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Measurement of Cavitation-Induced Pressure Fluctuation in a Large Cavitation Tunnel

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대형 공동 수조에서의 변동 압력 계측

°나윤철, 강관형, 김영기, 이무열

Key word : cavitation-induced fluctuating pressure, uncertainty analysis, thrust coefficient, cavitation number

ABSTRACT

The cavitation-induced fluctuating pressure of the container ship named "Sydney Express" is measured in Samsung Large Cavitation Tunnel(SCAT). In the measurements, a complete ship model is employed. The effects of thrust coefficient and cavitation number on cavity pattern and cavitation-induced fluctuating pressure were investigated experimentally. It is demonstrated that the fluctuating pressure coefficient is very sensitive to the cavitation number. The results of cavitation and pressure fluctuations are compared with those of ITTC and HSVA, which shows fairly good agreement. It is exhibited that the removal of rudder can significantly change the loading condition of a propeller, and can reduce the fluctuating pressure coefficient almost by half.

1. Introduction

The cavitation of marine propeller could induce the erosion of propeller blades, and becomes a main source of noise and hull vibration. Even though a propeller is designed to meet the respective criterion regarding such harmful effects of cavitation, the model test is necessary to verify the cavitation performance of a designed propeller.

Since a propeller operates behind a ship, its performance is strongly influenced by the wake of the ship. That is, due to the non-uniform inflow, a propeller blade experiences a significant change in inflow speed during one revolution, both in radial and circumferential directions. This results in the large variation of angle of attack of the blade section. Such variation in angle of attack causes the temporal variation in the extent of cavitation, which in turn produces the pressure fluctuation on the adjacent hull surface.

For the appropriate confirmation of the cavitation performance of a propeller, therefore, the simulation of ship's wake becomes very important. In a small cavitation tunnel, the wake is usually simulated by using a wire mesh. On the other hand, it is most desirable if a complete ship model can be used for the wake simulation. Recently, Samsung Cavitation Tunnel(SCAT) was built not only for the cavitation test of marine propulsor but also to assist the fundamental hydrodynamic researches. The tunnel has large test section and it is designed to employ a complete ship model so that measurements can be performed under the similar conditions to the full-scale situations.

There are lots of factors which can affect the cavitation and cavitation-induced fluctuating pressure in a model test. Even the facility itself becomes a factor in the measurement of the fluctuating pressure. Since the 16th ITTC(International Towing Tank Conference) meeting[1], a great deal of efforts has been devoted for the comparative study on the measurement of the cavitation-induced fluctuating pressure. Since then, the container ship named

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Samsung Heavy Industries, Samsung Ship Model Basin

"Sydney Express", which has a full-scale data on its wake and fluctuating pressure, has been widely adopted to determine the characteristic of world-wide facilities[2-10]

This ship is used to determine the characteristics of SCAT, in measuring the pressure fluctuation, by comparing the results with those obtained in other facilities. In this paper, the results obtained up to now is presented and several important matters associated with the cavitation test in a large cavitation tunnel is discussed.

2. Experimental Equipments and Test Procedure

The SCAT as a technologically advanced facility for hydrodynamic, cavitation and hydroacoustic investigations is designed for testing complete hull and propulsor systems such as surface ship, submarine, torpedoes and etc. The SCAT has two test sections. One, which is denominated as No. 1 test section, has 1.2 m in width, 1.2 m in depth and 6.0 m in length. Another, which is denominated as No. 2 test section, has 3.0 m in width, 1.4 m in depth, 12.0 m length, respectively. The maximum velocities in No. 1 and No. 2 test section are 28 m/s and 12 m/s, respectively. The deviation of the mean velocity in the test section is less than 0.5 %. The maximum power for the impeller shaft is 2,600 kW.

