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DESIGN OF SHIP RUDDERS
(Zur Formgebung von Schiffsrudern)

by

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Translated by E. N. Labouvie, Ph.D.

November 1965

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Translation 321

TABLE OF CONTENTS

	Page
ABSTRACT	1
A. INTRODUCTION	1
B. CRITERIA FOR ARRANGEMENT AND STRUCTURAL DESIGN	2
C. HYDROMECHANIC ASPECTS	10
D. ANALYTIC AND GRAPHIC REPRESENTATION OF PROFILE FORMS	16
E. COMPARISON AND DISCUSSION OF VARIOUS RUDDER PROFILE FORMS	18
F. SUPPLEMENTARY WIND-TUNNEL TESTS	27
G. MEASURES FOR SUBSEQUENT ALTERATION OF RUDDER CHARACTERISTICS	53
H. FUTURE TRENDS IN RUDDER FORMS	56
I. REFERENCES	57
APPENDIX - DISCUSSION BY OTHER INVESTIGATORS	60

LIST OF FIGURES

	Page
Figure 1 - Minimum Rudder Sizes for Directional Stability	3
Figure 2 - Rudder Size and Turning Ability at a 35-Degree Rudder Angle	4
Figure 3 - Rudder Effect on the Turning Ship	11
Figure 4 - Relationship between Rudder Angles δ_R , Drift Angles at the Center of Lateral Resistance ϵ_L , Drift Angles on the Rudder Axis ϵ_A , and Ship Rotation L_L/R	15
Figure 5 - Dimensional Ratios and Profile Parameter of Rudder Profiles	17
Figure 6 - Contour Equation and Contour Parameter for the Representation of Rudder Profiles	18
Figure 7 - Examples of Commonly Used Profiles of Guide-Head Rudders	22
Figure 8 - Common Profiles of Balanced Rudders of 15 Percent Relative Thickness	23
Figure 9 - Examples of Common Balanced Rudder Profiles of Greater Relative Thickness	23

	Page
Figure 10 - Symmetrical Flow Profiles from Familiar Experimental Investigations	23
Figure 11 - The New JfS Balanced Rudder Profiles	23
Figure 12 - Bow Rudder Profiles	26
Figure 13 - Profile Sections of the Plate Rudders Investigated	26
Figure 14 - Nose Contours of Several Balanced Rudder Profiles	26
Figure 15 - Tail Contours of Several Balanced Rudder Profiles	26
Figure 16 - Rudder Models Tested in the Wind Tunnel, Aspect Ratio $A_R = 1$	27
Figure 17 - Test Setup in the Former JfS Wind Tunnel at the Hamburg Engineering Institute	28
Figure 18 - Flow Forces on Rectangular Rudder TMB 075 075 15 ...	44
Figure 19 - Flow Forces on Rectangular Rudder TMB 075 075 15 in Astern Motion	44
Figure 20 - Flow Forces on Rectangular Rudder NACA 0015	45
Figure 21 - Flow Forces on Rectangular Rudder NACA 0015 in Astern Motion	45
Figure 22 - Flow Forces on Rectangular Rudder NACA 0025	45
Figure 23 - Flow Forces on Rectangular Rudder NACA 0025 in Astern Motion	45
Figure 24 - Flow Forces on Rectangular Rudder JfS 58 TR 15	46
Figure 25 - Flow Forces on Rectangular Rudder JfS 58 TR 15 in Astern Motion	46
Figure 26 - Flow Forces on Rectangular Rudder JfS 58 TR 25	46
Figure 27 - Flow Forces on Rectangular Rudder JfS 58 TR 25 in Astern Motion	46
Figure 28 - Flow Forces on Rectangular Rudder JfS 61 TR 25	47
Figure 29 - Flow Forces on Rectangular Rudder JfS 61 TR 25 in Astern Motion	47
Figure 30 - Flow Forces on Rectangular Rudder JfS 62 TR 25	47
Figure 31 - Flow Forces on Rectangular Rudder JfS 62 TR 25 in Astern Motion	47
Figure 32 - Flow Forces on Rectangular Bow Rudder JfS 55 BR 15 ..	48

	Page
Figure 33 - Flow Forces on Rectangular Bow Rudder JfS 55 BR 15 ..	48
Figure 34 - Flow Forces on Rectangular Bow Rudder JfS 59 BR 15 ..	48
Figure 35 - Flow Forces on Rectangular Bow Rudder JfS 57 BR 15 ..	48
Figure 36 - Flow Forces on Square Plate $B/L = 0.015$	49
Figure 37 - Flow Forces on Square Plate $B/L = 0.03$	49
Figure 38 - Flow Forces on Square Plate $B/L = 0.05$	49
Figure 39 - Flow Forces on Square Plate $B/L = 0.07$	49
Figure 40 - Efficiency of Various Rudder Profiles at Small Rudder Angles in Straight-Ahead Motion	50
Figure 41 - Comparison of the Rudder Moment Curve which Determines the Choice of the Location of the Turning Axis, for Various Rudder Profiles at Small Rudder Angles in Straight-Ahead Motion	50
Figure 42 - Drag Power Requirement of Various Rudder Profiles at Rudder Angle in Straight-Ahead Motion	51
Figure 43 - Drag Power Requirement and Efficiency of Profile JfS 55 TR 25 for Straight-Ahead Motion and for Motion along the Turning Circle $L_t/R = 0.5$	52
Figure 44 - Influence of Aspect Ratio on the Transverse-Force Coefficient for Various Rudders	52
Figure 45 - Influence of the Reynolds Number on the Transverse- Force Coefficient for Various Rudders	53
Figure 46 - Effect of Rudder Wedge Arrangement with and without Profile Shortening on Flow Forces Acting on Rectangular Rudder HACA 0015	55

LIST OF TABLES

	Page
Table 1 - Principal Form Parameters of Familiar Balanced Rudder Profiles	19
Table 2 - Form Parameters of the JdF Profiles	20
Table 3 - Profile Offsets of the Rudder Profiles of the Present JfS Investigation	24
Table 4 - Test Results for TMS 075 075 15	32

	Page
Table 5 - Test Results for NACA 0015	33
Table 6 - Test Results for NACA 0025	34
Table 7 - Test Results for JFS 58 TR 15	35
Table 8 - Test Results for JFS 58 TR 25	36
Table 9 - Test Results for JFS 61 TR 25	37
Table 10 - Test Results for JFS 62 TR 25	38
Table 11 - Test Results for JFS 55 BR 15	39
Table 12 - Test Results for JFS 54 BR 15	40
Table 13 - Test Results for JFS 59 BR 15	41
Table 14 - Test Results for JFS 57 BR 15	42
Table 15 - Test Results for Square Plate B/L = 0.015	42
Table 16 - Test Results for Square Plate B/L = 0.03	43
Table 17 - Test Results for Square Plate B/L = 0.05	43
Table 18 - Test Results for Square Plate B/L = 0.07	44
Table 19 - Rudder Efficiency and Drag Power Requirements of the Profiles Investigated	51

NOTATION

The symbols used here have been selected to avoid any confusion with the symbols used in earlier Shipbuilding Institute investigations of rudder and steering characteristics. Insofar as possible, they conform to the recommendations of the International Towing Tank Conference.

Points

- o_A Center of the turning axis of the rudder in the xy-plane of the ship
- o_L Center of lateral resistance of the ship without rudder

Lengths

- A Interval of abscissas (Figure 6)
- B Maximum breadth of ship
- B Maximum profile thickness
- B_n Thickness of profile nose at $dy/dx = 0$ (Figure 3)
- B_s Thickness of the trailing edge of the profile
- B_{sc} Original thickness at the trailing edge of a shortened profile
- g Length of the straight profile tail
- H_n Thickness of the rudder neck (Figure 5)
- H_R Rudder height
- L Profile length, in general
- $L_L = \frac{1}{A_L} \int_0^T L_L^2 \cdot dz$ Lateral length of the hull
- $(L_L/R)_{35}$ Ship's rotation at 35° rudder angle
- $L_{LR} = \frac{1}{A_R} \int_0^{H_R} L_{LR}^2 \cdot dz$ Lateral length of the rudder
- L_o Original length of the shortened profile
- L_{UR} Length of the upper edge of the rudder
- L_{pp} Length between perpendiculars
- L_R Rudder length
- L_{Rz} Length of the rudder at the height z
- L_{LR} Length of the lower edge of the rudder
- L_{WL} Length in the waterline of the ship
- L_z Length of a waterline at the height z
- n Length of the profile nose
- R Radius of path, in general
- R_L Radius of the path of the center of lateral resistance
- r_B Radius of curvature of the profile contour at the maximum thickness
- r_n Radius of the profile nose
- r_s Radius of the trailing edge of the profile
- σ Length of the profile tail of variable thickness (Figure 5)
- T Draft of the ship

x	Profile abscissa, longitudinal axis of the rudder, longitudinal axis of the ship
x_{Bn}	Distance of the profile nose thickness from the leading edge
x_{Hn}	Distance of the profile neck from the leading edge
x_{LA}	Horizontal distance of the turning axis of the rudder O_A from the center of lateral resistance O_L
y	Profile ordinate
z	Vertical distance of a waterline above the keel base or above the rudder base, respectively
$\eta = y/A$	Non-dimensional ordinate
ϱ_0	Contour parameter for the curvature on the profile nose (Figure 6)
$A_L = 2 \cdot T^2/A_L$	Aspect ratio of the hull
$A_R = H^2/A_R$	Aspect ratio of the rudder
$A_{Ro} = H^2/A_{Ro}$	Aspect ratio of the rudder with unshortened profile length
$\xi = x/A$	Non-dimensional abscissa
Areas	
A_L	Lateral area of the hull
A_R	Rudder area
A_{Ro}	Rudder area for unshortened profile length
A_S	Cross-sectional area of the slipstream in the test section of the wind tunnel
$\tau = A_L/(L_{WL} \cdot T)$	Fullness of the lateral area
Volumes	
V	Volume displacement of the ship
$\delta_L = V/(L_L \cdot B \cdot T)$	Fullness of the displacement, referred to the lateral length
$\delta_{pp} = V/(L_{pp} \cdot B \cdot T)$	Fullness of the displacement, referred to the length between perpendiculars
Angles	
δ_R	Rudder angle, positive for the stern rudder in the sense of the port side rotation
ϵ	Angle of oblique flow, in general
ϵ_A	Drift angle on the rudder axis, in general
ϵ_{An}	Drift angle on the rudder axis, determinative for non-linear forces
ϵ_{An}	Drift angle on the rudder axis, determinative for linear forces
ϵ_L	Drift angle at the center of lateral resistance of the ship
$\epsilon_{\max}$	Flow angle at the transverse force maximum
ϵ_R	Flow angle of the rudder, in general
ϵ_{Rs}	Flow angle of the rudder, determinative for the non-linear forces
ϵ_{Rw}	Flow angle of the rudder, determinative for the linear forces

Velocities

- v Relative velocity of the flow to the ship
 v_R Relative velocity of the flow to the rudder
 $Re = v \cdot L_R / \nu$ Reynolds number of the rudder

Forces and Moments

- C Transverse force of the rudder perpendicular to v_R and positive toward the right, as seen against the relative flow
- C_R Transverse force contribution of the rudder to the ship, perpendicular to v and positive toward the right, as seen against the relative flow
- $c_C = C / (A_{R0} \cdot v_R^2 \cdot \rho / 2)$ Transverse-force coefficient of the rudder
- $c_{C, \max}$ Maximum transverse-force coefficient of the rudder
- $c_D = D / (A_{R0} \cdot v_R^2 \cdot \rho / 2)$ Resistance coefficient of the rudder
- $c_M = M / (A_{R0} \cdot L_0 \cdot v_R^2 \cdot \rho / 2)$ Coefficient of the rudder moment referred to $L_0 / 2$
- $c_{M, 0}$ Corresponding coefficient of the rudder moment referred to $L_0 / 4$ from the leading edge
- c_{NRv} Drag power coefficient of the rudder, Equation [6]
- c_{NL} Coefficient of the non-linear transverse-force gradient
- c_{GL} Coefficient of the linear transverse-force gradient
- $c_X = X / (A_{R0} \cdot v \cdot \rho / 2)$ Longitudinal-force coefficient of the rudder
- c_Y Corresponding lateral-force coefficient of the rudder
- c_{YRv} Coefficient of the control force of the rudder, Equation [5]
- D Resistance of the rudder, positive in the direction of the relative flow of v_R
- D_R Contribution of the rudder to the ship's resistance
- M Moment about the vertical axis of the rudder at $L_0 / 2$, positive as seen from above, clockwise direction
- M_0 Moment about the turning axis of the rudder of any arbitrary location
- M_R Contribution of the rudder to the yawing moment about the center of lateral resistance of the ship
- M_{00} Moment about the vertical axis of the rudder at $L_0 / 4$ from the leading edge
- X Longitudinal force of the rudder, positive in the rudder-x-direction toward the bow
- X_R Contribution of the rudder to the longitudinal force of the ship
- Y Lateral force of the rudder, positive in the rudder-y-direction to starboard
- Y_R Contribution of the rudder to the lateral force of the ship

Physical Quantities

- ν Kinematic viscosity of the flow medium
- ρ Density of the flow medium

ABSTRACT

Starting from present day criteria for the choice of the size and arrangement of rudders, this paper discusses the suitable streamlining of guiding-head and balanced rudders. In addition to a purely visual comparison of conventional (usual) and newly developed profiles, the report includes profile offsets that have not been published previously and contrasts the form parameters of various rudder profiles which are based on a familiar mathematical method of profile representation. Comparative studies of several familiar foreign rudder profiles and of rudder profiles which have been developed in the Shipbuilding Institute in recent years indicate that the modern profiles definitely improve rudder efficiency, both when the ship is moving astern and ahead; this also applies to bow rudder profiles. The influence of the thickness ratio (proportion of thickness to length) in the case of plate rudders—which has not been established experimentally in publications thus far—is indicated in an additional test series. To illustrate the possibilities of subsequently improving the rudder profile either in efficiency or balancing, the use of a rudder wedge arrangement, with and without profile shortening, is discussed and examples are given from a special experimental investigation.

A. INTRODUCTION

Support received from the German Research Association and an extremely effective grant from the Ministry of Transport has enabled the Shipbuilding Institute of the University of Hamburg to carry out several theoretical and experimental investigations on the characteristics of rudders over a period of several years. Moreover, it was possible to observe that during this period of time, the range of problems concerning rudder and steering qualities of ships became larger and more acute. Thus, it was easily possible that the active pursuit of these investigations was promoted and broadened by a fruitful contact with present-day requirements, on one hand, and by benefiting from the investigations started in other research institutes on similar subjects, on the other.

The result was not so much a solution of individual problems taken up consecutively, but rather the pursuit of research work on a broad front; hence, it will be understandable that the broad investigations are not entirely completed but that it is inadvisable to delay all reports until final completion. A number of findings have already been arrived at on the

basis of the results obtained in several individual fields which may have fairly useful practical applications. Hence, the purpose of this paper is to supplement the subject matter area of the intermediate results reported thus far^{1,2} as well as the nearly concurrent intermediate results.^{20,30} In this connection, I must therefore ask the forbearance of the reader if the timing of this report appears to be too early in view of the whole range of problems to be tackled and too late in view of the many detailed results obtained.

Since the installation of the facilities required for these and similar experimental investigations is still incomplete, many compromises regarding technical execution of the investigations were required. Staff workers of the Shipbuilding Institute, especially Messrs. Böhme, Thiemann, and Malzahn, deserve credit for the fact that the quality of the test results was not adversely affected by this circumstance.

B. CRITERIA FOR ARRANGEMENT AND STRUCTURAL DESIGN

The first consideration when designing the rudder of a ship is, of course, determination of the surface area. As a consequence of the propeller arrangement and of certain real--or assumed--requirements for maneuvering characteristics, we then obtain in relation to the preselected surface area, a more or less arbitrary arrangement of the rudder or rudders in relation to the ship and especially in relation to its propulsion system. After this determination has been made, relatively little leeway remains for selecting the aspect ratio of the rudder ($A_R = H_R^2/A_R$), the surface outline, and the type of rudder. In making these last-mentioned decisions, it will often be found that structural and operational considerations play a decisive role and that the only remaining problem of the hydromechanical design is to utilize the structural conditions to attain the best possible hydrodynamic efficiency.

If for the time being we disregard the attempts at "hydrodynamic treatments" of undesirable effects of horizontal gaps and the rare

¹References are listed on page 57.

occasions to arrange for end disks and intermediate disks, then the only design element remaining for this hydrodynamic problem is the streamlining of the rudder. This last problem represents the core of this report. However, in order to see it in the proper context, we shall first consider the other problems involved in designing ship rudders.

