Special Lecture

On the Effectiveness of Side Thrusters

by

Masataka Fujino*

I. Introduction

It is a great honour for me to have a chance to give a lecture on the effectiveness of side thrusters. Before starting my lecture, I have to say that most of the contents of this paper are indebted not to me but to some other persons, and moreover the contents are not up to date. However, I think that they are still useful and helpful when a designer designs a side thruster for a particular ship.

As known well, the merits of equipping a ship with side thrusters are summarized as follows;

a) To assist a ship in approaching to a pier and in leaving from it quickly and without risk. This merit is invaluable for such ships as short distance passenger-ships, ferryboats, car-ferries, etc.

b) To assist the accurate positioning of ships such as dredgers, survey vessels, cable-layers, etc.

c) An auxiliary controle device of ship's direction, especially when the effectiveness of rudders is not expected, for instance when the ship's speed is considerably low or the propeller is rotating adversely.

The merits a) and b) are widely recognized, but the merit c) is not fully acknowledged and is still under examination, because the effectiveness of side thrusters is much affected by the ship's motion, especially by the ship's speed. However, because of the merits a) and b), most of newly-built ferryboats, car ferries and so on are equipped with side thrusters. However, at present, there does not exist a definite method to design the side thruster adequate for a particular ship. Therefore, the designer himself must estimate

a) the capacity of a side thruster necessary for the typical maneuvering of a particular ship

and also he must determine

b) the principal particulars of the duct and impeller system by taking account of the effects of such principal particulars on the fundmental characteristics of the side thruster.

To provide the basic data for the design and production of excellent side thrusters, the fundamental characteristics and operating performance of side thrusters were investigated and were published. Some of them will be quoted here, the list of which is found at the end of this paper.

II. Fundamental characteristics of the impeller and the duct system

The side force which is generated by a side thruster and acts on the ship's hull consists of two parts, one of which is the thrust of impeller itself and the other is the axial force of the duct. Therefore, it is necessary to consider the effects of the duct system and the effects of the principal particulars of the impeller separately. For this purpose, the thrust of the impeller and the axial force of the duct should be measured separately as shown in Figure 1 [1]*. The thrust of the impeller is picked up by the thrust and torque dynamometer⑤ and at the same time the axial force acting on the duct block is measured by the axial force dynamometer⑥.

As the fatcors which have influence on the fundamental characteristics of side thrusters, the following items should be considered.

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* Number in the bracket designates the reference at the end of this paper.

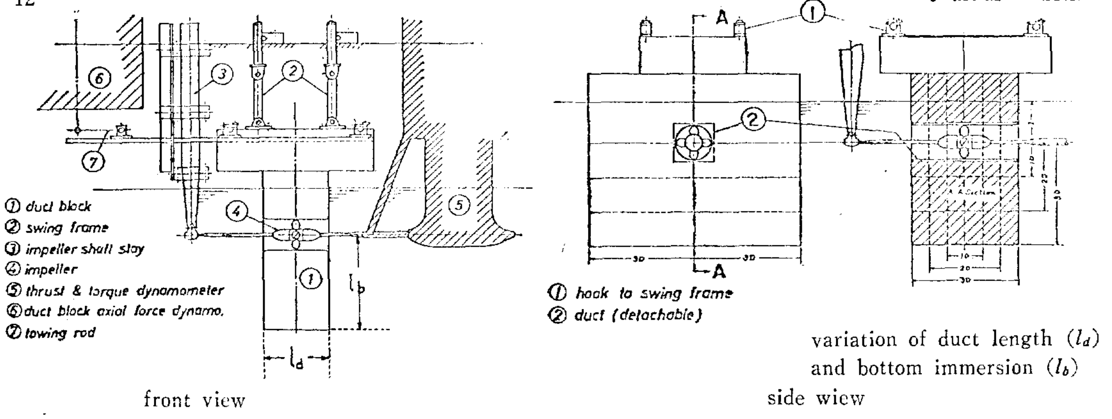


Fig. 1. Arrangement of the tests to investigate the fundamental characteristics of the impeller and the duct system (1).

(1) Duct system
- a) the height of the duct above the keel.
- b) the length of the duct.
- c) the corner radius of the duct entrance.
- d) the clearance between the inner wall of the duct and the tip of the impeller blade.
- e) the inner shape of the duct; parallel, convex or concave.
- f) the number of the guide vanes.
- g) the number of the grids.
- h) the inclination of the hull surface at the inlet and outlet of the duct.

(2) Principal particulars of the impeller
- a) the blade contour; ordinary type or Kaplan type.
- b) fixed pitch or controllable pitch.
- c) the blade area.
- d) the boss ratio.

The series tests to investigate the effects of the above stated items on the fundamental characteristics of the impeller and the duct system were conducted at the Experimental Tank of Mitsbishi Heavy Industries Co. Ltd., under the guidance of the 59th Research Committee of the Shipbuilding Research Association of Japan[1]. In what follows, some of the useful test results will be cited from the committee report.

The impellers were installed in a simplified duct shown in Figure 1, where the standard dimensions of the duct are as follows unless any particular modification is made;

duct length : 2.0 D (D:diameter of the impeller=200 mm)
diameter of the duct : 203 mm(namely, the tip clearance is equal to 1.5mm)
vertical distance between the water surface and the center of duct : 1.25 D
vertical distance between the center of duct and the keel : 3.0 D
corner radius : 10mm
horizontal length of duct block : 6.0 D

The results of experiments are represented in the form defined just below;

impeller thrust	T(kg)	$C_T=\dfrac{T}{\rho n^2 D^4}$
axial force of duct	F(kg)	$C_F=\dfrac{F}{\rho n^2 D^4}$
impeller torpue	Q(kg-m)	$C_Q=\dfrac{Q}{\rho n^2 D^5}$
resultant side force	$T+F$(kg)	$C_{TF}=\dfrac{T+F}{\rho n^2 D^4}$
efficiency	η	$\eta=\dfrac{(C_{TF}/\pi)^{1.5}}{C_Q}$

where n and ρ stand for the number of revolution per second and the density of the water respectively. Here, it should be noted that the above definition of efficiency is not exact, because the effective horse power of a side thruster cannot be defined strictly.

In Figure 2 is shown the effects of the bottom immersion, namely the effects of the height of the duct above the keel on the impeller thrust T, the axial force of the duct F, and the resultant side force T+F. The impeller used at the experiments is of the ordinary type, and the principal particulars of the impeller are as follows;

diameter (D) : 200mm
pitch ratio at 0.7 R : 0.750
expanded area : 0.01414(m^2)

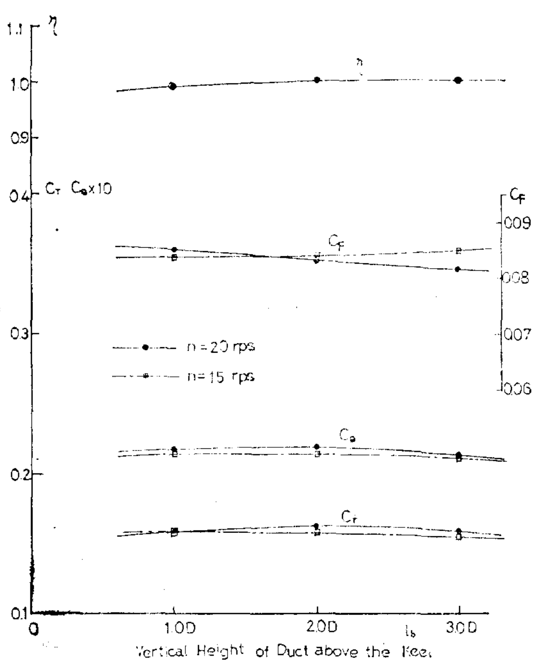


Fig. 2. Effects of the vertical height of the duct above the keel on the fundamental characteristics of side thrusters (1).