The hull model was manufactured by wood and Table 1 shows the principal dimensions of the hull. The model propeller, the designation number of SP079 was manufactured by aluminum alloy and the principal dimensions are shown in Table 2. The experimental conditions are described by the following non-dimensionalized numbers:

Table 1. The Principal Dimensions of Hull

Item	Value
LBP (m)	210.0
LWL (m)	215.8
Breadth (m)	30.5
Design Draught (m)	11.0
Block Coefficient C_B	0.616
Displacement, ∇ (m3)	43457.
DHP (Ps)	32454.
Speed (kts)	22.0

$$J = \frac{V}{nD}, \tag{1}$$

$$K_T = \frac{T}{\rho n^2 D^4}, \tag{2}$$

$$\sigma_n = \frac{P_\infty - P_v}{\frac{1}{2}\rho n^2 D^2}, \tag{3}$$

where, V is the flow speed, n the propeller revolution rates per second, D the diameter of propeller, T the thrust of propeller, ρ the density of water, and P_v the vapour pressure, respectively. The pressure coefficient, $Kp = \Delta P/(\rho n^2 D^2)$, can be expressed as follows

$$K_P = f(K_T, \sigma_n ;\ G/D, R_n, F_n), \tag{4}$$

where, G means the geometrical parameter of a propeller, R_n is Reynolds number and F_n is the Froude number. It is impossible to satisfy the similarity of all of the parameters, simultaneously. Moreover, it is well known from the previous investigations that the effect of Reynolds number and the Froude number on the performance of propeller becomes negligible beyond a certain critical limit. Therefore, in the present investigation, it is assumed that the effect of Reynolds number and the Froude number on the pressure fluctuation is negligible.

If the model propeller is not changed during a model test, the effect of G can also be neglected. Therefore, the K_P can be re-written as follows

$$K_P = f(K_T, \sigma_n). \tag{5}$$

Table 2. The Principal Dimensions of Propeller

Item	Value
Diameter (m)	0.250
Scale Ratio	28.00
Hub Ratio	0.167
P/D at 0.7r	0.970
P/D at Tip	0.954
P/D(Mean)	0.935
Ae/Ao	0.776
Number of Blades	5

Thus, the pressure coefficient is regarded as dependent only on the thrust coefficient and cavitation number.

In a small cavitation tunnel, the rudder is usually not installed. However, the thrust can be affected by the existence of rudder. In order to demonstrate the effect of rudder on thrust, the thrusts in the bollard condition were measured in the cases of with and without rudder. Fig. 1 shows the measured thrust in bollard conditions with and without rudder, respectively. The difference in thrust at each propeller revolutions is about 7%. This means the thrust increase is caused by the existence of rudder.

The pressure transducers are located on the hull surface from the center of propeller plane as shown in Fig. 2. The distance between two adjacent transducers is 30 mm. The specifications of pressure transducer are shown in Table 3.

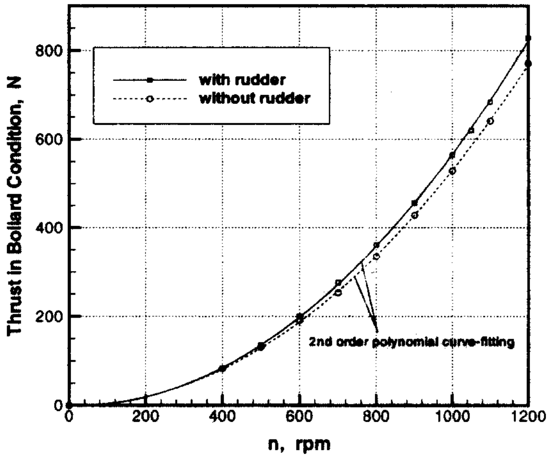


Fig. 1 Effect of the Removal Rudder on Thrust

Table 3 Specification of Pressure Transducer

Item	Contents
Manufacturer	ST(Japan)
Model Name	PF8-2Ⓢ
Sensor Type	Strain Gage
Maximum Range	2kg/cm2G
Water Resistance	Yes
Resonance Frequency	19 kHz
Temp. Sensitivity	±0.05% F.S./℃
Drift Sensitivity	Max. 0.5% F.S./month

