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https://doi.org/10.5109/7165068

出版情報：Reports of Research Institute for Applied Mechanics. 13 (46), pp.79-95, 1965. 九州大学応用力学研究所
バージョン：
権利関係：

Reports of Research Institute for Applied Mechanics
Vol. XIII, No. 46, 1965

ON THE MEASUREMENTS OF PROPELLER SURFACE FORCE OF THE SELF-PROPELLED MODEL OF A TANKER**

By T. KUMAI* and Y. SAKURADA*

Abstract The paper provides the experimental studies on the measurements of the propeller surface force of a self-propelled model that excites hull vibrations, especially in the horizontal direction. The partial surface forces were calculated from the measured strains of the reeds. Furthermore the total surfase force exciting hull vibration was calculated from the above partial surface forces, considering the phase difference of the vibratory forces.

Introduction

The vibration of ships excited by the hydrodynamic action of the propeller has become considerably important in the design of modern cargo ships and tankers. The effect of tip clearance of the propeller on the vertical vibrations have been observed and theoretically investigated by several researchers. There are, however, very few works as far as the authors know, on the axial clearance effect of the propeller on the horizontal exciting force of the single screw ships except Prof. Lewis' recent experimental investigation[1], in which he measured force on the half strut forward and force on the half rudder induced by the propeller. In connection with the above Lewis' experiments the authors believe it is necessary to investigate into the surface force around the screw aperture of a model ship.

This paper provides the experimental studies on the measurements of the propeller surface force of a self-propelled model that excites hull vibrations, especially in the horizontal direction. The model ship tested is 1/40 scale of 60,000 ton d.w. tanker, which one of the writers and his coleagues previously measured on her propeller bearing forces in 1961[2]. The present tests have been carried out at the new experimental tank in our institute.

The surface force along the boundary of the screw aperture of the model ship was measured at twelve points by the strain measurements of reeds which had been specially devised in our laboratory. The axial clearance and the rudder clearance are changed by moving axially the propeller and the rudder respectively for given

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** The paper was read before the spring meeting of Western Society of Naval Architects of Japan on May 1965, and also published on *European Shipbuilding* No. 3 1965.

stern frame of the ordinary U type. The effects of the number of blades of the propeller, the advance ratio, and the rudder clearance as well as the axial clearance on the surface force of the upper and lower parts of the stern frame and the rudder were observed. These partial surface forces were calculated from the measured strains of the reeds. Furthermore the total surface force exciting hull vibration was calculated from the above partial surface forces, considering the phase difference of the vibratory forces. The results were compared with some of the existing works[1)-6)].

Table 1 Particulars of model ship.

$L \times B \times D$ (cm)	500×70×50
d_{mean} (cm)	27
Displacement (full load) (kg)	750
C_b	0.794
Speed (m/sec)	1.40
Shaft revolution (rev/sec)	13.0
Thrust (kg)	2.43
Torque (kg-cm)	7.10