Even today statistical data are used—probably almost exclusively—in selecting the size of the rudder surfaces. Several sources^{3,4,6-9} indicate, in the "usual manner," as it were, the rudder area as a percentage of the lateral plane (A_R/A_L) as a function of the ship type or as a function of the volume displacement ∇ referred to the lateral plane A_L and the lateral length L_L . The results of References 3 and 4, conceived to be valid for "normal" merchant ships, are shown in Figure 1. They are

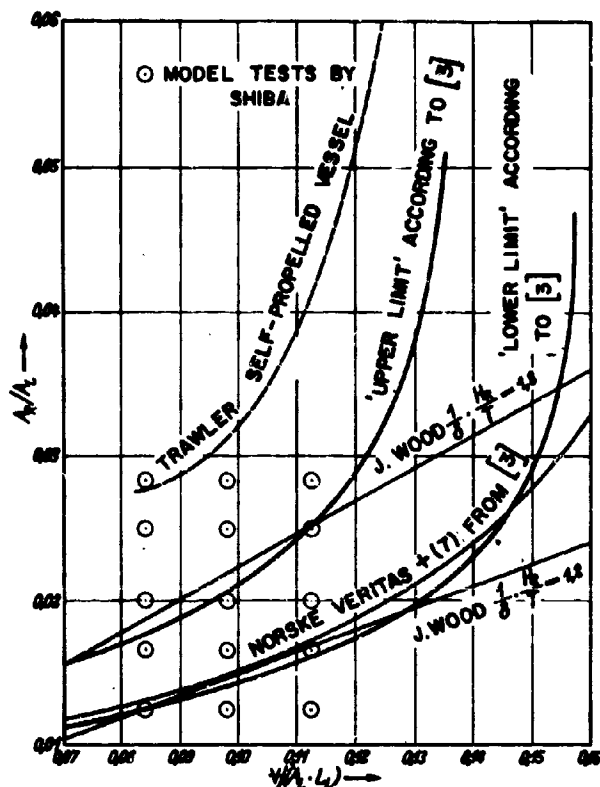
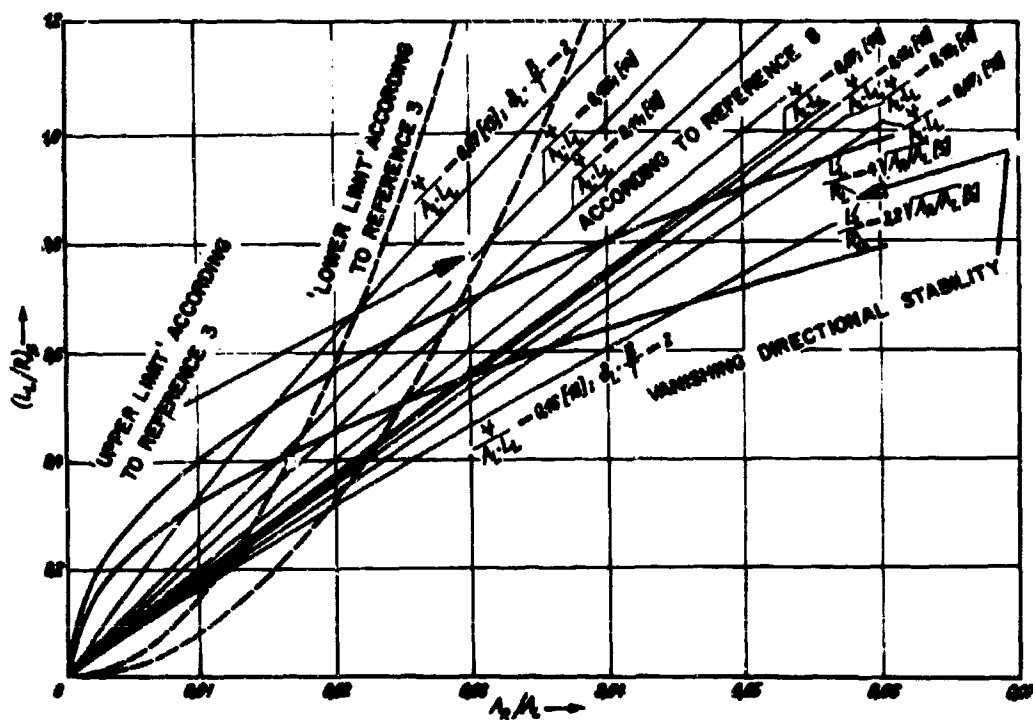


Figure 1 - Minimum Rudder Sizes for Directional Stability

reasonably consistent with one another as well as with the data of References 6 to 8. These data are based on the practical requirement of

providing ships with a high value $\Psi/(A_L \cdot L_L)$ with a rudder area which is sufficiently large for directional stability. In the case of ships with small values of $\Psi/(A_L \cdot L_L)$, on the other hand, this dimensioning criterion would result in an unusually small rudder area; it is true that directional stability of the ship would be attained, but the radius of the turning circle would be unusually large.

Thus, we have touched on the two steering qualities of a ship which are the most interesting for practical ship operation. Frequently, only the radius of the turning circle as such comes under discussion; by this we tacitly understand the smallest turning circle or, more precisely, the radius of the turning circle at approximately 35-deg rudder angle. This is represented nondimensionally as "rotation" $(L_L/R)_{35}$ in Figure 2. In



situation is altogether different in the case of directional stability; not even the experts have agreed on the definition, let alone on the "correct measure." There is substantial agreement on the fact that a properly designed vessel must have directional stability. However, even the question of whether a ship must have "natural" directional stability, i.e., not require automatic pilot, or whether it may suffice to attain directional stability, with the aid of an automatic pilot is by no means unanimously decided as yet.

Without doubt, however, directional stability is the most significant of all the steering qualities of a ship; ultimately, of course, a ship must first of all be able to keep a fixed course in an economical way, and the ability to alter this course will have to be of secondary importance. With this in mind, it may be somewhat surprising that References 10 and 11 offer statistical data for the choice of the rudder size as a function of the desired radius of the turning circle (see Figure 2). Probably the reason for this procedure, which may not seem to be altogether logical, consists solely in the fact that the greater obviousness of the radius of the turning circle holds a certain attraction compared to directional stability. It may also be that these procedures were originally conceived in such a manner that for a given ship with a given rudder surface, the radius of the turning circle to be expected was to be determined on the basis of statistical data or of adapted theoretical considerations; see References 12 to 14.

The diagrams of Figures 1 and 2 are based on the above-mentioned data, on an additional personal report of the Hamburg Model Basin (HSVA) on proven rudder sizes of trawlers and inland vessels (self-propelled vessels), and on qualitative derivations from the underlying theoretical principles contained in Reference 5; these diagrams serve to determine the rudder size as a function of the above-mentioned "mean breadth-length ratio"

$$\frac{V}{A_L \cdot L_L} = \frac{\delta_L \cdot L_L \cdot B \cdot T}{\tau \cdot L_{WL} \cdot T \cdot L_L} = \frac{\delta_L}{\tau} \cdot \frac{B}{L_{WL}}$$

for a specified constant or a statistical directional stability. Moreover, they serve to indicate the radii of the turning circle that are randomly obtained with this selection. In addition the changes necessary in the

rudder surface (beyond or below the size governed by directional stability) to attain a corresponding change in the radius of the turning circle may be estimated. The data of Polonski,⁸ Schoenherr,¹⁰ and Laube¹⁴ are useful for this purpose and agree very well with the analytical results obtained by Schmitz¹³ (see Figure 2). The data taken from Reference 3 are altogether different; they show implicitly the determination of A_R/A_L as a function of $v/(A_L \cdot L_L)$ and are thus unsuitable for determining subsequent changes in the rudder size. According to Reference 5, the two curves contain an implicit determination to the effect that the rudder size is always chosen in such manner that the directional stability barely vanishes so that directional instability prevails. Moreover, Figure 2 should not be used for values smaller than $A_R/A_L = 0.01$ and for values $(L_L/R)_{35}$ greater than approximately 1.2. In the case of every normal ship, a marked reduction in the rudder surface toward zero by no means leads to a maximum rotation approaching zero; even without rudder, a finite turning circle is still obtained. Conversely, in the case of a fixed rudder angle of 35 deg, an arbitrary increase in the rudder surface by no means produces a further increase in the obtainable rotation. As indicated in Reference 5, a rotation of approximately 1.2 represents the practical asymptotic boundary value for infinitely large rudders.

In Figures 1 and 2 the rudder surface area is presented as an obvious criterion both for attaining turning ability and for attaining directional stability and coupled with the latter for insuring "yaw-checking ability" for the ship as well. To be sure, this is a customary, but nevertheless coarse simplification of the actual relationships. Therefore, it should be expressly pointed out that the dimensioning of the deadwood in front of the propeller and the arrangement of fixed fins behind the propeller are also to be taken into consideration, both with and without the rudder, if certain characteristics of the ship are to be produced or changed. In this connection, it should also be pointed out that these measures are not nearly equivalent. An increase of the deadwood means

*Translator's note: Stutsfahigkeit = yaw-checking ability, ability to check swing of ship's head by laying the rudder to the opposite hand, "meeting" ability.

something totally different from an increase in the rudder area or an additional arrangement of fixed fins. Attention should also be called to the danger of cutting away the deadwood which is so popular today; the equivalence of the deadwood area and the rudder enlargement with regard to directional stability which exists in the case of a smooth sea is easily lost in a following sea, for instance. This danger is easily intensified if the areas of keel or bilge keels are dimensioned with extreme scantiness as is customary. It is too easily forgotten that the keels not only serve to stabilize the ship against rolling but also to improve directional stability by reducing the possibility of running off course.

An additional factor is implicitly contained in the above-mentioned statistical and simplified analytical results although it is not considered in a refined form. This is the effect of the aspect ratio of the rudder

$$A_R = \left(\frac{N_R}{T} \right)^2 \cdot \frac{\frac{A_L}{S}}{A_R/A_L} - \left(\frac{N_R}{T} \right)^2 \cdot \frac{\frac{V}{A_L \cdot L_L}}{\frac{B}{T} \cdot \delta_L \cdot A_R/A_L} \quad [1]$$

which varies with the rudder size for a given ship.

The ratio of the rudder height N_R to the draft T depends mostly on the basic design and lies in the vicinity of

$$(N_R/T)^2 = 0.3 \text{ to } 0.7 \text{ to } 0.8$$

if classified statistically by types of ships.

If we now exclude extreme cases, e.g., old river tug boats or old sailing vessels, then, according to Equation [1], we still obtain a spread of the rudder aspect ratios A_R from 0.7 for short full vessels with large rudder areas up to 2.5 for long slender ships with correspondingly small rudder areas. On the basis of the aspect ratio alone, however, the initial efficiency of the rudder is almost twice as high for a greater aspect ratio as for a smaller one. The smaller aspect ratios, on the other hand, have approximately 60 percent higher efficiency at maximum rudder angle. Thus it will indeed be possible to influence directional stability as well as turning ability and yaw-checking ability by the choice of a rudder aspect ratio. In actual practice, however, these facts can be utilized only in the transition to the multiple-surface arrangement.

While it is true, as mentioned above, that the rudder aspect ratio has a considerable effect on the efficiency of the rudder (although from a purely visual standpoint, it is not at all conspicuous in most cases), the situation is exactly the opposite as far as the rudder profile is concerned. The profile design as a rectangular or trapezoidal rudder and in certain rare cases also as an angular (broken) trapeze or as an ellipse becomes immediately conspicuous in most cases. However, the hydrodynamic effect on fundamental characteristics such as course keeping and turning ability is extremely slight. It is easier for such a design to influence the tendency of a vessel to veer off course at full speed ahead or at full speed astern when starting from the at-rest position. Obviously, however, this possibility is not interesting enough to restrain the general tendency toward the trapezoidal rudder for it is precisely the trapezoidal rudder which intensifies this tendency to veer off course compared to the rectangular rudder or even more compared to the rudder with the planform of a full ellipse. Hydrodynamically speaking, moreover, the trapezoidal rudder is somewhat inferior to the rectangular rudder because of its unfavorable pressure distribution. Superiority would be obtained only for the trapezoidal twin rudder whose upper edge would again have to be somewhat shorter than the maximum rudder length. Even the static advantages of the trapezoid are overestimated in the case of the spade rudder since the center of the application of the force for the bending moment of the rudder post is not located in the center of gravity of the surface, but always lies somewhat below.

According to a proven rule of thumb by Schrenk, this center lies between the actual center of gravity of the surface and the center of gravity of the surface of the equi-area full ellipse of equal position in a vertical sense and height. Hence, compared to the rectangular rudder, the apparent effect of the bending moment reduction through the trapezoidal form in reality is only one-half. If this factor is taken into account, it is possible that in many cases, the simpler structural design and the assured hydrodynamic improvement in the case of the rectangular rudder might influence the compromise in this direction. Of course for static reasons, the rectangular rudder calls for a greater relative profile thickness compared to the trapezoidal rudder. If, for instance, we start out

from a trapezoidal ratio of the length of the lower edge L_{LR} to the length of the upper edge L_{UR} of 2/3 ratio which is already quite large, then the equi-area rectangular rudder calls for an increase in the relative profile thickness of a little over 20 percent, i.e., from approximately $B/L = 0.20$ for the trapezoidal rudder to $B/L = 0.25$ for the corresponding rectangular rudder. The test data indicated in this report, however, are likely to favor such an increase in the profile thickness.

In making a hydrodynamic comparison between trapezoidal and rectangular rudder as it is practically expressed in the formation of the familiar coefficients for force components and moment, it must be borne in mind that for the trapezoidal rudder, the "lateral length" is to be used as the length in forming the moment coefficient; this "lateral length" of the rudder is obtained geometrically simply from the fundamental relation

$$L_{LR} = \frac{1}{A_R} \int_0^{H_R} L_R^2 \cdot ds \quad [2]$$

and amounts to

$$\frac{L_{LR}}{L_{UR}} = \frac{2}{3} \left(\frac{L_{UR}}{L_{UR}} + \frac{1}{1 + L_{UR}/L_{LR}} \right) \quad [3]$$

in the case of the trapezoidal rudder. In the case of the elliptical rudder contour, it amounts to

$$\frac{L_{LR}}{L_{UR}} = \frac{8}{3\pi} = 0.8488 \quad [4]$$

In this case, it will be seen that fundamentally the rectangular form must always yield the smaller rudder moment since the lateral lengths L_{LR} for the trapezoid and ellipse always turn out to be somewhat greater—although for practical forms only slightly so—then the mean rudder length which, of course, is also the lateral length for the rectangular rudder.

In addition to the static criteria, the structural and operational criteria also determine the type of the rudder bearings and in turn the choice of the rudder type as well. In most cases, factors such as convenient removability and the use of antifriction bearings or sleeve-type bearings determine whether a spade rudder or a semi-balanced rudder is chosen. Although this has not yet been taken into account experimentally in this paper, our attention is nevertheless directed to the fact that

considerable efforts are still required in the area of rudder design to offset the fundamental hydrodynamic inferiority of the semi-balanced rudder or at least to minimize it. The other special rudder design—different from the normal balanced rudder—is the one-piece through rudder with a continuous guiding head, or more briefly, the guide head rudder. It has recently lost some of its present-day significance, but it offers far greater possibilities of arriving at a hydrodynamically satisfactory design (see Figure 7).

All rudder forms have in common the structural and operational interest in choosing the location of the turning axis of the rudder in such manner that for the normal condition of ahead motion the zero position of the rudder with regard to the rudder moment curve is a stable condition in order to avoid flutter, noise, and additional bearing stresses. Unfortunately it is impossible to satisfy these desires by placing the turning axis far in front because in that case the rudder moments increase greatly at maximum rudder angles and under loadings in a seaway. Fortunately, the effect of the twist of the slipstream brings about a displacement of the pressure center to the rear; this must be borne in mind when using measurements without a propeller. Independently of this, however, there is the problem, based on structural requirements, of developing profile forms which have pressure centers, that are located as far as possible to the rear; this has, in fact, been achieved to a certain extent in the case of the measurements on newly developed profiles set forth in this report. Independently thereof or in addition thereto, experiments are to be carried forward by taking "artificial" measures such as removal by suction.¹

C. HYDROMECHANIC ASPECTS

The hydromechanic aspects supplement the structural aspects. Any work to effectively develop good rudder forms should consider carefully all structural requirements and desires and be receptive to resultant suggestions without however adopting them directly as the fundamental condition for each and every design. The hydrodynamic rudder development must retain sufficient scope for purely hydrodynamic aspects in order that

potentially significant effects which later might become structurally possible in some modified form are not excluded at the beginning. Not only forms that are structurally possible and hydrodynamically sound are to be presented as the highlights of a development for even forms which are now considered structurally unusual or which are even hydrodynamically unsatisfactory may yield interesting data and thus lay the useful foundation for further development.

In this text then, we shall report not only on the rudder with profile JfS 58 TR 25 which is structurally possible because of its thick rear edge and which is of an altogether "advanced design," hydrodynamically speaking (the last number indicates the maximum relative thickness in percent—see Figure 11) but on profile JfS 62 TR 25 as well. Profile JfS 62 TR 25 is hydrodynamically superior but because of its very thin trailing edge it certainly will not become popular in this form, structurally speaking. Even the form of a thick plate (Figure 13) beveled in the front and rear, which an earlier investigation² had shown to be inferior from the hydrodynamic standpoint, and the equally inferior, newly investigated plate bow rudder JfS 57 ER 15 (Figure 12) shall not be disregarded. We should not ignore even such crude forms as JfS 59 ER 15 or JfS 54 ER 15 (Figure 12) if these even more normal bow rudder forms are hydrodynamically superior.

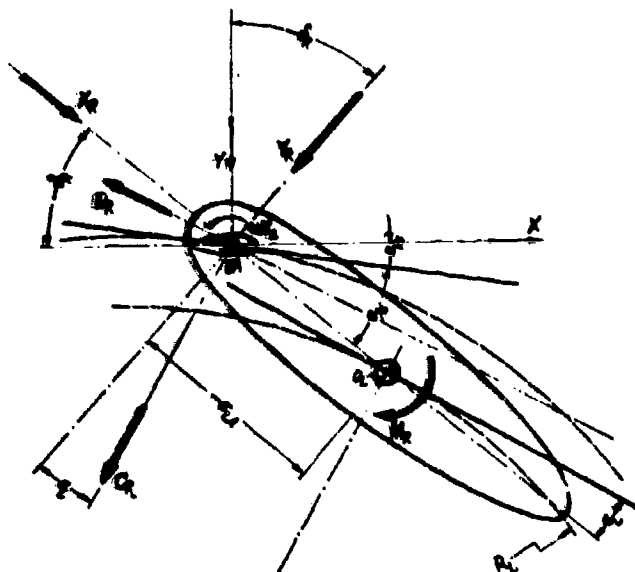


Figure 3 - Rudder Effect on the Turning Ship

The fundamental hydromechanic aspects for judging the quality of a rudder must, of course, be furnished by the purpose which the latter is to serve on the ship. The best results set forth here are immediately applicable to a ship underway in ahead motion. Customarily, such data are regarded as decisive for all of the purposes the rudder is to accomplish on the ship although the rudder effect in straight-ahead motion is only momentary and relatively weak in all cases. To round out the picture, we should also consider the rudder effect on the turning ship (Figure 3) which, after all, is more pronounced in most cases.

