Investigation into the Propeller Cavitation in Oblique Flow

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Summary

In order to serve the improvement of performance prediction of high-speed vessels, theoretical and experimental investigations into the propeller cavitation in oblique flow condition have been carried out.

A series of supercavitating propellers were tested in cavitating oblique flow condition. The test results show that in non-cavitating condition the variation of propeller characteristics due to the shaft inclination is related closely with pitch ratio but little with expanded area ratio, while in cavitating condition the variation decreases with cavitation number and the effect of geometrical particulars of propeller is not so clear as in non-cavitating condition.

In view of the analysis and the application of the test results, a quasi-steady method was developed to calculate the propeller characteristics in oblique flow condition from those in axial flow condition. The comparison of the experimental and the calculated results showed pretty good coincidence.

1. Introduction

There have been carried out many cavitation tests in order to provide propeller design data and to serve performance prediction of high-speed vessels. It should be noted, however, that most of the propellers of high-speed vessels are operated in oblique flow conditions. In the case of non-cavitating propellers, the effect of oblique flow on the performance of propeller has been studied by several investigators treating the problem theoretically(1) and experimentally(2)(3), while in the case of cavitating propellers there are at present no published data or available informations on this effect. It is highly desirable, therefore, to carry out propeller cavitation tests in oblique flow condition and to study the effect of oblique flow on the performance of propeller, from which we should be able to get a more reliable model-ship correlation of high-speed vessels and to predict better the cavitation pattern relating to the cavitation erosion on the propeller blades.

In Mitsubishi Experimental Tank (Nagasaki) cavitation tests in oblique flow condition were carried out on a series of supercavitating propellers consisting of the variation of pitch ratio and expanded area ratio. The test results show that in non-cavitating condition the variation of propeller characteristics due to the shaft inclination is related closely with pitch ratio but little with expanded area ratio, while in cavitating condition the variation decreases with cavitation number and the effect of geometrical particulars of propeller is not so clear as in non-cavitating condition.

In view of the analysis and the application of the test results, a quasi-steady method of calculation was developed and the propeller characteristics were calculated for oblique flow conditions in cavitating

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as well as non-cavitating conditions by the use of axial flow characteristics. The comparison of such calculations and the experimental results showed pretty good coincidence.

2. Test Scheme

2.1 Propeller models

Five propeller models with Tulin's super-cavitating blade section \(^{(4)}\) were tested in the present study. As described schematically in Fig. 1, the particulars of the propellers were varied systematically on the basis of P. 1329, which is a scale-model of the propellers of a high-speed boat.

P. 1369, P. 1329 and P. 1370 constitute a series of pitch ratio, while P. 1329, P. 1371 and P. 1372 constitute a series of expanded area ratio.

The particulars of the propeller models are presented in Table 1 and the drawing of P. 1329 is shown in Fig. 2.

![Fig. 1. Particulars of Propeller Models](image-url)

Table 1. Propeller Particulars

<table>
<thead>
<tr>
<th>Propeller No.</th>
<th>1329</th>
<th>1369</th>
<th>1370</th>
<th>1371</th>
<th>1372</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>230.00</td>
<td>230.00</td>
<td>230.00</td>
<td>230.00</td>
<td>230.00</td>
</tr>
<tr>
<td>Pitch (0.7R) (mm)</td>
<td>265.71</td>
<td>230.00</td>
<td>368.00</td>
<td>295.71</td>
<td>295.71</td>
</tr>
<tr>
<td>Pitch Ratio (0.7R)</td>
<td>1.286</td>
<td>1.000</td>
<td>1.600</td>
<td>1.286</td>
<td>1.286</td>
</tr>
<tr>
<td>Disc Area (m²)</td>
<td>0.04155</td>
<td>0.04155</td>
<td>0.04155</td>
<td>0.04155</td>
<td>0.04155</td>
</tr>
<tr>
<td>Expanded Area (m²)</td>
<td>0.02572</td>
<td>0.02572</td>
<td>0.02572</td>
<td>0.02336</td>
<td>0.01708</td>
</tr>
<tr>
<td>Expanded Area/Disc Area</td>
<td>0.6190</td>
<td>0.6190</td>
<td>0.6190</td>
<td>0.5141</td>
<td>0.4110</td>
</tr>
<tr>
<td>Boss Ratio</td>
<td>0.1819</td>
<td>0.1819</td>
<td>0.1819</td>
<td>0.1819</td>
<td>0.1819</td>
</tr>
<tr>
<td>Thick-Chord Ratio at 0.7R (%)</td>
<td>6.118</td>
<td>6.118</td>
<td>6.118</td>
<td>6.516</td>
<td>7.088</td>
</tr>
<tr>
<td>Number of Blades</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
2.2 Test Procedure