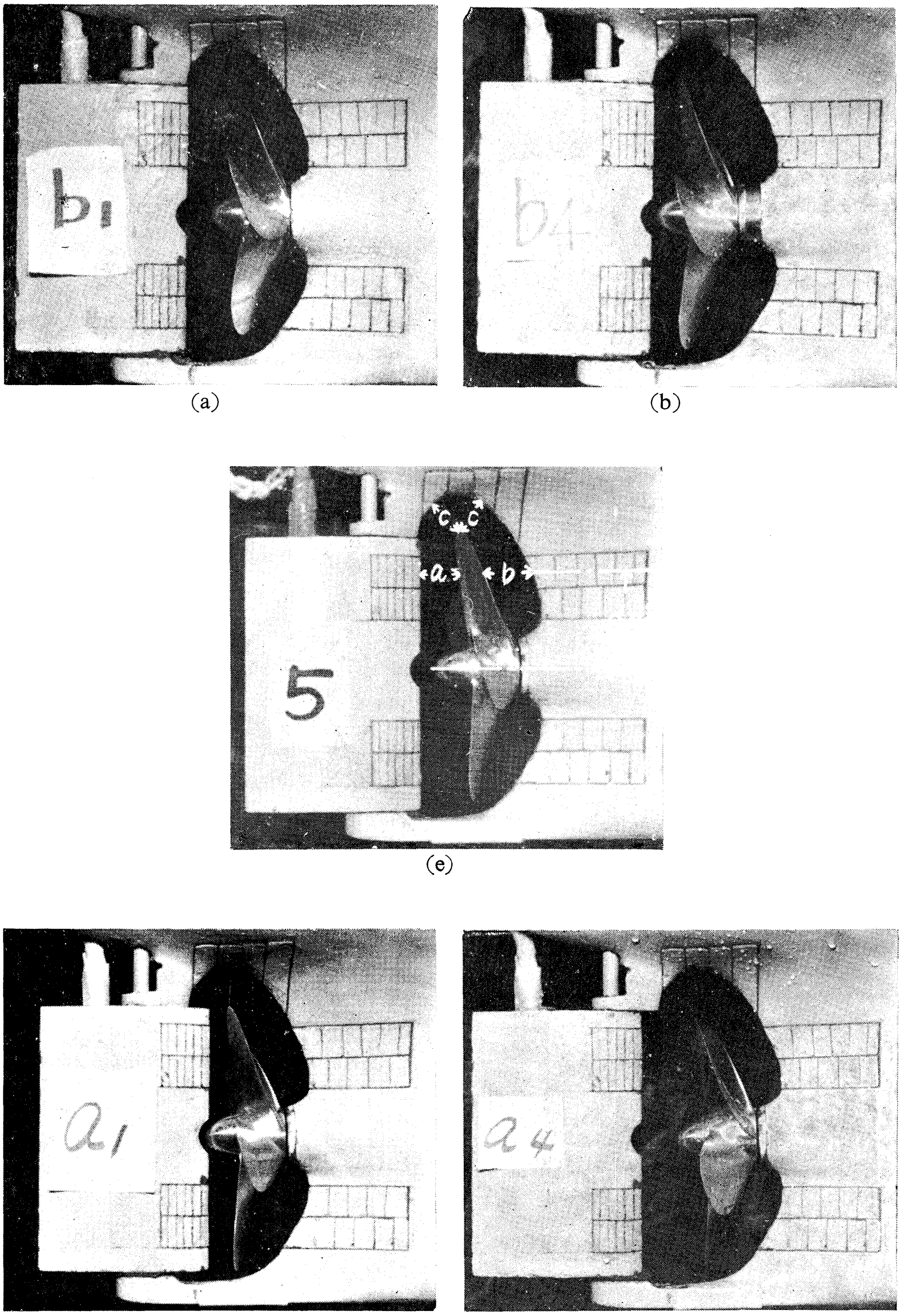
Table 2 Particulars of model propellers

Type: Troost				
Number of blades	3	4	5	6
Diam. (cm)	17.05	17.05	17.05	17.05
Pitch ratio	0.728	0.696	0.670	0.648
Devel. area ratio	0.44	0.56	0.66	0.72
Blade thickness ratio	0.05	0.05	0.05	0.05
Boss ratio	0.2	0.2	0.2	0.2
Angle of rake (degree)	10	10	10	10
Shaft revolution (rev/sec)	13.0	12.8	13.0	13.2
Thrust (kg)	2.11	2.03	2.43	2.18
Torque (kg-cm)	6.55	6.35	7.10	6.35

Table 3 Various clearances of model ship with 5-bladed propeller.

Axial clearance	Rudder clearance	Tip clearance	
b/D	a/D	c/D	
		Fore	Aft.
0.147	0.0663	0.114	0.154
0.179*	0.111	0.138*	0.136
0.197	0.141*	0.151	0.123
0.226	0.176	0.155	0.098
	0.214		

* Normal position



(a) (b) (e) (c) (d)

Fig. 1 Standard and extreme positions of propeller and rudder.

1. Measurement of surface force

1. 1 Experimental apparatus and method of measurements

A self-propelled model ship is made by steel plate in a parallel body, and the main part of the stern including screw aperture is made by cast duralumin. The particulars of the model ship is shown in Table 1. The four kinds of propellers with three to six blades respectively were tested for the effect of number of blades in the standard condition of the advance ratio and screw aperture. The particulars of the propellers used in this experiments are shown in Table 2.

Table 4 Advance coefficients of model with 5-bladed propeller.

V (m/sec)	n (rev/sec)	J
1.20	10.7	0.395
1.30	11.8	0.387
1.40*	13.0	0.379
1.45	13.7	0.373

* Design speed

The axial clearance of the propeller was changed by removing propeller with main shaft and driving motor, and also the rudder clearance was changed by shifting the rudder in design speed with five-bladed propeller. Numerical values of the ratio of the above clearances with the propeller diameter are shown in Table 3. Figures 1(a), (b) and (c), (d), show the extreme cases of positions of the propeller and the rudder respectively, and (e) the standard screw aperture. Table 4 shows various advance coefficients which were tested for the effect of advance coefficient on the surface vibratory force.

Regarding the measurement of surface vibratory forces, the steel reeds were secured inside model structure or rudder, and about a half length from the free end of the reeds, original surface of the hull or the rudder is furnished with cork strip. The natural frequencies of the above reeds are about three to six times higher than the blade frequencies of the model propellers. The high magnitude semiconductive strain gauges were set up on the above reeds at two points near from the fixed end of the reed for estimating the distribution pattern of the horizontal surface force along reed. The method of this estimation is as follows.

We assume as an approach the distribution of the pressure or force along a given axis of the reed as following decay curve,

$$P=P_0\xi e^{-k\xi} \tag{1}$$

where, P_0 : unit force.
ξ : length coordinate of reed with origin at free end, $\xi=1$ at fixed end.
k : constant obtained by calibration and measurements.

The statical calibration of the strain of the reed is made possible only by loading the concentrated load F. Putting ξ_1 for the distance from the free end to the point of action of the concentrated load, the strains ε_a and ε_b at the two points ξ_a and ξ_b ($\xi_b>\xi_a>\xi_1$) respectively are easily obtained while the ratio of ε_a with ε_b are determined by the calibration for respective reeds. The relation between $\varepsilon_a/\varepsilon_b$ and ξ_1 is presented by calibration as given in Figures 2 and 3(a) as an example. The force acted on the reed is easily computed by integrating

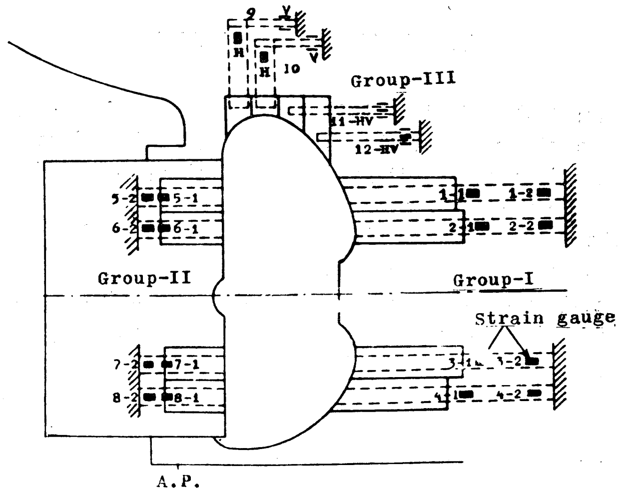


Fig. 2 Locations of reeds and strain gauges.

