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# MEASUREMENT OF PROPELLER FORCES EXCITING HULL VIBRATION BY USE OF SELF-PROPELLED MODEL

by

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**Summary**

The present report provides the experimental study on the measurements of propeller forces exciting hull vibration by use of self-propelled model. The special considerations are given for measuring the components of the reactions of propeller shaft at the bearing, and surface forces applied at the end parts of the stern as well as those of the thrust and torque variations.

The experiments were carried out by making model ship selfpropel along about 200 m straight course in a reservoir, where manipulation, operation of the meters equipped in the ship and recording were all conducted by wireless instructions. The effects of number of blades of propeller on the vibratory exciting forces on the ordinary stern and Weser stern are obtained by replacing 3, 4, 5 and 6-bladed propellers for two models. The effect of screw aperture on the vibratory propeller forces in the ordinary stern is also obtained.

## Introduction

The model experiment on the measurement of propeller exciting forces was originated by F. M. Lewis. In the model experiment carried out on a single screw cargo ship of four bladed propellers by F. M. Lewis and A. J. Tachminji, vertical and horizontal forces on stern and the moment around the central axis of hull were measured as apparent exciting forces and then the effects of clearance of propeller and hull or rudder on that were examined. Furthermore, removing bearing force from all exciting forces by putting propeller in the condition of behind test, surface force was evaluated [1]. Lewis' method is an indirect measurement of exciting force. On the other hand, in K. Taniguchi's experiment by self-propelled model, only bearing force has been measured by direct measure-

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ment, in which effects of the form of rudder on both vertical and horizontal forces at propeller boss were examined supporting the propeller axis elastically and availing this displacement [2]. Also in the recent experiment [3] of van Manen-Wereldsma, the variation of vertical and horizontal bending moment conveyed from propeller to main shaft was directly measured by putting a strain gauge close to the propeller boss of main shaft, and the effects of stern form and the number of propeller blades upon these and the variation of thrust and torque were investigated. Again in K. Taniguchi's theory and experiment [4], pressure change caused on the bottom of box-type model ship by the propeller revolution was evaluated on various kinds of propeller and tip clearance, where a method of estimating surface force on the bottom of a twin screw ship and a cruiser stern is shown. K. H. Pohl [5] also carried out similar experiment on a single screw model ship, measuring the vertical pressure variation imposed on stern with respect to verious kinds of propellers.

Propeller exciting force can be generally divided into six components, i. e., vertical and horizontal forces $P_V$, $P_H$, moments $M_V$, $M_H$, torque Q and thrust T.

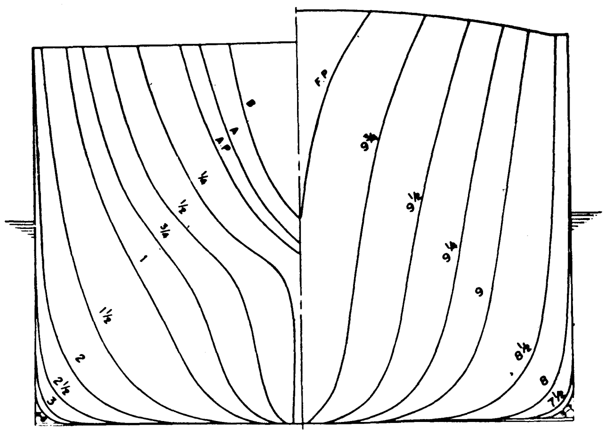
In the present experiment, vertical and horizontal forces and moments imposed on propeller boss and thrust and torque were measured by making a model of 50,000 ton tanker (5.0 m length, 1/44 in scale) propel by itself and by supporting the propeller shaft elastically, and then effects of the number of propeller blades and the form of stern on these values were investigated. Furthermore, taking Weser type stern, its vertical and horizontal surface forces imposed on the part near stern were also measured by a special device, and then a synthetic experiment on propeller exciting forces, including the measurements of thrust, torque, bearing forces and surface forces was attempted.

The experiments were carried out by making a model ship self-propel along about 200 m straight course in a reservoir, where manipulation, operation of the meters equipped in the ship and recording were all conducted by wireless instructions.

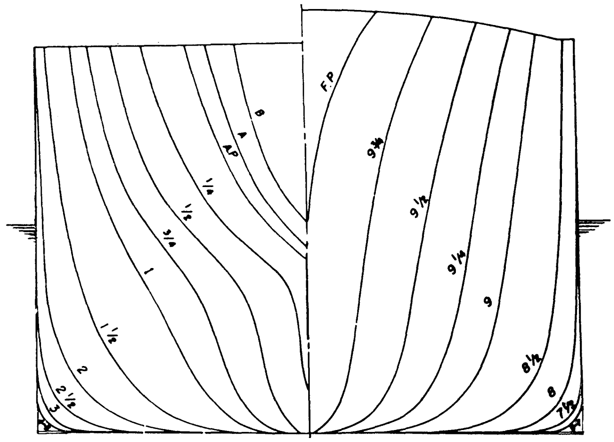
## 1. Model ship and self-propelling apparatus