(a) Cavitation tests

Cavitation tests in oblique flow condition were carried out with a special attachment as shown in Fig. 3. A propeller shaft (900mm long and 38mm in diameter) was connected to the ordinary propeller shaft by means of a couple of universal joints, and the downstream end of the shaft was supported by a vertical strut, which enabled the variation of the inclination of the shaft.

Thrust and torque were measured by the propeller dynamometer for ordinary cavitation tests so that the measured thrust was in the direction of general flow.

Photographs were taken to record the cavitation pattern of both starboard and portside.

The test conditions were as follows:

Inclination of the shaft: $\theta$

$\theta = 0^\circ$, $4^\circ$ and $8^\circ$

Advance ratio: $J = \frac{v}{nD}$
\( J = 0.7 - 1.1 \) for P. 1329, P. 1371 and P. 1372
\( J = 0.5 - 0.9 \) for P. 1369
\( J = 0.9 - 1.5 \) for P. 1370
each covering the range 10–45% in slip ratio.

Cavitation number: \( \sigma_n \)
\( \sigma_n = 0.3 - 1.0 \) and atmospheric condition
for P. 1329, P. 1369, P. 1371 and P. 1372
\( \sigma_n = 0.5 - 1.5 \) and atmospheric condition
for P. 1370

**Open-water tests**

In order to obtain a reasonable method of correction to the test results in tunnel for the tunnel wall effect and for the rotational wake of the rotating propeller shaft upstream of propeller, open-water test in oblique flow condition were carried out on all the models. A special propeller dynamometer of a strain gauge type was developed and it was so arranged that the propeller shaft could be inclined in the vertical plane. The immersion of the propeller was kept about one propeller diameter for all the angles of shaft inclination. It should be noted that the thrust measured by this dynamometer is in the direction of the propeller shaft, while in the cavitation tunnel it is in the direction of general flow.

**2.3 Correction to the measured results in tunnel**

In the axial flow condition, in which the direction of flow coincides with that of the propeller axis, the test results in tunnel under atmospheric pressure agree well with the open-water test results, when compared at the same Reynolds number. In oblique flow condition, however, both results do not agree with one another; \( K_T \) and \( K_Q \) in tunnel decrease with shaft inclination, while those in open-water* increase with shaft inclination. Such discrepancy was found by several investigations to be due to the

* For the comparison, the thrust measured in open-water (in the direction of propeller shaft) was corrected to the direction of general flow.
rotational wake of the rotating propeller shaft in the cavitation tunnel. The rotational wake was measured by a two-hole pressure probe under atmospheric pressure, and the results are shown in Fig. 5. The effective correction for the revolution of propeller, $J_n$ can be obtained from the results of such measurement. Application of the correction $J_n$ to the test results in tunnel shows a fairly good agreement with open-water test results.