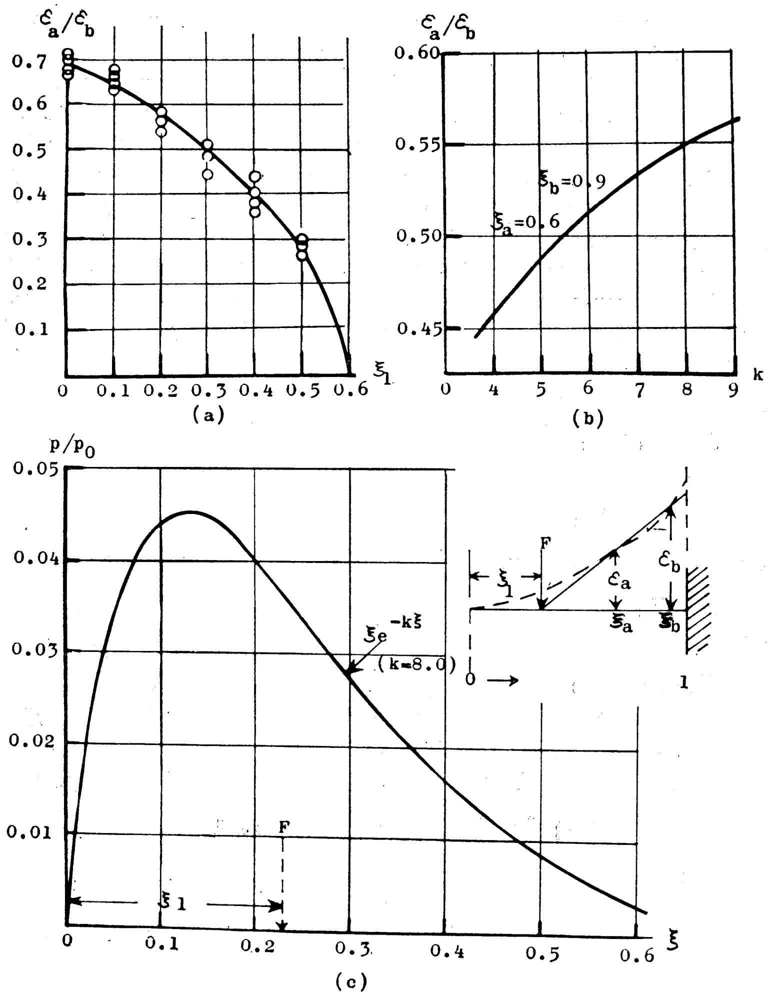


Fig. 3 A sample of calibration of strain ratio and estimate of distribution of surface force.

equation (1) from $\xi=0$ to $\xi=1$, and the bending moment is also obtained by the integration of the above force. From these simple calculations the relation between $\varepsilon_a/\varepsilon_b$ and k in equation (1) is obtained as given in the Figure 3(b) as an illustration. By the use of these calibrated curves (a) and computed relation of $\varepsilon_a/\varepsilon_b$ and k, the approximate distribution of the horizontal force along the reed axis is drawn as shown in Figure 3(c).

The surface force forwarding the propeller and the rudder force are measured at four points in each force by the apparatus mentioned above, while the force at the upper part of the propeller is also measured at four points in both the vertical and horizontal directions by the use of combined reeds as be seen in Figure 2.

1. 2 Experimental analysis of the vibratory forces

The maximum amplitude of the vibratory forces per unit breadth of the reeds and the point of action of the equivalent concentrated load as well as the phase lag of the vibratory forces of each position around the screw aperture were obtained. Figure 4(a) shows an example of the measured results of force distribution for the horizontal direction. Plotting these forces on the base of the contour of the screw aperture (see Figure 4(b)) and graphycally integrating the unit force distributions with respect to each quadrant around aperture, the surface forces F_{S1}, F_{S2}, F_{R2} and F_{R1} around the screw aperture are obtained, as given in Figure 4(a) as an example. The vertical force at the upper part of the propeller is also obtained as will be seen in Figure 4(b). In our present experiments, measurement of the phase difference between F_{S1} and F_{S2}, or that between F_{R1} and F_{R2} is always zero in the even-number-bladed propeller, whereas in the odd-number-bladed propeller this shows π. The resultant maximum vibratory forces are therefore accounted as;

$$\left.\begin{array}{l}\text{surface force forward propeller:}\\ \qquad F_S=F_{S1}+F_{S2}\\ \text{rudder force:}\\ \qquad F_R=F_{R1}+F_{R2}\end{array}\right\} \text{for odd-number-bladed propeller} \qquad (2)$$

$$\left.\begin{array}{l}\text{surface force forward propeller:}\\ \qquad F_S=F_{S1}-F_{S2}\\ \text{rudder force:}\\ \qquad F_R=F_{R1}-F_{R2}\end{array}\right\} \text{for even-number-bladed propeller} \qquad (3)$$

It is self-evident that the total harizontal surface force exciting hull vibration is rightly presented by the vector sum of the force before the propeller, F_S, and force at the rudder surface, F_R. The resultant surface force is thus computed by

$$F=\{F_S^2+F_R^2+2F_SF_R\cos(\phi_1-\phi_2)z\}^{1/2} \qquad (4)$$

where, ϕ_1, ϕ_2: phase lag of F_S and F_R respectively
z: number of blades of the propeller

numerical values of the phase lag ϕ_1 and ϕ_2 are obtained from the record of oscillograms for various clearances of the propeller. It is to be noted that if the