### 1. 1 A model ship and model propellers

Design of a model ship and model propellers were made for an actual ship of $L_s \times B_s \times d_s = 220\,\text{m} \times 30.89\,\text{m} \times 11.67\,\text{m}$, $Cb=0.80$, $SHP=25{,}000\,HP$, $N=110\,r.p.m.$ and $18.5\,K.t$ under ballast condition. The model ship is $L_m \times B_m \times D_m = 5.0\,\text{m} \times 0.7\,\text{m} \times 0.5\,\text{m}$, whose body plan is shown in Fig. 1, and general view in Fig. 2. Displacement of ship at the time of experiment was 820 kg, average draught for it 29.9 cm and trim 6 cm in stern. In order to prevent hull vibration it is necessary to make rigidity of hull and damping coefficient of vibration as large as possible. The model used here, therefore, was made of steel plate in its deck and bottom over the whole length and its outside shell was of steel plate about $L/2$ in the mid part. Though the bow, stern and bilge are of wood, the part in the stern are made of duralumin, and by changing this part the form of stern was altered. (cf. Fig. 2) .As bolts were used for all joints, damping coefficient of the vibration of ship itself became large and it was confirmed that the effect of the vibration of a model ship on measurements is negligible. Hull weight, however, increased because of that, and the draught became larger than 26.6 cm, which is in excess of the corresponding load water draught of the actual ship by about 10 %.

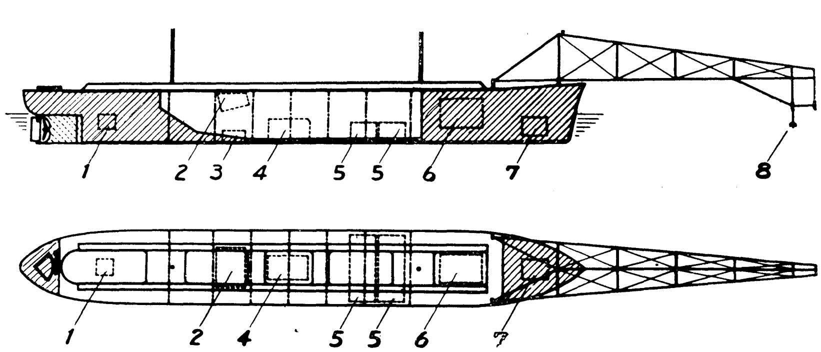


Ordinary stern (G-stern)



Weser stern (W-stern)

Fig. 1 Body plan.




1. Main motor
2. Dynamic strain meter
3. Dry cell
4. Electro-magnetic oscillograph
5. Main battery (100 v)
6. Radio receiver and relay
7. Battery (12 v)
8. Speed meter

Fig. 2. General view of hull structure and arrangement of measuring apparatus.

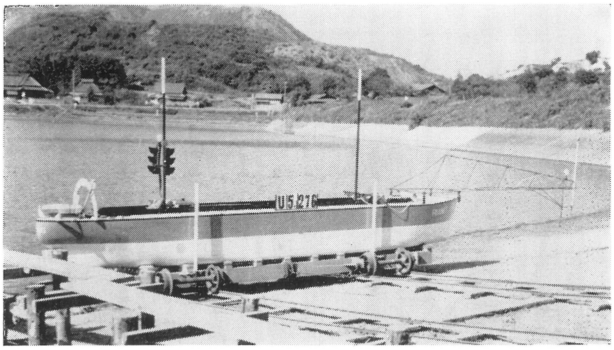



Photo. 1

In order to investigate the effects of the stern arrangement, tip clearance and screw aperture, the part of stern was changed into the following three kinds. Namely, ordinary stern $G_1$, $G_2$ and Weser stern $W$. $G_2$ is an ordinary stern corresponding to an actual ship. $G_1$ was designed by slightly lengthening $G_2$ under water line and making the screw aperture before the propeller small. (Fig. 6). With a view to investigating the effect of the number of propeller blades on exciting force, four kinds of blades 3, 4, 5 and 6 were used. All of them were aluminum alloy of 170.5 mm in diameter with Troost type section, principal items of which are given in Table 1. Ship's speed was measured by a method in which a small propeller type tachometer installed at the position about 20 cm below the surface of water and approximately 2.5 m ahead of stem was led on to the oscillograph to be automatically recorded.

Table 1 Paticulars of model propellers.

| Propeller model No. | | I | II | III | IV |
|---|---|---|---|---|---|
| Diameter *mm* | $D$ | 170.5 | 170.5 | 170.5 | 170.5 |
| Number of blades | $Z$ | 3 | 4 | 5 | 6 |
| Pitch ratio (constant pitch) | $p$ | 0.728 | 0.690 | 0.670 | 0.648 |
| Developed area ratio | $a_d$ | 0.44 | 0.56 | 0.66 | 0.72 |
| Blade thickness ratio | | 0.05 | 0.05 | 0.05 | 0.05 |
| Boss ratio | | 0.20 | 0.20 | 0.20 | 0.20 |
| Angle of rake | | 10° | 10° | 10° | 10° |

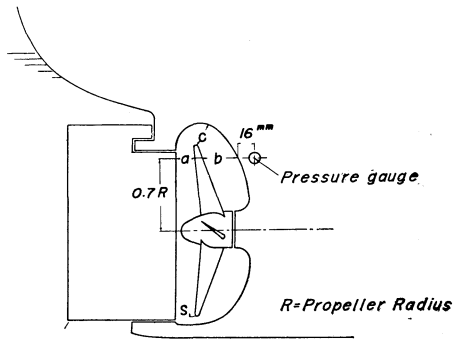
### 1. 2 Main engine and radio control apparatus

The main engine of the propeller used for a self-propelled model ship is a $DC$ motor (100V, 1/8 HP), and its electric source was supplied by 100 V battery, 5 AH equipped in ship. Two sets of radio control apparatuses were used for main instruction and operation, and the former was used for turning off and on the switch of main motor and the motor sending the recording paper of electro magnetic oscillograph. For transmitter and receiver, five channel of 27 $MC$ were used. They are composed of multiplex control method and ratching-relay circuit. Each sign is therefore independent and can be sent at all times. And for operation pulse width modulation method of 40 *MC* was adopted.

