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Acoustic Characteristics of Cavitating Flow around a Twisted Hydrofoil*

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ABSTRACT

Cavitation is one of the main sources of radiated noise for ships under fast speed. It's essential to know its typical noise characteristic in the detection and control of cavitation noise. In this paper, cavitating flows around a twisted hydrofoil were investigated in a cavitation tunnel. A series of cases with various cavitation number and incoming flow velocity were compared to analyze the effect of cavitation intensity and velocity. The spectrum results indicated that the sound pressure level (SPL) tends to increase with the decrease of cavitation number and the increase of flow velocity, but there existed a saturation phenomenon when the dominant parameters reach a certain value. Part of high frequency band in SPL spectrum under cavitation conditions showed a similar distribution and a possible explanation was speculated. In addition, wavelet time frequency analysis method was used to emphasize on the instantaneous characteristics of acoustic signal and its contribution to the noise band.

Keywords

Spectral characteristics, acoustic signals, cavitating flow, hydrofoil

1 INTRODUCTION

For fast running ships, cavitation is generally unavoidable on propellers, shaft brackets and rudders, which can produce distinct noise which is much higher than wet flows. It could affect the life of marine animals and cause some undesired noise in the cabin. Therefore, many investigations have been focus on this subject.

Since the radiated acoustic signal of cavitating flows is not only related to the complicated behavior of cavitation structures, but also has some relationship on its propagation. Consequently, there's still many confusions that still not understood yet in this field.

In this paper, we use a hydrophone to monitor the dynamics of cavitating flows around a 3D twisted hydrofoil. The acoustic spectrum and time domain signals were compared to shed light on the basic characteristics of typical cavitating flows.

2 TEST FACILITY AND EXPERIMENTAL SETUP

Cavitation tests were conducted in a 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 and the size of the square cross section is 225mm×225mm. The maximum flow velocity can reach 25m/s and the background pressure can be easily adjusted from 5kPa to 500kPa, which allows the cavitation number to be easily changed. Besides, this tunnel has a fast degassing system allowing to degass the water in limited time. The cavitation number σ is defined as follows,

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

Where U is the incoming flow velocity, p_∞ is the inlet pressure of test section, p_v is the vapor pressure, ρ is the density of water.

The test model used in this test is a NACA16012 3D twisted hydrofoil (as shown in figure 2) with a cord 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 distribution of the angle in spanwise can be calculated from formula 2. The AOA (angle of attack) was set to be 0 degree based on the end of straight part in spanwise.

$$\alpha = \begin{cases} 0, & 0 \le z < 12.5 \\ 11(16\left|\frac{z-12.5}{200}-\frac{1}{2}\right|^3 - 12\left|\frac{z-12.5}{200}-\frac{1}{2}\right|^2 + 1), & 12.5 \le z \le 212.5 \\ 0, & 212.5 < z \le 225 \end{cases} \tag{2}$$

Figure 3 shows the location of hydrophone. It was installed inside a cylindrical water chamber filled with water. The chamber was fixed on the outside wall of side window. The center of the chamber was the same with the base center of hydrofoil in flow direction and 57mm down to the foil base center on the suction side of foil. The hydrophone used in this test is B&K 8103. The sampling rate was set to be 195652.18Hz. The original signal was preprocessed using an amplifier and then connected to the sampling system to record and save the signals.

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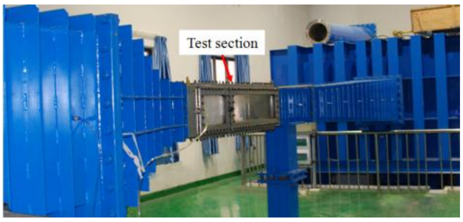

Figure 1 The high speed cavitation tunnel in CSSRC

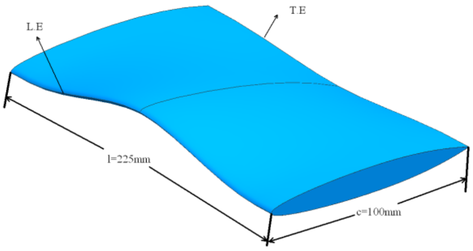

Figure 2 A sketch of NACA16012 3D twisted hydrofoil

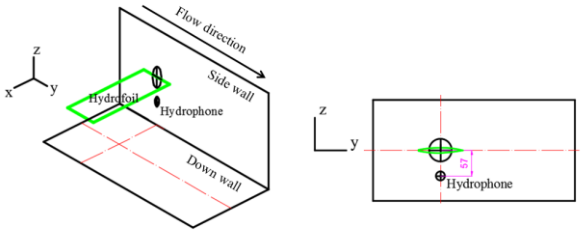

Figure 3 Location of hydrophone

3 RESULTS AND DISCUSSION

3.1 Spectrum of Acoustic Signal

The acoustic signal in time domain was converted to frequency domain by FFT and transformed into SPL in the form of 1/3 octave band spectrum. Every case was averaged with ten group's data to ensure a more reliable result. The SPL in this paper was expressed as follows,