Figure 3 is a schematic drawing of the hydrodynamically interesting drift angles at the center of lateral resistance c_L on the rudder axis c_{As} , and for the rudder $-c_{Rs}$ deflected by $-\delta_R$. The rudder forces are represented, on the one hand, as the longitudinal rudder force X and the lateral rudder force Y , and the rudder shaft moment M_R ; and on the other hand, they are represented as a rudder contribution to the longitudinal force of the ship X_R , to the lateral force of the ship Y_R , and to the yawing moment about the vertical (normal) axis M_R of the center of lateral resistance. The rudder contributions to the transverse force of the ship and to the ship resistance are C_R and D_R . The hydromechanically interesting effects of the rudder on the ship as a whole are the control force Y_R , which is decisive for the contribution M_R and which thus brings about the turning of the ship, the rudder contribution to the drag power requirement of the ship N_R , which is determinative for the speed loss in the turning circle, and finally the contribution to the transverse force of the ship C_R . The contribution to the transverse force of the ship has only a very indirect effect on the steering characteristics of the ship whereas it can hardly be influenced independently of the control force; hence, it is not given any further attention in this connection. From Figure 3, it is easily possible to establish a relationship for the control force with force components referred to rudder axes.

$$c_{Y_R} = c_Y \cdot \cos \delta_R + c_X \cdot \sin \delta_R \quad [5]$$

In this connection, we immediately introduce the customary non-dimensional form; see the Notation. In connection with the drag

coefficient, we have disregarded in Equation [6] the contribution to the shaft moment (shaft torque) M_A which is insignificant compared to the steering moment M_R .

$$c_{N R r} = c_Y \sin (\epsilon_L + \delta_R) - c_X \cos (\epsilon_L + \delta_R) - \frac{L}{R_L} \cdot \frac{x_{LA}}{L_L} \cdot c_{Y R r} \quad [6]$$

According to Equation [5], when the ship is moving straight ahead, $c_{Y R r}$ is exactly equal to the transverse force coefficient of the rudder as indicated by c_C in Section F for the test results in wind tunnels; According to Equation [6] $c_{N R r}$ becomes equal to the rudder resistance coefficient c_D from Section F when the ship moves straight ahead. In this case, the oblique inflow toward the rudder, quite generally designated as ϵ in Section F, coincides with the angle of rudder deflection δ_R . In accordance with the definitions of the symbols in the Notation, for a positive rotation L_L/R_L of the ship, the rudder angle in terms of the rotation must be regarded as negative.

According to Figure 3, moreover, we find that for the turning ship, the inflow at the location of the rudder axis o_A (which inflow is to be determined on a purely geometrical basis) amounts to

$$\tan \epsilon_{Aa} = \tan \epsilon_L + \left(\frac{-x_{LA}}{L_L} \right) \frac{L_L/R_L}{\cos \epsilon_L} \quad [7]$$

However, in order to determine the circulation-dependent rudder lift--characterized by the index "w" according to Equation [5]--the hydrodynamically effective angle of inflow at the rudder axis ϵ_{Aw} must be reduced by approximating the size of the drift angle at the center of lateral resistance ϵ_L .

$$\tan \epsilon_{Aw} = \left(\frac{x_{LA}}{L_L} \right) \cdot \frac{L_L/R_L}{\cos \epsilon_L} \quad [8]$$

Thus, we obtain the unfortunate theoretical result, which indeed is supported experimentally, that the circulation-dependent so-called linear or "waterline" components of the rudder forces are functions of the inflow angle of the rudder

$$\epsilon_{Rw} = \delta_R + \arctan - \left[\frac{-x_{LA}}{L_L} \cdot \frac{L_L/R_L}{\cos \epsilon_L} \right] \quad [9]$$

whereas the so-called nonlinear or "frame" components of the rudder forces remain functions of the purely geometrical inflow angle of the rudder.

$$\epsilon_{Rs} = \delta_R + \arctan \left[\tan \epsilon_L + \frac{-x_{LA}}{L_L} \cdot \frac{L_L/R_L}{\cos \epsilon_L} \right] \quad [10]$$

The unavoidable consequence is that the relationship between oblique inflow toward the rudder and rudder force components (polar curve of the rudder) varies somewhat with the rotation of the ship. It is necessary, therefore, that rudder measurements also be carried out behind the turning ship or ship model or that the rudder measurements for the ship moving straight ahead must be converted in a certain way to the turning circle measurement. To do so, we can fall back on the method for computing nonlinear rudder forces which is touched upon and indicated in more detail in Reference 5. With sufficient accuracy, we can neglect the effect on the c_X required in Equations [5] and [6]. In a simplified representation, c_Y is computed as:

$$c_Y = c_{we} \cdot \epsilon_{Rw} + c_{ws} \cdot \epsilon_{Rs}^2 \cdot \frac{\epsilon_{Rs}}{|\epsilon_{Rs}|} \quad [11]$$

Thereby, we obtain approximately

$$\epsilon_{Rs} = \delta_R + \frac{1}{2} \frac{L_L}{R_L} + \epsilon_L = \epsilon_{Rw} + \epsilon_L \quad [12]$$

and finally as a correction formula

$$\begin{aligned} c_Y &= c_Y(\text{bei } \epsilon = \epsilon_{Rw}) + c_{ws} \cdot (2\epsilon_{Rw} \cdot \epsilon_L + \epsilon_L^2) \\ c_X &= c_X(\text{bei } \epsilon = \epsilon_{Rw}) \end{aligned} \quad [13]$$

In this case, the coefficient c_{we} as a gradient of the nonlinear component must also be determined from the measurements for straight-ahead motion. In order to convert the measurements for the ship in straight-ahead motion to turning circle measurements we must, of course, also know the drift angle and the corresponding rudder deflection. An absolute normalization is, of course, impossible in this case. However, for the

15

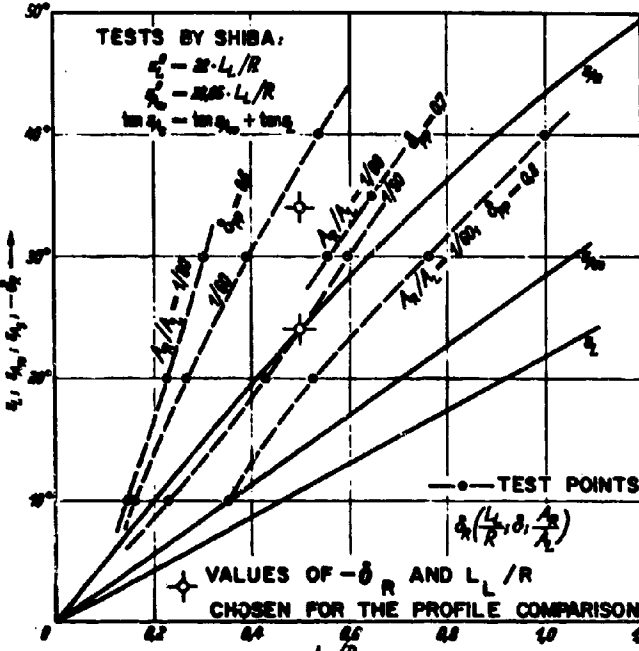


Figure 4 - Relationship between Rudder Angles δ_R ,
Drift Angles at the Center of Lateral Resistance ϵ_L ,
Drift Angles on the Rudder Axis ϵ_A , and Ship Rotation L_1/R

Thus, the results of rudder tests are then to be examined with a view to the criteria for hydrodynamic quality. A great control force and a small drag power requirement are the first prerequisites for ships moving straight ahead or going into a turn. It is true that in actual practice a high maximum transverse force is utilized during ship rotation only if rudder angles exceeding 35 deg are used. However, when checking the yaw, this characteristic has effect for almost every ship. Finally, we are to develop the astern characteristics of the rudder to as high a degree as possible, both for small rudder angles and for the maximum

transverse force. Of course, the best astern characteristics of a rudder are of no avail if this rudder is located so closely behind the deadwood that in astern motion, the transverse flow toward the rudder produces a counterforce of practically equal magnitude on the deadwood thus almost completely cancelling the rudder effect. However, the modern trend toward larger propeller apertures provides an opportunity to attain a certain control efficiency in astern motion with rudders which have good astern characteristics.

D. ANALYTIC AND GRAPHIC REPRESENTATION OF PROFILE FORMS

From the foregoing considerations, the importance of streamlining the rudder has developed into a measure for obtaining favorable rudder characteristics which may indeed be chosen rather freely. The structural limitations in this case are not so incisive as in the choice of the aspect ratio, for instance. Surprising as it may be, however, the material on ship rudder profiles scattered throughout the literature does not offer a very systematic picture. Form systematization is an effective means of utilizing practical experience quickly and effectively and with statistical accuracy; this is the more important, the fewer the quantitative hydrodynamic investigations that are available.

In view of this situation, it appears wise to use the rudder profile systematization^{19,20} developed at the Hamburg Model Basin and the Shipbuilding Institute¹⁸ and subsequently developed even further as a basis for this investigation. In Figure 5, we proceed to show this systematized notation for the dimensional ratios—the "outer" proportions of the profile, as it were—and the form parameters of the individual curved sections which comprise the total profile. Correspondingly, the form parameters might be designated as the "inner" proportions of the profile.

Figure 6 shows the notation used for the computation of the profile contours, all of which consist of polynomials and are split up into so-called influence functions, one such function being used for each form parameter. Thereby, it is possible to represent every conceivable—reasonable and unreasonable—profile form of a rudder. As an inevitable consequence, we also obtain the possibility of analyzing clearly unusual

INITIAL PROFILE

RUDDER WEDGE

FINAL PROFILE

	$\frac{s}{L}$	$\frac{n}{L}$	$\frac{s}{L}$	$\frac{n}{L}$	$\frac{s}{L}$	INVARIANT AGAINST RELATED VARIATIONS
$\frac{s}{L}$	$\frac{s/L}{(s/L)^2}$					
$\frac{n}{L}$	$\frac{s/L}{(s/L)^2}$					
$\frac{1}{s}$	$\frac{1}{s} \cdot \frac{s}{L}$					
$(\frac{d}{ds})_{s=L}$	$(\frac{d}{ds})_{s=L} - \frac{s}{L} \frac{d}{ds}$					
$(\frac{d}{ds})_{s=L}$	$(\frac{d}{ds})_{s=L} - \frac{s}{L} \frac{d}{ds}$					
$(\frac{d^2}{ds^2})_{s=L}$	$(\frac{d^2}{ds^2})_{s=L} - \frac{s}{L} \frac{d}{ds}$					
$(\frac{d^2}{ds^2})_{s=L}$	$(\frac{d^2}{ds^2})_{s=L} - \frac{s}{L} \frac{d}{ds}$					
$\int \frac{1}{L} ds$	$\frac{\int \frac{1}{L} ds}{s/L}$					
$\frac{s}{L}$	$\frac{s}{L}$					
$\frac{n}{L}$	$\frac{n}{L}$					

It should be noted, moreover, that the profiles are generally correlated with so-called profile families. In that case, the profiles of one family essentially differ only in the maximum relative thickness which,

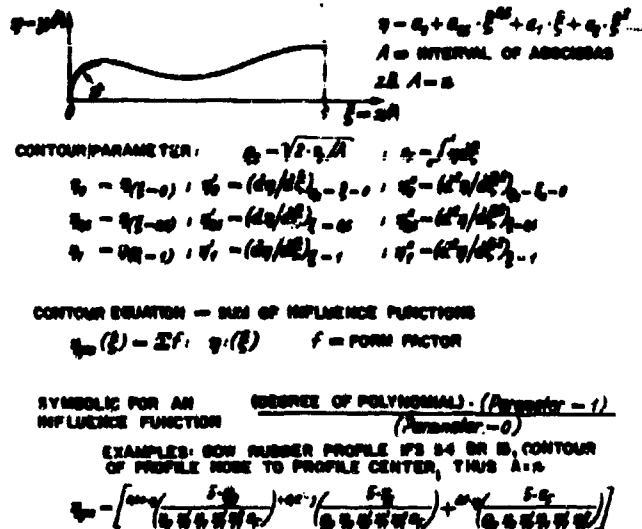


Figure 6 - Contour Equation and Contour Parameter for the Representation of Rudder Profiles

in most cases, lies between 35 and 20 percent of the total length from the front. The relative maximum thicknesses B/L which are to be considered are obtained both from available systematic test data which begin mostly at $B/L = 0.12$ (see Reference 26) and from extreme structural desires which lead to $B/L = 0.25$. Most profile families consist of simple profiles whose entire related variations differ only in the thickness ratio B/L . Such families are for instance the familiar NACA 00 .. -profiles and the more recent family JfS 58 TR .. Nonrelated families are the familiar Joukowski profiles as well as the family JfS 52 TR .. and JfS 62 TR ... from the Shipbuilding Institute. A glance at Tables 1 and 2 shows the characteristic features of these profile families.

For years profile development at the Shipbuilding Institute has always proceeded in such manner that the particular data of available profile forms are carefully examined with regard to their relation with the form parameters and that all further steps are derived from this by parameter modifications which promise to yield results.

The experiments discussed in this report (Section F) cover balanced rudders only. However, there is already a need to extend the experiments

[illegible]

to guide head rudder forms as well. In any event, a survey of rudder profile forms cannot disregard the profiles of the guide head rudders. In Figure 7, therefore, we have summarized the guide head profiles according to References 3, 22, and 27 which are probably the most familiar ones of all. From the standpoint of the present time, a continued development would probably be worthwhile especially for Seabeck-Oertz rudders and for the NSVA guide head rudder, particularly if hollow profile flanks are used.

TABLE 2
Form Parameters of the JdF Profiles

PROFILE	SE TR 15	SE TR 15	SE TR 15	SE TR 15	SE TR 15	SE TR 15	SE TR 15
PARAMETERS							
B/L	0.12	0.15	0.18	0.15	0.25	0.15	0.25
B_n/L	0	0	0	0.03	0.05	0.03	0.05
B_n/B	0	0	0	0.2	0.2	0.2	0.2
n/L	0.25	0.25	0.25	0.25	0.25	0.2	0.2
q/L	0.75	0.75	0.75	0.85	0.85	0.7	0.7
q/L	0	0	0	0.10	0.10	0.1	0.1
r_n/L	0.0808	0.06235	0.0894	0.0804	0.134	0.0802	0.1676
$(r_n/L)(B/L)^2$	2.146	2.146	2.146	2.146	2.146	2.88	2.88
$(r_n/n)(B/n)^2$	0.5365	0.5365	0.5365	0.5365	0.5365	0.5365	0.5365
r_n/L	0	0	0	0	0	0	0
$(r_n/L)(B/L)^2$	0	0	0	0	0	0	0
L/r_n	0.436	0.5326	0.54	0.5326	0.896	0.4325	1.39
$(L/r_n)(B/L)$	2.552	2.552	2.552	2.552	2.552	5.56	5.56
$(n/r_n)(B/n)$	0.222	0.222	0.222	0.222	0.222	0.222	0.222
$(dy/dx)_{r_n=x=0}$	-0.387	-0.323	-0.4	-0.323	-0.555	-0.417	-0.694
$(dy/dx)_{r_n=x=0(B/L)}$	-2.22	-2.22	-2.22	-2.22	-2.22	-2.776	-2.776
$(dy/dx)_{r_n=x=0(B/n)}$	-0.555	-0.555	-0.555	-0.555	-0.555	-0.555	-0.555
$-(dy/dx)_{r_n=0; x=L}$	0.1086	0.1086	0.1086	0	0	0	0
$-(dy/dx)_{r_n=0; x=L(B/L)}$	0.868	0.7111	0.592	0	0	0	0
$(L \cdot d^2y/dx^2)_{r_n=x=0}$	0.1032	0.129	0.1546	0.129	0.215	0.1775	0.296
$(L \cdot d^2y/dx^2)_{r_n=x=0(B/L)}$	0.86	0.86	0.86	0.86	0.86	1.163	1.163
$(n \cdot d^2y/dx^2)_{r_n=x=0(B/n)}$	0.05375	0.05375	0.05375	0.05375	0.05375	0.0473	0.0473
$(L \cdot d^2y/dx^2)_{r_n=0; x=L}$	0	0.213	0.426	0	0	0	0
$(L \cdot d^2y/dx^2)_{r_n=0; x=L(B/L)}$	0	1.42	2.366	0	0	0	0
$\int_0^1 (y/L) d(x/L)$	0.0386	0.0467	0.0579	0.0453	0.0755	0.0432	0.0730
$\frac{2L}{B} \int_0^1 (y/L) d(x/L)$	0.86	0.8683	0.8433	0.804	0.804	0.876	0.876
x_{pn}/L	—	—	—	—	—	—	—
x_{gn}/L	—	—	—	—	—	—	—
B_n/B	—	—	—	—	—	—	—
H/L	—	—	—	—	—	—	—
H/B	—	—	—	—	—	—	—