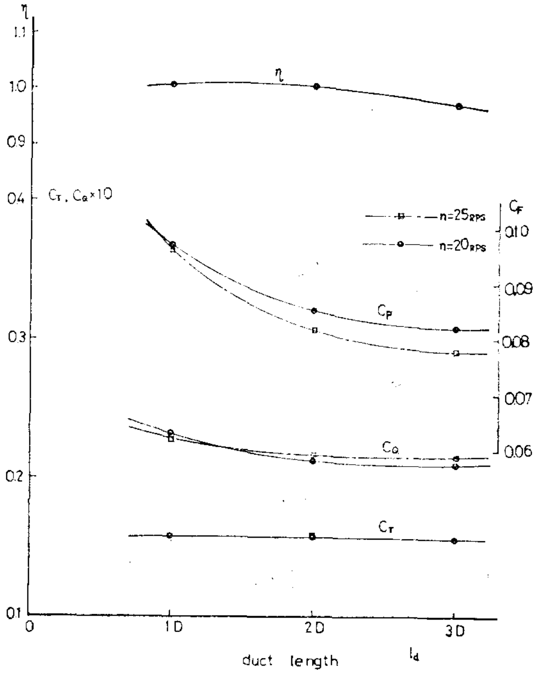


Fig. 3. Effects of the duct length on the fundamental characteristics of side thrusters (1).

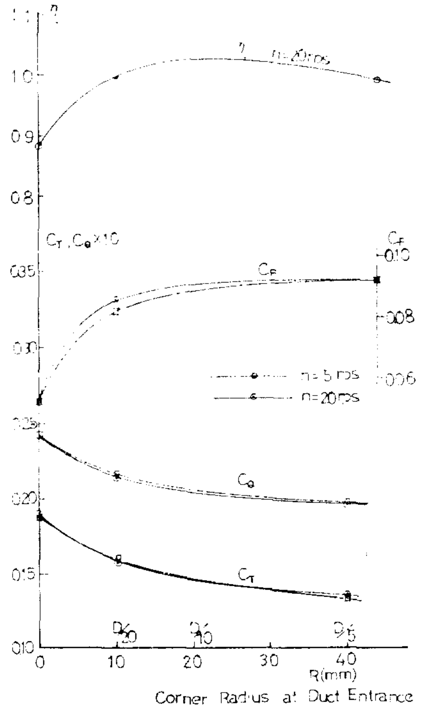


Fig. 4. Effects of the corner radius of the duct entrance on the fundamental characteristics of side thrusters (1).

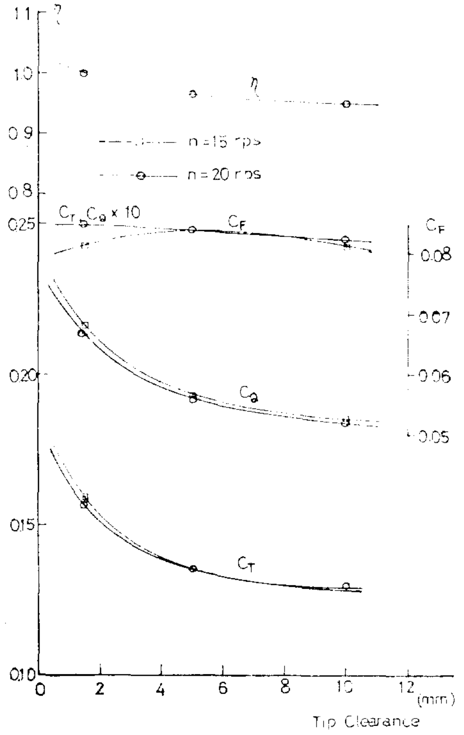


Fig. 5. Effects of the tip clearance on the fundamental characteristics of side thrusters (1).

expanded area/disc area : 0.450
boss dia./D : 0.400
blade section : aerofoil(symmetric)
number of blades : 4

This impeller was used throughout the series tests to investigate the effects of the duct system.

From Figure 2, it can be concluded that the coefficients C_T, C_Q and C_F are almost constant for the bottom immersion ranging from 1.0 D to 3.0 D.

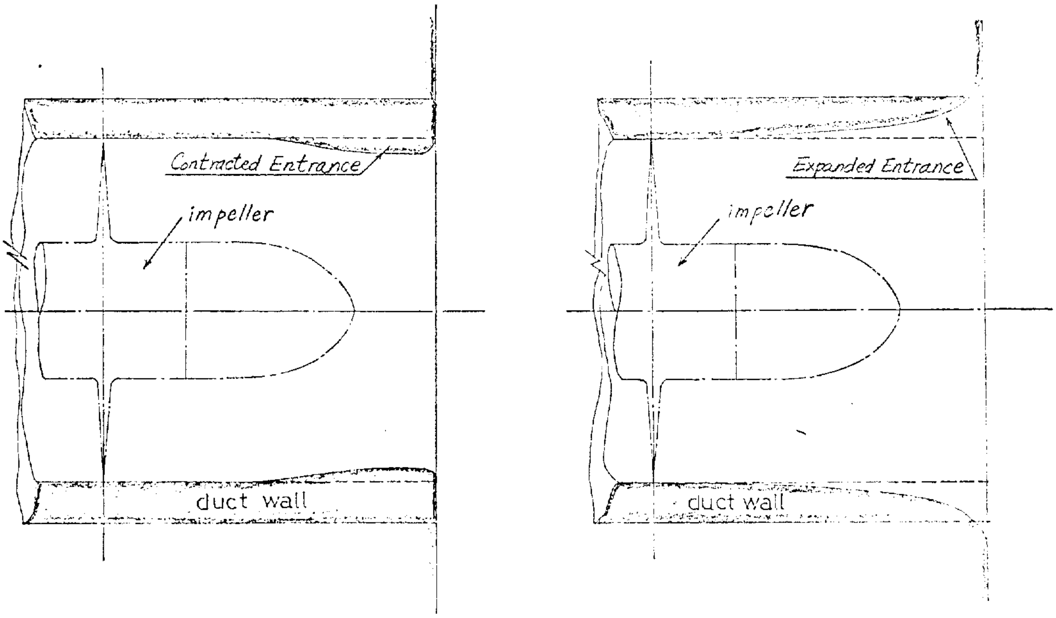
The effects of the duct length on the fundamental characteristics of a side thruster are shown in Figure 3, which tells us that C_T is almost constant in despite of the duct length but C_F and C_Q decrease with increase of the duct length so that the efficiency η decreases with the duct length.

Figure 4 shows the effects of the corner radius of the duct entrance. From this figure, it can be deduced that the separation of the flow generated at the duct entrance because of the small corner radius diminishes considerably the efficiency of the side thruster.

The effects of the tip clearance of the coefficients C_T, C_Q, C_F and η are shown in Figure 5. Namely, the impeller's thrust and torque decrease as the tip clearance increases, and moreover the axial force as well decreses, but slightly compared with the thrust and the torque.

In order to examine the effects of the inner shape along the centerline of the duct, two kinds of the duct, besides the standard duct, are added to the series test which are called as the convex duct and the concave duct in what follows (see Figure 6). The sectional area of the duct tube of the convex duct increases near the inlet and the outlet, but the concave duct has almost the same sectional area along the centerline of the duct. Comparing the test results, it can be concluded that the concave duct has the largest C_T and C_Q coefficients, and the standard duct, that is to say the parallel duct is in the second rank, so that the convex duct is the worst. However, from the viewpoint of the efficiency, the standard duct is the best, and the convex duct is remarkably worse compared with the others(see Figure 7).