The measurement of the rotational wake of the propeller shaft was made, however, at only the four angular positions and more extensive measurements will be necessary to obtain the rigorous correction factor $J_n/n$ for wider range of angle. At present, therefore, the correction factor $J_n/n$ was obtained by the comparison of the propeller characteristics in open-water and in tunnel, viz. $J_n/n$ was obtained in such a way that $K_Q - J$ curve in tunnel should be connected with $K_Q - J$ curve in open-water (after the correction for Reynolds number) satisfying the relations,

$$K_Q(\text{open-water}) = K_Q(\text{tunnel}) \left(1 + \frac{J_n}{n}\right)^2 \quad (1)$$

$$J(\text{open-water}) = J(\text{tunnel}) \left(1 + \frac{J_n}{n}\right) \quad (2)$$

For cavitating conditions this correction factor was equally applied, because a significant variation of rotational wake is not expected by the change of the static pressure in tunnel.

3 Test Results

3.1 Presentation of the test results

The measured thrust and torque were reduced to non-dimensional coefficients $K_T^\theta$ and $K_Q^\theta$,

$$K_T^\theta = \frac{T}{\rho n^2 D^4}$$
$$K_Q^\theta = \frac{Q}{\rho n^2 D^5}$$
$$J_n = \frac{n}{nD}$$

These coefficients were corrected for the rotational wake of the rotating propeller shaft by the correction factor $J_n/n$.

$$K_T = K_T^\theta \left(1 + \frac{J_n}{n}\right)^2 \quad (3)$$
$$K_Q = K_Q^\theta \left(1 + \frac{J_n}{n}\right)^2 \quad (4)$$
$$J_n = J^\theta \left(1 + \frac{J_n}{n}\right) \quad (5)$$

In Figs. 6-15 the corrected $K_T$ and $K_Q$ are plotted to the base of the corrected $J_n$. Although the correction of the rotational speed affects also the cavitation number $\sigma_n = \frac{p_s - e}{\frac{1}{2} \rho (nD)^2}$ by the factor $\left(1 + \frac{J_n}{n}\right)^2$, the parameter $\sigma_n$ in these figures were not corrected for the sake of simplicity and the measured points
were plotted directly instead of cross-faired curves of $K_T$ and $K_Q$ with respect to $\sigma_n$ and $J$. *

* The cavitation tests were carried out with constant revolution of the propeller and constant static pressure, viz. constant $\sigma_n$, for each test. The correction of the cavitation number $\sigma_n$ for the rotational speed therefore results in the variation of $\sigma_n$ for each test and the presentation of the test results with the corrected $\sigma_n$ as parameter requires the cross-faring with respect to $\sigma_n$ and $J$. 
Though the correlation analysis of the trial data of the high-speed boat is not presented in this report due to the limitation of space, it was shown that the model-ship correlation was improved by the use of propeller characteristics obtained in oblique flow condition.
3.2 Comparison with a quasi-steady calculation

In order to serve the analysis and the application of the test results, a simple quasi-steady method was developed to calculate the effect of the oblique flow\(^{35}\). The quasi-steady method is based on the assumption that thrust (in the direction of propeller shaft) and torque in oblique flow condition (angle of shaft inclination $\theta$) may be approximated by the circumferential mean value of the local thrust and torque, which are calculated on the basis of the resultant inflow velocity at $0.7R$ in axial flow condition, viz.

\[
K_T' = \frac{1}{2\pi} \int_{0}^{2\pi} K_{T_0}(u/u_0)^2 d\psi
\]

\[
K_Q = \frac{1}{2\pi} \int_{0}^{2\pi} K_{Q_0}(u/u_0)^2 d\psi
\]

where $\psi$ is the angular position of blade (0° at the top)

\[
J = 0.7\pi \tan \beta = \frac{J_0 \cos \theta}{u/u_0}
\]

\[
u/u_0 = 1 + \frac{1}{0.7\pi} \sin \psi \sin \theta
\]

\[
\sigma_n = \sigma_{n_0}(u_0/u)^2
\]

and the suffix $o$ refers to the axial flow condition.

Hence $K_T'$ and $K_Q$ can be calculated by integrating $K_{T_0}$ and $K_{Q_0}$ corresponding to $[J(\theta, \psi), \sigma_n(\theta, \psi)]$.