Table 2 continued

41 TR 15	52 TR 15	53 B 15	54 BR 15	59 BR 15	57 BR 17	NACA 6015 FOR THE PURPOSE OF COMPARISON	NACA 6025	PROFILE PARAMETERS
0.15	0.25	0.15	0.15	0.15	0.15	0.15	0.25	B/L
0.015	0.015	0	-0.1085	0.0865	0.015	0.003	0.005	B_3/L
0.10	0.05	0	-0.7323	0.8433	0.1	0.03	0.02	B_3/B
0.20	0.2	0.5	0.5	0.5	0.5	0.20	0.20	n/L
0.75	0.75	0.5	0.5	0.5	0.5	0.70	0.70	a/L
0.05	0.05	0	0	0	0	0	0	g/L
0.0802	0.1676	0.0112	0.04623	0.04825	0	0.02475	0.00875	r_n/L
2.48	2.48	0.5	2.165	2.165	0	1.1	1.1	$(r_n/L)/(B/L)^2$
0.5365	0.5365	0.25	1.072	1.072	0	0.330	0.330	$(r_n/n)/(B/n)^2$
0	0	0.0112	0.04623	0.04825	0	0	0	r_n/L
0	0	0.5	2.165	2.165	0	0	0	$(r_n/L)/(B/L)^2$
0.5325	1.29	0.3	0	5.59	1.82	0.39887	0.04438	L/r_n
5.56	5.56	2	0	43.9	10.8	2.65714	2.65714	$(L/r_n)/(B/L)$
0.222	0.222	0.5	0	10.26	2.7	0.239	0.239	$(n/r_n)/(B/n)$
-0.417	-0.694	0	0	0	0	-0.0717	-0.1195	$(dy/dx)_{r_n} = x = 0$
-2.776	-2.776	0	0	0	0	-0.4781	-0.4781	$(dy/dx)_{r_n} = x = 0 (B/L)$
-0.555	-0.555	0	0	0	0	-0.143	-0.143	$(dy/dx)_{r_n} = x = 0 (B/n)$
0	0	0	0	0	0	0.1755	0.2925	$-(dy/dx)_{r_n} = 0; x = L$
0	0	0	0	0	0	1.17	1.17	$-(dy/dx)_{r_n} = 0; x = L (B/L)$
0.1775	0.296	0	-7.45	0	1.82	-0.81497	-1.29827	$(L \cdot d^2y/dx^2)_{r_n} = x = 0$
1.123	1.123	0	-69.5	0	10.8	-5.4331	-5.4331	$(L \cdot d^2y/dx^2)_{r_n} = x = 0 (B/L)$
0.0672	0.0672	0	12.417	0	2.7	-0.06171	-0.06171	$(n \cdot d^2y/dx^2)_{r_n} = x = 0 (B/n)$
0	0	0	-7.45	0	1.82	-0.1028	-0.1714	$(L \cdot d^2y/dx^2)_{r_n} = 0; x = L$
0	0	0	-69.5	0	10.8	-0.8657	-0.8657	$(L \cdot d^2y/dx^2)_{r_n} = 0; x = L (B/L)$
0.0410	0.0682	0.0589	0.05	0.0406	0.04125	0.05140	0.02867	$\int_0^1 (y/L) d(x/L)$
0.5467	0.5296	0.7854	0.986	0.5413	0.5500	0.68536	0.62536	$\frac{2L}{B} \int_0^1 (y/L) d(x/L)$
-	-	-	-0.995	0.04825	-	-	-	x_{n0}/L
-	-	-	-0.2075	0.19225	-	-	-	x_{n1}/L
-	-	-	-0.1085	0.0965	-	-	-	B_n/L
-	-	-	-0.7323	0.8433	-	-	-	B_n/B
-	-	-	-0.085	0.05	-	-	-	H/L
-	-	-	-0.433	0.23	-	-	-	H/B

Balanced rudder profiles are summarized as profile sketches in Figures 8 to 11. Table 3 contains the profile offsets of all of the IfS rudder profiles with the exception of the effects of the IfS 52 TR... family already published in Reference 3. The form parameters are summarized in their entirety in Table 2. The principal form ratios of

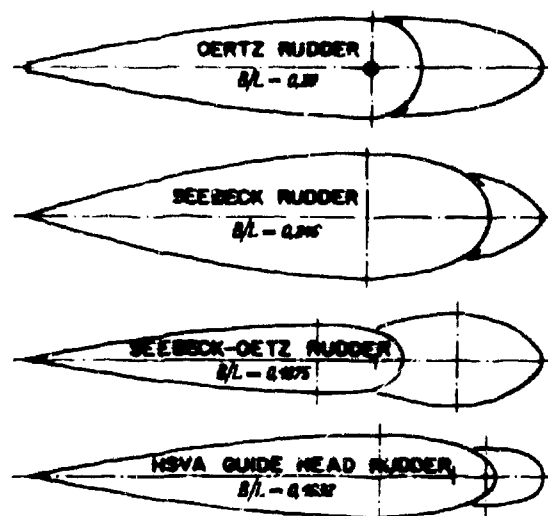


Figure 7 - Examples of Commonly Used Profiles of Guide-Head Rudders

foreign profiles are indicated in Table 1. Figure 12 shows the profiles of bow rudders and Figure 13 the profile sections of the plate rudders investigated or taken into consideration. In order to demonstrate more clearly and graphically the development into profiles with a relatively thick "nose" and a relatively flat "tail" (which proved successful according to the experiments reported here), Figure 14 shows a greatly enlarged representation of the nose contours and Figure 15 shows the tail contours of the old and new balanced rudders of particular interest to us.

The rudder profiles^{22,27} shown in Figure 9 are very ineffective on the basis of all practical experience and theoretical analysis. In spite of their "aesthetic" contour, the two profiles do not exhibit any

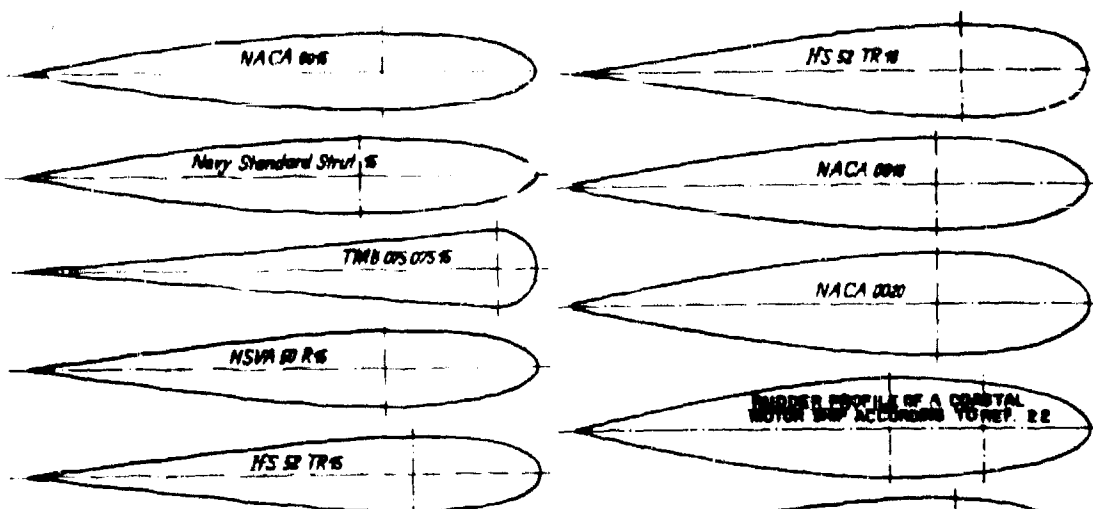


Figure 8 - Common Profiles of Balanced Rudders of 15 Percent Relative Thickness

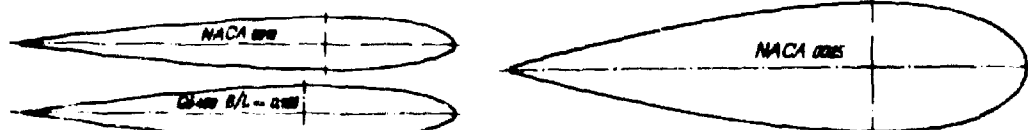


Figure 9 - Examples of Common Balanced Rudder Profiles of Greater Relative Thickness

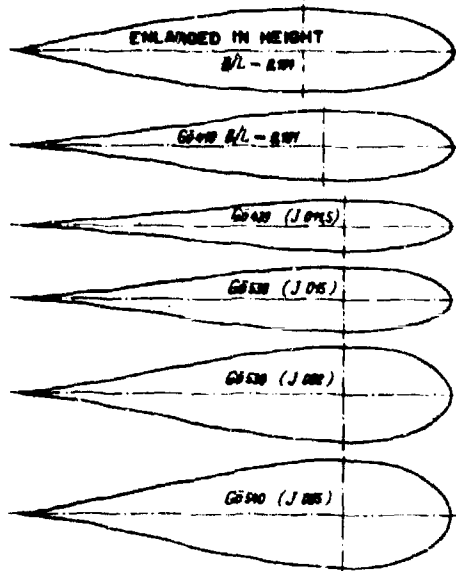


Figure 10 - Symmetrical Flow Profiles from Familiar Experimental Investigations

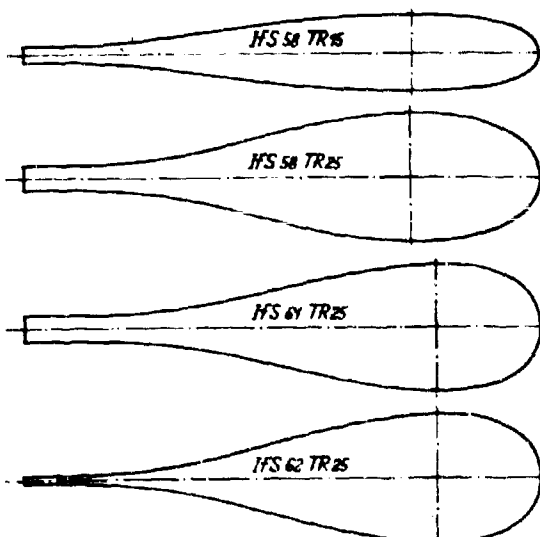


Figure 11 - The New JFS Balanced-Rudder Profiles

TABLE 3

Profile Offsets of the Rudder Profiles of the Present JFS Investigation

JFS 62 TR 15				25		JFS 55 BR 15		JFS 54 BR 15	
$\frac{x}{L}$	$\frac{y}{n}$	$\frac{y}{L}$	$\frac{y}{L}$	$\frac{x}{L}$	$\frac{y}{L}$	$\frac{x}{L}$	$\frac{y}{L}$	$\frac{x}{L}$	$\frac{y}{L}$
0	0	0	0	0	0	0	0	0	0
0,004	0,02	0,00025	0,03374	0,01	0,01499	0,01	0,00050		
0,010	0,05	0,00063	0,05104	0,025	0,02342	0,02	0,04091		
0,030	0,1	0,00159	0,06814	0,05	0,03209	0,05	0,05314		
0,040	0,2	0,00301	0,08825	0,10	0,04500	0,10	0,06575		
0,060	0,3	0,00445	0,10075	0,15	0,03356	0,15	0,08766		
0,080	0,4	0,00549	0,10916	0,20	0,06000	0,20	0,08170		
0,120	0,5	0,07149	0,11915	0,30	0,06574	0,25	0,09431		
0,160	0,6	0,07434	0,12374	0,40	0,07349	0,30	0,04405		
0,200	1,0	0,07500	0,12500	0,50	0,07500	0,35	0,06579		
	$\frac{x-n}{n}$					0,40	0,06781		
0,200	0	0,07500	0,12500			0,45	0,07385		
0,275	0,1	0,07371	0,12115			0,50	0,07560		
0,330	0,2	0,06629	0,11090						
0,425	0,3	0,05576	0,09378						
0,500	0,4	0,04547	0,07430						
0,575	0,5	0,03362	0,05405						
0,650	0,6	0,02253	0,03580						
0,725	0,7	0,01541	0,02150						
0,800	0,8	0,01021	0,01231						
0,875	0,9	0,00789	0,00619						
0,950	1,0	0,00750	0,00750						
1,000		0,00750	0,00750						

JFS 59 BR 15			JFS 57 BR 15	
$\frac{x}{L}$	$\frac{x}{x_{Rn}}$	$\frac{y}{L}$	$\frac{x}{L}$	$\frac{y}{L}$
0	0	0	0	0,00750
0,00096	0,02	0,00859	0,05	0,00939
0,00341	0,05	0,01505	0,10	0,01452
0,00483	0,10	0,02101	0,15	0,02158
0,00694	0,20	0,02893	0,20	0,03126
0,01446	0,30	0,03443	0,25	0,04125
0,01838	0,40	0,03857	0,30	0,05124
0,02883	0,50	0,04419	0,35	0,06042
0,03357	0,60	0,04724	0,40	0,06796
0,04821	1,00	0,04821	0,45	0,07311
	$\frac{x-x_{Rn}}{x_{Rn}-x_{Bn}}$		0,50	0,07500
0,04821	0	0,04821		
0,06317	0,1	0,04632		
0,07813	0,2	0,04211		
0,10606	0,4	0,03282		
0,13797	0,6	0,02702		
0,16789	0,8	0,02516		
0,19781	1,0	0,02500		
	$\frac{x-x_{Hn}}{x_{Hn}-x_{Rn}}$			
0,19781	0	0,02500		
0,25825	0,2	0,02537		
0,31869	0,4	0,03396		
0,37912	0,6	0,04676		
0,43956	0,8	0,05596		
0,49978	0,9	0,07239		
0,50000	1,0	0,07500		

Table 3 Continued

JIS 58 TR 15				25				JIS 61 TR 15				25			
$\frac{x}{L}$	$\frac{x}{n}$	$\frac{y}{L}$	$\frac{y}{L}$	$\frac{x}{L}$	$\frac{x}{n}$	$\frac{y}{L}$	$\frac{y}{L}$	$\frac{x}{L}$	$\frac{x}{n}$	$\frac{y}{L}$	$\frac{y}{L}$	$\frac{x}{L}$	$\frac{x}{n}$	$\frac{y}{L}$	$\frac{y}{L}$
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0,0050	0,02	0,02025	0,03374	0,004	0,02	0,02025	0,03374	0,004	0,02	0,02025	0,03374	0,004	0,02	0,02025	0,03374
0,1025	0,05	0,03032	0,05104	0,010	0,05	0,03062	0,05104	0,010	0,05	0,03062	0,05104	0,010	0,05	0,03062	0,05104
0,0250	0,1	0,04089	0,06811	0,020	0,1	0,04089	0,06811	0,020	0,1	0,04089	0,06811	0,020	0,1	0,04089	0,06811
0,0500	0,2	0,05301	0,08835	0,040	0,2	0,05301	0,08835	0,040	0,2	0,05301	0,08835	0,040	0,2	0,05301	0,08835
0,0750	0,3	0,06045	0,10075	0,060	0,3	0,06045	0,10075	0,060	0,3	0,06045	0,10075	0,060	0,3	0,06045	0,10075
0,1000	0,4	0,06650	0,10916	0,080	0,4	0,06549	0,10916	0,080	0,4	0,06549	0,10916	0,080	0,4	0,06549	0,10916
0,1500	0,6	0,07149	0,11915	0,120	0,6	0,07149	0,11915	0,120	0,6	0,07149	0,11915	0,120	0,6	0,07149	0,11915
0,2000	0,8	0,07425	0,12374	0,160	0,8	0,07424	0,12374	0,160	0,8	0,07424	0,12374	0,160	0,8	0,07424	0,12374
0,2500	1,0	0,07500	0,12500	0,200	1,0	0,07500	0,12500	0,200	1,0	0,07500	0,12500	0,200	1,0	0,07500	0,12500
	$\frac{x-n}{s}$				$\frac{x-n}{s}$				$\frac{x-n}{s}$				$\frac{x-n}{s}$		
0,2500	0	0,07500	0,12500	0,200	0	0,07500	0,12500	0,200	0	0,07500	0,12500	0,200	0	0,07500	0,12500
0,3150	0,1	0,07366	0,12277	0,270	0,1	0,07300	0,12166	0,270	0,1	0,07300	0,12166	0,270	0,1	0,07300	0,12166
0,3800	0,2	0,06922	0,11536	0,340	0,2	0,06734	0,11224	0,340	0,2	0,06734	0,11224	0,340	0,2	0,06734	0,11224
0,4450	0,3	0,06174	0,10290	0,410	0,3	0,05891	0,09819	0,410	0,3	0,05891	0,09819	0,410	0,3	0,05891	0,09819
0,5100	0,4	0,05206	0,08677	0,480	0,4	0,04890	0,08149	0,480	0,4	0,04890	0,08149	0,480	0,4	0,04890	0,08149
0,5750	0,5	0,04148	0,06913	0,550	0,5	0,03862	0,06437	0,550	0,5	0,03862	0,06437	0,550	0,5	0,03862	0,06437
0,6400	0,6	0,03145	0,05242	0,620	0,6	0,02934	0,04990	0,620	0,6	0,02934	0,04990	0,620	0,6	0,02934	0,04990
0,7050	0,7	0,02330	0,03882	0,690	0,7	0,02209	0,03681	0,690	0,7	0,02209	0,03681	0,690	0,7	0,02209	0,03681
0,7700	0,8	0,01790	0,02983	0,760	0,8	0,01743	0,02905	0,760	0,8	0,01743	0,02905	0,760	0,8	0,01743	0,02905
0,8350	0,9	0,01542	0,02570	0,830	0,9	0,01535	0,02558	0,830	0,9	0,01535	0,02558	0,830	0,9	0,01535	0,02558
0,9000	1,0	0,01500	0,02500	0,900	1,0	0,01500	0,02500	0,900	1,0	0,01500	0,02500	0,900	1,0	0,01500	0,02500
1,0000		0,01500	0,02500	1,000		0,01500	0,02500	1,000		0,01500	0,02500	1,000		0,01500	0,02500