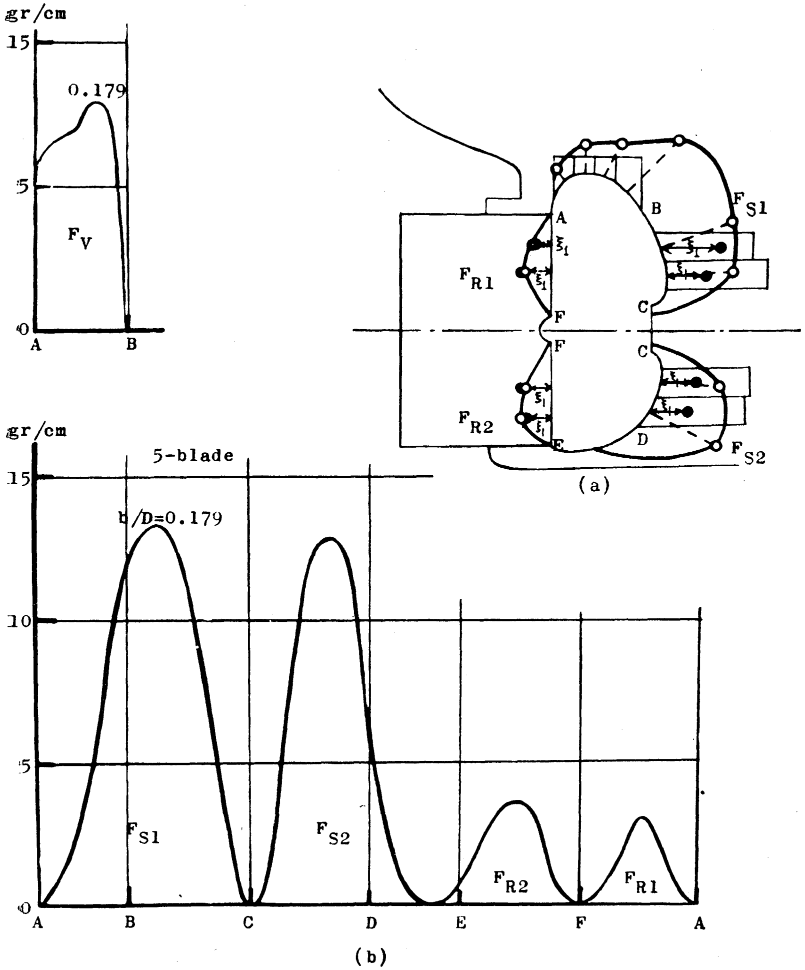


Fig. 4 An example of distribution of surface forces along the boundary of screw aperture.

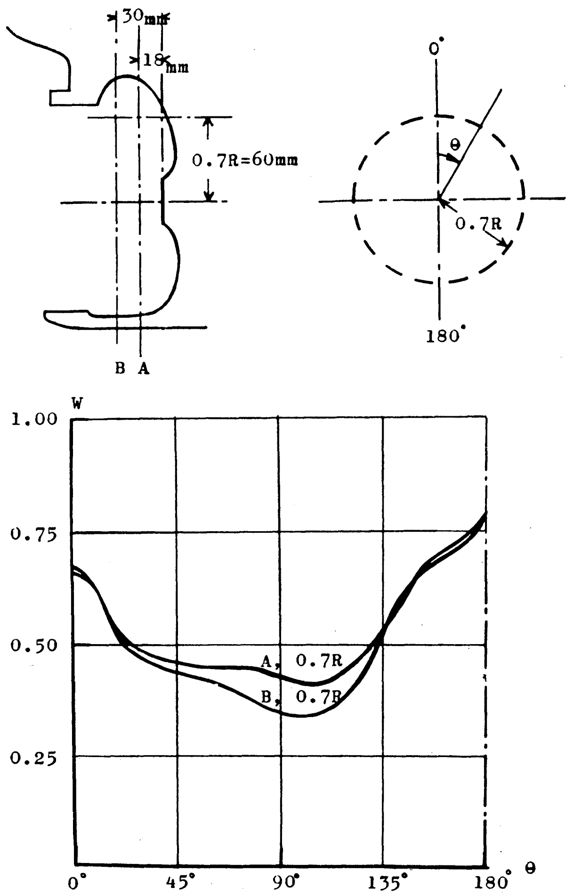


Fig. 5 Wake distribution at 0.7R of propeller disc.

$|\phi_1-\phi_2|z$ takes π, the total surface force becomes minimum, where z is the number of blades of the propeller.

Figure 2 shows the arrangement of reeds and strain gauges around the screw aperture of the model ship.

In the present study, the non-dimensional expressions[1] of the force and moment are used in the present paper as follows;

$$\left.\begin{aligned} K_F &= \frac{F}{\rho n^2 D^4} \\ K_M &= \frac{M}{\rho n^2 D^5} \end{aligned}\right\} \qquad (5)$$

where, F, M: force and moment respectively
$\rho=\gamma/g$, γ: density of water
n: shaft revolution
D: diameter of the propeller

2. Results of experiments

2. 1 Wake survey

The longitudinal wake distributions were measured at the propeller discs of two positions A and B, as shown in Figure 5. The figure shows the circumferential wake distributions at 0.7R of the disc. There are no considerable differences in the distribution at both positions in the present model. These measurements were carried out by courtesy of Prof. Tasai of our institute.

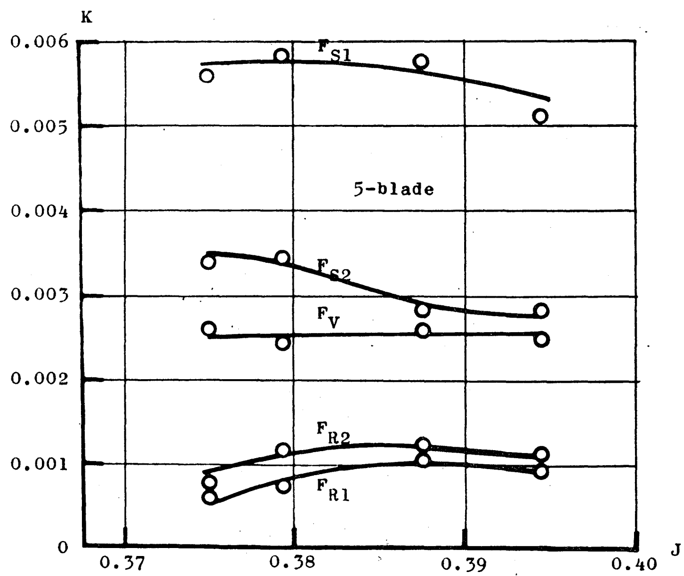


Fig. 6 Effect of advande coefficients upon F_{S1}, F_{S2} and etc.