To examine the effects of the number of guide vanes on the fundamental characteristics, the tests were conducted under the condition that both the lateral projected area and the blockage area of the guide vanes are kept unchanged even if the number of guide vanes is varied. As a result, it was verified that there



Concave duct ***Convex duct***

Fig. 6. Concave duct and convex duct (1).

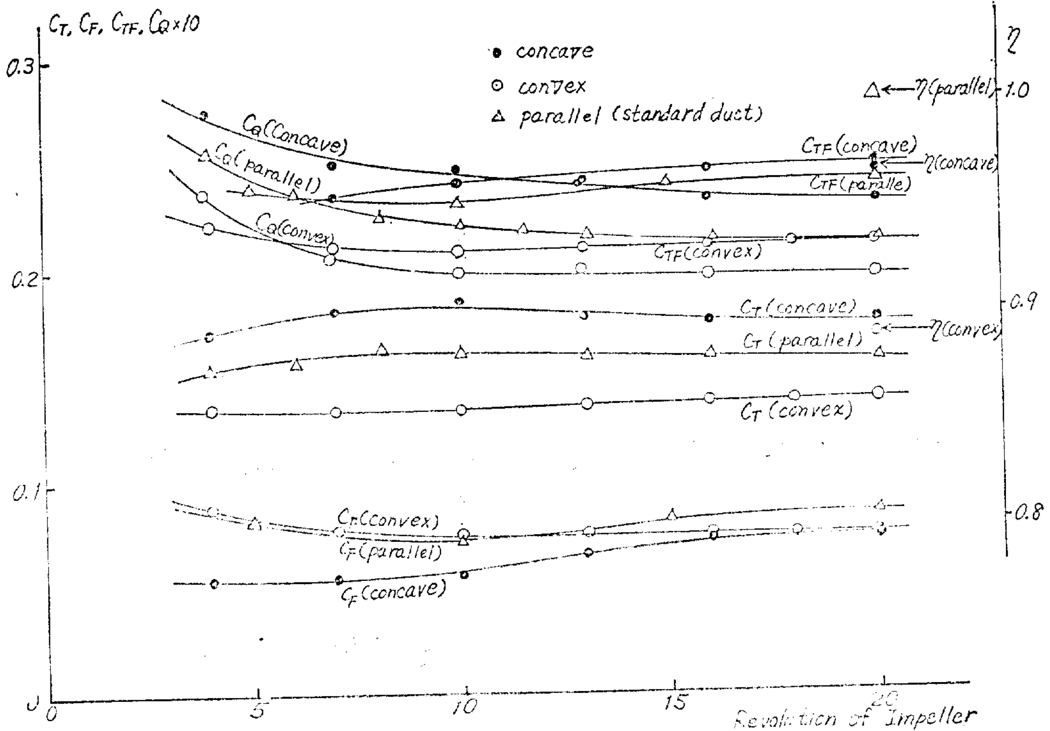


Fig. 7. Effects of the inner shape of the duct tube on the fundamental characteristics of side thrusters (1)

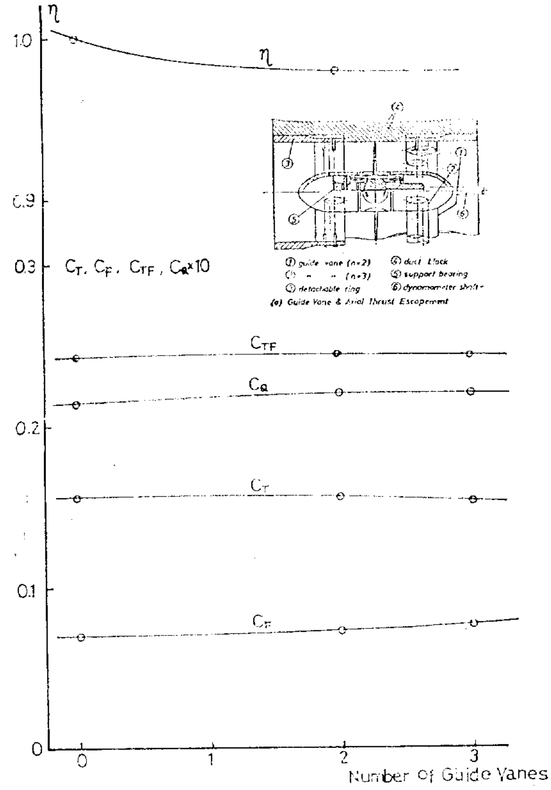
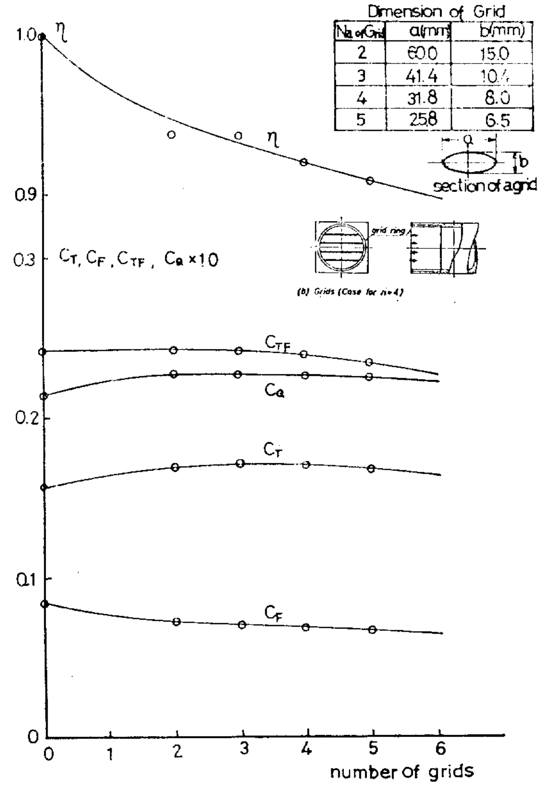


Fig. 8. Effects of the number of guide vanes on the fundamental characteristics of side thrusters(1)


Dimension of Grid

No. of Grid	a(mm)	b(mm)
2	60.0	15.0
3	41.4	10.4
4	31.8	8.0
5	25.8	6.5

Fig. 9. Effects of the number of grids on the fundamental characteristics of side thrusters (1)

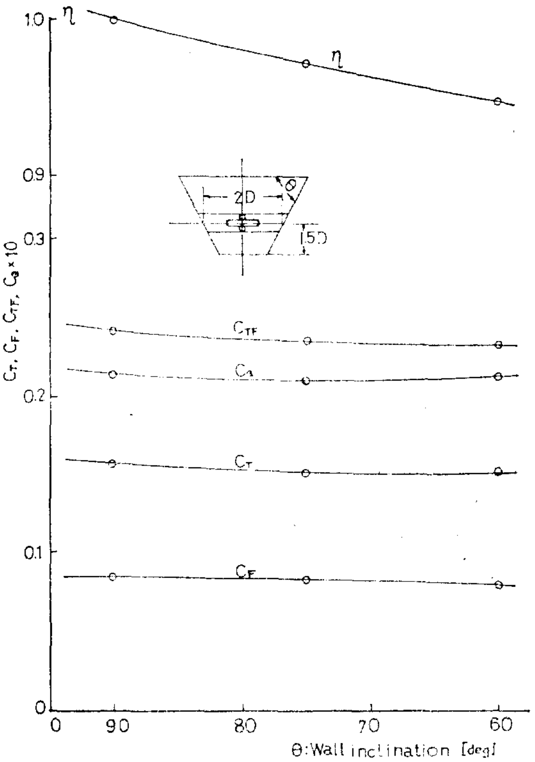


Fig. 10 Effects of the wall inclination on the fundamental characteristics of side thrusters (1)

did not seem to exist any definite difference of the fundamental characteristics due to the number of guide vanes(see Figure 8). Similarly under the condition of the same blockage area, the effects of the number of grids were examined. According to Figure 9, it is obvious that the increase of the number of grids diminishes slightly both the thrust and the torque of impeller, but the axial force of the duct decreases definitely so that the efficiency decreases remarkably with increase of the number of grids. Figure 10 shows the effects of the inclination of the hull surface at the duct entrance on the characteristics of side thrusters.