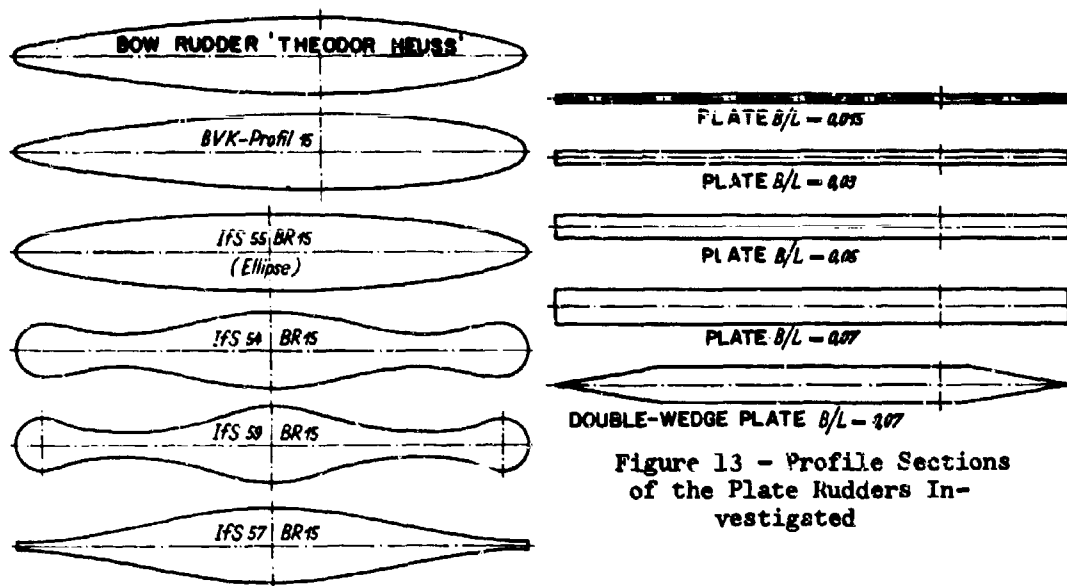


Figure 12 - Bow-Rudder Profiles

Figure 13 - Profile Sections
of the Plate Rudders In-
vestigated

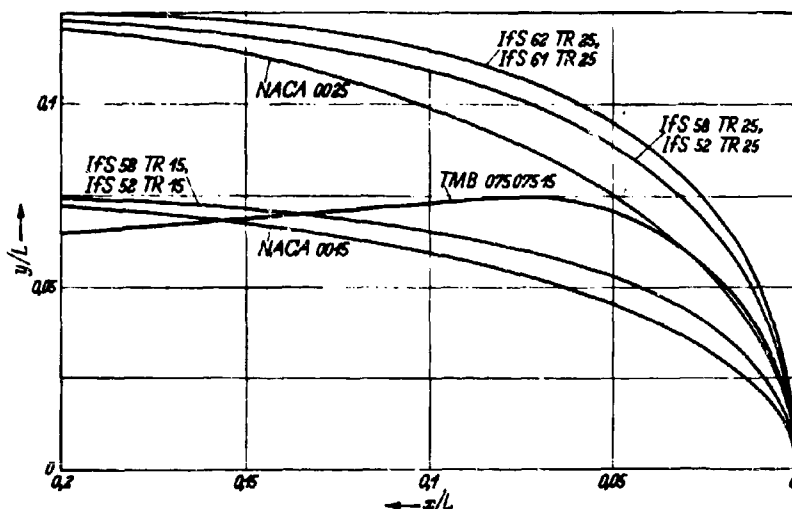


Figure 14 - Nose Contours of Several Balanced Rudder Profiles

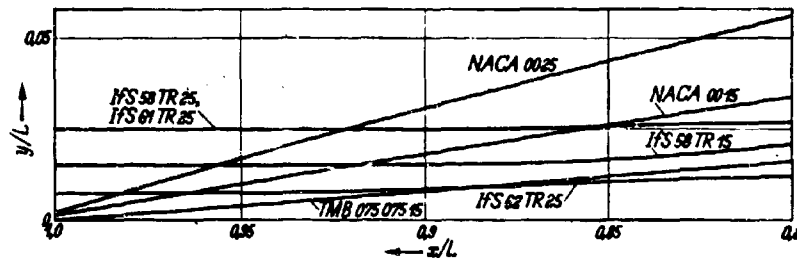


Figure 15 - Tail Contours of Several Balanced Rudder Profiles

great performances in the experiments carried out in the place cited. Conversely, profile TMB 075 075 15 which is a fairly primitive design (consisting only of a leading-edge circle and two tangent straight profile flanks) shows fairly good results if the Reynolds numbers are sufficiently large.²⁵ The good characteristics with respect to astern motion proved their worth even at the smaller Reynolds numbers of the JfS investigation. Therefore, the TMB profile is included in Figure 8 as well as in Figures 14 and 15.

F. SUPPLEMENTARY WIND-TUNNEL TESTS

Our published literature does not contain an excessively large number of special and systematic tests with free-running ship rudders. Not very much new material has been published since a summary of such test results was made in 1955.²⁶ Now that it has become pretty clear what the fundamental influence of the aspect ratio and Reynolds number amounts to (see Figures 44 and 45 in this connection), the need has arisen for carrying out comparative profile investigations. The fact that the profiles of the NACA 00.. series which, after all, had originally been intended for other purposes in the field of aeronautics, suggested the question whether it might not be possible to produce even more suitable profiles for use as ship rudders. Thus, new profile forms were produced at the Shipbuilding Institute which, however, were not yet sufficiently verified experimentally although, on occasion, they had already been used for comparative tests^{1,22,30} and have found practical application as well.



Figure 16 - Rudder Models Tested in the Wind Tunnel, Aspect Ratio $A_R = 1$

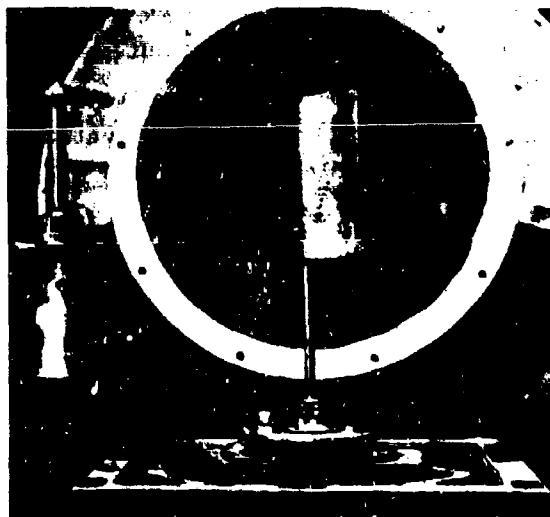


Figure 17 - Test Setup in the Former JfS Wind Tunnel at the Hamburg Engineering Institute

For the supplementary tests which appeared to be necessary in view of the influence of profile forms, the following JfS profiles newly developed in recent years were used:

Balanced-rudder profiles	JfS 58 TR 15
	25
	JfS 61 TR 25
	JfS 62 TR 25
Bow-rudder profiles	JfS 54 BR 15
	JfS 29 BR 15
	JfS 57 BR 15

For purposes of comparison, the following profiles were investigated:

Balanced-rudder profiles	TMB 075 075 15
	NACA 00 15
	25
Bow-rudder profile	JfS 55 BR 15 (ellipse)
Plate rudder	B/L = 0.015
	0.03
	0.05
	0.07

The large number of tests were carried out in the wind tunnel of the Hamburg Engineering Institute (formerly JfS Wind Tunnel). Figures 16 and 17 indicate the models and test setup used. All of the models had a square planform of 0.4 X 0.4 m. The slipstream cross section had a diameter

of 1 m so that a tank blockage of $A_R/A_S = 0.204$ was obtained. As a scale for these measurements we used a flexible-joint spring balance with electrical metering elements, which is also suitable for tank experiments. The testing path is practically zero so that it is not necessary to make any geometrical correction for the rudder angle. The capacity of the tunnel permitted a Reynolds number of approximately 0.8×10^6 . Several characteristic values for the profiles were investigated to obtain a clue to their dependence on the characteristic in question. By way of supplementing these tests, we also carried out experiments in a slipstream diameter of 0.5 m with the profiles NACA 0015 and JfS 58 TR 15 with models of 0.1 X 0.1 m. Thereby, for a tunnel blockage of $A_R/A_S = 0.0501$, a Reynolds number of approximately 0.13×10^6 was included as the minimum. The rudder measuring device for small ship models as used for the small rudders of the investigation² served as a wind-tunnel scale.

All of the data obtained are included in Tables 4-18 in the form of the familiar coefficients c_Q for the transverse force, c_D for the resistance, c_Y for the lateral force, c_X for the longitudinal force, and $c_{M,25}$ for the moment about an imaginary turning axis referred to the $L/4$ point of the rudder length. As examples for the graphical representation, Figures 18 to 39 show these coefficients as a function of the angle of attack ϵ . In doing so, we have generally represented the largest of the Reynolds numbers investigated. In the case of the profiles designated as bow rudders, we have measured and plotted the moment coefficient c_M which represents in nondimensional form the moment referred to the center of the rudder length rather than plotting the coefficient $c_{M,25}$. These bow rudders and the plate with $B/L = 0.05$ were provided with a shaft at $L_R/2$ for mounting support on the scale (all the other rudders had the shaft at $L_R/4$ from the front). A rod correction for this rudder shaft was deducted from the measured resistance. No further corrections were made since at the time the measurements were undertaken no sufficiently reliable procedures had yet been worked out for correcting the wind tunnel measurements of rudder surfaces with small aspect ratios. Since it is a fact, on the other hand (see Reference 26) that the use of the wind tunnel corrections for measurements on airfoils (hydrofoils) with larger aspect ratios would lead to an undercorrection for the transverse force maximum in the case of

rudders with an aspect ratio of 1 and to an overcorrection within the remaining range, the method used here probably represents the lesser of two evils. In any event, the omission of the correction is of minor importance for comparing the profile forms investigated here.

However, if we compare the data with foreign measurements, as in Figures 44 and 45, for instance, this factor should be borne in mind. The foreign measurements used in these figures are all corrected in the usual manner; that is to say that the transverse forces are somewhat too low in the case of the maximum transverse force and otherwise somewhat too high. However, since the tunnel blockages are lower there for the most part, than in the case of the JfS measurements with the 0.4 m rudders, the corrections are not so great either and therefore they cannot be decisive for the quality of the comparison with the new measurements.

As for the rest, the results of the measurements have been represented exactly as they have been measured geometrically. In doing so, we have used the definitions which have been recommended by the International Towing Tank Conference (ITTC). Thus, in each case a clockwise moment—clockwise as seen from above—is figured positive. The resistance is always calculated positive in the direction of the relative flow. The longitudinal force is figured positive in the direction from the profile center toward the nose of the profile. The lateral force, accordingly, is figured positive at a right angle toward the right starting from the positive x-direction. It should be borne in mind especially that the transverse force is figured positive to the right—always seen contrary to the relative flow—and that a positive angle of flow always results from a rotation which is positive in the direction of the moment. Thus, for instance, all of the measurements for astern motion indicated here have been measured and represented with flow angles between 180 and 90 deg.

We decided not to undertake here a comparative tabulation of precise force coefficients of the individual profiles. In most cases, the performance differences of the various profiles are obvious enough in the figures. Thus, the greatest transverse force coefficient measured was 1.478 for the JfS 62 TR 25 profile and the lowest transverse force maximum of the balanced-rudder profiles was 0.88 for the TMB 075 075 15 profile if the Reynolds number was equally high. In astern motion, however, the TMB

075 075 15 profile with $c_{C,Max} = 1.115$ is the best of these profiles whereas the NACA profile 0025 yields the poorest value, that is, 0.908. Among the bow rudders, JfS 57 BR 15 is best (maximum transverse force of 1.03) and the elliptical profile JfS 55 BR 15 is the worst (maximum transverse force of 0.743). For the purpose of carrying out a curve comparison, exact profiles have been selected. As for the effectiveness at smaller rudder angles, Figure 40 shows that the JfS 62 TR 15 profile is particularly good and the figure also shows the relatively good position of the two JfS 58 TR profiles. Figure 41 indicates the balancing possibility for the new JfS profiles, clearly an improvement over the NACA profiles; the turning axis may lie farther back without risking any danger of overbalance. The form of the familiar polar curves (Figure 42) indicates the effectiveness and the drag power requirement, especially at larger angles.

Profile JfS 58 TR 25 whose practical application is sturdy in form and performs very well; Figure 43 compares the polar curves in straight-ahead motion and motion along the turning circle with $L_L/R_L = 0.5$. In doing so, we have made the conversions starting out from the straight-ahead motion and using Equations [5] to [13]. In this case, we have introduced a drift angle on the ship $\epsilon_L = 11$ deg (see Figure 4) as well as a standard value $x_{LA}/L_L = -1/2$ and a (value) $c_{sc} = 1.0$ as it may be derived from Figure 40 with the aid of the method of Reference 26. This cautious method of estimating the rudder effect when turning and when checking the yaw in the turning circle already confirms the empirical fact that the drag power requirement is greater when checking the yaw than when turning. By way of supplementing the above data, Table 19 lists several comparative values for the control force and the drag power requirement for various profiles at a 35 deg rudder angle, both in straight-ahead motion and in motion along the turning circle. The method of calculation is the same as for Figure 43. Note that the superiority of the more recent profiles over the NACA profiles is also retained in the turning circle.

Figures 44 and 45 serve to compare foreign measurements and to illustrate the influence of the aspect ratio and Reynolds number. The results are in line with the general trend; thus there is every indication that the comparable results obtained here will remain valid even if the Reynolds numbers are extended further and if other aspects ratios are used.

TABLE 4
Test Results for TMB 075 075 15

Re = 0,38 · 10 ⁴						Re = 0,54 · 10 ⁴					
α°	c _C	c _D	c _Y	c _X	c _{M,α}	α°	c _C	c _D	c _Y	c _X	c _{M,α}
-2	-0,065	0,040	-0,056	-0,038	0,002	-2	-0,062	0,038	-0,063	-0,036	-0,002
0	0	0,040	0,000	-0,040	0	0	0	0,031	9	-0,031	-0,001
2	0,060	0,040	0,051	-0,038	0,002	2	0,062	0,033	0,063	-0,031	0,004
5	0,134	0,065	0,139	-0,063	-0,008	5	0,130	0,054	0,135	-0,043	-0,004
10	0,271	0,109	0,286	-0,081	-0,037	10	0,291	0,111	0,205	-0,059	-0,034
15	0,438	0,179	0,469	-0,080	-0,071	15	0,435	0,175	0,465	-0,056	-0,060
20	0,562	0,259	0,617	-0,061	-0,105	20	0,567	0,262	0,623	-0,052	-0,013
25	0,662	0,363	0,753	-0,049	-0,129	25	0,667	0,357	0,756	-0,042	-0,131
30	0,776	0,482	0,913	-0,029	-0,153	30	0,776	0,475	0,910	-0,023	-0,150
35	0,851	0,602	1,042	-0,005	-0,176	35	0,847	0,603	1,040	-0,006	-0,173
40	0,856	0,682	1,093	0,028	-0,183	40	0,861	0,700	1,110	0,018	-0,189
41	0,806	0,672	1,049	0,021	-0,181	43	0,743	0,678	1,006	0,011	-0,175
42	0,756	0,682	1,019	-0,001	-0,181	44	0,719	0,667	0,981	0,019	-0,169
45	0,662	0,692	0,957	-0,021	-0,174	45	0,716	0,672	0,981	0,031	-0,164
50	0,642	0,726	0,969	0,025	-0,176	50	0,648	0,719	0,967	0,034	-0,172
55	0,577	0,756	0,950	0,040	-0,176	55	0,582	0,755	0,952	0,044	-0,175
60	0,502	0,786	0,931	0,042	-0,178	60	0,502	0,766	0,914	0,052	-0,173
70	0,348	0,806	0,876	0,061	-0,181	70	0,350	0,792	0,865	0,058	-0,176
80	0,229	0,881	0,908	0,073	-0,215	80	0,225	0,873	0,899	0,071	-0,212
90	0,090	0,960	0,960	0,090	-0,261	90	0,097	0,972	0,972	0,097	-0,256

Re = 0,69 · 10 ⁴						ASTERN MOTION Re = 0,56 · 10 ⁴					
α°	c _C	c _D	c _Y	c _X	c _{M,α}	180° -α°	c _C	c _D	c _Y	c _X	c _{M,α}
-2	-0,068	0,033	-0,059	-0,030	-0,002	0	-0,010	0,067	0,010	0,057	-0,050
0	0	0,030	0	-0,030	0	5	-0,182	0,073	0,188	0,057	-0,073
2	0,065	0,030	0,056	-0,028	0,003	10	-0,336	0,121	0,352	0,061	-0,148
5	0,136	0,058	0,141	-0,046	-0,001	15	-0,532	0,213	0,569	0,068	-0,224
10	0,294	0,108	0,309	-0,055	-0,030	20	-0,705	0,319	0,772	0,059	-0,317
15	0,441	0,182	0,473	-0,062	-0,069	25	-0,885	0,466	0,999	0,052	-0,387
20	0,575	0,280	0,639	-0,047	-0,102	30	-1,033	0,634	1,211	0,032	-0,429
25	0,670	0,361	0,760	-0,044	-0,122	35	-1,104	0,811	1,370	0,031	-0,467
30	0,780	0,491	0,921	-0,035	-0,154	40	-1,095	0,972	1,444	0,041	-0,483
35	0,866	0,617	1,053	-0,014	-0,178	45	-1,022	1,061	1,487	0,041	-0,473
40	0,862	0,715	1,150	0,007	-0,194	50	-0,624	0,861	1,062	0,076	-0,341
41	0,824	0,694	1,077	0,016	-0,184	55	-0,539	0,910	1,054	0,080	-0,335
42	0,772	0,680	1,029	0,012	-0,178	60	-0,447	0,942	1,040	0,084	-0,324
45	0,717	0,686	0,992	0,022	-0,171	70	-0,272	0,996	1,029	0,085	-0,307
50	0,664	0,717	0,976	0,048	-0,170	80	-0,088	1,017	1,016	0,091	-0,289
55	0,596	0,745	0,946	0,052	-0,171	90	-0,092	0,982	0,982	0,092	-0,259
60	0,515	0,772	0,926	0,060	-0,174						
70	0,364	0,788	0,864	0,073	-0,177						
80	0,226	0,879	0,905	0,070	-0,213						
90	0,096	0,963	0,963	0,096	-0,250						

