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CALCULATION OF RUDDER FORCE

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CALCULATION OF RUDDER FORCE

(Berechnung der Ruderkraft)

by

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Abstract

In designing the rudder of a new ship, it is not the ratio of the inboard profile to the rudder area of the ship that should be used as a basis, but the ratio inboard profile to rudder force. The various factors governing the rudder force are given. The influence of the sectional form and the profile of the rudder and the influence of the position of the rudder with respect to the propeller race are investigated. By means of an example it is shown to what extent the rudder area can be lessened without decrease in rudder force, by selecting a suitable sectional form and distributing the total rudder area in multiple-screw ships among a number of rudders, located in the propeller race, corresponding to the number of propellers.

It has long been known that in designing the rudder of a new vessel the ratio of the inboard profile to the rudder area of similar ships can be adopted merely as a point of departure. The ratio of the inboard profile to rudder area may be taken as a basis only if the rudders of the ships under comparison have

1. the same profile (aspect ratio F/b^2),
2. the same sections,
3. the same position relative to ship and propeller race.

In order to be independent of these details of the individual rudder, the ratio of inboard profile to rudder force must be taken as the basis, - not the ratio of inboard profile to rudder area.

Detailed information on recent theories of rudder design is given in a paper by Kucharski presented at the 31st general meeting of the Schiffbautechnische Gesellschaft. In an excerpted dissertation by Fischer published in WRH, 1936, No. 7 to 11, a report is made on tests of full-scale ships and analysis of test data.*

No publication is known that takes into account the practical application of this knowledge in new designs. This is the object of this paper.

In order to define the scope of our problem, it is presupposed that for the present the rudder will be considered only in its characteristic function of bringing about and maintaining changes in course. The effect of the rudder in improving the propulsive efficiency will be considered only very briefly. Moreover, only the rudder force generated by the rudder (commonly known as "rudder pressure"), will be investigated, and not the torque on the rudder post (rudder moment), nor the output of the rudder engine. This will be done in a subsequent paper.

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*See EMB Translation No. 42.

For completeness, let us repeat that the resultant force R acting on a rudder is made up of lift and drag components, exactly as in the case of an airfoil. Since even in the most favorable instance the drag amounts to only a few per cent of the lift, it may be neglected in considering a design. Hereafter, therefore, only the lift force will be referred to as rudder force or rudder pressure.

The rudder force R amounts to

$$R = F\rho/2\, v^2(C_a + C_w);$$

C_w is neglected, whence

$$R = F\rho/2\, v^2 C_a$$

F is the rudder area in m^2,

ρ is the density of the water $[kg \cdot sec^2/m^4] = 102$,

v is the velocity of flow at the rudder $[m/sec]$,

C_a is the lift coefficient; non-dimensional, depending on the section form, aspect ratio of the rudder and the angle of incidence.

A rudder can be drawn when the following factors are known: Rudder area F, the shape of the sections, the aspect ratio F/b^2, and the balance and consequent energy requirement of the rudder engine.

In determining what will be the most suitable rudder for a given ship, we may proceed as follows:

For similar ships known to possess good steering qualities, the rudder pressures at maximum speed and for various angles of incidence are calculated from the known data for the rudder (area, section, aspect ratio). The velocity of flow v at the rudder can be assumed with sufficient accuracy from the location of the rudder relative to the ship and its propellers:- in the case of a rudder lying in the propeller race, approximately as the speed of advance of the propellers, and for other rudders, depending upon their disposition on the ship, as about 80 to 100% of the ship's speed (see 2 in bibliography).

The calculation is carried out according to the formula given above for the rudder force R. The lift coefficients for the various sections can be taken from the publications of the Aerodynamic Experimental Station at Göttingen (see 3 in bibliography).

Having determined the rudder forces of several ships with good steering qualities, it is possible to estimate what rudder force will be required of the new design.

In the subsequent calculation, the required rudder force R can therefore be considered as known. It is required to find the rudder area, the aspect ratio of this area, F/b^2, and the section form. We have,

$$F = \frac{R}{\rho/2\, C_a\, v^2}$$

Since R, by assumption, has a given value, and $\rho/2$ is known, this can be written:

$$F = f(\frac{1}{C_a} \cdot \frac{1}{v^2})$$

The requirement being to generate the greatest possible rudder force with the smallest possible rudder area, we shall consider to what extent the coefficient C_a and the velocity of inflow v can be influenced by permissible measures.