2. 2 Effect of advance coefficient

F_{S1}, F_{S2}, F_{R1} and F_{R2} denote the horizontal surface forces at the first-, the fourth-, the second-and the third-quadrants of the screw aperture and the vertical force F_{V}. These forces were obtained in various advance coefficients, J, with the standard axial clearance in the five-bladed propeller, as shown in Figure 6. The measured thrust and torque coefficients and the resultant horizontal force are also shown in Figure 7. As will be seen in the figures, there are no considerable effect of advance ratio upon the surface force.

2. 3 Effect of number of propeller blades

Figure 8 shows the K-values of F_{S1}, F_{S2} etc. versus number of propeller blades. It has been confirmed that the vibratory surface force of each quadrant decreases with increase of the number of blades of propeller, as suggested by foreign researchers in the case of tip clearance effect. It is to be noted, however, that the

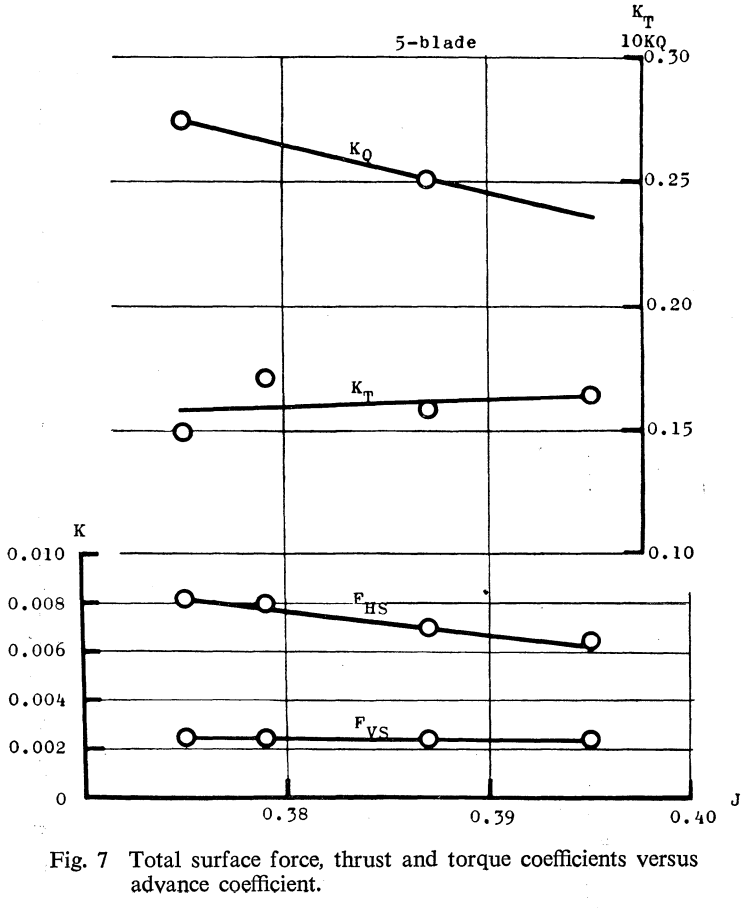


Fig. 7 Total surface force, thrust and torque coefficients versus advance coefficient.

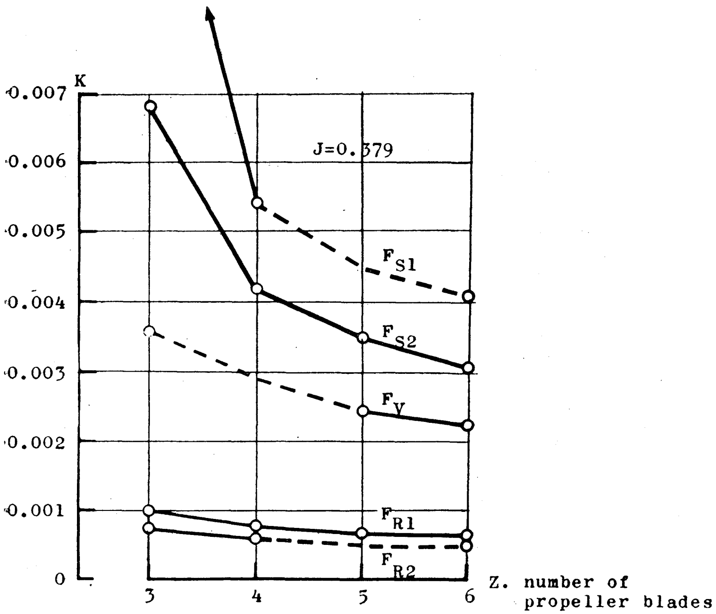


Fig. 8 Effect of number of blades upon each surface force.

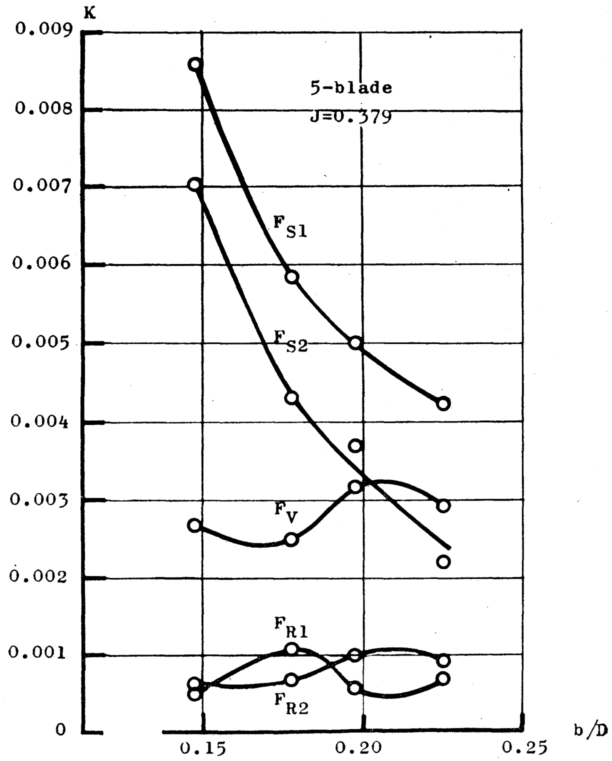


Fig. 9 Effect of axial clearance upon each surface force.

