The Influence and Analysis of Gas Content on the Pressure Fluctuation induced by Cavitating Propeller

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Abstract. A ship hull model with all accessories is used to simulate the wake field of the propeller of a twin propeller ship in a large circulating water channel. The similarity of propeller wake field is guaranteed. The influence of air content in water on pressure fluctuation by cavitating propeller is studied. The cavity form of propeller was observed under the condition of different air content in water. The pressure fluctuations induced by cavitating propeller behind ship hull is also measured. The results showed that the air content has a significant influence on the pressure fluctuations. Each measuring points and each order frequency of pressure fluctuations amplitudes increase with the decrease of air content. The main reasons of influence of air content on pressure fluctuations are analyzed. It is proposed that how to set the air content in the model tests.

1. Introduction

With the development of the international shipping industry, the main engine power of the ship is continuously increasing, and the diameter of the propeller can not be increased correspondingly due to various restrictions. The single propeller load is increasing. The propeller of high-speed surface ships will inevitably produce cavitation. The cavitation phenomenon of the propeller will not only reduce the performance of the propeller and cause cavitation erosion, but also lead to a sharp increase in the fluctuating pressure of the hull. The fluctuating pressure induced by propeller cavitation has become the main source of vibration and noise for high-speed ships. At present, the fluctuating pressure induced by propeller on the hull surface has been taken as a criterion for the success of propeller design. In order to make a correct judgment on the fluctuating pressure induced by propeller cavitation at the design stage, it is necessary to predict the fluctuating pressure by model test.

In the model test of pulsating pressure, the correct simulation of wake flow is the basic requirement of pulsating pressure measurement. It is very important to correctly simulate the three-dimensional flow of propeller when measuring the pulsating pressure. Because of the size limitation, it is difficult to simulate wake flow with full-appendage ship model, and it is difficult to simulate the axial velocity distribution with grid. The measurement of propeller fluctuating pressure will be affected by water quality, and the air content in water is the main factor of water quality. Traditionally, it is also the air content in water to define water quality. The air content in water reflects the concentration of cavitation nuclei, which has an important impact on water tension. Therefore, the air content in water will certainly have a greater impact on the fluctuating pressure of hull induced by cavitating propeller [1,2]. Because it is difficult to consider air content in numerical calculation, the influence of air content is not taken into account in most numerical prediction of propeller cavitation [3,4] and numerical
calculation of ship hull fluctuating pressure \[^5,6\]. In the model test of the fluctuating pressure of a cavitating propeller, the influence of air content on the fluctuating pressure of a cavitating propeller can be studied by adjusting the air content in water. This is of great significance to the analysis of the law and causes of the influence of air content and how to set the appropriate air content in the model test. In this paper, the cavitation shape of propeller is observed under different air content in water, and the fluctuating pressure of ship hull induced by propeller is measured. The law of the influence of air content on fluctuating pressure is summarized, the main reason of the influence of air content on fluctuating pressure is analyzed, and the guidance on how to set the air content in model test is put forward.

2. Test facilities and test models

The experiment was carried out in a large circulating flume of the State Key Laboratory of Hydropower. The section of the working section of the flume is rectangular with tangential angle, 2.2m wide, 2m high, 4.28m\(^2\) cross-sectional area and 10.5m length. The range of water speed regulation in working section is 1m/s-15m/s, and the range of pressure regulation in the center of test section is 0.005MPa-0.4MPa.

According to the size limitation and installation requirements of the test section of the circulating flume, the ship model is made according to the scale ratio. The full length of the model is 6.76m, and the two propellers rotate inward. The appendages include a bulbous bow, two bilge keels, two anti-rolling fins, two axle sleeves, a single arm bracket, a double arm bracket and a rudder. The model is made of FRP and the stiffness of the back half of the model is strengthened. The ship model number is SM0404. The installation photos of the ship model and propeller model are shown in Figure 1.

![Figure 1. Installation of ship model and propeller model.](image)

The criteria of geometrical similarity, motion similarity and dynamic similarity should be satisfied in the tests of cavitation and pulsating pressure:

1) Making ship model and propeller model according to scale ratio to ensure geometric similarity;

2) The number of vacuoles is the same: the number of vacuoles at the speed of 0.8R is the same as that of the real ship;

3) Reynolds number of blade section chord length at 0.75R exceeds critical Reynolds number;

4) The load of the propeller and the propeller model is the same, and the thrust coefficient is the same in this test.

Eight pulsating pressure sensors are embedded on the bottom surface of the stern part and the upper part of the left propeller model. The diameter of the pressure surface of the sensor is 3.7 mm, which is equal to the surface of the ship model. The spacing between the sensors is 0.1D(0.1D is the diameter of the propeller die). The specific arrangement is shown in Figure 2. The second sensor is located directly above the center of the propeller disk.