The Lift Coefficient C_a

The lift coefficient C_a depends upon: First, the angle of incidence of the section, second, the form of section and, third, the aspect ratio of the surface. In Fig. 1, the coefficient C_a has been plotted as a function of the angle of incidence for five different sections, which differ from each other only with regard to the thickness ratio d/t (d = greatest thickness of the section, t = chord length of the section). In Fig. 2 the coefficient C_a has been plotted for the Göttingen section No. 538 (d/t = 0.15), for various aspect ratios F/b^2.

(a) The Section Form d/t.

Fig. 1 shows that the maximum lift coefficients for sections with thickness ratios up to d/t = 0.20 increase, while for thicker sections than d/t = .20, they decrease again. The drag coefficients C_w for all sections have approximately the same value. From this it is evident that Göttingen section No. 539 may advantageously be used for rudders. To develop equal rudder forces, other values remaining the same, it would be possible, for example, to reduce the rudder area F_1 of a rudder with the section 539, as compared to the area F_2 of a rudder with the section 537, in the ratio of the lift coefficients $C_{a2}:C_{a1} = 0.70 : 1.16 = 0.60$. These are worth-while savings, which are the result solely of proper selection of the rudder section.

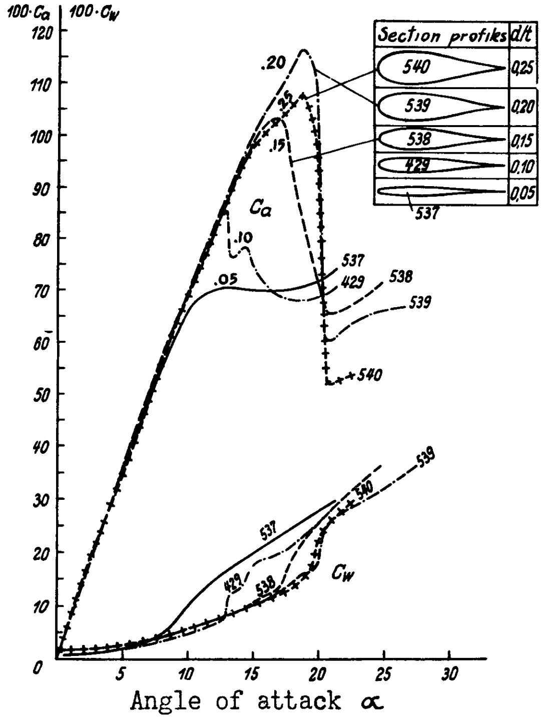

Fig. 1. Lift coeffients C_a for several sections.

(b) The Aspect Ratio F/b^2.

The constructor is not wholly free in the choice of the aspect ratio F/b^2; the draft of the ship and the shape of the afterbody impose restrictions. However, the smaller the required area, the less will be the effect of these restrictions in rudder design. Fig. 2 shows that in the case of narrow rudders ($F/b^2 = 0.2$) the maximum lift coefficients C_a are already attained at an angle of incidence of 17°, while in the case of wide rudders ($F/b^2 = 1.5$), these values are reached only at 41°. It is useless in steering a ship to use rudder angles in excess of the critical angle of incidence of the rudder, i.e., the angle at which C_a reaches its maximum, since then the flow separates from the rudder surface and violent shocks are transmitted to the steering gear (see 2 in bibliography, pp. 19–20).

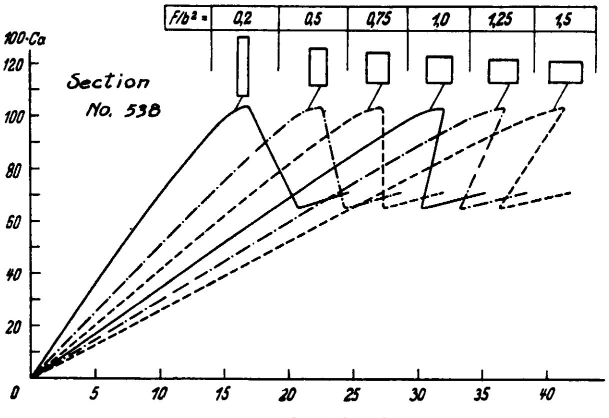

Fig. 2. Lift coefficients C_a for various aspect ratios F/b^2.

Narrow rudders as well as wide ones have their advantages and disadvantages, the relative magnitude of which is governed by the shape of the hull.

Since with narrow rudders the greatest rudder angles need be only half as large as with wide rudders, the steering gear requires less space. On the other hand, a ship with a narrow rudder steers less steadily because even at small rudder angles the rudder forces attained are about three times those of wide rudders. With extremely wide rudders ($F/b^2 = 1.5$), the high C_a-coefficients are not reached even at large rudder angles, since the angles of incidence on the rudder are considerably smaller than the rudder angles, because of the turning of the ship (see bibliography, 2, p. 11).

