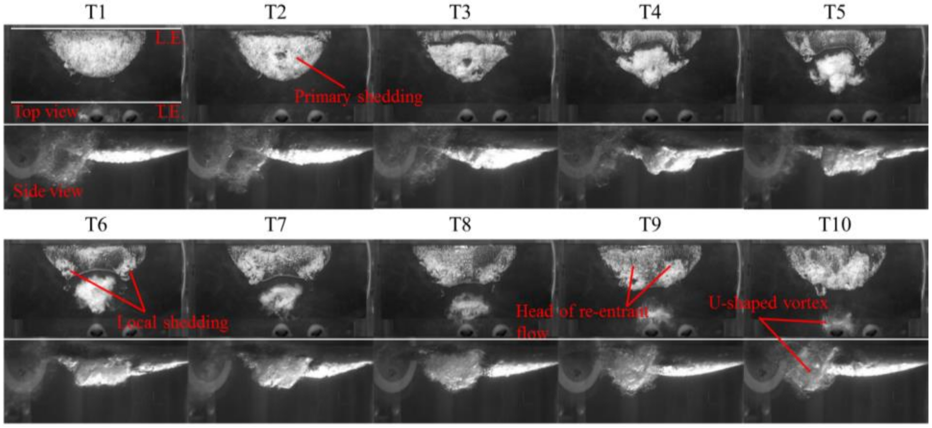

Figure 5 Cavitation behavior in a period (U=7m/s, $\sigma = 1.0$)

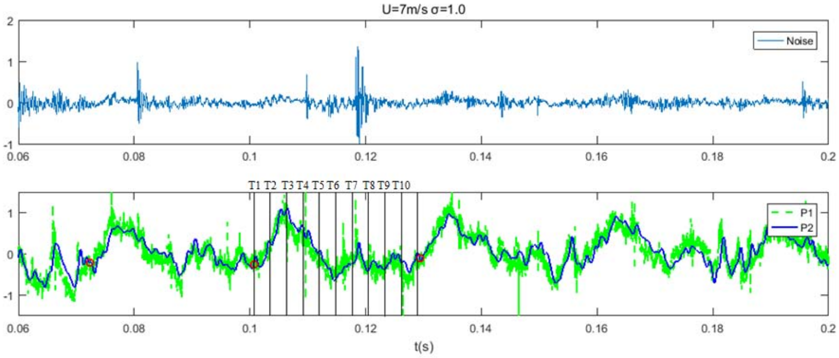

Figure 6 Dynamic signals in a period (U=7m/s, $\sigma = 1.0$)

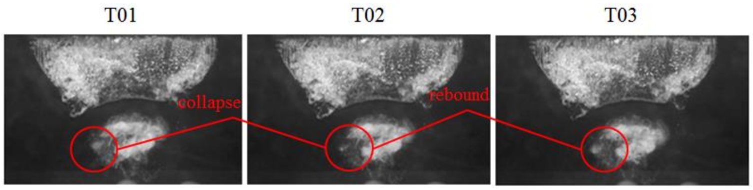

Figure 7 Collapse and rebound of part of cavitation cloud (U=7m/s, $\sigma = 1.0$)

Spectrum of dynamic signals

The spectrum of noise and pressure signals is shown in Figure 8 and Figure 9 respectively. It can be seen that when cavitation appears, the noise magnitude rises rapidly all over the frequency domain, especially in high frequency segment, whereas the pressure magnitude rises mainly in the low frequency part. Combining the time domain results described above, it can be speculated that the high magnitude fluctuations in low frequency part seems to be mainly related to the sheet and high frequency signals mainly related to the shed cloud. The peak around 800-900Hz was the vibration induced by the interaction between the flow and the foil structure, which can be heard obviously during the test.

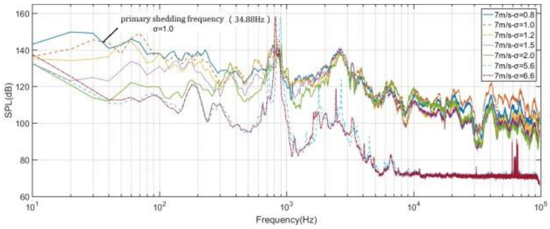

Figure 8 Spectrum of noise signals

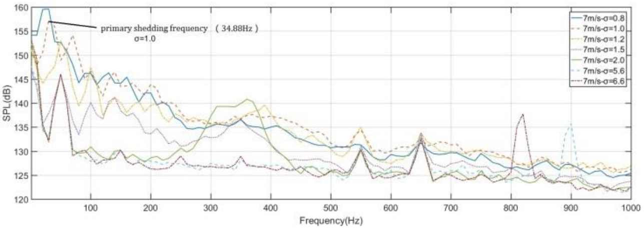

Figure 9 Spectrum of pressure signals measured by P2

Conclusions

This paper introduced the recent experimental work of measurement of cloud cavitation dynamics around a 3D twisted hydrofoil in CSSRC. Combining high speed cameras, pressure transducers and hydrophone, the relationship between cavitation structure and corresponding pressure signals was compared. It is revealed that the maximum magnitude of cavitation fluctuation pressure was related to the initial stage of cloud cavitation evolution, when sheet cavity just breakup into cloud, whereas the high magnitude pulse noise signal seemed to be related to the collapse behavior of cloud.

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