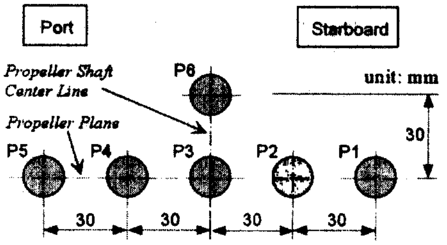


Fig. 2 The Position of Pressure Transducers

3. Results and Discussion

Various tests were performed under the different test conditions as described in Table 4. For the comparison of the pressure fluctuation, the experimental condition is chosen to be identical to those performed in HYKAT. The thrust coefficient in Table 4 was set based on the propeller open water test in towing tank. In addition, the repeated tests were carried out to confirm the repeatability of measurements.

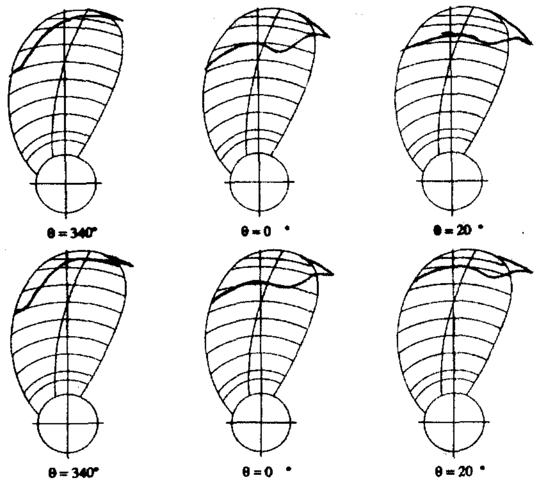
Table 4 Test Conditions of SCAT

Test Name	F-1	F-2	F-3	F-4	F-5	F-6
Impeller rpm	80.0	85.0	80.0	80.3	80.0	78.4 80.0 82.5
K_T	0.175	0.175	0.175	0.175	0.175	0.163 0.175 0.185
Propeller rpm	1740	1800	1750	1900	1755	1755
Tunnel Press.(bar)	0.600	0.64	0.60	0.606 ~ 1.200	0.55 ~ 1.20	0.595 0.606 0.620
Rudder Exist.	○	○		×	○	
Water Temp.(℃)	23.3	24.0		24.4	27.4	
Air Contents(%)	77.0	78.6		64.0	61.0	
Atm. Press.(bar)	1.017	1.019		1.012	1.019	
Date	10-06	10-07		10-11	10-12	

3.1 Cavitation Observation

Fig. 3 shows the comparison of cavitation pattern on propeller blades for different blade angles. The cavitation sketches were obtained at 340, 0 and 20 degree from the propeller top position. Each result of cavitation pattern is similar to the full scale condition except the angular position of 20 degree. The cavitation sketches for each test show slight differences in cavity extent and intermittency. It is conjectured that these differences may be caused by the difference in experimental conditions such as water temperature, tunnel pressure, flow speed, air content and so on.

Full Scale



SSMB

K_T = 0.175, σ_n = 1.826

Fig. 3 Comparison of Cavitation Sketches

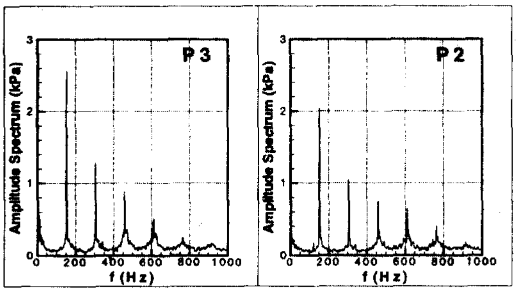


Fig. 4 The Spectral Analysis of Pressure Fluctuations

3.2 Measurement of Pressure Fluctuation

The pressure fluctuations were measured for several experimental conditions. The experimental results are described by using the pressure coefficient, K_P. The amplitude spectrum of a pressure signal can be estimated by using the Fast Fourier Transform method. The amplitude spectrum at the measured positions of P2 and P3 are shown in Fig. 4.