$$SPL = 20\log(p/p_{ref}) \qquad (3)$$

Where p is the sound pressure and $p_{ref} = 10^{-6}$ Pa is the reference pressure.

Figure 4~7 shows the SPL spectrum at the same flow velocity and various cavitation number. The data under cavitation number over 2.0 stands for the cases without cavitation and could be considered as the background noise. It could be seen from the results that the most obvious discrepancy between cases with and without cavitation is in the band over 1000 Hz. Consequently, we focus on the band over 1000 Hz in this part since signals under 1000 Hz seem to be much more complicated.

The intensity of the acoustic signal seems to increase with the decrease of cavitation number in certain extent. It accords with the physical process that the cavitation intensity increases with the drop of cavitation number. However, there exists a saturation point that cavitation number reaches a certain value (1.0) and the radiated noise does not grow but decrease. As is shown in Figure 4 and 5, the SPL under $\sigma = 0.8$ is lower than $\sigma = 1.0$. This might come from the change of cavitation behavior that when further decreasing the cavitation number, the unstable sheet to cloud cavitation tends to turn into supercavitation. As is shown in figure 8, the maximum cavity length is about 0.5 of the chord length at $\sigma = 1.0$ and it has nearly though not yet approached to the chord length at $\sigma = 0.8$. Supercavitation tends to be more stable than sheet shedding flow, hence the corresponding acoustic signal might go down with the change of cavitaion type.

It could not be deny that some special cases inconsistent with the trend of the majority. Like the condition at 5m/s with cavitation number 2.0, which seems much higher than other cases at the same velocity and should have been lower since the cavitation is weaker than other cavitation cases. A possible explanation for this may be the cavitation structure under this condition is mainly composed of small shedding vortices, as is shown in figure 9. There's not a main cavity wrapping the scattered structures. Consequently, the pressure pulses could propagate to the sampling site much easier.

Another trend shown from the results is that the shapes of the SPL curves in high frequency part are similar with each other. According to the fact that this part in the noise band mainly comes from cavitation with the comparison between cavitating and wet conditions, it could be comprehended that the cavitation dynamic behaviors under various cavitation intensity should be similar. Considering the whole process of cavitation, all the stages (including the inception, the evolution and the collapse) share similarity in dynamics in despite of cavitation intensity. Firstly, the generation of cavitation is similar that cavitation is related to the sudden growth of nuclei under certain low pressure circumstances. Thereby the emergence of cavitation might share parallel points in the dynamic characteristics. Secondly, the development of cavitation on the foil is similar since the shedding vortical structures behave in analogous ways governed by vortex kinematics and dynamics. Hence the dynamics in this stage may be similar. Thirdly, the collapse behavior is similar from the collapse of macro vapor structures to the collapse of micro bubbles. In respect that all cavitating flows share these similarities, it could be deduced that the acoustic dynamic signals behave alike from a statistic point of view.

Additionally, as is illustrated in figure 4 and figure7, the difference in the high frequency band part between a strong cavitation case (relatively lower cavitation number at the same velocity, such as 1.0) and a weak one (relatively higher cavitation number at the same velocity, such as 2.0) diminishes with the increase of flow velocity. It implies that the cavitation intensity at high velocities is strong enough that the effect of cavitation number on the dynamic signals tends to vanish.