Figures 11 and 12 are comparison of the characteristics of impeller itself between the blade contour of the ordinary type, namely the elliptic blade contour and that of Kaplan type. The abscissa of both figures stands for the pitch ratio at 70% of the radius. From these figures, it is obvious that the impeller of Kaplan type has the bigger C_T, C_Q and C_F coefficients than the impeller with the elliptic blade contour does. This fact means that the thrust generated by the impeller

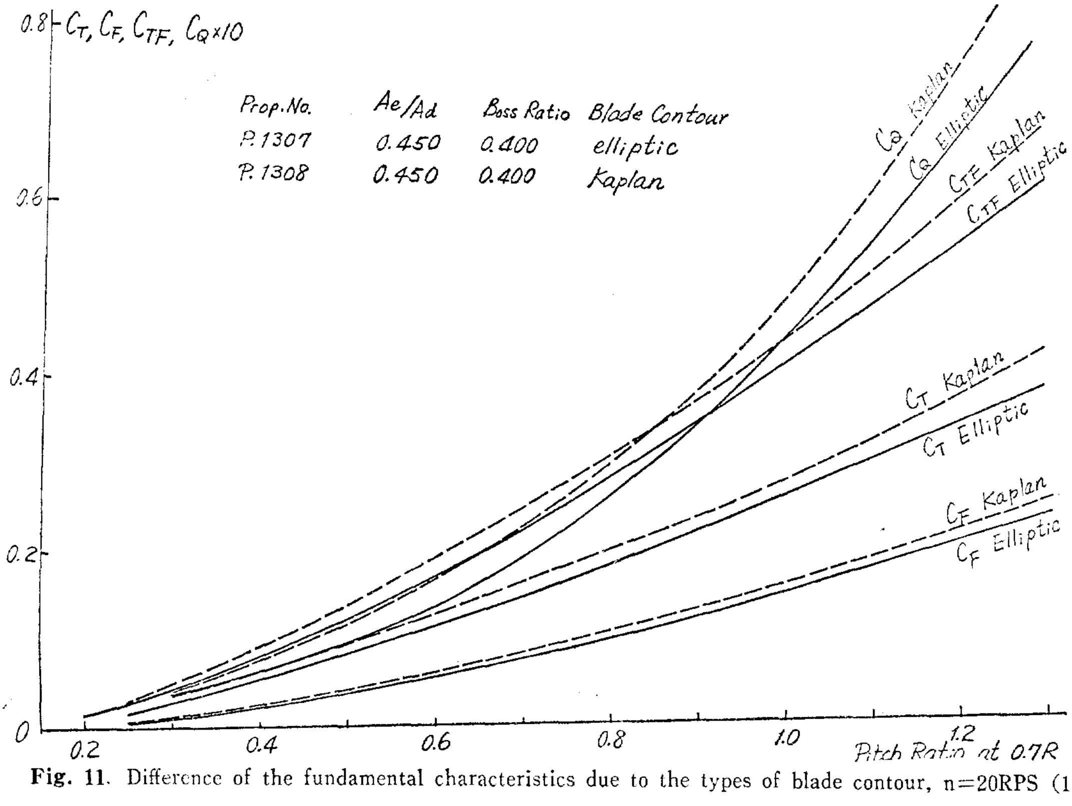


Fig. 11. Difference of the fundamental characteristics due to the types of blade contour, n=20RPS (1)

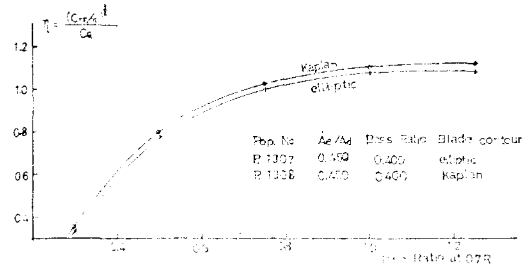


Fig. 12. Efficiency of the impeller with Kaplan blade or elliptic blade, n=20RPS (1).

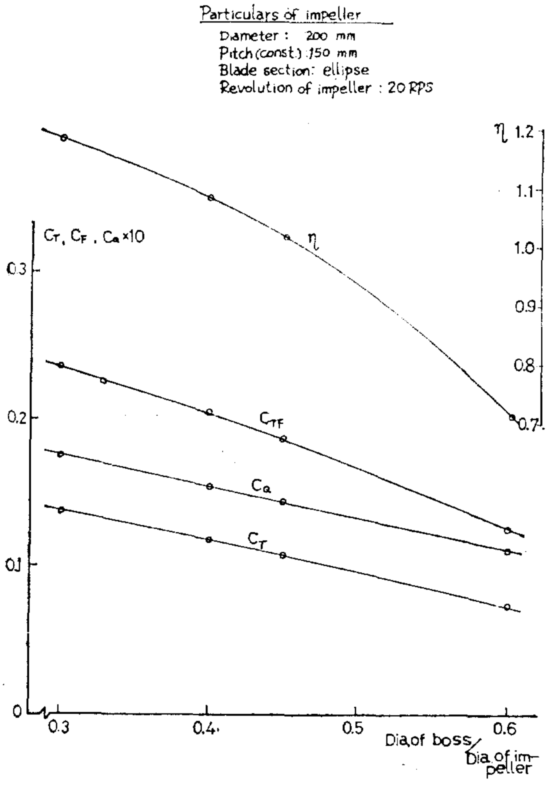


Fig. 14. Effects of the boss ratio on the fundamental characteristics of an impeller with elliptic blade contour (1).

of Kaplan type is greater than the impeller with the elliptic contour. Moreover, the efficiency of Kaplan impeller is better than the ordinary impeller.

In Figure 13 are shown the effects of the expanded area ratio on the efficiency of an impeller with Kaplan type blades. Among three impellers with different expanded areas, the impeller with the largest expanded area ratio, to say 0.600 is the worst from the viewpoint of the efficiency. Figure 14 shows the effects of

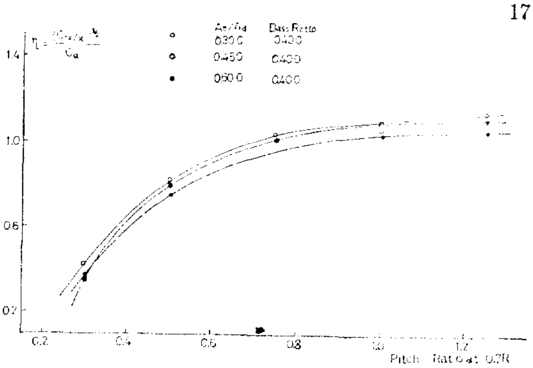


Fig. 13. Effects of the expanded area ratio on the efficiency of an impeller with Kaplan type blades, n=20RPS (1).