surface force in front of the propeller or the rudder force induced by the propeller with odd number of blades is considerably larger than that with even number of blades, as was shown in previous section of this paper. On the contrary, vibratory moment about the longitudinal axis in the propeller of the even number blades is larger than that of the odd number blades.

2. 4 Effect of axial clearance

Regarding the effect of axial clearance upon the surface force at each place, the most conspicuous influence is apparent in the surface force before the propeller, as seen in Figure 9. There appears clear decay curve in the relation between force and axial clearance. It is however to be noted that the total vibratory force of the hull is given by the vector sum of the surface force forward propeller and the rudder force, hence we should measure the phase lag between the above two forces.

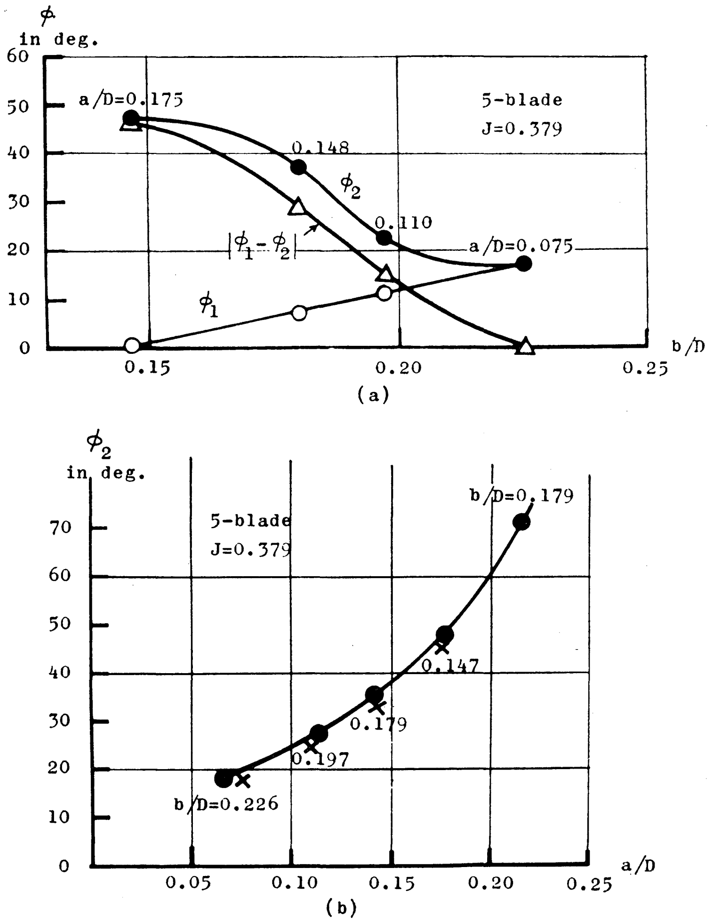


Fig. 10 Variations of phase differences for axial- and rudder-clearances.

2. 5 Phase difference between force in front of propeller and that in rudder

Denoting ϕ_1 and ϕ_2 the phase angles measured from an axis at the maximum amplitude of the vibratory forces in front of propeller and rudder force respectively. The phase difference $|\phi_1-\phi_2|z$ should be required for calculation of the total surface force. The minimum surface force occurs at

$$|\phi_1-\phi_2|z=\pi \tag{6}$$

where, z is the number of blades of the propeller.

Figure 10(a) and (b) illustrate the measured phase angle ϕ_1, ϕ_2 and $|\phi_1-\phi_2|$ for various axial clearance and rudder clearance respectively. As will be seen in the figures, there is considerable variation of the phase angle for the change of axial clearance of the propeller.

2. 6 Total horizontal surface force

As was shown in the expression (4), the resultant force of the surface forces at the stern frame and the rudder depends primarily upon the phase difference of both vibratory forces. It is of interest that the present result shows minimum

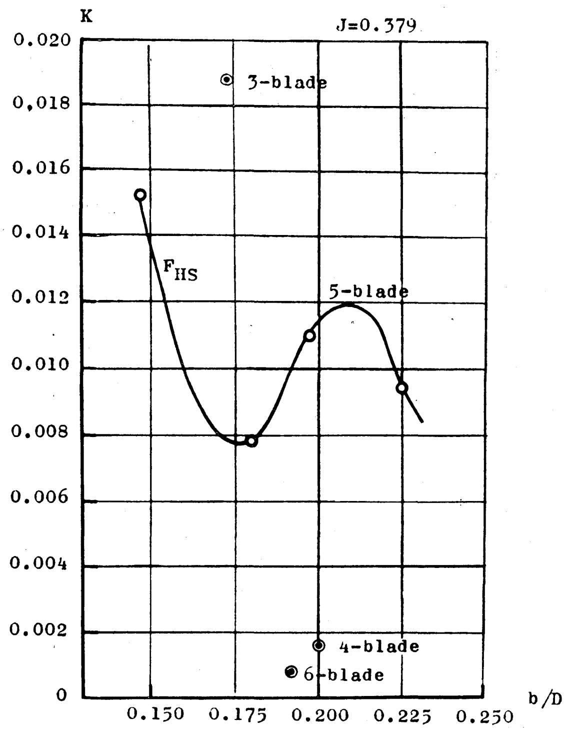


Fig. 11 Total surfaces force versus axial clearance and comparison of the forces induced by propellers with even- and odd-number-blades.

value of K at $b/D=0.178$ as will be seen in the figure. It may prove of far-reaching importance to determination of the location of a propeller for given screw aperture.