3.3 Effects of Cavitation Number

The cavitation-induced pressure fluctuations are governed by the thrust coefficient and cavitation number that are dependent on the rotational speed of propeller and the tunnel pressure. The sensitivity coefficient of K_T and σ_n can be expressed by the summation of the partial derivatives of dependent variables.

$$\begin{aligned} S_{K_P,P_T} &= \frac{\partial K_P}{\partial K_T}\frac{\partial K_T}{\partial P_T} + \frac{\partial K_P}{\partial \sigma_n}\frac{\partial \sigma_n}{\partial P_T} \\ &= \frac{\partial K_P}{\partial \sigma_n}\frac{\partial \sigma_n}{\partial P_T} \end{aligned} \tag{6}$$

To obtain the sensitivity coefficient empirically, the pressure fluctuations are measured as changing the tunnel pressure while the thrust coefficient(K_T = 0.175) is kept constant. The other test conditions are kept identical except the tunnel pressure in varying the cavitation number. Fig. 5 shows the variation of pressure coefficients with the cavitation number at the position of P2.

Table 5 Comparison of Pressure Coefficient

Blade Freq.	K_{P5}	K_{P10}	K_{P15}
Full Scale	0.025	0.016	0.008
SCAT model	0.032	0.017	0.014
HSVA model	0.035	0.024	0.013
SRI model	0.042	0.023	0.024
SRI mesh	0.035	0.020	0.015
SRC mesh	0.061	0.025	0.030
MHI mesh	0.052	0.028	0.026
UT mesh	0.045	0.042	0.046
IHI mesh	0.037	0.022	0.016

In the figure, it is shown that the pressure coefficients are constant in the range of $\sigma_n > 2.5$. On the other hand, the pressure coefficients are rapidly increased in the range of $\sigma_n < 2.5$. In the range of $\sigma_n > 2.5$, the tip vortex cavitation does not contribute to the pressure fluctuation even though it develops at blade tips. Such an abrupt increase in the pressure coefficient when $\sigma_n < 2.5$ seems to be concerned with the inception of cavitation on propeller blades. The sensitivity coefficient at the cavitation number of 1.826, as shown in Fig. 5, is about 0.05. This value is more or less dependent on the measured positions. Based on this value, when the error in setting the tunnel pressure is 1 kPa, the error in pressure coefficient, ε_{K_P}, becomes

$$\begin{aligned} \varepsilon_{K_P} &\simeq \frac{\partial K_P}{\partial \sigma_n}\frac{\partial \sigma_n}{\partial P_T} \times \varepsilon_{P_T} \\ &\simeq S_{\sigma_n, K_P} S_{P_T, \sigma_n} \times \varepsilon_{P_T} \\ &= 0.05 \times \left(\frac{1}{\rho n^2 D^2 / 2} \right) \times \varepsilon_{P_T} \\ &\approx 0.002 \end{aligned} \tag{7}$$

The resulting error in the pressure coefficient is about 0.002. In some cases, the error in setting the tunnel pressure becomes 3 kPa. Therefore, the tunnel pressure is very sensitive parameter affecting the magnitude of the pressure fluctuation.

3.4 Effects of Thrust Coefficient

The thrust coefficient is one of the most important parameter affecting the cavitation pattern and pressure fluctuations. To quantify the measurement uncertainty of the pressure fluctuation caused by the uncorrect setting of the thrust coefficient, the sensitivity of the fluctuating pressure on the thrust coefficient is obtained experimentally.