TABLE 5

Test Results for NACA 0015

 $Re = 0.20 \cdot 10^6$ $Re = 0.56 \cdot 10^6$

α°	c_c	c_D	c_Y	c_X	$c_{M,x}$	α°	c_c	c_D	c_Y	c_X	$c_{M,x}$
-2	-0.076	0.040	-0.077	-0.037	-0.017	-2	-0.047	0.021	-0.048	-0.020	-0.001
0	-0.016	0.040	-0.016	-0.040	-0.009	0	0	0.019	0	-0.019	0.004
2	0.042	0.044	0.042	-0.055	-0.009	2	0.037	0.021	0.057	-0.019	0.008
5	0.143	0.074	0.148	-0.081	-0.004	5	0.140	0.028	0.142	-0.016	0.016
10	0.345	0.123	0.361	-0.081	-0.009	10	0.279	0.047	0.283	0.002	0.002
15	0.408	0.308	0.508	-0.077	-0.025	15	0.442	0.083	0.448	0.034	0.031
20	0.534	0.316	0.628	-0.108	-0.105	20	0.622	0.147	0.634	0.075	0.004
25	0.682	0.438	0.780	-0.108	-0.132	25	0.782	0.215	0.781	0.127	-0.002
30	0.715	0.525	0.882	-0.087	-0.159	30	0.837	0.277	0.888	-0.140	-0.013
35	0.722	0.608	0.941	-0.084	-0.171	35	0.887	0.417	0.785	-0.041	-0.028
40	0.704	0.675	0.973	-0.085	-0.178	40	0.872	0.428	0.796	-0.033	-0.009
45	0.655	0.744	0.989	-0.083	-0.202	45	0.705	0.537	0.896	-0.035	-0.129
50	0.619	0.811	1.019	-0.047	-0.222	50	0.682	0.612	0.917	-0.031	-0.137
55	0.605	0.890	1.076	-0.014	-0.224	55	0.630	0.657	0.909	-0.037	-0.140
60	0.543	0.924	1.072	0.008	-0.255	60	0.538	0.719	0.910	-0.035	-0.149
65	0	1.009	1.009	0	-0.350	65	0.502	0.738	0.893	-0.011	-0.153
						70	0.440	0.768	0.885	-0.003	-0.157
						75	0.307	0.799	0.856	0.015	-0.170
						80	0.185	0.868	0.885	0.032	-0.213
						90	0.0015	0.980	0.980	0.062	-0.256

 $Re = 0.87 \cdot 10^6$ $Re = 0.79 \cdot 10^6$

α°	c_c	c_D	c_Y	c_X	$c_{M,x}$	α°	c_c	c_D	c_Y	c_X	$c_{M,x}$
-2	-0.052	0.025	-0.053	-0.023	-0.001	-2	-0.055	0.021	-0.055	-0.019	-0.001
0	0	0.022	0	-0.022	0.003	0	0	0.020	0	-0.020	0.003
2	0.062	0.024	0.063	-0.021	0.007	2	0.056	0.023	0.056	-0.021	0.008
5	0.144	0.027	0.145	-0.014	0.014	5	0.141	0.028	0.143	-0.014	0.014
10	0.284	0.039	0.287	0.011	0.018	10	0.289	0.042	0.292	0.009	0.021
15	0.453	0.074	0.456	0.046	0.018	15	0.441	0.089	0.444	0.048	0.019
20	0.632	0.138	0.641	0.087	0.001	20	0.622	0.135	0.630	0.086	0.006
25	0.762	0.220	0.784	0.123	-0.004	25	0.775	0.217	0.785	0.130	-0.004
30	0.927	0.325	0.948	0.183	-0.029	30	0.926	0.320	0.962	0.186	-0.028
35	0.982	0.387	1.038	0.192	-0.063	35	1.025	0.405	1.081	0.218	-0.080
40	0.692	0.491	0.848	-0.034	-0.122	40	1.052	0.505	1.153	0.111	-0.121
45	0.719	0.538	0.897	-0.028	-0.129	45	0.713	0.528	0.897	-0.023	-0.128
50	0.689	0.610	0.920	-0.025	-0.139	50	0.685	0.605	0.914	-0.023	-0.137
55	0.631	0.658	0.911	-0.019	-0.141	55	0.631	0.645	0.902	-0.010	-0.141
60	0.574	0.708	0.910	-0.014	-0.149	60	0.583	0.700	0.911	-0.004	-0.152
65	0.512	0.741	0.901	-0.006	-0.153	65	0.528	0.731	0.902	0.013	-0.155
70	0.441	0.768	0.886	-0.002	-0.163	70	0.448	0.761	0.883	0.007	-0.161
75	0.314	0.809	0.867	0.019	-0.175	75	0.322	0.791	0.853	0.031	-0.175
80	0.186	0.894	0.912	0.028	-0.214	80	0.209	0.875	0.898	0.054	-0.211
90	0.061	0.991	0.991	0.061	-0.261	90	0.065	0.969	0.969	0.065	-0.255

ASTERN MOTION $Re = 0.56 \cdot 10^6$

180° α°	c_c	c_D	c_Y	c_X	$c_{M,x}$
0	0	0.050	0	0.050	0.001
5	-0.241	0.089	0.246	0.047	-0.077
10	-0.385	0.102	0.397	0.033	-0.157
15	-0.532	0.180	0.561	0.036	-0.222
20	-0.643	0.258	0.692	0.022	-0.287
25	-0.771	0.376	0.857	0.015	-0.339
30	-0.918	0.532	1.061	0.002	-0.418
35	-1.022	0.719	1.249	0.003	-0.458
40	-1.059	0.885	1.380	-0.003	-0.489
45	-1.010	1.041	1.450	0.022	-0.492
50	-0.572	0.886	0.986	0.079	-0.347
55	-0.511	0.861	0.906	0.070	-0.341
60	-0.431	0.911	1.005	0.083	-0.336
70	-0.277	0.881	1.017	0.075	-0.315
80	-0.111	1.024	1.028	0.068	-0.297
90	-0.059	0.989	0.989	0.059	-0.283

TABLE 6
Test Results for NACA 0025

Re = 0.56 · 10 ⁶						Re = 0.66 · 10 ⁶					
α°	c _C	c _D	c _F	c _X	c _{M,α}	α°	c _C	c _D	c _F	c _X	c _{M,α}
-2	-0.052	0.036	-0.063	-0.034	-0.004	-2	-0.050	0.036	-0.051	-0.034	-0.004
0	0	0.033	0	0.033	-0.002	0	0	0.034	0	-0.034	-0.001
2	0.052	0.036	0.063	-0.034	0.003	2	0.053	0.034	0.054	-0.033	0.004
5	0.130	0.036	0.133	-0.036	0.008	5	0.129	0.040	0.132	-0.039	0.009
10	0.269	0.039	0.275	-0.012	0.014	10	0.272	0.055	0.278	-0.006	0.015
15	0.431	0.060	0.439	0.022	0.014	15	0.433	0.080	0.431	0.022	0.013
20	0.572	0.144	0.587	0.060	0.009	20	0.577	0.138	0.589	0.068	0.005
25	0.728	0.232	0.754	0.107	-0.006	25	0.732	0.221	0.757	0.109	-0.007
30	0.862	0.317	0.922	0.167	-0.025	30	0.895	0.317	0.933	0.174	-0.028
35	1.057	0.440	1.117	0.245	-0.080	35	1.039	0.447	1.107	0.229	-0.062
40	1.178	0.593	1.283	0.300	-0.102	40	1.188	0.600	1.296	0.305	-0.104
45	1.318	0.809	1.497	0.396	-0.162	45	1.315	0.778	1.490	0.390	-0.150
47	1.313	0.847	1.515	0.362	-0.173	48	1.330	0.874	1.532	0.396	-0.177
48	1.308	0.890	1.529	0.394	-0.186	49	1.313	0.910	1.548	0.394	-0.185
49	0.534	0.964	0.851	-0.032	-0.130	50	1.305	0.935	1.555	0.398	-0.190
50	0.531	0.999	0.847	-0.031	-0.132	51	0.537	0.679	0.859	-0.017	-0.133
55	0.485	0.734	0.871	-0.018	-0.147	55	0.485	0.719	0.867	-0.015	-0.144
60	0.433	0.745	0.857	-0.007	-0.154	60	0.435	0.746	0.863	0.003	-0.151
70	0.305	0.788	0.844	0.029	-0.169	70	0.319	0.780	0.842	0.033	-0.165
80	0.194	0.961	0.882	0.039	-0.210	80	0.198	0.851	0.872	0.047	-0.206
90	0.065	0.936	0.936	0.065	-0.255	90	0.063	0.828	0.928	0.063	-0.254

Re = 0.78 · 10 ⁶						ASTERN MOTION Re = 0.56 · 10 ⁶					
α°	c _C	c _D	c _F	c _X	c _{M,α}	180° -α°	c _C	c _D	c _F	c _X	c _{M,α}
-2	-0.050	0.032	-0.051	-0.030	-0.005	0	0	0.064	0	0.064	-0.004
0	0	0.031	0	-0.031	0.001	5	-0.267	0.095	-0.274	0.071	-0.088
2	0.055	0.036	0.056	-0.033	0.003	10	-0.412	0.142	-0.431	0.068	-0.165
5	0.132	0.036	0.134	-0.034	0.010	15	-0.553	0.199	-0.585	0.049	-0.235
10	0.270	0.052	0.275	-0.005	0.015	20	-0.672	0.289	-0.730	0.041	-0.300
15	0.419	0.069	0.428	0.023	0.015	25	-0.738	0.381	-0.830	0.033	-0.340
20	0.586	0.145	0.599	0.065	0.008	30	-0.767	0.511	-0.921	0.059	-0.362
25	0.732	0.217	0.756	0.112	-0.004	35	-0.672	0.548	-0.864	0.064	-0.332
30	0.883	0.319	0.916	0.166	-0.026	37	-0.908	0.719	-1.157	0.028	-0.436
35	1.033	0.446	1.102	0.227	-0.058	40	-0.894	0.816	-1.210	0.050	-0.447
40	1.192	0.595	1.294	0.310	-0.099	45	-0.529	0.705	-0.872	0.124	-0.333
45	1.325	0.768	1.479	0.393	-0.146	50	-0.478	0.773	-0.899	0.131	-0.335
46	1.336	0.805	1.507	0.401	-0.153	55	-0.412	0.628	-0.915	0.138	-0.332
47	1.321	0.832	1.509	0.398	-0.165	60	-0.341	0.858	-0.914	0.134	-0.323
48	1.315	0.864	1.521	0.399	-0.177	70	-0.203	0.937	-0.949	0.130	-0.311
49	1.312	0.894	1.535	0.404	-0.183	80	-0.055	0.956	-0.952	0.112	-0.284
50	1.310	0.918	1.545	0.413	-0.187	90	-0.065	0.901	-0.901	0.065	-0.252
51	1.292	0.947	1.549	0.409	-0.194						
52	0.515	0.685	0.857	-0.016	-0.135						
55	0.495	0.710	0.863	-0.001	-0.139						
60	0.434	0.747	0.855	0.002	-0.152						
70	0.341	0.771	0.841	0.056	-0.164						
80	0.216	0.815	0.840	0.071	-0.197						
90	0.066	0.924	0.924	0.066	-0.247						

TABLE 7
Test Results for Jfs TR 15

Re = 0.15 · 10 ⁶						Re = 0.15 · 10 ⁶					
°	c _c	c _D	c _Y	c _X	c _{M,∞}	°	c _c	c _D	c _Y	c _X	c _{M,∞}
-1.2	-0.036	0.000	-0.007	-0.009	0.011	-1	-0.007	0.001	-0.000	-0.000	0.000
0.7	0.046	0.000	0.017	-0.000	0.019	0	0.007	0.000	0.007	-0.000	0.000
1.7	0.071	0.001	0.075	-0.000	0.010	1	0.075	0.000	0.075	-0.000	0.000
2.7	0.170	0.001	0.175	-0.045	0.009	2	0.007	0.000	0.007	-0.000	0.000
10.7	0.230	0.119	0.202	-0.065	0	3	0.075	0.000	0.075	-0.000	0.000
15.7	0.230	0.156	0.200	-0.073	-0.000	4	0.175	0.074	0.101	-0.000	0.000
20.7	0.200	0.230	0.075	-0.062	-0.117	10	0.204	0.120	0.200	-0.000	0
22.7	0.717	0.455	1.044	-0.000	-0.167	15	0.230	0.274	0.002	-0.130	-0.000
24.7	0.704	0.200	0.073	-0.004	-0.177	20	0.200	0.431	0.717	-0.100	-0.133
26.7	0.704	0.001	1.001	-0.075	-0.100	25	0.730	0.240	0.000	-0.100	-0.145
40.7	0.720	0.720	1.000	-0.070	-0.210	30	0.700	0.075	1.012	-0.100	-0.104
42.7	0.677	0.775	1.020	-0.006	-0.227	35	0.700	0.001	1.042	-0.112	-0.220
44.7	0.000	0.200	1.000	-0.007	-0.200	40	0.704	0.701	1.001	-0.000	-0.220
46.7	0.000	0.000	1.070	-0.030	-0.227	45	0.000	0.775	1.017	-0.001	-0.220
60.7	0.000	0.047	1.070	-0.010	-0.200	50	0.012	0.000	1.047	-0.070	-0.200
90.7	0	1.000	1.000	0.012	-0.200	55	0.007	0.015	1.114	-0.000	-0.201
						60	0.570	0.000	1.120	0.001	-0.200
						90	0	1.000	1.000	0	-0.270

Re = 0.55 · 10 ⁶						Re = 0.55 · 10 ⁶					
°	c _c	c _D	c _Y	c _X	c _{M,∞}	°	c _c	c _D	c _Y	c _X	c _{M,∞}
-1	-0.007	0.031	-0.000	-0.000	-0.000	-1	-0.004	0.002	-0.005	-0.000	-0.000
0	0	0.000	0	-0.000	-0.001	0	0	0.000	0	-0.000	-0.001
1	0.002	0.000	0.002	-0.000	0	1	0.001	0.004	0.002	-0.000	0
5	0.100	0.002	0.100	-0.010	0.001	5	0.100	0.000	0.100	-0.004	0
10	0.215	0.007	0.200	-0.001	0.001	10	0.215	0.000	0.200	-0.002	0.001
15	0.402	0.005	0.401	0.002	-0.000	15	0.404	0.000	0.400	0.000	-0.007
20	0.677	0.100	0.000	0.070	-0.002	20	0.007	0.100	0.700	0.070	-0.002
25	0.000	0.200	0.004	0.100	-0.000	25	0.003	0.202	0.000	0.100	-0.047
30	1.034	0.370	1.002	0.102	-0.002	30	1.044	0.304	1.000	0.100	-0.077
31	0.007	0.534	0.002	-0.000	-0.200	31	1.001	0.410	1.121	0.000	-0.007
35	0.000	0.034	1.000	-0.007	-0.100	35	1.112	0.440	1.110	0.210	-0.007
40	0.000	0.704	1.000	-0.010	-0.215	40	0.075	0.002	1.000	-0.010	-0.170
42	0.000	0.731	1.000	-0.002	-0.100	45	0.000	0.000	1.007	-0.011	0.101
45	0.700	0.721	1.002	0.012	-0.101	50	0.000	0.700	1.171	0.004	0.270
50	0.000	0.775	0.007	0.001	-0.100	55	0.004	0.704	1.111	0.012	0.204
55	0.000	0.770	0.000	0.012	-0.100	60	0.741	0.731	1.071	0.007	-0.100
60	0.000	0.705	0.010	0.010	-0.104	65	0.000	0.751	0.000	0.007	0.100
70	0.221	0.012	0.073	0.024	-0.100	70	0.000	0.770	0.001	0.017	-0.107
80	0.000	0.010	0.000	0.044	-0.231	80	0.477	0.700	0.001	0.013	-0.107
90	0.002	0.000	0.000	0.002	-0.271	90	0.222	0.017	0.070	0.002	0.100
						95	0.212	0.022	0.045	0.050	0.230
						99	0.000	1.000	1.000	0.000	-0.200