Figure 11 also shows the comparison of K-values of the even number blades propellers and odd number ones for given axial clearance. We may easily understand considerable difference of vibratory forces in both types of the propellers, to which reference has already been made in the expressions (2) and (3).

2. 7 Effect of rudder clearance and tip clearance

As is seen in the Figure 12, there seems no considerable change of the partial surface forces for the rudder clearance in the present experiment. Whereas the minumum value appears at $a/D=0.07$ in the test result obtained by Prof. Lewis[1].

Figure 13 shows the effect of tip clearance. It is seen in the figure that there is also no considerable change of vertical force variation in the present experiment.

2. 8 Comparisons of K-values with other works

The K-value of the 7.75″ upper half strut in front of the five-bladed propeller,

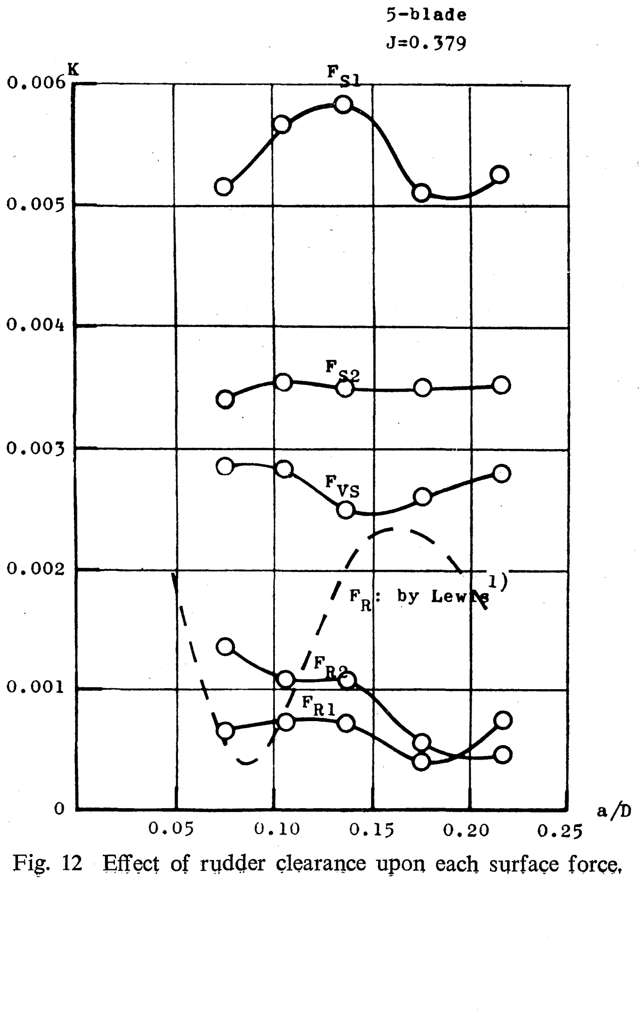


Fig. 12 Effect of rudder clearance upon each surface force.

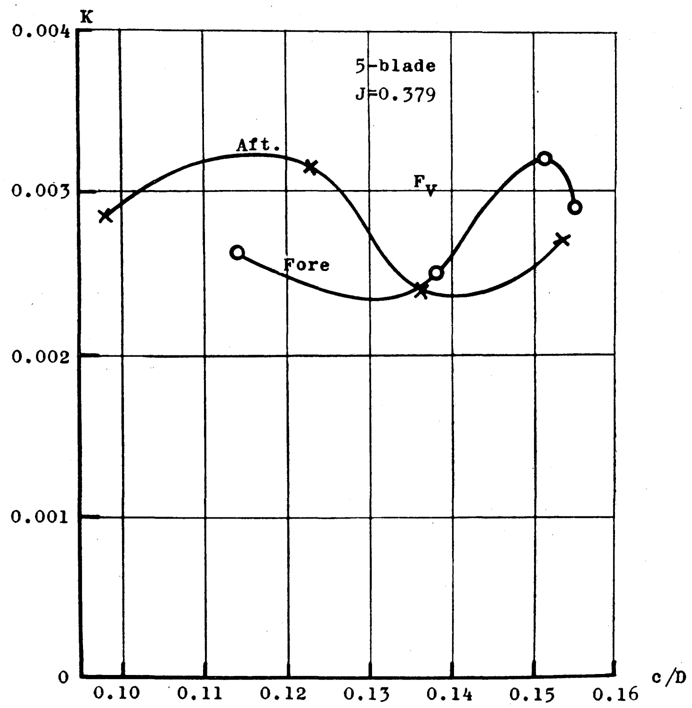


Fig. 13 Effect of tip clearance upon the vertical surface force.

one of the results obtained by the Prof. Lewis[1], was compared with the K_{S1} of the present model ship for the same axial clearance b/D as shown in the Figure 14. The K_{S1}-value is considerably higher than that of strut. It is presumed that the cause of discrepancy is that the concentration of the axial wake in the propeller disk of the model ship induce the surface force more conspicuously than that of strut.

The K_{S1}-value in the present test was compared with that measured on actual tanker[4] as an example. The relation between the vibratory pressure of the stern frame at 0.7R of the model ship which was measured in the previous work[2] and that measured on an actual tanker at the same position was established as an approach. Both the results show good agreement as seen in Figure 14.