Thrust in the direction of general flow is obtained by assuming the side force is equal to $0.7R \sin \psi$ and

\[
K_T = K_T' \cos \theta - \frac{1}{2\pi} \int_{0}^{2\pi} K_{Q_0} \sin \theta \frac{\sin \psi}{0.35} (u/u_0)^2 d\psi
\]

The variation of $K_T'$ and $K_Q$ due to the effect of oblique flow can be expressed by an even function of the shaft inclination $\theta$. For a small angle of shaft inclination, $K_T'$ and $K_Q$ are approximated by

\[
K_T' = K_{T_0} + A\theta^2
\]

\[
K_Q = K_{Q_0} + B\theta^2
\]

In non-cavitating condition, $K_T'$ and $K_Q$ are not affected by the variation of local cavitation number and they are nearly linear with respect to advance coefficient $J$. In such a case, the factors $A$ and $B$ can be written as\(^{35}\)

\[
A_{cal} = -\frac{1}{2} \frac{\partial K_{T_0}}{\partial J} J + \frac{1}{2} C_{to} (J/0.7\pi)^2
\]

\[
B_{cal} = -\frac{1}{2} \frac{\partial K_{Q_0}}{\partial J} J + \frac{1}{2} C_{qo} (J/0.7\pi)^2
\]

where $C_{to}$ and $C_{qo}$ show $K_{T_0}$ and $K_{Q_0}$, respectively, as extrapolated linearly to $J=0$.

In Table 2, comparison of the coefficients $A$ and $B$ as obtained by the experiments and the theory is given in terms of the ratios $a$ and $b$

\[
a = A_{exp}/A_{cal}
\]

\[
b = B_{exp}/B_{cal}
\]

where $A_{exp} = (K_T' - K_{T_0})/\theta^2$

\[
A_{exp} = (K_Q - K_{Q_0})/\theta^2
\]

$A_{exp}$ and $B_{exp}$ were obtained from the open-water test results. It is to be noted that $a$ and $b$ are generally larger than unity and $b$ increases with pitch ratio. Further study both on theory and on experiments will be necessary to make clear this discrepancy. If we compare $K_Q$ itself, however, instead of its increment due to the inclination of the shaft, the differences between the measured values and those calculated by the quasi-steady method are about 2% except for $P$. 1370 with the highest pitch ratio ($p=1.6$), for which the difference amounts to $3-5\%$. 
In cavitating condition, the estimation of the propeller characteristics in oblique flow from those in axial flow condition is much more difficult and complicated than in non-cavitating condition. The instantaneous thrust and torque at each angular position of a blade are functions of local cavitation number as well as local advance coefficient. Besides $K_{T0}$ and $K_{Q0}$ versus $J$ curves can no longer be approximated by a linear relation due to thrust and torque breakdown caused by cavitating on the blades. The integrals in eqs. (6) and (7) were therefore performed numerically. In Figs. 16 and 17 the calculated $K_T$ (corrected to the direction of general flow) and $K_Q$ are compared with those measured at $\theta=8^\circ$. The measured $K_Q$'s agree quite well with those calculated by the quasi-steady method except for P. 1370, for which the measured torque is slightly larger than that calculated. As for $K_T$, measured values are slightly smaller than those calculated. In general, however, it may be said that the agreement is pretty good and is within the accuracy of the measurement.

For a propeller blade in oblique flow condition, local advance ratio and cavitation number change with its angular position. It is interesting to compare the cavitation pattern on the blade in oblique flow condition with that in axial flow at the corresponding $J$ and $\sigma_n$. Fig. 18 shows a comparison of