## 2. Measuring apparatus of exciting force and method of measurement

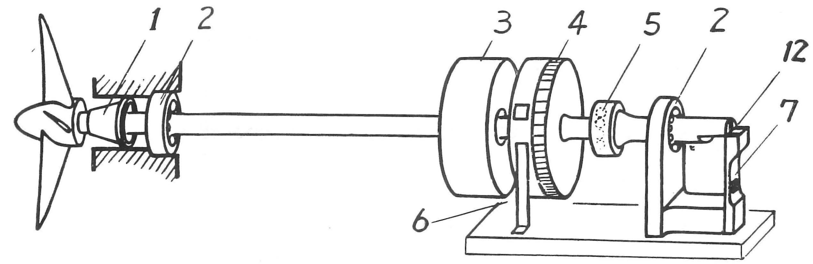
### 2. 1 Thrust and torque

The measuring apparatus of thrust and torque are shown in Fig. 4, (a), (b) and in Photograph 3. In the case of Fig. 4 (b), the thrust imposed on the main shaft is conveyed to the thrust measuring element through the 0.8 mm$\phi$ piano chords from thrust bearing and the force is measured by a strain gauge. It was to convey only the thrust from the main shaft and to prevent the force parpendiculer to it, that 0.8 mm $\phi$ piano chorde were used in Fig. 4 (b). In measuring torque, torque-meter with a strain guage was used.

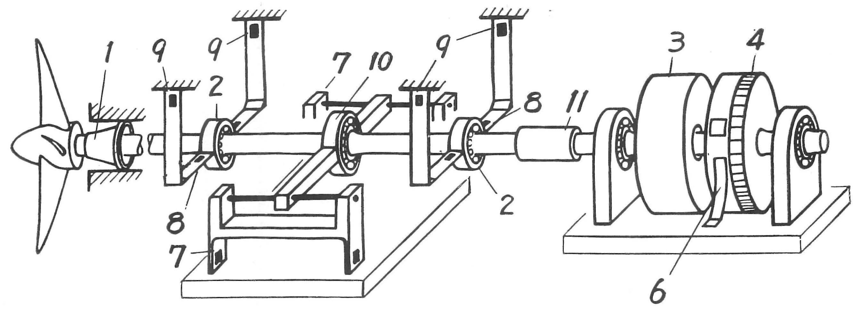



| Stern | Experiments | Clearance | 3 Blade | 4 Blade | 5 Blade | 6 Blade |
|---|---|---|---|---|---|---|
| $G_1$ | A, C | *a* | 9.7 | 9.9 | 12.4 | |
| | | *b* | **13.8** | **15.0** | **13.9** | |
| | | *c* | 8.4 | 9.9 | 8.8 | |
| | | *s* | 2.6 | 2.4 | 2.4 | |
| | B | *a* | 7.1 | 8.5 | 9.8 | |
| | | *b* | **16.4** | **16.4** | **16.4** | |
| | | *c* | 8.5 | 10.0 | 9.0 | |
| | | *s* | 2.5 | 2.3 | 2.3 | |
| $G_2$ | D, E | *a* | 11.2 | 10.2 | 12.4 | 11.5 |
| | | *b* | **17.8** | **18.8** | **18.4** | **19.5** |
| | | *c* | 14.1 | 14.1 | 14.1 | 14.2 |
| | | *s* | 3.1 | 2.5 | 2.4 | 1.6 |
| W | F, H, J | *a* | 11.1 | 11.1 | 14.4 | 12.7 |
| | | *b* | **15.5** | **15.9** | **13.8** | **14.7** |
| | | *c* | 10.0 | 9.3 | 8.1 | 8.0 |
| | | *s* | | | | |

Fig. 3. Screw aperture of model ship (in % of Diameter of propeller)




(a) Shaft System I




(b) Shaft System II

1. Rubber packing
2. Thrust free bearing
3. Torque meter
4. Reduction gear
5. Thrust bearing
6. Tachometer
7. Thrust measuring element
8. Bearing force measuring element (vertical)
9. Bearing force measuring element (horizontal)
10. Thrust bearing
11. Rubber coupling
12. Cross hinge
13. Piano wire (0.8 mm$\phi$)

Fig. 4 (a). Measuring apparatus for thrust and torque used on experiments (G-A, B).
(b). Measuring apparatus for vibratory forces excited by propeller.