The best distribution of rudder area is obtained when F/b^2 is approximately 0.75 to 1.0, because with such rudders the rudder forces for small rudder angles used in normal steering do not increase too rapidly, yet large forces are developed at a rudder angle of 30 degrees.

The Velocity of Inflow v.

On the afterbody of a ship the velocity distribution is non-uniform. In the propeller race the velocity is greatest and in the layers of water near the shell plating it is least. The rudder forces on otherwise similar rudders, one of which is located directly behind a propeller and the other one amidships between the two propellers – as for instance on a twin-screw vessel – are proportional to the squares of the inflow velocities. Assuming that the slip in the case of heavily-loaded propellers is 25%, and that for the rudder not situated in the propeller race the wake is neglected and thus the velocity of inflow is equal to the ship's velocity, the rudder forces will be in the ratio of $1.25^2 : 1 = 1.56$.* This means that in order to get equal rudder forces, a rudder lying in the propeller race requires only $1/1.56 = 0.65$, i.e., 2/3 of the area of a rudder located outside the propeller race. Additional advantages of a rudder located in the propeller race are:

1. Large rudder forces are exerted even when the ship is not under way.
2. The turning of the ship reduces the angle of attack of the rudder to a smaller extent, since the propeller race is deflected only through about half as great an angle as the other water masses (see bibliography 2, pp. 12 and 18). Large rudder angles coincide therefore with high C_a values and large rudder forces, which cannot be obtained with rudders located outside the propeller race on account of the decrease in the angle of attack due to the turning of the ship.
3. In multi-screw ships.the revolutions of all propellers are changed alike when the rudder is put over, since the rudders located in the propeller race produce the same flow conditions for each propeller. This may be of advantage with respect to ship vibration.

Additional advantages will be discussed in the following.

Summary.

1. The most suitable section for rudders is section No. 539, since this section has the highest lift coefficients.
2. The most suitable aspect ratio is obtained when F/b^2 is approximately 1.0, but must be chosen to suit the special steering requirements of the type of ship in question.
3. It is advantageous to locate the rudders in the propeller race.

The extent to which the rudder area can be reduced will be demonstrated by an example in the following.

In addition to the advantages cited in the foregoing, placing the rudder in the propeller race has the further advantage that it effects an improvement in the propulsive efficiency, first because the rudder acts as a guide-vane and, second,

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*Editor's Note: This increase in effectiveness is questionable. It implies (a) that the wake is the same at the central and side rudder positions, and (b) that the flow is as uniform in the propeller race as it is amidships between two propellers. Neither assumption is justifiable. While some increase in effectiveness due to slip is reasonable, it is believed that the use of the full slip ratio may lead to an appreciable over-estimate of rudder effectiveness.

because it increases the pressure in the propeller race and thus retards cavitation on the propeller. Locating the rudder in the propeller race thus permits an increase in the economic loading of marine propellers.

Example.

In the following example it will be shown how the rudder force R can be calculated from the known rudder values, and what dimensions may be given the rudder in view of the foregoing statements, maintaining equal rudder forces.

(a) Completed Installation.

Twin-screw vessel; rudder amidships
Width of rudder $b = 3.5$ m
Height of rudder $t = 5.1$ m
Rudder area $F = 17.8$ m^2
Aspect ratio $F/b^2 = 1.46$
Section No. 411 (See Fig. 3)
Greatest rudder angle $\alpha_{max} = 38^\circ$
Lift coefficient for α_{max} $C_a = 0.72$
Ship's velocity $v_{sch} = 16$ m/sec
Velocity of inflow at rudder $v = v_{sch}$
Velocity of advance of the propellers of pitch H and rpm n $n/60.H = 20$ m/sec

From these values the greatest possible rudder force can be computed:

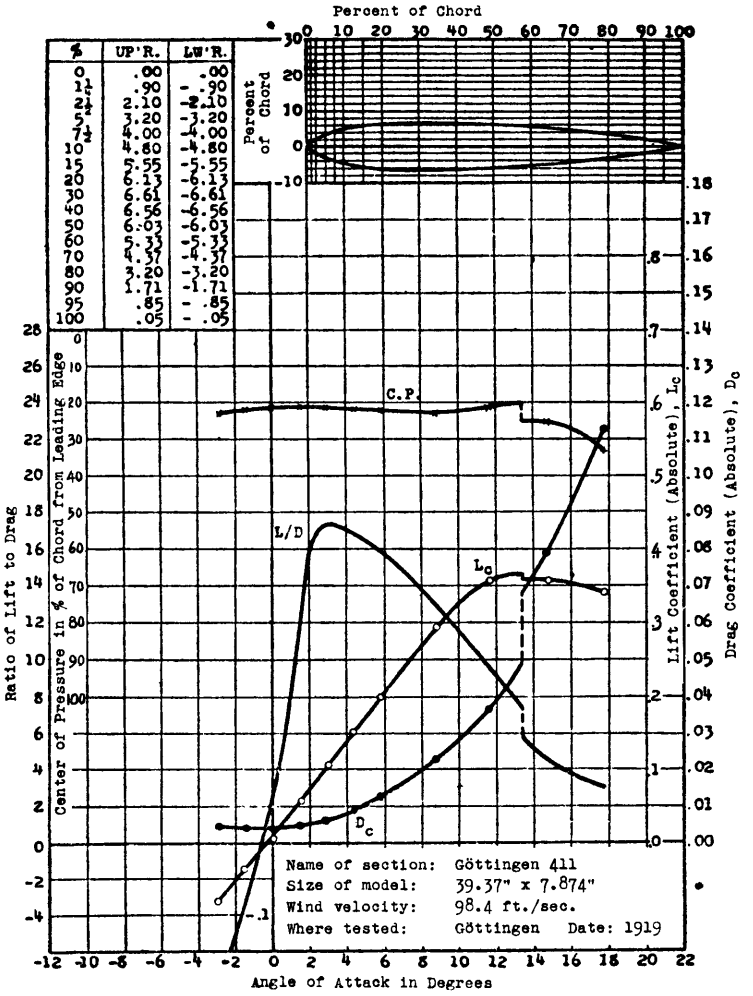
$$R_{max} = F \cdot \rho/2 \cdot v^2 \cdot C_{a\ max}$$
$$= 17.8 \cdot 51 \cdot 16^2 \cdot 0.72 = 168 \text{ T.}$$

(b) Dimensions of the Rudders using a More Favorable Section and Placing the Rudders in the Propeller Race.

It is desired to find the rudder area F.

Twin-screw vessel; total rudder area F divided between two rudders, each of which is placed behind one of the two propellers.

The following are known:
Section No. 539
Greatest rudder angle $\alpha_{max} = 30^\circ$
Lift coefficient for α_{max} $C_a = 1.16$
Aspect ratio about $F/b^2 = .75$ to 1
Velocity of flow at the rudder v = velocity of advance of the propellers $= 20$ m/sec



%	UP'R.	LW'R.
0	.00	.00
1¼	.90	- .90
2½	2.10	-2.10
5	3.20	-3.20
7½	4.00	-4.00
10	4.80	-4.80
15	5.55	-5.55
20	6.13	-6.13
30	6.61	-6.61
40	6.56	-6.56
50	6.03	-6.03
60	5.33	-5.33
70	4.37	-4.37
80	3.20	-3.20
90	1.71	-1.71
95	.85	- .85
100	.05	- .05

Name of section:	Göttingen 411
Size of model:	39.37" x 7.874"
Wind velocity:	98.4 ft./sec.
Where tested:	Göttingen Date: 1919

Fig. 3

From these values the rudder area F required to produce the same rudder force R = 168 T can be calculated:

$$F = \frac{R}{\rho/2 \cdot C_a \cdot v^2} = \frac{168,000}{51 \cdot 1.16 \cdot 20^2} = 7.1 \text{ m}^2$$

This area, F = 7.1 m², is divided between two rudders, so that each rudder will have an area of about 3.5 to 4 m².

The result shows that when a suitable rudder section is chosen and the rudders located in the propeller race, the rudder area required will be only 7.1/17.8 = 0.4 of the previous area.

It is recognized that in the case of multi-screw vessels, it is structurally more difficult to install a rudder behind each propeller than it is to install a single rudder amidships. The better steering properties of the ship and the superior performance of the propellers, however, should be sufficient incentive to find the most suitable structural solution in each individual case for the arrangement of propeller and rudder and the shape of the afterbody.

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1. Kucharski: New Viewpoints in the Design of Ship Rudders. Paper presented at the 31st General Meeting of the STG.

2. Fischer: Investigations on Ships during Steering Maneuvers. Dissertation 1934; Excerpts published in WRH 1936, No. 7 to 11. (See EMB Translation No. 42).

3. Data of the Aerodynamic Testing Laboratory at Göttingen, 1st and 3rd issues.