In order to observe the cavity shape of the propeller die, a small water-tight CCD is fixed on the front, upper and rear of the left propeller die. Under the illumination of stroboscopic light, the
development and change of the cavity on the back and surface of the propeller die are monitored respectively, and recorded by video recorder.

Figure 2. Layout of pulsating pressure sensor

According to the thrust coefficients and the number of rotating speed cavitations at each speed, the model speed and the water speed and pressure in the working section of the propeller are calculated. The test conditions corresponding to the real ship speed are shown in Table 1. After adjusting the relative air content of water in the flume is 0.58 and reaching a stable test condition, the following measurements are made.

| $K_T$ | $\sigma_n$ | $J_s$ | $V_s$(m/s) | $n_m$(r/s) |
|------|-------|------|-------------|-------------|
| 0.170 | 1.296 | 0.999 | 6.056 | 29.06 |

1) Firstly, the sensitivity coefficients of each pressure sensor are calibrated, and then the fluctuating stern pressure induced by propeller is measured under different working conditions to obtain the pressure coefficients.

During the test, the measured pulsating pressure signal in time domain was transformed by fast Fourier transform (FFT) to obtain the amplitude (single amplitude) $P_i$ of each order with the propeller blade frequency as the fundamental frequency and its harmonic frequency, and the phase angle of each order with a specified blade tip positioned directly above the blade tip as the reference angle.

$$
\bar{p} = \bar{p}_0 + \sum_{i=1}^{\infty} P_i \cdot \cos(i\omega t + \phi_i)
$$

The magnitude of each order is expressed by dimensionless coefficient $K_p_i$.

$$
K_{p_i} = \frac{P_i}{\rho n^2 D_n^2}, i \geq 5
$$

2) Cavitation observation: After the cavitation appears on the propeller blade, the region and shape of the cavitation on the corresponding radius at different circumferential angles are drawn.

Changing the relative air content in water to 0.50, 0.68 and 0.82, and repeat the experiment to change the air content in water. According to the test rules, the cavity shape of the propeller model is observed, and the fluctuating pressure is measured and analyzed.

3. Test results and analysis

3.1. Cavitation Observation and Analysis

When the relative air content $\alpha / \alpha_c$ is 0.58, the cavity shape of the propeller model in the circumferential angle range of 350 to 40 degrees is depicted in Figure 3.
By adjusting the relative air content $\alpha / \alpha_s$ in water as 0.82, 0.68 and 0.50 respectively, there is no obvious difference in the shape of propeller cavitation observed by CCD photography results. This is mainly because the air content has little influence on the stable range of sheet cavitation, mainly on the initial, unstable sheet cavitation and bubble cavitation, but it is difficult to quantitatively identify by existing observation equipment.

3.2. Measurement and Analysis of Pulse Dynamic Pressure

When the gas content $\alpha / \alpha_s$ in water is equal to 0.82, 0.68, 0.58 and 0.50 respectively, the fluctuating pressure coefficients measured in the experiment are shown in Figure 4. From the law of fluctuating pressure amplitude varying with frequency at each measuring point, the fluctuating pressure amplitude basically decreases with the increase of blade frequency order. The fluctuating pressure amplitude of first-order and second-order blade frequency is obviously larger than that of third-to-forth-order blade frequency, which indicates that the fluctuating pressure mainly consists of first-order and second-order blade frequency fluctuating pressure. At some measuring points, the second-order blade frequency fluctuating pressure amplitude is higher than the first-order amplitude, which should be related to the spatial distribution characteristics of the propeller wake field.

According to the law of the fluctuating pressure amplitude of each measuring point with space variation, the fluctuating pressure of the hull induced by propeller is the largest at 6 # measuring point, i.e. the right side of the propeller disk, which is mainly related to the distribution characteristics of the wake field and the hull shape characteristics. In the angular direction near the measuring point 6, the relative casual fraction is larger, the propeller cavitation is more serious, and the cavitation volume changes more dramatically. The close linear distance between the point and the propeller leads to a larger fluctuating pressure amplitude in the angle direction.

It can be seen from Figure 4. that different air content in water has obvious influence on the measurement results of fluctuating pressure. Except for the second-order blade frequency fluctuating pressure amplitude at some measuring points, the first-order to forth-order fluctuating pressure amplitude at each point increases with the decrease of gas content. Taking the first order amplitude of 6 # measuring point as an example, the gas content is 14.4% larger than that of the time.