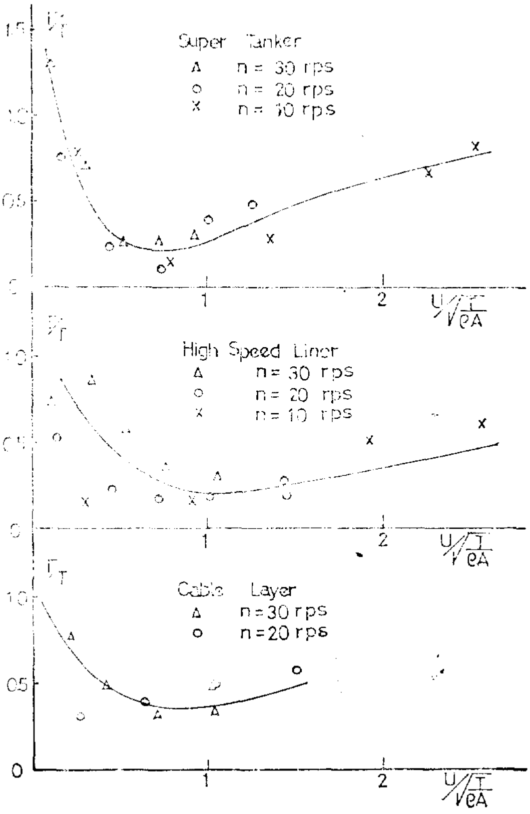


Fig. 15. Effects of the ship's speed on the resultant side force F acting on the ship's hull (1). Here, it should be noted that F of this figure corresponds to the resultant side force T+F of Figure 2 to Figure 14.

the boss ratio on the characteristics of the impeller with elliptic blade contour.

III. Operating performance of side thrusters

Besides the fundamental characteristics of side thr usters, some considerations should be paid with respect to performance of side thrusters under the various situations. Among others, the items stated just below are important;

a) the influence of ship's speed on the side force generated by side thrusters,

b) the effects of the restricted water surface and the restricted water depth on the effectiveness of side thrusters,

c) the additional resistance derived by opening the duct of side thruster on the ship's hull under the water surface, etc..

It is well recognized that the effectiveness of side thrusters is fully realized when the ship does not have advance speed. On the contrary, it is said that the effectiveness of side thrusters decreases with increase of the ship's speed. One of the reasons why the effectiveness of side thrusters gets worse when the ship has advance speed is that the side force generated on the ship by a side thruster is decreased by the longitudinal motion of a ship. Besides, the decrease of the effectiveness of side thrusters can be explained by considering the fundamental characteristics of maneuvering motion of ships.

In order to confirm the former reason, the captive model tests is suitable; the side force and the turning moment acting on the ship are measured directly while the ship's model is at rest or advance steadily with the rudder amidiship.

On the other hand, in order to investigate the latter reason, the free-running model test is suitable; the turning ability of ships is measured and is compared when a ship is turned by the rudder or by the side thruster.

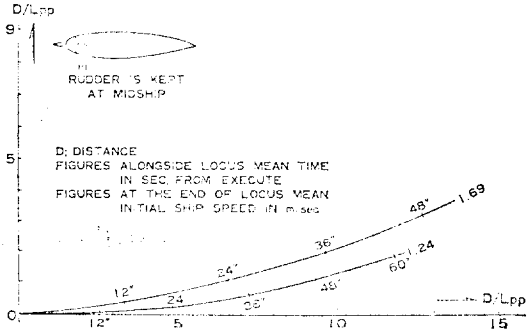


Fig. 16. Adverse turning of the ship's model against the direction of turning moment of the stern thruster (4).

Especially for the purpose of clarifying the speed dependence of the effectiveness of side thrusters, it is very important that the thrust of impeller and the resultant side force acting on the ship's hull should be measured separately. According to the series tests conducted by the 59th Research Committee above cited, it can be concluded that the thrust itself of impeller remains almost unchanged inspite of the existance of ship's speed. However, the resultant side force acting on the ship's hull is considerably affected by the ship's speed. In general, the resultant side force of the bow thruster is diminished by the longitudinal motion of ships. In Figure 15 are shown the effects of ship's speed on the resultant side force of bow thrusters for three different types of ships. The abscissa stands for the ratio of the ship's speed to the speed of the water spouted out of the bow thruster, where T, A and ρ stand for the thrust of impeller, the sectional area of the duct and the density of the water respectively. The strong dependence of the resultant side force F on the ship's speed is explained by Chislett [2] and Inoue and Kijima [3] as the interference between the jet flow spouted out of the bow thruster and the main flow.

On the contrary, the effect of the ship's speed on the effectiveness of the stern thruster is not definite or is not unique. According to the free-running model

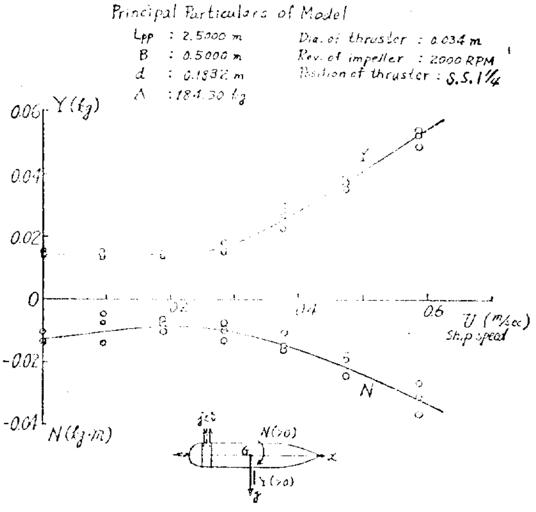


Fig. 17. Effects of the ship's speed on the force and the moment generated by the stern thruster (5).

tests conducted by Okamoto and others [4], it can be deduced that the turning moment due to the stern thruster may change its direction when ship's speed is high. Because the locus of the center of gravity of the model showed that the model was forced to turn against the direction in which the ships was turned by the stern thruster when it was at rest(see Figure 16). On the other hand, there exists an experimental result obtained by the captive model test, which shows that the turning moment of the stern thruster does not change its direction at high speed and the effectiveness of stern thruster increases as the ship's speed increases(see Figure 17) [5]. Therefore, it is necessary to continue to investigate the speed dependence of stern thrusters both experimentally and theoretically.

The decrease of the effectiveness of side thrusters, for instance, bow thrusters can be explained by the kinematic consideration on the forces acting on the ship's hull: roughly speaking, the hydrodynamic force acting on the ship's hull under the water surface is proportional to the square of the ship's speed, but the resultant side force due to the bow thruster is at most of the same order independently of the ship's speed, so that the effectiveness of the bow thruster decreases relatively as the ship's speed increases.

Moreover, there is another aspect to be considered on the effectiveness of the bow thruster [6]. Under the assumption that the side force of the bow thruster remains constant independently of the ship's motin, namely the ship's speed, drifting velocity and turnng rate, the maneuvering equations of motion can be approximated by simple linear equation as follows;

$$-(m'+m_y')\frac{d\beta'}{dt'}=Y_\beta'\beta'+(Y_r'-m')r'+Y_b' \qquad (1)$$

$$(I_{zz}'+J_{zz}')\frac{dr'}{dt'}=N_\beta'\beta'+Nr'r'+N_b' \qquad (2)$$

where Y_b' and N_b' stand for side force and the turning moment due to the bow thruster respectively, and the prime(′) means the non-dimensional quantities, and moreover β' and γ' stand for the drift angle and the yaw angular velocity of a ship respectively. Then, the turning rate of ship r' is determined by the equation

$$r'=\frac{Y_b'Y_\beta'\left(\frac{N_\beta'}{Y_\beta'}-\frac{N_b'}{Y_b'}\right)}{Y_\beta'N_r'-N_\beta'(Y_r'-m')}\left[1+\left(1+\frac{\lambda_1'D'}{E'}\right)\frac{\lambda_2'e^{\lambda_1't'}}{\lambda_1'-\lambda_2'}\right.$$

$$\left.-\left(1+\frac{\lambda_2'D'}{E'}\right)\frac{\lambda_1'e^{\lambda_2't'}}{\lambda_1'-\lambda_2'}\right] \qquad (3)$$

where $D'=-(m'+m_y')N_b'$ and $E'=N_\beta'Y_b'-Y_\beta'N_b'$, and $\lambda_1'$and λ_2' (which are assumed to be real) are two solutions of the algebraic equation $-(m'+m_y')(I_{zz}'+J_{zz}')\lambda'^2+[(m'+my')N_r'-Y_\beta'(I_{zz}'+J_{zz}')\lambda'+Y_\beta'N_r'-N_\beta'(Y_r'-m')=0$.