Re = 0.70 · 10 ⁶						ASTERN MOTION Re = 0.50 · 10 ⁶					
°	c _c	c _D	c _Y	c _X	c _{M,∞}	100°	c _c	c _D	c _Y	c _X	c _{M,∞}
-1	0.035	0.033	0.050	-0.031	0.001	0	0	0.052	0	0.052	0
0	0	0.020	0	-0.020	0	5	0.132	0.002	0.137	0.000	0.003
1	0.000	0.032	0.002	0.030	0	10	0.272	0.002	0.204	0.000	0.107
5	0.101	0.034	0.104	-0.020	0.001	15	0.537	0.100	0.570	0.051	0.220
10	0.322	0.033	0.327	0.001	0.001	20	-0.640	0.200	0.707	0.047	0.201
15	0.500	0.000	0.500	0.035	0.007	25	-0.771	0.400	0.000	0.030	-0.330
20	0.670	0.100	0.000	0.073	0.023	30	-0.932	0.550	1.000	0.017	-0.415
25	0.007	0.202	0.007	0.120	-0.040	35	-1.050	0.735	1.200	0.005	0.403
30	1.051	0.207	1.104	0.101	0.074	40	-1.114	0.000	1.422	0.037	-0.404
33	1.140	0.477	1.230	0.223	0.100	45	1.000	1.043	1.402	0.010	-0.400
34	1.102	0.512	1.205	0.237	0.100	50	0.610	0.021	1.021	0.001	0.353
35	0.001	0.037	1.000	0.011	0.100	55	0.525	0.000	1.012	0.000	0.342
40	0.000	0.702	1.104	0.001	0.210	60	0.445	0.023	1.022	0.007	0.330
45	0.740	0.720	1.000	0.000	0.103	70	0.200	0.000	1.030	0.073	0.320
50	0.000	0.705	0.000	0.001	0.100	80	0.111	1.015	1.010	0.000	0.207
55	0.570	0.705	0.073	0.021	0.100	90	-0.002	0.004	0.004	0.002	0.200
60	0.492	0.001	0.000	0.025	0.105						
70	0.320	0.011	0.075	0.032	-0.100						
80	0.200	0.012	0.037	0.035	-0.200						
90	0.002	0.000	0.000	0.002	0.204						

TABLE 8
Test Results for JFS 58 TR 25

Re = 0.56 · 10 ⁶						Re = 0.67 · 10 ⁶					
α°	c _C	c _D	c _Y	c _X	c _{M,α}	α°	c _C	c _D	c _Y	c _X	c _{M,α}
-2	-0.063	0.045	-0.084	-0.043	-0.006	-2	-0.060	0.046	-0.082	-0.044	-0.006
0	0	0.045	0	-0.045	-0.006	0	0	0.044	0	-0.044	-0.006
2	0.062	0.045	0.003	-0.043	-0.006	2	0.062	0.044	0.004	-0.042	-0.007
5	0.156	0.080	0.160	-0.086	-0.009	5	0.161	0.044	0.165	-0.080	-0.011
10	0.317	0.078	0.326	-0.082	-0.014	10	0.319	0.075	0.337	-0.019	-0.014
15	0.482	0.123	0.496	0.006	-0.025	15	0.491	0.136	0.507	0.006	-0.025
20	0.672	0.192	0.697	0.060	-0.045	20	0.670	0.197	0.696	0.044	-0.043
25	0.856	0.293	0.899	0.097	-0.069	25	0.846	0.290	0.890	0.065	-0.070
30	1.080	0.418	1.118	0.163	-0.102	30	1.021	0.404	1.066	0.161	-0.105
35	1.323	0.572	1.330	0.233	-0.143	35	1.206	0.568	1.313	0.226	-0.139
40	1.586	0.736	1.460	0.277	-0.177	40	1.321	0.719	1.474	0.298	-0.163
41	1.530	0.719	1.466	0.323	-0.185	41	1.324	0.747	1.499	0.305	-0.169
42	0.766	0.679	1.033	0.007	-0.204	42	1.354	0.778	1.527	0.328	-0.177
45	0.661	0.606	0.975	-0.011	-0.200	43	1.364	0.805	1.547	0.341	-0.181
50	0.629	0.707	0.947	0.027	-0.205	44	1.379	0.839	1.574	0.354	-0.189
55	0.577	0.778	0.968	0.027	-0.208	45	1.399	0.880	1.611	0.367	-0.196
60	0.506	0.789	0.945	0.038	-0.207	46	0.692	0.704	0.987	0.010	-0.196
70	0.359	0.818	0.893	0.067	-0.202	50	0.645	0.728	0.971	0.025	-0.197
80	0.230	0.887	0.912	0.063	-0.231	55	0.570	0.778	0.964	0.021	-0.205
90	0.099	0.956	0.956	0.099	-0.265	60	0.512	0.787	0.937	0.049	-0.202
						70	0.367	0.810	0.887	0.068	-0.199
						80	0.229	0.864	0.891	0.076	-0.224
						90	0.078	0.936	0.936	0.098	-0.258

Re = 0.78 · 10 ⁶						ASTERN MOTION Re = 0.56 · 10 ⁶					
α°	c _C	c _D	c _Y	c _X	c _{M,α}	180° -α°	c _C	c _D	c _Y	c _X	c _{M,α}
-2	-0.059	0.047	-0.061	-0.045	-0.006	0	-0.014	0.085	0.014	0.085	-0.005
0	0	0.043	0	-0.043	-0.006	5	-0.151	0.099	0.160	0.086	-0.069
2	0.062	0.044	0.063	-0.042	-0.009	10	-0.293	0.139	0.313	0.087	-0.168
5	0.149	0.080	0.153	-0.087	-0.009	15	-0.428	0.196	0.464	0.079	-0.233
10	0.313	0.076	0.321	-0.080	-0.014	20	-0.674	0.356	0.755	0.086	-0.297
15	0.499	0.123	0.503	0.007	-0.024	25	-0.785	0.475	0.912	0.098	-0.361
20	0.680	0.191	0.685	0.047	-0.042	30	-0.885	0.589	1.071	0.067	-0.415
25	0.844	0.288	0.887	0.084	-0.067	35	-0.927	0.714	1.169	0.053	-0.437
30	1.022	0.411	1.091	0.156	-0.100	40	-0.975	0.873	1.308	0.041	-0.461
35	1.306	0.559	1.309	0.233	-0.132	45	-0.610	0.735	0.952	0.068	-0.345
40	1.324	0.711	1.472	0.307	-0.160	50	-0.558	0.797	0.970	0.085	-0.344
45	1.410	0.877	1.617	0.377	-0.194	55	-0.478	0.863	0.990	0.104	-0.340
46	1.416	0.906	1.635	0.369	-0.197	60	-0.385	0.892	0.966	0.113	-0.329
47	1.431	0.941	1.664	0.405	-0.206	70	-0.229	0.952	0.972	0.111	-0.311
48	1.448	0.972	1.691	0.425	-0.211	80	-0.069	0.987	0.984	0.104	-0.293
49	0.654	0.756	1.000	-0.003	-0.206	90	+0.104	0.952	0.952	0.104	-0.263
50	0.643	0.743	0.963	0.015	-0.200						
55	0.590	0.785	0.962	0.033	-0.204						
60	0.530	0.803	0.960	0.057	-0.205						
70	0.377	0.821	0.901	0.073	-0.202						
80	0.253	0.873	0.903	0.097	-0.227						
90	0.105	0.954	0.954	0.105	-0.263						

TABLE 9
Test Results for JfS 61 TR 25

Re = 9,56 · 10 ⁴						Re = 0,70 · 10 ⁴					
α°	c_C	c_D	c_Y	c_X	$c_{M,n}$	α°	c_C	c_D	c_Y	c_X	$c_{M,n}$
-2	-0,054	0,052	-0,056	-0,050	0,005	-2	-0,056	0,050	-0,058	-0,048	0,006
0	0	0,047	0	-0,047	0,004	0	0	0,049	0	-0,049	-0,004
2	0,068	0,050	0,066	-0,047	0,004	2	0,062	0,050	0,064	-0,048	0,004
5	0,161	0,054	0,165	-0,040	0,004	5	0,161	0,058	0,166	-0,043	0,003
10	0,317	0,083	0,326	-0,027	-0,002	10	0,323	0,084	0,333	-0,027	-0,002
15	0,501	0,133	0,516	0,002	-0,014	15	0,509	0,130	0,526	0,006	-0,015
20	0,676	0,203	0,704	0,040	-0,033	20	0,692	0,204	0,719	0,045	-0,034
25	0,866	0,307	0,915	0,088	-0,058	25	0,873	0,309	0,921	0,089	-0,059
30	1,056	0,442	1,137	0,147	-0,094	30	1,047	0,437	1,126	0,145	-0,091
31	1,083	0,475	1,174	0,161	-0,102	35	1,231	0,598	1,352	0,216	-0,132
32	1,131	0,506	1,227	0,170	-0,109	36	1,254	0,636	1,388	0,222	-0,139
33	1,166	0,539	1,270	0,183	-0,118	37	1,269	0,658	1,409	0,238	-0,142
34	1,188	0,572	1,305	0,190	-0,127	38	1,292	0,691	1,444	0,250	-0,150
35	0,780	0,638	1,005	-0,074	-0,191	39	0,901	0,710	1,069	-0,048	-0,202
40	0,799	0,723	1,077	-0,040	-0,203	40	0,795	0,725	1,075	-0,044	-0,206
45	0,691	0,717	0,996	-0,018	-0,191	45	0,707	0,736	1,021	-0,021	-0,201
50	0,633	0,755	0,985	-0,001	-0,196	50	0,640	0,756	0,990	0,004	-0,195
55	0,579	0,780	0,970	0,027	-0,194	55	0,599	0,783	0,984	0,042	-0,197
60	0,506	0,808	0,953	0,034	-0,200	60	0,512	0,806	0,954	0,041	-0,200
70	0,355	0,818	0,890	0,053	-0,194	70	0,385	0,807	0,884	0,067	-0,195
80	0,229	0,880	0,907	0,072	-0,224	80	0,226	0,884	0,909	0,069	-0,227
90	0,104	0,963	0,963	0,104	-0,263	90	0,101	0,953	0,953	0,101	-0,259

Re = 0,79 · 10 ⁴						ASTERN MOTION Re = 0,56 · 10 ⁴					
α°	c_C	c_D	c_Y	c_X	$c_{M,n}$	α°	c_C	c_D	c_Y	c_X	$c_{M,n}$
-2	-0,058	0,047	-0,060	-0,045	0,004	0	+0,005	0,086	-0,005	0,088	0,001
0	0	0,046	0	-0,046	0,003	5	-0,142	0,102	0,150	0,089	-0,077
2	0,060	0,047	0,061	-0,045	0,004	10	-0,298	0,149	0,319	0,095	-0,153
5	0,147	0,051	0,151	-0,038	0,002	15	-0,444	0,222	0,486	0,099	-0,219
10	0,322	0,076	0,330	-0,019	-0,002	20	-0,562	0,376	0,751	0,127	-0,281
15	0,495	0,126	0,511	0,007	-0,014	25	-0,771	0,475	0,900	0,105	-0,333
20	0,678	0,192	0,703	0,052	-0,031	30	-0,894	0,593	1,071	0,066	-0,412
25	0,856	0,296	0,900	0,095	-0,057	35	-0,955	0,709	1,189	0,033	-0,436
30	1,037	0,422	1,109	0,154	-0,087	40	-0,999	0,870	1,324	0,024	-0,466
35	1,213	0,578	1,325	0,223	-0,125	45	-0,636	0,728	0,111	0,064	-0,342
40	1,327	0,732	1,487	0,292	-0,154	50	-0,596	0,820	1,011	0,070	-0,349
41	1,342	0,731	1,083	-0,027	-0,208	55	-0,502	0,880	1,009	0,094	-0,345
45	0,720	0,728	1,024	-0,006	-0,200	60	-0,413	0,910	0,985	0,093	-0,332
50	0,646	0,738	0,980	0,021	-0,195	70	-0,248	0,967	0,994	0,098	-0,313
55	0,602	0,795	0,996	0,037	-0,204	80	-0,078	0,985	0,994	0,096	-0,294
60	0,530	0,810	0,966	0,054	-0,201	90	-0,104	0,963	0,963	0,104	-0,265
70	0,377	0,818	0,898	0,074	-0,198						
80	0,256	0,868	0,899	0,101	-0,222						
90	0,109	0,943	0,109	0,109	-0,260						

TABLE 10
Test Results for JfS 62 TR 25

Re = 0.56 · 10 ⁶						Re = 0.69 · 10 ⁶					
α°	c _C	c _D	c _Y	c _X	c _{M,α}	α°	c _C	c _D	c _Y	c _X	c _{M,α}
-2	-0.052	0.038	-0.053	-0.036	0.002	-2	-0.055	0.040	-0.056	-0.038	0.001
0	0	0.036	0	-0.036	0.001	0	0	0.036	0	-0.036	0
2	0.062	0.036	0.063	-0.033	0.001	2	0.065	0.039	0.066	-0.036	0.001
5	0.161	0.040	0.164	-0.026	0	5	0.166	0.043	0.169	-0.028	0
10	0.324	0.073	0.332	-0.016	-0.007	10	0.334	0.071	0.341	-0.012	-0.008
15	0.516	0.123	0.531	0.015	-0.020	15	0.521	0.123	0.535	0.016	-0.020
20	0.698	0.196	0.713	0.055	-0.039	20	0.706	0.200	0.731	0.054	-0.039
25	0.894	0.307	0.940	0.100	-0.067	25	0.894	0.305	0.940	0.102	-0.068
30	1.088	0.449	1.167	0.155	-0.105	30	1.072	0.442	1.149	0.153	-0.090
35	1.254	0.617	1.383	0.213	-0.145	35	1.236	0.608	1.361	0.210	-0.135
38	1.320	0.712	1.478	0.251	-0.164	40	1.373	0.762	1.541	0.250	-0.156
39	0.799	0.705	1.065	-0.045	-0.202	41	1.379	0.783	1.554	0.314	-0.155
40	0.790	0.707	1.060	-0.034	-0.220	42	1.397	0.828	1.592	0.320	-0.162
45	0.714	0.705	1.004	0.006	-0.191	45	1.461	0.925	1.687	0.379	-0.174
50	0.648	0.745	0.988	0.017	-0.182	46	0.698	0.723	1.005	0	-0.185
55	0.596	0.792	0.992	0.034	-0.200	50	0.691	0.747	0.997	0.025	-0.194
60	0.527	0.906	0.962	0.053	-0.200	55	0.605	0.780	0.966	0.047	-0.196
70	0.381	0.823	0.903	0.075	-0.197	60	0.532	0.903	0.961	0.090	-0.197
80	0.251	0.892	0.923	0.092	-0.226	70	0.381	0.824	0.904	0.076	-0.197
90	0.111	0.960	0.960	0.111	-0.256	80	0.248	0.868	0.897	0.063	-0.218
						90	0.117	0.952	0.952	0.117	-0.255

Re = 0.78 · 10 ⁶						ASTERN MOTION Re 0.56 · 10 ⁶					
α°	c _C	c _D	c _Y	c _X	c _{M,α}	180° -α°	c _C	c _D	c _Y	c _X	c _{M,α}
-2	-0.056	0.039	-0.057	-0.037	0.001	0	0	0.073	0	0.073	-0.001
0	0	0.036	0	-0.035	0.001	5	-0.147	0.078	0.153	0.065	-0.062
2	0.064	0.037	0.065	-0.034	0.001	10	-0.423	0.166	0.445	0.090	-0.163
5	0.162	0.042	0.165	-0.027	0	15	-0.577	0.240	0.620	0.063	-0.236
10	0.329	0.072	0.337	-0.014	-0.005	20	-0.705	0.345	0.780	0.073	-0.305
15	0.516	0.122	0.530	0.016	-0.019	25	-0.866	0.466	0.962	0.056	-0.387
20	0.708	0.199	0.733	0.055	-0.039	30	-0.976	0.603	1.147	0.034	-0.446
25	0.893	0.305	0.938	0.101	-0.064	35	-1.039	0.747	1.280	0.016	-0.477
30	1.084	0.442	1.159	0.159	-0.097	40	-1.148	0.903	1.382	0.015	-0.499
35	1.259	0.601	1.376	0.230	-0.131	45	-0.975	1.050	1.431	0.053	-0.481
40	1.378	0.751	1.538	0.311	-0.153	50	-0.553	0.820	0.983	0.104	-0.342
45	1.467	0.930	1.695	0.379	-0.181	55	-0.471	0.875	0.987	0.116	-0.336
46	1.478	0.966	1.721	0.382	-0.188	60	-0.388	0.922	0.992	0.125	-0.330
47	1.457	1.004	1.728	0.381	-0.184	70	-0.225	0.988	1.005	0.176	-0.313
48	1.451	1.010	1.720	0.402	-0.198	80	-0.050	1.003	0.997	0.125	-0.288
49	0.673	0.739	1.040	0.023	-0.195	90	-0.111	0.963	0.963	0.111	-0.259
50	0.668	0.743	0.998	0.034	-0.194						
55	0.613	0.794	1.002	0.047	-0.202						
60	0.548	0.818	0.982	0.065	-0.202						
70	0.405	0.855	0.942	0.088	-0.205						
80	0.278	0.872	0.907	0.123	-0.219						
90	0.120	0.960	0.960	0.120	-0.255						