If we carry out the generator test on board of an actual ship, the relation between the exciting force and the response of the hull is obtained. In addition, if the response is measured on board the same ship again at the same conditions as the generator test in the trial trip, the propeller force exciting hull vibration on board ship will be approximately estimated. The propeller forces measured by means of the above method in term of K_H-value of several tankers[5] are plotted for the axial clearance in the Figure 14. It is to be noted that the K-value of the total surface force obtained by the present experiment is presented in the same figure. So far as the comparison of the K-value in this figure goes, the difference between the mean value of the K in actual ships and the model ship is roughly

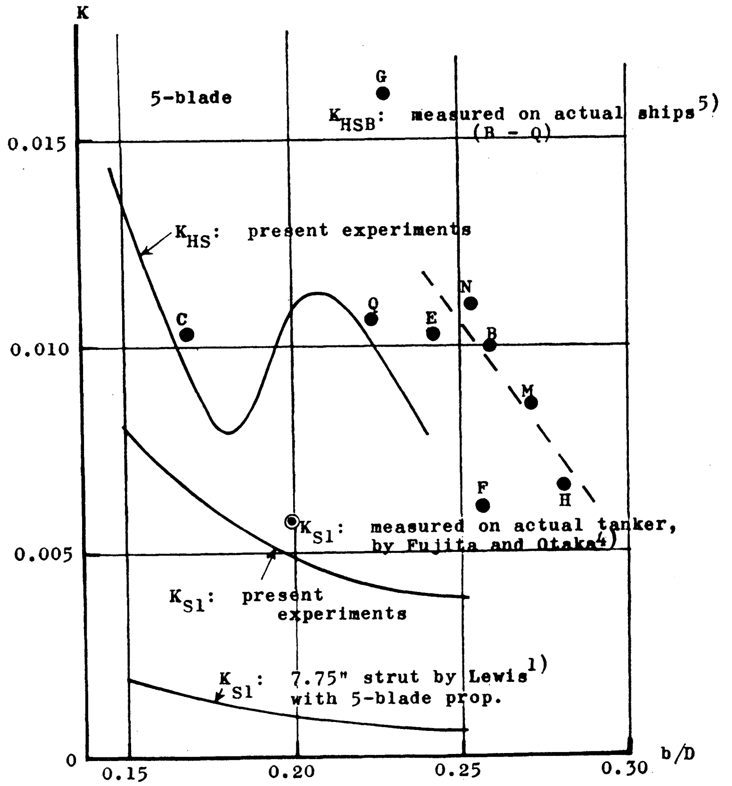


Fig. 14 Comparison of K_H-value obtained by the present experiments with other experimental results.

presumed to be the horizontal bearing force.

On the other hand, the horizontal bearing forces in term of K_{HB} of the same model previously measured[2] and calculated[3] by quasi steady method show a value considerably higher than that what was obtained in Figure 15(a). The K_{HB}-value in cargo ship tested by Krohn[6] is also compared with the present results in Figure 15(a).

The bearing force exciting the vertical vibration which was denoted by K_{VB} in calculation and measurements on models and vertical surface force K_{VS} measured in the present test are compared with the mean value of total vertical force K_V in actual ships previously cited[5] as seen in the Figure 15(b).

Conclusions

As a result, the effect of number of blades on the axial clearance upon the surface force of the stern frame was confirmed as follows. The horizontal vibratory surface force at the stern frame or the rudder surface induced by the propeller of even number blades is less than that induced by that of odd number blades

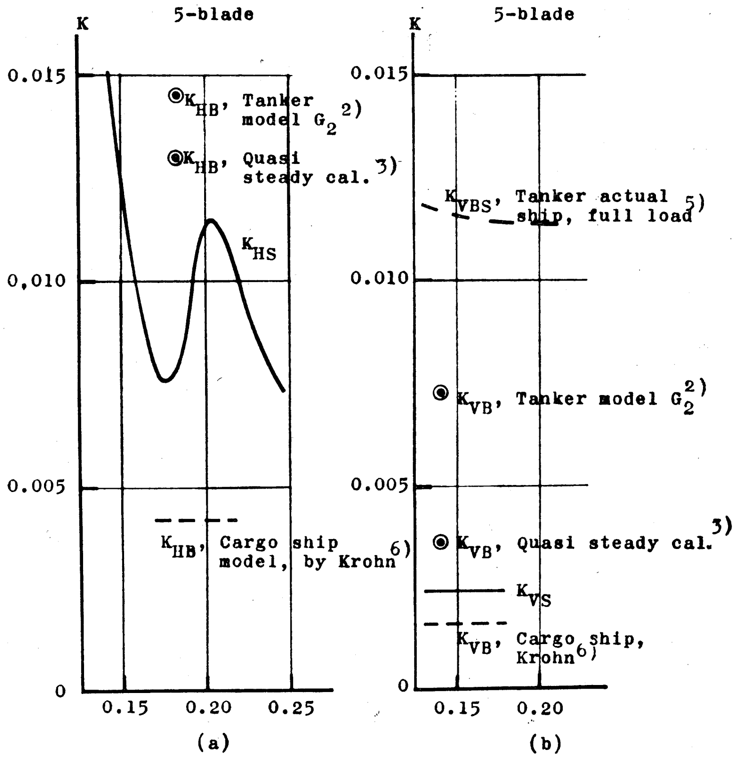


Fig. 15 Comparison of total horizontal surface force obtained by the present experiments with horizontal bearing forces by other works (a), and of the vertical surface force in the present experiment with vertical bearing forces obtained by other works (b).

propeller. On the other hand, the exciting force of the stern frame decreases with the increase of the number of blades of the propellers.

It is to be noted that the resultant horizontal surface force at the stern frame and the rudder are far from bearing a simple decay curve for the axial clearance, because the phase difference between both surface forces of the stern frame and the rudder are considerably changed for the axial clearance, and there is the minimum surface force for axial clearance in the present experiment.

Since we have to estimate the propeller exciting force of the single screw ship as the vector sum of the wake bearing force and the resultant surface force mentioned above, it is necessary to study further the bearing force with its phase lag and confirm the propeller exciting force by measuring the response of the hull vibration of the model ship.

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(Received August 11, 1965)