From this equation, it is obvious that the steady turning rate achieved under the constant side force Y_b' and the constant turning moment N_b' is proportional to the difference between N_β'/Y_β' and N_b'/Y_b', which stand for the position of application of the sway damping force and the hydrodynamic center of the side force of the bow thruster respectively. Consequently, it can be deduced that the bow thruster is in general less effective than the stern thruster, which is the very reason why the stern rudder is more effective the bow rudder, and that the direction of steady turning which is reached after infinite lapse of time is determined by the sign of the difference between

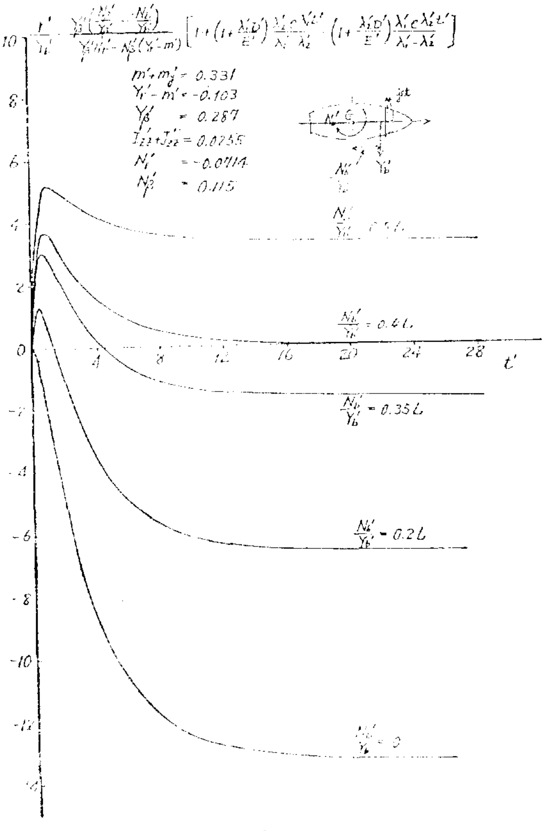


Fig. 18. Time history of turning rate under the operation of bow thruster [6].

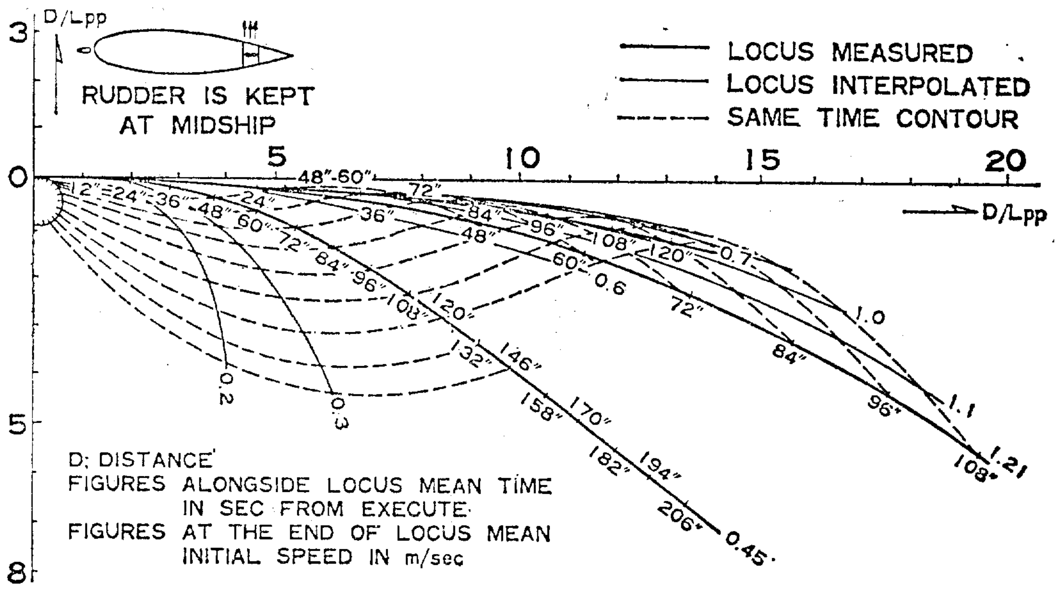


Fig. 19. Locus of the center gravity of an oil-tanker model when when it is turned by the bow thruster (4).

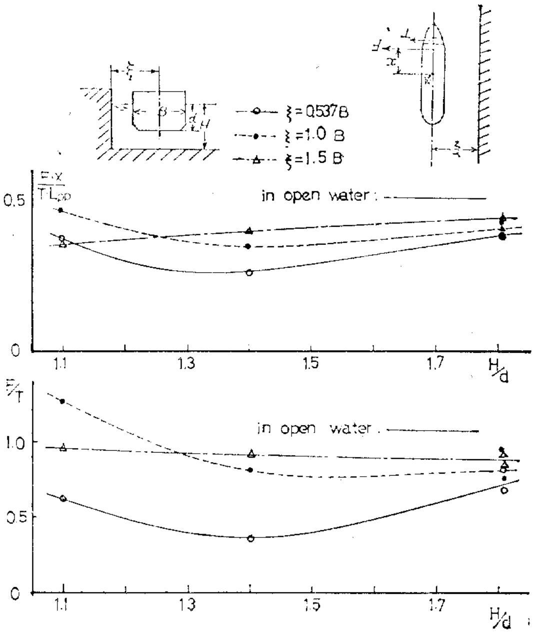


Fig. 20. Effectiveness of the bow thruster in the proximity of the wall and the bottom [1].
(F: resultant side force including the thrust of impeller, T: thrust of impeller)

N_β'/Y_β' and N_b'/Y_b'. The time history of the turning rate under the operation of bow thruster is shown in Figure 18 for the various cases of the position of the hydrodynamic center of the side force of the bow thruster. It is interesting that in the case when the hydrodynamic center of bow thruster, namely N_b'/Y_b' is positive and is nearer to the midship than the point of application of the sway damping force, the ship, at first, begins to turn to the starboard but then it changes the direction of turning, namely to the port.

In Figure 19 is shown the locus of the center of gravity of an oil-tanker model of which the length between perpendiculars is equal to 6m, when it is turned by only the bow thruster[4]. This figure supports the fact found by the captive model tests, namely Figure 15, that the effectiveness of the bow thruster diminishes with increase of the ship's speed but when the ship's speed gets higher, the bow thruster recovers its effectiveness.

The effects of the solid wall and the shallow water on the operating performance of the bow thruster are shown in Figure 20. According to this figure, it can be concluded that roughly speaking, the shallow water effect is relatively small compared with the wall effect.

It is anticipated that the duct opening on the hull surface increase the resistance of a ship. Hence, some experiments were conducted by using three kinds of ships in order to investigate the effects of the duct opening on the resistance[1]. A high speed liner whose block coefficient is equal to 0.6066 does not show the resistance increase derived by the duct opening, but the resistance of a cable layer, of which C_b is equal to 0.6138, with the duct opening is larger by 4% than that without the duct opening. The resistance of the tanker model, of which C_b is equal to 0.7848, was increased by 10% at the low speed and by 5% at the high speed respectively compared with the resistance in case of no duct opening. Therefore, it is deduced that the effect of the duct opening on the resistance is much dependent of the fullness of ships.