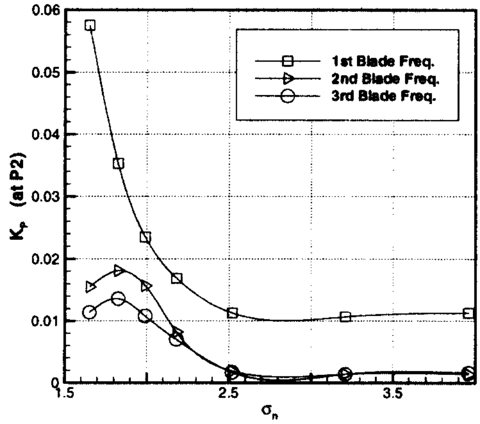


Fig. 5 The Effect of Cavitation Number on Pressure Coefficients at P2

For this purpose, the experiment is performed for three different thrust coefficients at an identical cavitation number, 1.826. To eliminate the effect of Reynolds number which can be resulted from the change in the rotational speed of propeller, the tunnel speed is controlled to change the thrust coefficient while the rotational speed of propeller rate is kept constant. In Fig. 6, the resulting pressure coefficient is shown, in which the thrust coefficient is changed about ±5 %, with respect to the standard condition of $K_T = 0.184$. It is considered that the error in setting the thrust coefficient is less than 5 % in general. It is shown that the fluctuating pressure coefficient is almost invariant to such an extent of change in the thrust coefficient.

Although it is conjectured that further increase of thrust coefficient may increase the fluctuating pressure in some degree, the fluctuating pressure is insensitive to such an amount of change in the thrust coefficient.

3.5 Effects of Rudder Existence

Fig. 7 shows the resulting pressure coefficient in the condition that the rudder is removed from the hull. The pressure coefficient is decreased about 50 % even if the thrust coefficient is identical. It means that the rudder is also an important experimental parameter in a large cavitation tunnel.

4. Conclusions

From the foregoing investigation, the following conclusions are obtained:

1) The measured pressure coefficients show fairly good agreement with the results of full scale. Also the cavitation patterns are similar to those of full scale and other facilities,

2) The sensitivity of the pressure fluctuations on the thrust coefficient and the cavitation number is obtained experimentally. It is demonstrated that the magnitude of fluctuating pressure of the Sydney Express is very sensitive to the cavitation number,

3) It is shown that the removal of rudder can significantly change the loading condition on the propeller blades. Moreover, it is exhibited that the

fluctuating pressure can be decreased by half when the rudder is removed. The influence of rudder on the cavity pattern and the fluctuating pressure will be investigated in the later investigations.

5. Acknowledgement

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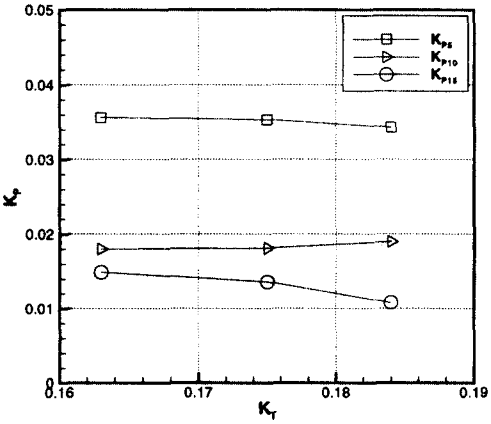

Fig. 6 The Effect of Thrust Coefficient on Pressure Coefficients at P2

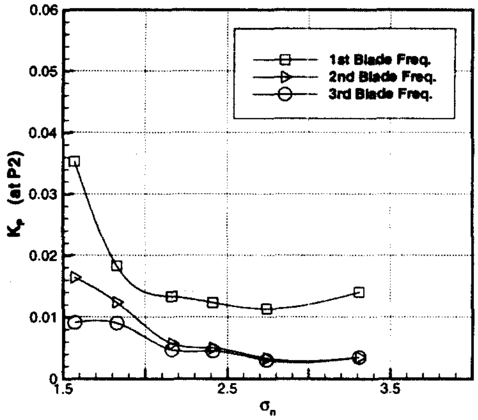

Fig. 7 The Effect of Rudder Removal on Pressure Coefficients at P2

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