**Table 2. Comparison of experiments and theory in non-cavitating condition**

<table>
<thead>
<tr>
<th>P. No</th>
<th>( p )</th>
<th>( \Delta e/\Delta d )</th>
<th>( a(\theta=8^\circ) )</th>
<th>( b(\theta=8^\circ) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. 1329</td>
<td>1.286</td>
<td>0.619</td>
<td>3.24</td>
<td>1.92</td>
</tr>
<tr>
<td>P. 1369</td>
<td>1.000</td>
<td>0.619</td>
<td>2.07</td>
<td>1.55</td>
</tr>
<tr>
<td>P. 1370</td>
<td>1.600</td>
<td>0.619</td>
<td>1.29</td>
<td>2.34</td>
</tr>
<tr>
<td>P. 1371</td>
<td>1.286</td>
<td>0.514</td>
<td>3.15</td>
<td>1.97</td>
</tr>
<tr>
<td>P. 1372</td>
<td>1.286</td>
<td>0.411</td>
<td>2.28</td>
<td>1.92</td>
</tr>
</tbody>
</table>
the cavitation patterns between oblique flow and axial flow conditions. The sketch in the middle of this figure represents the cavitation pattern in oblique flow conditions ($\theta=8^\circ$, $\varphi=90^\circ$). The local advance ratio $J(\theta, \varphi)$ and the local cavitation number $\sigma_n(\theta, \varphi)$ calculated by (8) and (10) are

$$J=0.93 \text{ and } \sigma_n=0.44$$

Comparing this cavitation pattern with the sketches in axial flow condition (at the corners of this figure) we may say that the propeller blade operates in nearly the same condition as is predicted by the quasi-steady calculation.

### 3.3 Effect of pitch ratio and expanded area ratio

In non-cavitating condition the effect of oblique flow can be expressed, as mentioned above, by the increase of thrust and torque which is in proportion to the square of shaft inclination. From (12), (14) and (16) we obtain,

$$K_T(J, \theta)=K_{T0}-\frac{a}{2} \frac{\partial K_{T0}}{\partial J} J-C_{T0}(J/0.7)^2$$

and similarly from (13), (15) and (17)

$$K_Q(J, \theta)=K_{Q0}-\frac{b}{2} \frac{\partial K_{Q0}}{\partial J} J-C_{Q0}(J/0.7)^2$$

Since a propeller with large pitch ratio operates in general at large advance ratio and the factor $b$ increases with pitch ratio as mentioned above, the increments of $K_T$ and $K_Q$ increase with pitch ratio.

As for expanded area ratio, there is no significant variation of the factors $a$ and $b$. $\frac{\partial K_{T0}}{\partial J}$ and $\frac{\partial K_{Q0}}{\partial J}$ increase slightly with expanded ratio. In non-cavitating condition, therefore, the effect of oblique flow varies little with expanded area ratio.

In cavitating condition, such a simplified analysis is not suitable for the discussion on the effect of pitch ratio and expanded area ratio. In general the increments of $K_Q$ due to shaft inclination decreases with the variation of $\frac{\partial K_{Q0}}{\partial J}$ with cavitation number. In the range of $\sigma_n<0.5$ and $s>0.3$ (the design point of supercavitating propellers usually lies in this range) no appreciable variation in $K_Q$ is found with the angle of shaft inclination except for P. 1370, which has the highest pitch ratio ($p=1.6$) among the propellers tested, $K_Q$ increases still at $\sigma_n=0.5$ with the angle of shaft inclination.

On the other hand, $K_T$ (measured in the direction of general flow) decreases in oblique flow cavitating condition in contrast with non-cavitating condition. The decrement of $K_T$ increases slightly with pitch ratio, while expanded area ratio does not have a definite influence on the decrease of $K_T$ due to shaft inclination.

### 4. Conclusions

The results of the above-mentioned investigations may be summarized as follows:

(a) In non-cavitating condition, the increments of $K_T$ and $K_Q$ due to shaft inclination increase with pitch ratio, but little with expanded area ratio. In cavitating condition, however, the effect of shaft inclination is not in such a simple relation with the geometry of a propeller. In general.
it was observed that the increment of $K_T$ decreases with the decrease of cavitation number and that $K_T$ decreases in oblique flow in contrast with non-cavitating condition.

(b) Quasi-steady calculation can be used to predict the propeller characteristics in oblique flow in cavitating condition as well as in non-cavitating condition.

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References