IV. Determination of the capacity of side thrusters

There exist some design criteria useful for determ-

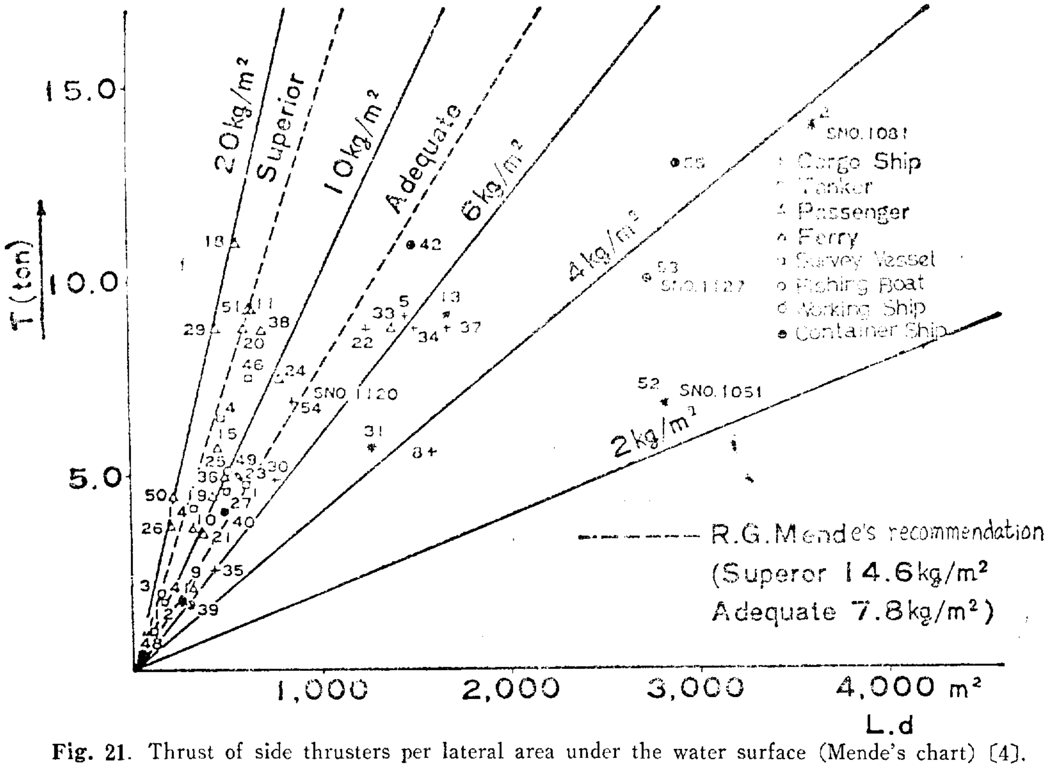


Fig. 21. Thrust of side thrusters per lateral area under the water surface (Mende's chart) [4].

Table 1. A List of Existing Ships with Side Thrusters

S. No.	SHIP KIND	L_{pp}(m)	B(m)	d(m)	A_U(m^2)	A_L(m^2)	T(ton)	⊠S(m)
1	training ship	105.00	16.00	5.80	944.5	609.0	4.7	41.3
2	tanker	262.13	41.44	14.00	2132.3	3631.3	14.0	117.3
3	fishing boat	43.10	9.00	3.50	97.6	150.9	2.0	17.1
4	survey vessel	86.00	14.80	5.50	644.6	473.0	6.5	34.2
5	cargo ship	152.40	23.47	9.60	1356.6	1463.0	9.1	49.4
8	cargo ship	160.02	24.23	9.93	972.0	1589.1	5.7	66.0
9	ferryboat	84.00	15.80	3.73	891.1	313.3	2.1	33.6
10	passenger ship	82.00	13.40	3.90	828.4	319.8	3.6	31.2
11	ferryboat	123.00	17.90	5.20	1427.5	639.6	9.3	44.5
12	survey vessel	45.00	9.20	3.75	203.6	168.8	1.9	16.6
13	tanker	172.35	25.50	9.80	1857.9	1680.0	9.1	73.2
14	survey vessel	66.68	11.75	5.00	510.0	331.0	4.4	18.4
15	ferryboat	84.00	16.20	5.35	975.0	450.0	5.7	31.0
18	passenger ship	108.50	19.50	5.20	1650.0	570.0	11.0	40.9
19	car ferry	108.00	17.60	3.95	1290.0	428.0	4.5	41.5
20	ferryboat	130.00	17.70	4.60	1020.0	596.0	8.8	54.2
21	ferryboat	96.50	15.90	3.82	1065.0	368.0	3.5	35.0
22	cargo ship	153.90	22.40	8.20	1870.0	1250.0	8.8	49.0
23	cargo ship	107.00	16.28	5.00	985.0	535.0	4.9	46.0
24	car ferry	123.50	21.50	6.45	1890.0	790.0	7.5	44.4
25	working ship	85.00	16.00	5.80	372.0	492.4	5.1	34.6
26	car ferry	63.00	12.60	3.15	444.4	198.5	3.7	20.6
27	survey vessel	82.00	15.00	5.73	522.5	470.0	4.6	27.7
29	car ferry	99.00	17.25	4.60	1331.8	455.7	8.8	33.8
30	cargo ship	107.65	16.17	7.01	699.2	754.5	4.9	45.9
31	tanker	148.00	20.90	8.60	864.0	1272.8	5.7	62.5
33	passenger ship	167.64	24.30	8.23	2940.9	1380.0	8.8	70.0
34	cargo ship	156.67	23.17	9.62	1544.2	1507.0	8.8	66.0
35	cargo ship	85.34	13.87	5.08	491.1	433.7	2.6	35.3
36	ferryboat	98.20	18.80	5.05	1513.2	496.0	5.0	34.4
37	cargo ship	196.70	22.86	8.54	1521.3	1680.0	8.8	86.5
38	P/C ferry	125.00	19.30	5.50	1539.5	687.5	8.8	46.8
39	container ship	68.00	13.00	4.22	439.7	286.9	1.7	25.9
40	container ship	111.60	16.20	4.30	661.7	479.9	4.1	46.8
41	container ship	71.00	13.00	3.72	339.2	264.1	1.8	29.9
42	container ship	183.71	26.40	8.23	2588.6	1512.0	10.9	88.1
46	survey vessel	120.00	16.00	5.20	1128.3	624.0	7.5	47.1
48	survey vessel	35.00	7.40	2.60	100.0	90.8	1.5	12.5
49	container ship	103.00	17.00	4.90	953.3	504.7	5.0	41.0
50	passenger ship	63.00	13.50	3.60	553.6	226.8	4.5	25.6
51	ferryboat	123.00	17.90	5.20	1515.0	639.6	9.3	45.0
52	tanker	235.00	36.50	12.00	2243.9	2830.0	6.8	107.75
53	container ship	168.00	25.00	8.23	1789.5	2750.0	10.0	66.85
54	cargo ship	134.50	20.40	6.37	1267.4	856.0	6.9	59.55
55	container ship	265.00	32.00	10.97	4200.0	2910.0	13.0	100.50

A_L: lateral area under under the water line($L_{pp}\times d$) A_U: lateral area above the water line

T : Thrust of side thruster   ⊠S: distance between midship and side thruster ination of the necessary capacity of side thrusters. In what follows, some of them will be introduced[4].

1) Mende's method

One of the most primitive methods is called as Mende's method. Mende analyzed a lot of the existing data of ships equipped with side thrusters by dividing the thrust T of a side thruster with the lateral area below the water surface, namely $Lpp \cdot d$. Figure 21 is an example of Mende's chart, in which about fourty-five examples(see Table 1) are plotted together with Mende's recommendation lines "superior" and "adequate". According to Mende, the thrust per area of the "adequate thruster" is 7.8kg/m^2 and that of the "superior thruster" is 14.6kg/m^2. These values recommended by Mende can provide a designer with a rough criterion of the capacity of side thruster appropriate for a certain ship, but they lack the reasonable background.