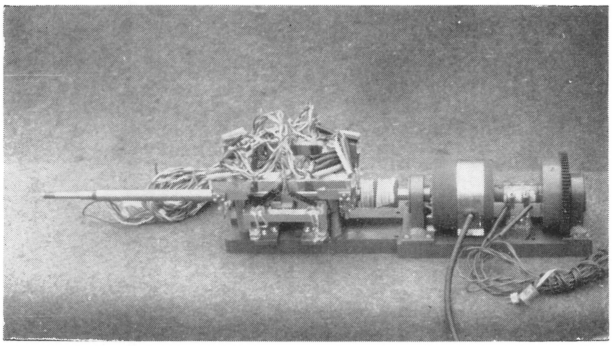


Photo. 2

## 2. 2 Bearing forces

The measuring apparatus of vertical and horizontal forces are shown in Fig. 4 (b). In order to measure vertical and horizontal forces and moments imposed on propeller, the propeller shaft was hung at two position (at thrust-free bearing). Measuring the vertical and horizontal reactions at these points $R_{1V}$, $R_{1H}$, $R_{2V}$, and $R_{2H}$, the force $P$ and moment $M$ on propeller boss were calculated by the following equation. (Fig. 5)

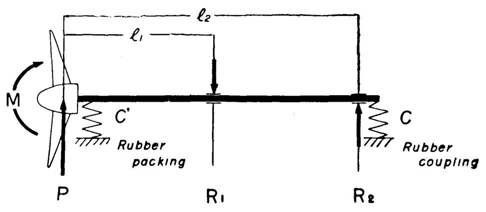



Fig. 5. Moments and forces which act on propeller shaft.

$$P=\frac{1}{1-C'}\left\{R_1-(1+C)\,R_2\right\}$$

$$M=l_1R-l_2(1+C)\,R_2$$

provided that $C$, $C'$ are the correction factors for rubber coupling and rubber packing, which is smaller in value than 1.

2. 3 Surface forces and surface pressure

The measuring apparatus of surface forces on the Weser type stern is shown in Fig. 6. Calibration of these was executed for $F_H$ by imposing horizontal point-load on the position on the water line 0.7 $R$ upward from the main shaft and 5 mm from the trailing edge and for $F_V$, by imposing vertical point-load on the central line right above the propeller tip, while for $F_s$ the same process was followed by imposing horizontal point-load at the position on the water line passing 0.7 $R$, similarly as in the case of $F_H$, and the 5 mm from the front edge. The arrangement of the pressure gauge for measuring surface pressure is shown in Fig. 6. The diaphragm is made of steel, 15 mm in diameter and 0.04 mm in thickness.

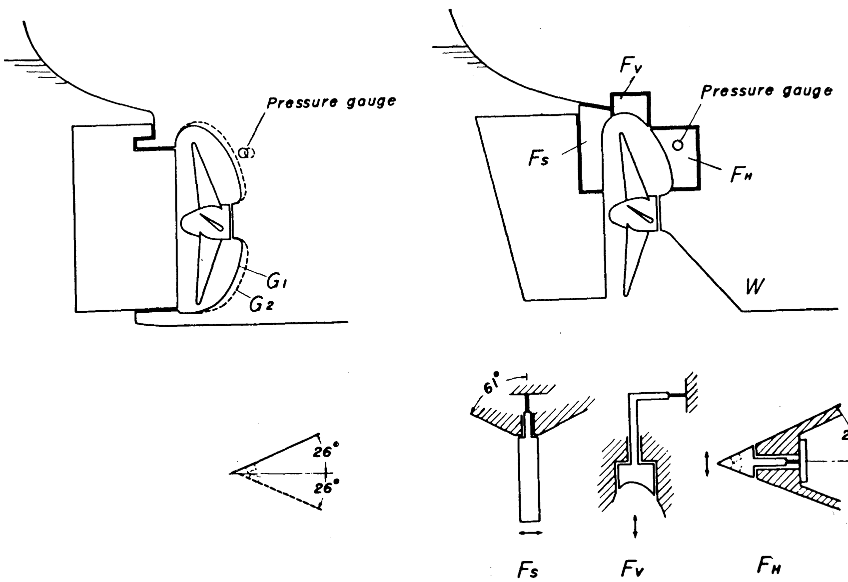



Fig. 6 Position and apparatus of measuring surface force and surface pressure.

## 2. 4 Recording apparatus

For recording the forces or the pressure, a portable electro-magnetic oscillograph of six elements was used.

## 3. Method and sort of experiments

Normal measurement was made when a model ship has reached a condition of steady straight course sailing 80～100 m after its starting (Photo. 2). It was turned at about 5°～6° helm angle after it passed the afore-said measuring point, and then stopping of main engine and reversion test were conducted by lowering speed on its return. On low speed, astern test was done immediately after stopping the ship. The measurement of thrust, torque, bearing force, surface pressure and

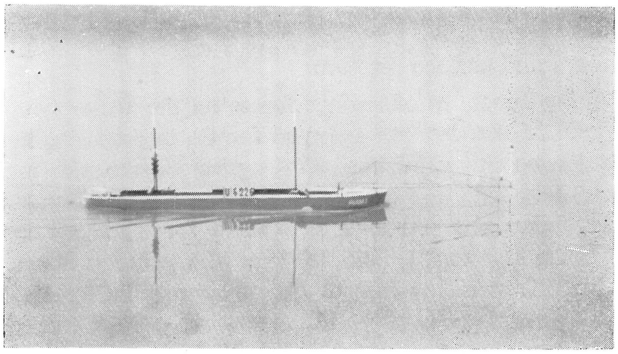


Photo. 3.