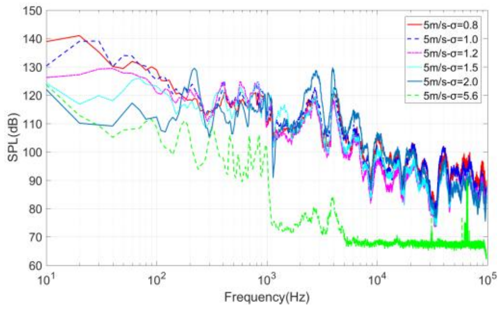

Figure 4 Acoustic spectrum under various cavitation number at $U = 5m/s$

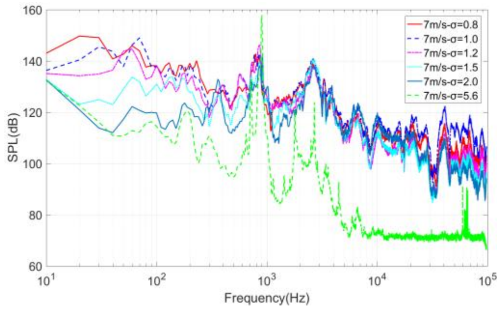

Figure 5 Acoustic spectrum under various cavitation number at $U = 7m/s$

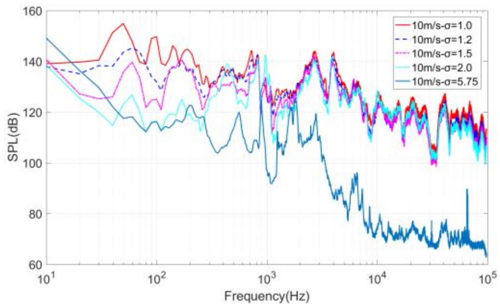

Figure 6 Acoustic spectrum under various cavitation number at $U = 10m/s$

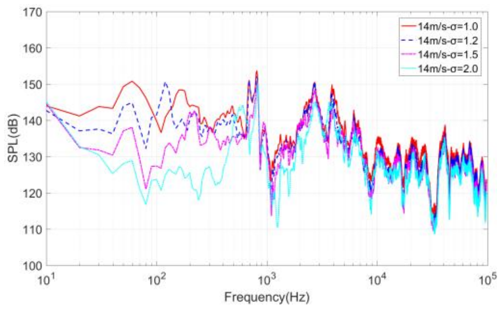

Figure 7 Acoustic spectrum under various cavitation number at $U = 14m/s$

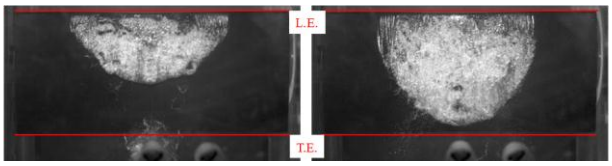

Figure 8 Cavitaion behavior at $U = 5m/s$

(Left: $\sigma = 1.0$, Right: $\sigma = 0.8$)

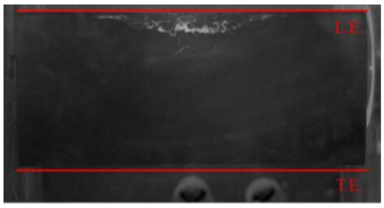

Figure 9 Cavitaion behavior at $U = 5m/s$, $\sigma = 2.0$

Figure 10~13 shows the reorganized data based on the equal cavitation number. As is depicted from the results, the SPL tends to rise with the increase of flow velocity at the same cavitation number. Franc et al. (2014) summarized two reasons for the effect of flow velocity at constant cavitation number on pitting rate. Here it could be introduced to understand the velocity effect. Firstly, to keep a constant cavitation number, the ambient pressure has also to be increased in order to conserve the cavitation number when the velocity is increased. The cavitating structures then experience a larger pressure during their dynamic process and it results in a stronger collapse and an impulsive pressure of higher amplitude. Another reason is that the bubble production rate also increases with flow velocity so that the emergence of pressure pulses increases.

In addition, the similarity phenomena in high frequency band could also be exposed at the same cavitation number.