2) Capacity of side thrusters necessary to overcome the wind force

One of the reasons why the side thruster is now widely used is that the side truster enables ships to drift against the wind force. Accordingly, the capacity of side thrusters can be determined to overcome both the wind force acting on the hull above the water surface and the water pressure acting on the hull under the water surface. Provided that the side thruster sustains a half of the sum of the wind force and the water pressure, the necessary capacity of the side thruster is given as follows;

$$T=\frac{1}{2}\left(\frac{1}{2}C_{DU}\rho_a A_U U^2+\frac{1}{2}C_{DL}\rho_w A_L V^2\right) \cdots\cdots\cdots\cdots\cdots (4)$$

where

T: thrust of side thruster(kg).

C_{DU}, C_{DL}: drag coefficients of the ship's structure above and under the water surface respectively.

ρ_a, ρ_w: density of the air and the water respectively(kg sec^2/m^4).

A_U, A_L: the lateral area of the ship above and under the water surface respectively(m^2).

U, V: the wind velocity and the drifting speed of the ship respectively(m/sec).

As an adequate value of the drifting speed of ships, 0.25m/sec will be used at the calculation of the necessary capacity of side thrusters. In Figure 22 are plotted the T/A_U values of the ships listed in Table 1 gainst the ratio A_L/A_U. By using this figure, it is possible to determine the capacity of side thruster if the wind velocity which should be overcome by side thruster is given a priori.

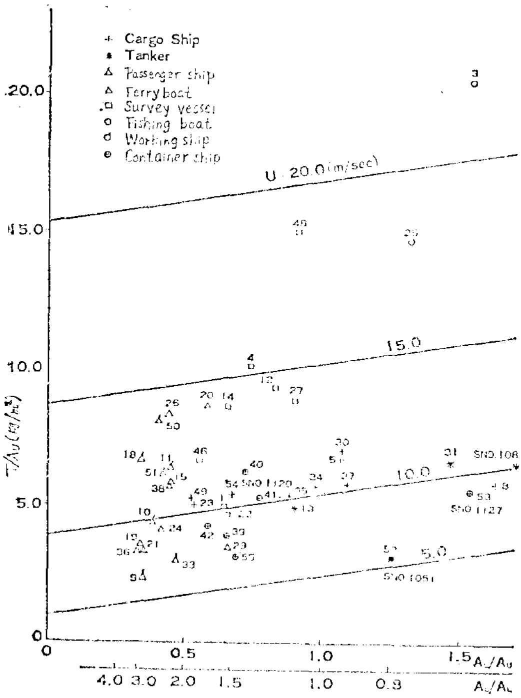


Fig. 22. Capacity of side thrusters necessary to overcome the wind force [4].

The data of the existing side thrusters which are plotted in this figure show that the critical wind velocity for the ship of a particular type is classified as follows;

for cargo ships(including container ships): 8~12m/sec
for passenger ship and ferryboat : 6~14m/sec
for oil-tankers : 10m/sec
for survey vessels : 10~19m/sec

3) Angular velocity of turning achieved by side thruster

Another criterion to determine the capacity of side thrusters is the time necessary for a ship to turn 360 degrees when the ship does not have advance speed. Assuming that the flow around the ship's hull is two-dimensional, namely, parallel to a plane normal to the longitudinl axis of the ship, the drifting speed v and the turning rate r at the midship are determined by solving the equations describing the balance of the

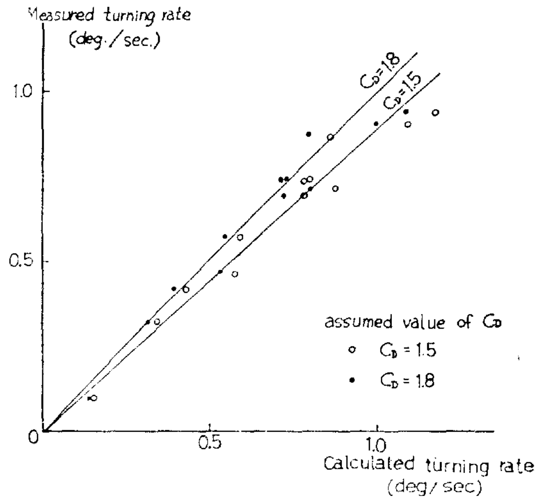


Fig. 23. Determination of drag Coefficient C_D appropropriate for estimating the turning rate by means of the equations (5) and (6).

lateral force and the turning moment acting on a ship respectively

$$T=\int_{-L/2}^{L/2}\tfrac{1}{2}C_D(x)\rho_w d(x)(v+rx)|v+rx|dx\cdots\cdots(5)$$

$$T\cdot l=\int_{-L/2}^{L/2}\tfrac{1}{2}C_D(x)\rho_w d(x)(v+rx)|v+rx|xdx\cdots(6)$$

where C_D and d denote the drag coefficients of a two-dimensional body and the local draft, which are functions of the position of section considered and l is the distance between the bow thruster and the midship. However, in the following analysis, C_D and d are assumed to be constant for the sake of simplicity. Namely, $d(x)$ is substituted by the mean draft of a ship and $D_D(x)$ is assumed to be always equal to 1.8. This value of the drag coefficient was determined by adjusting the value of C_D so that the calculated turning rate may fit best the measured turning rate(see Figure 23).

Under the assumption stated just above, the turning rate of the ships listed in Table 1 are calculated and are shown in Figure 24, in which the abscissa is $\sqrt{Tl/dL_{pp}^3}$. According to this figure, it can be concluded that the above equations to determine the turning rate and the assumption made to solve them are legitimate because most of the existing ships with bow thruster concentrate in a narrow region. Therefore, if the desired turning rate is prescribed, it is possible to estimate the thrust of bow thruster necessary for a given ship to get the prescribed turning rate from Figure 24.

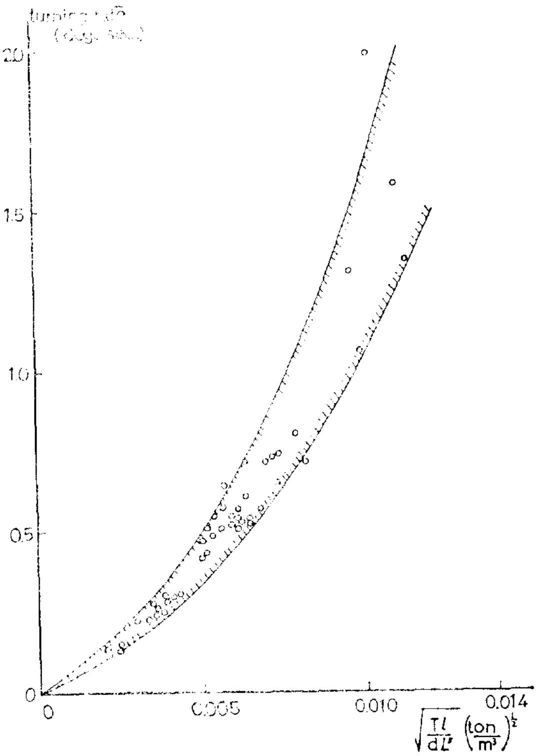


Fig. 24. Capacity of side thrusters necessary for a ship to get a pescribed turning rate.

V. Acknowledgement

Needless to say, this paper does not provide the complete design data of side thrusters, but it is hoped that this paper will help the ship-designer, especially when he designs the side thruster of a particular ship. In this conext I should like to express my sincere thanks to the Shipbuilding Research Association of Japan and Kawasaki Heavy Industries Co. Ltd., to which most of the contents of this paper are indebted.

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