Table 2 The sort of experiments and measurement.

| Shaft | Stern | Fxperi-ments | Measurement | | | | | | | | | | | | | Propeller |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $T$ | $Q$ | $P_P$ | $P_s$ | $r_s$ | $V_s$ | $R_{1V}$ | $R_{1H}$ | $R_{2V}$ | $R_{2H}$ | $F_H$ | $F_V$ | $F_s$ | |
| I | $G_1$ | $A$ | ○ | ○ | ○ | ○ | ○ | ○ | | | | | | | | 3.4.5. $B1$ |
| | | $B$ | ○ | ○ | ○ | ○ | ○ | ○ | | | | | | | | |
| II | $G_1$ | $C$ | ○ | | | | ○ | ○ | ○ | ○ | ○ | ○ | | | | 〃 |
| | $G_2$ | $D$ | ○ | ○ | ○ | ○ | ○ | ○ | | | | | | | | 3.4.5.6. $B1$ |
| | | $E$ | ○ | | | | ○ | ○ | ○ | ○ | ○ | ○ | | | | |
| | $W$ | $F$ | ○ | ○ | | | ○ | ○ | | | | | ○ | ○ | ○ | 〃 |
| | | $H$ | ○ | | | | ○ | ○ | ○ | ○ | ○ | ○ | | | | |
| | | $J$ | ○ | ○ | ○ | ○ | ○ | ○ | | | | | | | | |

$G_1$, $G_2$: Ordinary stern
$W$ : Weser stern
$T$ : Thrust
$Q$ : Torque
$P_P$: Port side pressure
$P_s$: Starboard side pressure
$n_s$: r.p.s. of propeller
$V_s$: Speed of model ship
$R_{1V}$, $R_{2V}$: Vertical bearing reaction
$R_{1H}$, $R_{2H}$: Horizontal bearing reaction
$F_H$: Horizontal surface force at stern
$F_V$: Vertical surface force at stern
$F_s$: Horizontal surface force at rudder stock

others were made seven times; at starting (slip 100%), normal sailing, turning, low speed sailing, stopping of main engine, reversion of propeller and further at sailing astern. In the above experiments, the straight course of reservoir was about 200 m, water depth about 3.5 m near the normal measuring point and about 2 m in average through the whole course.

Though the present paper deals with only the result of measurement at normal sailing, it corresponds to an actual ship with the speed of about 17 kt. As mentioned before, since the draft was considerably larger than the value corresponding to an actual ship and no frictional correction was done, the number of revolution of main engine was increased about 15%, being $n=14$ *r. p. s.* The zero base was recorded before and after sailing.

The variety of experiments are as shown in Table 2, where thrust, torque and surface pressure are measured for the propelles with 3, 4 and 5 blades with respect to $G_1$ type stern using shaft system I at first. Incidentally, with this $G_1$ type stern, the effects of tip clearance and screw aperture were investigated by putting rings of appropriate thickness before propeller boss and changing the position of propeller into two kinds of A and B. In the next place, measurement of bearing force, surface pressure and surface force beside thrust and torque was made using the shaft system II, but in this case 3-, 4-, 5- and 6-bladed propellers were used. Tip clearance and screw aperture are shown enbloc in the supplementary table of Fig. 3.

## 4. Results of experiment

### 4. 1 Expression of results

Let $M_V$ and $M_H$ vertical and horizontal components of the moment acting on the propeller boss respectively. In the present section, the value divided by $M_0=T_0\times 0.7R$ was used in order to express these values in non dimension. Here $T_0$ is average thrust and $R$ the radius of propeller. Then putting $P_V$, $P_H$ vertical and horizontal forces acting on the center of propeller disk, they were expressed with the ratio to the value of $P_0=\frac{Q_0}{0.7R}$ provided that $Q_0$ is average torque. $M$, $P$ can be evaluated from the values of $R_{1V}$, $R_{2V}$, $R_{1H}$, $R_{2H}$ measured as shown in Fig. 5, and here these variational parts are expressed with $\Delta M$, $\Delta P$, adopting their double amplitude. In the result of measurement, the first harmonic (blade frequency) and 2nd harmonic are all evaluated by harmonic analyser, and the harmonics higher than the 2nd are omitted. In the measurements of bearing force and surface force, though more or less different, average values of number of shaft revolution $n$, ship's velocity $v_s$, thrust $T_0$ and torque $Q_0$ were $n=14.0$ *r. p. s.* $v_s=1.30$ m/sec., $T_0=3.6$kg, $Q_0=7.3$kg-cm respectively. Assuming as wake coefficient $\mathrm{w}\doteqdot 0.4$ from the result of self-propelled model experiment of an allied ship, we have advance coefficient $J=\frac{v_s(1-\mathrm{w})}{nd}=0.32$.

### 4. 2 Variation of thrust and torque

In Fig. 7 the amount of variation of thrust is given, which shows that, in 1st harmonic, the one in the case of four bladed propeller is seen to be larger