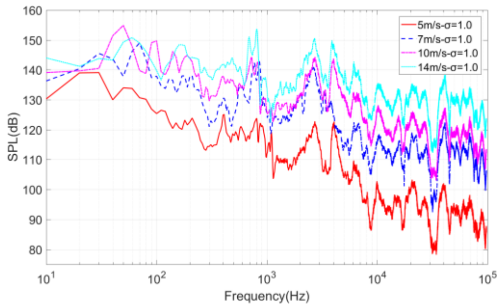

Figure 10 Acoustic spectrum under various velocity at $\sigma = 1.0$

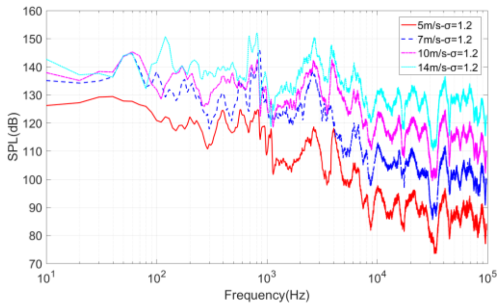

Figure 11 Acoustic spectrum under various velocity at $\sigma = 1.2$

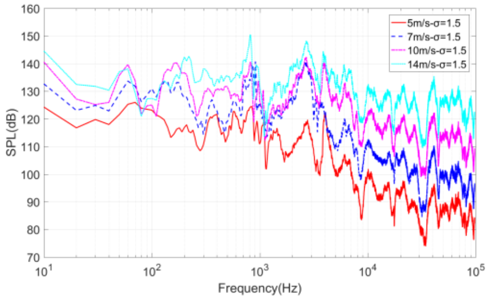

Figure 12 Acoustic spectrum under various velocity at $\sigma = 1.5$

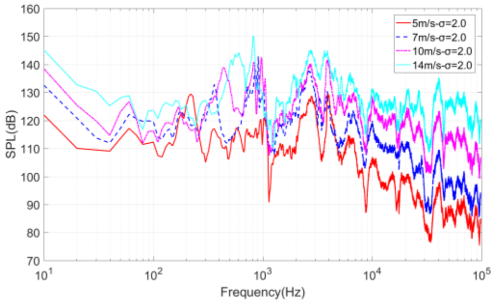

Figure 13 Acoustic spectrum under various velocity at $\sigma = 2.0$

3.2 Time frequency characteristics of acoustic signal

Recently, continuous wavelet transform (CWT) in the analysis of cavitating and bubbly flows has been broadly applied to classical cloud shedding physics (Brandner et al.). To see the contribution of typical instantaneous cavitation behavior on the band, the CWT method with Morlet wavelet was employed in this part to analyze the time frequency characteristics of acoustic signal.

Figure 14 shows part of the acoustic signal in time domain and its relevant CWT result at $\sigma = 1.0$, $U = 7m/s$. The typical characteristic of cavitation noise is that it is composed of the relatively flat part and some random pulses with magnitudes usually much higher than the averaged part. Cao et al. (2018) demonstrated that these pulses are related to the local collapse and rebound of cloudy structure with high speed video simultaneously recorded with acoustic signal, whereas the relatively flat part in time domain signal is related to the break and evolution of the whole cavity. The CWT results show the role of different behaviors of the cavitating structures. It is revealed that the pulses are actually high frequency components mainly ranging from 2×10^4 Hz to 10×10^4 Hz based on the sampling frequency around 2×10^5 Hz. And the relatively flat parts are relative low components under 5×10^3 Hz. It could be deduced from above that the volume change of the main cavity contributes to the low frequency band within 5000 Hz in spectrum, whereas the collapse and rebound contributes mostly to the high frequency band above 10000Hz. Here the volume change refers to the unsteady behavior excluding the collapse and rebound to distinguish the two different behaviors.

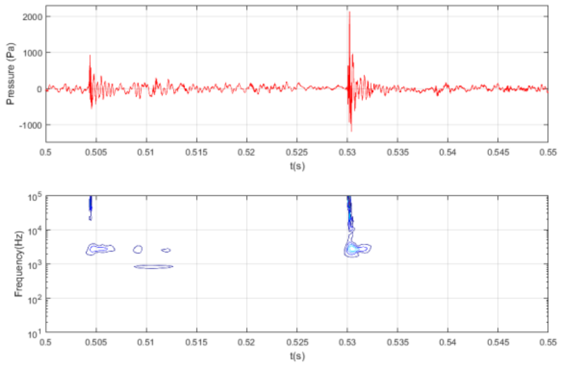

Figure 14 Acoustic signal in time domain and relative CWT at $\sigma = 1.0, U = 7m/s$

4 Conclusions

This paper focused on the recent experimental work on the acoustic signals of cloud cavitation in CSSRC. By changing the flow velocity and cavitation number, the SPL under different conditions was obtained. Some basic conclusions could be speculated from the results.

(1) The SPL tends to grow with the drop of cavitation number and the increase of flow velocity when the other parameters are kept the same.

(2) The CWT of the acoustic signal in time domain implies that the pulses due to the local collapse and rebound of cloudy structure mainly contribute to the high frequency band in the spectrum.

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