In order to analyze the reason why the fluctuating pressure amplitude increases with the decrease of air content, the main source of the fluctuating pressure on the hull surface should be analyzed first. The fluctuating pressure on hull surface induced by propeller mainly comes from the squeezing effect of propeller blade thickness, the influence of propeller load, the squeezing effect of cavity thickness and the change of cavity volume when the propeller produces cavitation. When the propeller is cavitated, the fluctuating pressure caused by the change of cavitation thickness and volume occupies...
the main component. In the course of rotating, the wake velocity of the blade is different at different angles. When the blade enters the high wake region, the cavitation volume is larger. As the blade leaves the high wake region, the cavitation disappears again. The fluctuation of the unsteady void volume is the main reason for the dramatic increase of the pressure fluctuation of the hull. The fluctuation pressure amplitude on the hull surface is mainly related to the variation of the volume of the propeller void with time. Chemical rate is correlated.

The larger the wake fraction is, the heavier the propeller load is, the larger the cavitation volume on the blade surface. When the blade rotates from the low wake position to the high wake position, the cavitation on the blade surface starts from scratch and grows from small to large. Near the highest wake position, the cavitation volume on the blade surface reaches the maximum, while the blade continues to rotate from the highest wake position to the low wake position. The void volume decreases gradually until the void disappears. As shown in Figure 4., when the blade rotates to a low wake position, no blade cavitation occurs on the back of the blade. When the blade continues to rotate near the 350° angle, the blade back cavitation begins to appear. During the process of continuous rotation from 350° angle, the area and volume of the blade back cavitation gradually increase. When the blade is near the 30° angle position, the cavity volume reaches its maximum, and the blade continues to rotate from the 30° angle position.

The fundamental reason for the influence of air content on the fluctuating pressure is that it affects the cavitation characteristics of propeller. The decrease of air content in water reduces the number of effective air nuclei and enlarges the role of water tension, which mainly affects the initial production of propeller cavitation. Cavitation initiation is closely related to water tension and the number of effective air nuclei. Therefore, with the decrease of the number of gas nuclei, the number of effective gas nuclei decreases, and the effect of water tension increases, which will delay the occurrence of blade cavitation.

Therefore, when the air content decreases, the minimum value of the blade back cavity volume remains zero, the maximum value remains basically unchanged, and the change amplitude of the blade back cavity volume remains basically unchanged. However, the time from the minimum to the maximum value of the blade back cavity becomes shorter, that is, the change rate of the cavity volume increases with time, while the fluctuating pressure amplitude mainly changes with the bubble volume. The fluctuating pressure amplitude increases with the change rate of time, which is the main reason why the fluctuating pressure amplitude increases with the decrease of gas content.

![Figure 4](a) first order  (b) second order  (c) third order  (d) forth order

Figure 4. Comparisons of fluctuating pressure amplitudes of different hulls with different gas content.
3.3. Setting of Gas Content in Model Test

For viscous fluids, the cavitation nucleus in water can be regarded as one of the defects, which will lead to the decrease of viscous force. Therefore, the concentration of cavitation nucleus has an important impact on the water tension. The larger the gas content, the more the number of cavitation nuclei, the smaller the water tension effect. In addition, according to the knowledge of viscous fluid mechanics, the effect of viscous force is related to Reynolds number. The higher the Reynolds number, the smaller the effect of tension. Because the Reynolds number of real ship propeller is often much higher than that of model propeller, in order to minimize the scale effect, the test should be carried out at high Reynolds number and high velocity, and the content of cavitation nucleus should be increased by increasing the dissolved amount of air.

4. Summary

In large circulating flume, the cavitation observation and pulsating pressure measurement experiments of propeller behind ship were carried out. The wake was simulated by full-appendage proportional ship model. The cavitation of propeller was observed while the pulsating pressure was measured. The effect of different air content in water on the pulsating pressure induced by propeller on ship hull surface was studied.

Under the same test conditions and different air content in water, the measurement results of fluctuating pressure are obviously different, and the amplitude of fluctuating pressure increases with the decrease of air content. The main reason is that the decrease of air content in water reduces the number of effective gas nuclei and increases the effect of water tension, which delays the occurrence of blade cavitation, while the influence of air content on the full development of cavitation is small. When the air content decreases, the change amplitude of the void volume basically remains unchanged, but the time from the minimum to the maximum of the back blade void becomes shorter, that is, the change rate of the void volume increases with time, and the fluctuating pressure amplitude increases accordingly. This is the main reason why the fluctuating pressure amplitude increases when the air content decreases.

It is suggested that in the future, in order to minimize the scale effect, the model test of ship hull fluctuating pressure induced by cavitating propeller should be carried out at high Reynolds number and high flow rate, and the content of cavitation nucleus should be increased by increasing the dissolved amount of air.

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