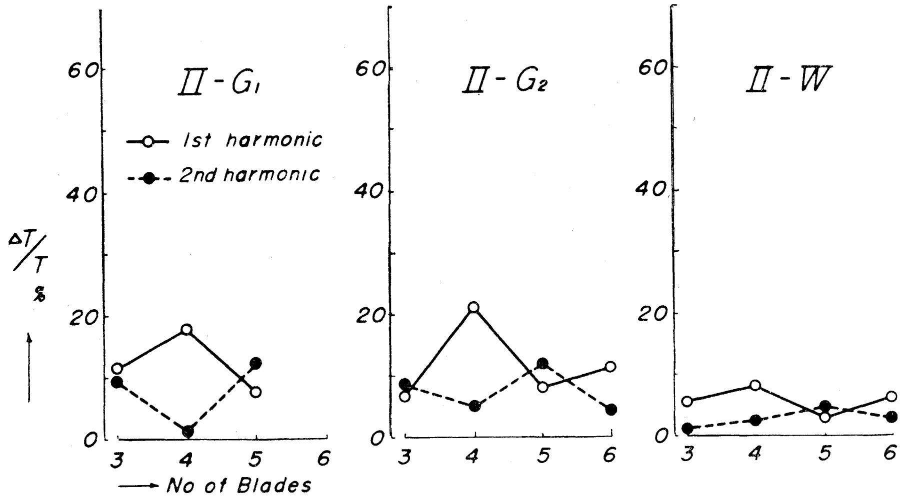



Fig. 7. The effect of blade number on thrust variation.

than that in five bladed propellers, what over type the stern may be. Also with the 2nd harmonic, a tendency reverse to it is shown.

And in the case of W type stern in the present experiment, the amount of variation is generally seen to be smaller than $G$ type stern through all the blades.

Thrust variation obtained by van Manen and Wereldsma's experiment [3] and calculated values by one of the authors are in good coincidence with our results as shown in Fig. 8.

As for the variation of torque, no accurate amount of change could be evaluated in case of shaft system II because of the rubber coupling equipped to it.

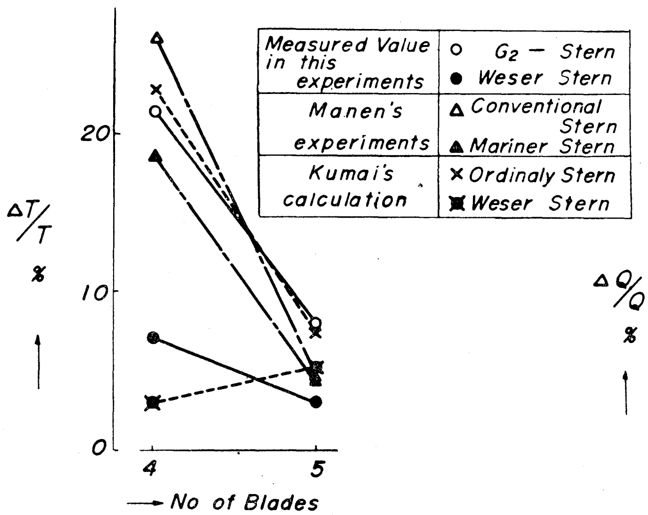



Fig. 8. Comparison between experiment and calculation of thrust variation.

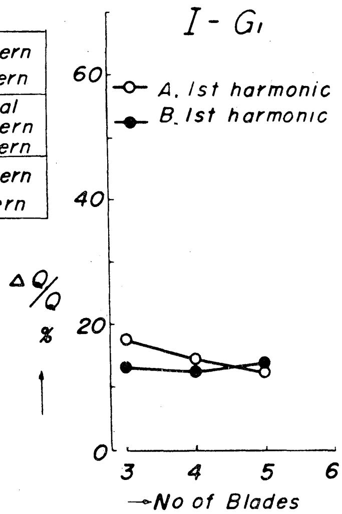



Fig. 9. The effect of blade number on torque variation.

Fig. 9 shows variation of each torque when the position of propeller was shifted back and forth on $G$ type stern, using system I. In this case, the effect of the number of propeller blades shows no definite tendency as seen in the variation of thrust.

4. 3 Bearing force

The difference in the values of $\frac{\Delta M_V}{M_0}$, $\frac{\Delta M_H}{M_0}$, $\frac{\Delta P_V}{P_0}$ and $\frac{\Delta P_H}{P_0}$ for each blade and the effects of the form of stern on those values are as shown in Figs. 10, 11, 12 and 13. Among those values the one of the 1st harmonic or blade frequency shows as a whole gradual decrease with the increase of the number of blades,

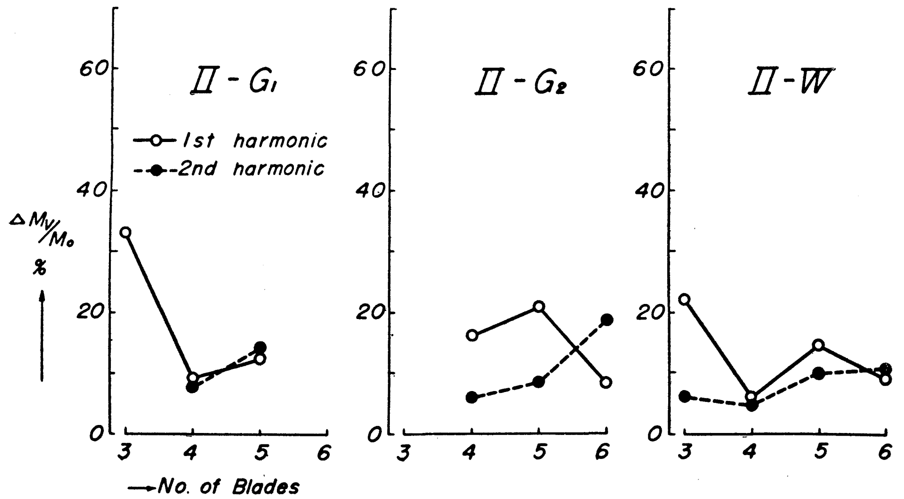



Fig. 10. The effect of blade number on $\Delta M_V/M_0$.

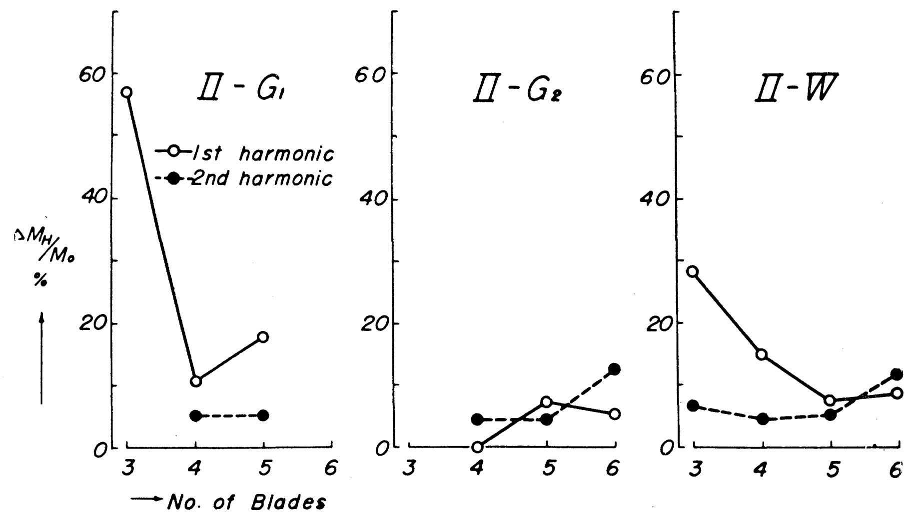



Fig. 11. The effect of blade number on $\Delta M_V/M_0$.

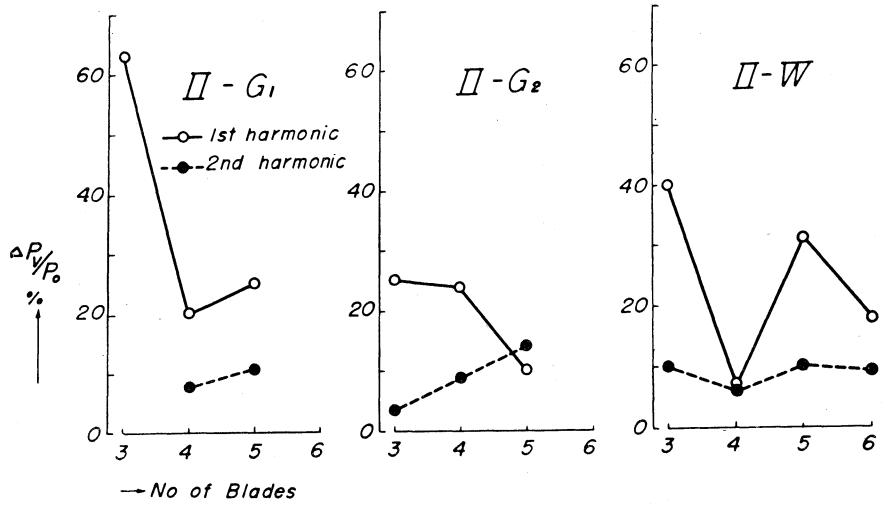



Fig. 12. The effect of blade number on $\Delta P_V/P_0$.

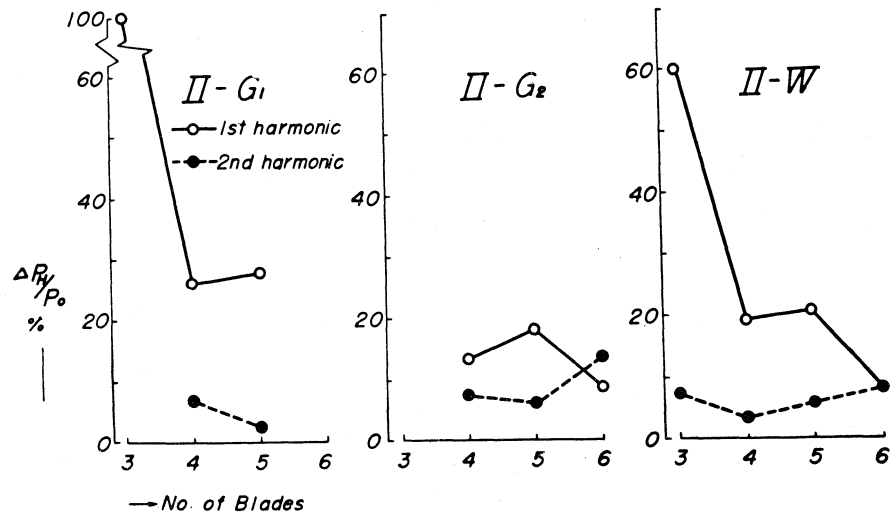



Fig. 13. The effect of blade number on $\Delta P_H/P_0$.

whereas the propeller with odd number of blades shows the tendency to surpass the one with even number of blades in its value. The results obtained in van Manen and Wereldsma's experiment [3] and the calculation by one of the authors [6] show nearly the same tendency.

## 4. 4 Surface pressure and surface force

Surface pressure was measured by choosing representative positions (cf. Fig. 6) on both boards. Evaluating maximum amplitude of the variation of pressure on both boards separately and comparing it for the number of propeller blade, the result was shown in Fig. 14. When the number of blades increases in

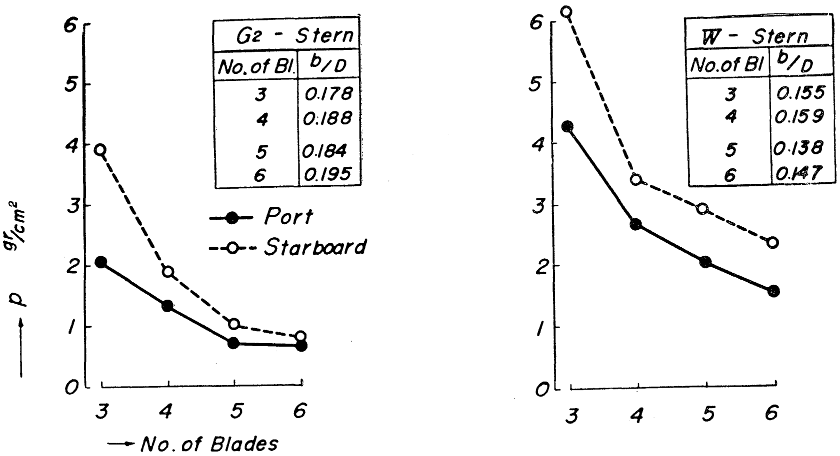



Fig. 14. The effect of blade number on pressure variation.

case screw aperture $b/D$ is nearly constant, surface pressure decreases. This is the same with the result obtained by K. H. Pohl [5]. The $W$ type stern of Fig. 14 is larger in pressure change than the $G_2$ type stern, which is presumed mainly due to the difference in screw aperture. In the present experiment, the propeller turns clockwise, but in either case of Figs. 14, the pressure change of starboard side is larger than that of port side.

Fig. 15 is the result of pressure measurement made by changing ship's speed, but for the change of ship's speed as much as shown in the figure, the increase of surface pressure attending to the increase of ship's speed is slight. With respect

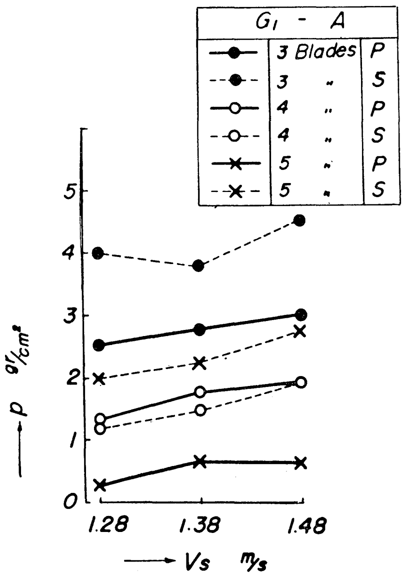



Fig. 15. The effect of ship speed on pressure.

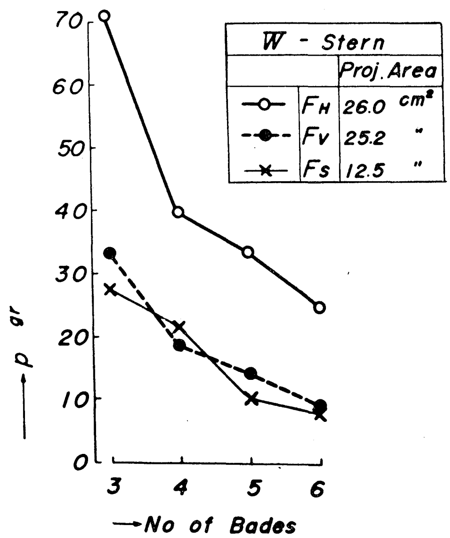



Fig. 16. The effect of blade number on surface force variation.

to the $W$ type stern, the surface forces $F_H$, $F_V$ on a part of stern and the force $F_s$ on the rudder stock were measured. The result shows decrease in value with the increase of the blade number similarly with the surface pressure, as shown in Fig. 16. As it is also plain in the figure, the area subject to pressure is almost equal, but $F_H$ is considerably larger than $F_V$.

## Conclusion

In order to detect the effects of the difference in the number of blade and the form of stern on the variation of bearing force, surface force and thrust, and torque as propeller exciting forces of a single screw ship, a synthetic experimental measurements were made using a self-propelled model ship. Though analysis on a part of the experiments is still kept up, the results of the present study will be summarized as follows:

1. The variation of thrust is larger in case of blades in even number than in case of those in odd number. Also in case of $W$ type stern, the amount of change is smaller than in case of $G$ type stern.
2. Bearing force has a tendency to become smaller the more the number of propeller blades increases, and reversely to the change of thrust, it is inclined to become large in case of propeller bladed in odd number and small in case of propeller blades in even number.
3. Surface force and surface pressure decrease with the increase in the number of blades. With the propeller of clockwise revolution, the pressure variation is larger on the starboard side than on the port side.

Also in other experiments lately published, nearly the same tendency has been obtained partly. Though the present experiment deals with propeller exciting forces, further studies are desired to be forwarded in the future on the relation between wake distribution and bearing force, measurement of the distribution of the pressure on the surface of shell plate and rudder, effect of mutual position of rudder and propeller as well as the measurement of all the exciting forces including bearing and surface forces.

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