TABLE 11
Test Results for JfS 55 BR 15

Re = 0,56 · 10 ⁶						Re = 0,71 · 10 ⁶					
α	c_C	c_D	c_Y	c_X	c_M	α	c_C	c_D	c_Y	c_X	c_M
2	-0,073	0,031	-0,074	-0,028	-0,010	2	-0,080	0,031	-0,081	-0,028	-0,012
0	0,005	0,033	0,005	-0,033	-0,002	0	0	0,028	0	-0,028	-0,001
2	0,083	0,031	0,084	-0,028	0,010	2	0,080	0,031	0,081	-0,028	0,011
5	0,303	0,040	0,206	-0,022	0,027	5	0,186	0,037	0,189	-0,021	0,030
10	0,352	0,089	0,359	-0,006	0,084	10	0,335	0,059	0,340	-0,000	0,088
15	0,506	0,106	0,517	0,028	0,101	15	0,478	0,097	0,486	0,029	0,105
20	0,608	0,185	0,634	0,025	0,133	20	0,601	0,182	0,627	0,035	0,139
25	0,674	0,329	0,749	-0,013	0,103	22	0,618	0,244	0,664	0,005	0,013
30	0,743	0,447	0,867	-0,015	0,124	25	0,664	0,331	0,742	-0,019	0,110
35	0,690	0,542	0,876	-0,049	0,102	30	0,721	0,438	0,844	-0,018	0,119
36	0,681	0,548	0,873	-0,043	0,101	35	0,692	0,529	0,870	-0,036	0,098
37	0,657	0,568	0,867	-0,069	0,097	36	0,670	0,541	0,880	-0,044	0,097
40	0,644	0,601	0,882	-0,043	0,097	37	0,668	0,560	0,870	-0,045	0,099
45	0,582	0,645	0,888	-0,044	0,085	30	0,640	0,594	0,872	-0,043	0,095
50	0,548	0,712	0,897	-0,039	0,089	45	0,595	0,654	0,883	-0,041	0,097
55	0,478	0,754	0,891	-0,041	0,085	50	0,538	0,704	0,885	-0,041	0,090
60	0,407	0,775	0,875	-0,036	0,073	55	0,485	0,751	0,893	-0,034	0,083
70	0,277	0,840	0,884	-0,027	0,052	60	0,411	0,790	0,890	-0,039	0,072
80	0,137	0,856	0,867	-0,014	0,029	70	0,284	0,840	0,888	-0,020	0,050
90	0	0,870	0,870	0	-0,002	80	0,141	0,849	0,880	-0,008	0,029
						90	0	0,876	0,876	0	0,001

TABLE 12
Test Results for JFS 54 BR 15

Re = 0.56 · 10 ⁶						Re = 0.71 · 10 ⁶					
α°	c_c	c_D	c_Y	c_X	c_M	α°	c_c	c_D	c_Y	c_X	c_M
-2	-0.059	0.073	-0.062	-0.071	-0.017	-2	-0.056	0.071	-0.059	-0.069	-0.018
0	0	0.069	0	-0.069	-0.003	0	0.003	0.067	0.003	-0.067	-0.003
2	0.064	0.071	0.066	-0.069	0.009	2	0.068	0.068	0.070	-0.066	0.017
5	0.163	0.083	0.170	-0.068	0.029	5	0.167	0.073	0.173	-0.059	0.031
10	0.333	0.121	0.349	-0.061	0.057	10	0.340	0.117	0.355	-0.056	0.060
15	0.492	0.185	0.523	-0.051	0.075	15	0.449	0.182	0.481	-0.059	0.078
20	0.629	0.277	0.686	-0.045	0.093	20	0.633	0.277	0.689	-0.043	0.096
25	0.762	0.395	0.858	-0.036	0.093	25	0.760	0.404	0.860	-0.045	0.102
30	0.873	0.534	1.023	-0.025	0.114	30	0.864	0.540	1.018	-0.036	0.116
35	0.967	0.688	1.187	-0.008	0.114	35	0.945	0.692	1.171	-0.025	0.117
40	0.965	0.820	1.266	-0.007	0.094	40	0.922	0.826	1.237	-0.040	0.103
41	0.861	0.783	1.163	-0.026	0.087	41	0.840	0.785	1.155	-0.049	0.103
42	0.799	0.750	1.095	-0.022	0.086	42	0.789	0.772	1.103	-0.046	0.092
45	0.723	0.759	1.040	-0.026	0.086	45	0.720	0.754	1.042	-0.024	0.088
50	0.652	0.792	1.026	-0.009	0.075	50	0.654	0.785	1.030	-0.010	0.078
55	0.577	0.825	1.007	0	0.068	55	0.577	0.828	1.009	-0.002	0.073
60	0.489	0.844	0.976	0.001	0.060	60	0.491	0.858	0.989	-0.004	0.063
70	0.326	0.884	0.941	0.004	0.045	70	0.321	0.890	0.946	-0.003	0.049
80	0.163	0.879	0.894	0.010	0.026	80	0.158	0.887	0.901	0.002	0.029
90	0.005	0.901	0.901	0.005	0.001	90	0.003	0.906	0.908	0.003	0.002

Re = 0.78 · 10 ⁶					
α°	c_c	c_D	c_Y	c_X	c_M
-2	-0.064	0.089	-0.066	-0.067	-0.014
0	0	0.080	0	-0.080	-0.003
2	0.060	0.083	0.061	-0.081	0.014
5	0.149	0.085	0.154	-0.052	0.033
10	0.341	0.121	0.357	-0.060	0.053
15	0.492	0.189	0.524	-0.056	0.075
20	0.630	0.284	0.689	-0.052	0.093
25	0.767	0.406	0.867	-0.044	0.094
30	0.863	0.544	1.019	-0.039	0.104
35	0.965	0.700	1.192	-0.020	0.111
40	0.962	0.837	1.275	-0.024	0.088
41	0.905	0.837	1.232	-0.038	0.079
42	0.812	0.778	1.124	-0.035	0.077
45	0.732	0.769	1.082	-0.026	0.070
50	0.649	0.803	1.032	-0.019	0.061
55	0.576	0.838	1.016	-0.009	0.053
60	0.489	0.867	0.995	-0.011	0.048
70	0.317	0.904	0.957	-0.011	0.034
80	0.165	0.890	0.906	0.007	0.016
90	0.006	0.905	0.905	0.006	-0.002

TABLE 13
Test Results for JFS 59 BR 15

$Re = 0,56 \cdot 10^6$

α°	c_C	c_D	c_Y	c_X	c_M
-2	-0,059	0,078	0,062	-0,076	-0,008
0	0	0,080	0	-0,080	0,002
2	0,066	0,080	0,069	-0,078	0,011
5	0,163	0,095	0,171	-0,080	0,028
10	0,338	0,140	0,357	-0,079	0,048
15	0,492	0,199	0,528	-0,084	0,064
20	0,634	0,269	0,695	-0,055	0,083
25	0,785	0,404	0,883	-0,034	0,088
30	0,953	0,570	1,110	-0,016	0,113
35	1,022	0,738	1,260	-0,018	0,106
40	1,029	0,887	1,358	-0,018	0,089
41	1,023	0,908	1,368	-0,014	0,080
42	0,792	0,752	1,091	-0,029	0,035
45	0,743	0,776	1,074	-0,025	0,068
50	0,669	0,802	1,045	-0,004	0,061
55	0,574	0,830	1,009	-0,006	0,052
60	0,487	0,854	0,983	-0,005	0,051
70	0,321	0,894	0,950	-0,005	0,035
80	0,159	0,903	0,917	-0,001	0,014
90	0	0,913	0,913	0	0,002

$Re = 0,71 \cdot 10^6$

α°	c_C	c_D	c_Y	c_X	c_M
-2	-0,058	0,084	-0,061	-0,082	-0,008
0	0	0,080	0	-0,080	0,002
2	0,065	0,083	0,068	-0,080	0,011
5	0,152	0,096	0,160	-0,083	0,027
10	0,342	0,138	0,361	-0,076	0,047
15	0,494	0,193	0,528	-0,064	0,084
20	0,640	0,300	0,704	-0,063	0,087
25	0,782	0,429	0,890	-0,058	0,093
30	0,930	0,577	1,094	-0,035	0,115
35	1,024	0,757	1,273	-0,033	0,113
40	1,020	0,906	1,364	-0,039	0,098
41	1,009	0,923	1,366	-0,037	0,091
42	0,808	0,747	1,099	-0,015	0,074
45	0,729	0,775	1,063	-0,033	0,065
50	0,661	0,809	1,045	-0,014	0,061
55	0,581	0,835	1,017	-0,003	0,053
60	0,492	0,858	0,989	-0,003	0,047
70	0,315	0,891	0,935	-0,005	0,037
80	0,160	0,899	0,913	0,001	0,012
90	0	0,921	0,921	0	-0,001

$Re = 0,78 \cdot 10^6$

α°	c_C	c_D	c_Y	c_X	c_M
-2	-0,059	0,088	-0,062	-0,086	-0,012
0	0	0,085	0	-0,085	0
2	0,066	0,087	0,069	-0,084	0,012
5	0,173	0,096	0,181	-0,081	0,028
10	0,341	0,140	0,360	-0,078	0,049
15	0,502	0,209	0,539	-0,072	0,071
20	0,649	0,296	0,711	-0,056	0,089
25	0,791	0,428	0,898	-0,053	0,096
30	0,928	0,573	1,090	-0,032	0,116
35	1,019	0,749	1,263	-0,029	0,109
40	1,019	0,891	1,353	-0,027	0,094
41	1,005	0,926	1,365	-0,039	0,089
42	0,808	0,779	1,121	-0,039	0,075
45	0,747	0,780	1,079	-0,023	0,067
50	0,660	0,820	1,052	-0,022	0,063
55	0,583	0,852	1,032	-0,011	0,056
60	0,503	0,874	1,008	-0,002	0,047
70	0,322	0,901	0,956	-0,007	0,033
80	0,163	0,910	0,924	0,002	0,017
90	0,005	0,918	0,918	0,005	-0,000

TABLE 14
Test Results for JFS 57 BR 15

Re = 0.56 · 10 ⁶						Re = 0.72 · 10 ⁶					
α°	c _C	c _D	c _Y	c _X	c _M	α°	c _C	c _D	c _Y	c _X	c _M
-2	-0,057	0,028	-0,058	-0,096	-0,013	-2	-0,056	0,030	-0,057	-0,028	-0,011
0	0	0,026	0	-0,026	0,001	0	0,003	0,028	0,003	-0,028	0,005
2	0,059	0,031	0,060	-0,029	0,019	2	0,059	0,031	0,060	-0,029	0,022
5	0,147	0,043	0,150	-0,029	0,044	5	0,148	0,037	0,150	-0,024	0,045
10	0,293	0,069	0,300	-0,017	0,078	10	0,293	0,068	0,300	-0,016	0,081
15	0,435	0,123	0,452	-0,006	0,099	15	0,435	0,123	0,452	-0,006	0,101
20	0,579	0,213	0,617	-0,002	0,106	20	0,572	0,217	0,612	-0,008	0,111
25	0,717	0,336	0,792	-0,002	0,092	25	0,698	0,349	0,780	-0,021	0,097
30	0,894	0,511	1,030	0,015	0,121	27	0,735	0,401	0,837	-0,023	0,101
35	1,010	0,588	1,222	0,016	0,130	28	0,751	0,427	0,863	-0,024	0,104
40	1,053	0,675	1,370	0,006	0,124	29	0,825	0,470	0,949	-0,011	0,117
42	1,046	0,922	1,394	0,014	0,102	30	0,877	0,506	1,013	0,001	0,123
43	0,706	0,707	0,997	-0,036	0,078	35	0,985	0,703	1,210	-0,011	0,140
45	0,672	0,726	0,988	-0,038	0,078	40	1,038	0,889	1,368	-0,014	0,127
50	0,601	0,776	0,982	-0,038	0,070	42	0,996	0,965	1,385	-0,051	0,120
55	0,534	0,825	0,981	-0,036	0,062	43	0,704	0,724	1,009	-0,050	0,086
60	0,454	0,868	0,978	-0,041	0,058	45	0,667	0,736	0,992	-0,048	0,086
70	0,300	0,908	0,956	-0,028	0,047	50	0,603	0,794	0,995	-0,048	0,077
80	0,149	0,929	0,941	-0,014	0,023	55	0,535	0,841	0,998	-0,045	0,073
90	-0,005	0,964	0,964	-0,005	-0,002	60	0,455	0,880	0,990	-0,046	0,067
						70	0,307	0,940	0,987	-0,033	0,048
						80	0,154	0,944	0,956	-0,013	0,030
						90	0,001	0,962	0,962	-0,002	0

TABLE 15
Test Results for Square Plate B/L = 0.015

Re = 0.56 · 10 ⁶						Re = 0.71 · 10 ⁶					
α°	c _C	c _D	c _Y	c _X	c _{M, u}	α°	c _C	c _D	c _Y	c _X	c _{M, u}
-2	-0,057	0,018	-0,057	-0,016	0,004	-2	-0,056	0,022	-0,057	-0,020	-0,002
0	0	0,017	0	-0,017	0,001	0	0	0,018	0	-0,018	0,001
2	0,057	0,017	0,057	-0,015	-0,003	2	0,056	0,019	0,057	-0,017	0,004
5	0,156	0,024	0,158	-0,010	-0,004	5	0,151	0,030	0,153	-0,016	0,007
10	0,338	0,071	0,345	-0,011	-0,008	10	0,349	0,077	0,357	-0,015	-0,006
15	0,553	0,149	0,573	-0,001	-0,037	15	0,544	0,155	0,565	-0,009	-0,034
20	0,762	0,272	0,809	0,006	-0,082	20	0,749	0,271	0,797	0,001	-0,077
25	0,929	0,423	1,021	0,010	-0,129	25	0,925	0,413	1,013	0,017	-0,120
30	1,070	0,587	1,220	0,027	-0,175	30	1,047	0,587	1,201	0,016	-0,165
35	1,155	0,762	1,382	0,038	-0,213	35	1,159	0,758	1,384	0,043	-0,002
40	1,178	0,939	1,505	0,038	-0,256	40	1,177	0,944	1,508	0,033	-0,230
41	1,153	0,939	1,488	0,049	-0,256	41	1,157	0,936	1,487	0,052	-0,247
42	0,803	0,714	1,123	0,050	-0,202	42	0,954	0,725	1,119	0,032	-0,199
45	0,773	0,747	1,074	0,018	-0,201	45	0,785	0,748	1,083	0,027	-0,195
50	0,681	0,768	1,026	0,020	-0,184	50	0,689	0,768	1,031	0,034	-0,187
55	0,599	0,785	0,985	0,038	-0,188	55	0,599	0,784	0,985	0,042	-0,181
60	0,502	0,802	0,945	0,034	-0,184	60	0,506	0,821	0,964	0,027	-0,186
70	0,336	0,863	0,926	0,021	-0,192	70	0,334	0,840	0,903	0,027	-0,186
80	0,180	0,975	0,991	0,008	-0,234	80	0,182	0,946	0,964	0,015	-0,223
90	0	1,048	1,048	0	-0,265	90	0,003	1,036	1,036	0,003	-0,262

TABLE 16
Test Results for Square Plate $B/L = 0.03$

$Re = 0.57 \cdot 10^6$						$Re = 0.71 \cdot 10^6$					
α°	c_C	c_D	c_Y	c_X	$c_{M,u}$	α°	c_C	c_D	c_Y	c_X	$c_{M,u}$
-2	-0.064	0.033	-0.056	-0.031	-0.002	-2	-0.061	0.036	-0.062	-0.033	-0.002
0	0.007	0.033	0.007	-0.033	0.002	0	0.003	0.033	0.003	-0.033	0.001
2	0.062	0.035	0.063	-0.033	0.005	2	0.061	0.036	0.063	-0.033	0.004
5	0.155	0.080	0.159	-0.031	0.006	5	0.155	0.044	0.159	-0.031	0.005
10	0.338	0.092	0.349	-0.032	-0.009	10	0.342	0.092	0.353	-0.031	-0.009
15	0.539	0.170	0.555	-0.025	-0.036	15	0.527	0.167	0.552	-0.025	-0.036
20	0.724	0.286	0.778	-0.022	-0.077	20	0.722	0.289	0.778	-0.024	-0.060
25	0.887	0.428	0.965	-0.013	-0.116	25	0.876	0.404	0.965	0.004	-0.117
30	1.036	0.592	1.193	0.005	-0.160	30	1.016	0.584	1.171	0.002	-0.164
35	1.119	0.762	1.353	0.018	-0.202	35	1.106	0.764	1.343	0.008	-0.203
40	1.154	0.920	1.476	0.038	-0.246	40	1.142	0.914	1.453	0.034	-0.240
41	1.147	0.951	1.489	0.035	-0.253	41	1.132	0.937	1.468	0.035	-0.243
42	0.853	0.716	1.112	0.038	-0.194	42	0.849	0.728	1.118	0.027	-0.198
45	0.816	0.743	1.103	0.053	-0.194	45	0.796	0.756	1.097	0.029	-0.198
50	0.681	0.771	1.028	0.026	-0.186	50	0.695	0.754	1.047	0.028	-0.197
55	0.582	0.780	0.973	0.029	-0.176	55	0.604	0.798	0.999	0.037	-0.182
60	0.489	0.797	0.935	0.024	-0.176	60	0.494	0.807	0.946	0.024	-0.177
70	0.321	0.863	0.921	0.007	-0.188	70	0.333	0.855	0.917	0.020	-0.182
80	0.177	0.953	0.970	0.006	-0.217	80	0.175	0.960	0.975	0.005	-0.217
90	0.007	1.062	1.062	0.007	-0.259	90	0.005	1.066	1.066	0.005	-0.263

TABLE 17
Test Results for Square Plate $B/L = 0.05$

$Re = 0.58 \cdot 10^6$							$Re = 0.67 \cdot 10^6$						
α°	c_C	c_D	c_Y	c_X	c_M	$c_{M,u}$	α°	c_C	c_D	c_Y	c_X	c_M	$c_{M,u}$
-2	-0.054	0.052	-0.056	-0.050	-0.013	0.002	-2	-0.051	0.056	-0.053	-0.054	-0.012	0.001
0	0.005	0.050	0.008	-0.050	0.001	-0.000	0	0	0.054	0	-0.054	0.003	0.0025
2	0.062	0.057	0.063	-0.055	0.018	0.002	2	0.061	0.058	0.063	-0.055	0.018	0.0021
5	0.161	0.069	0.166	-0.054	0.039	-0.003	5	0.166	0.071	0.171	-0.056	0.040	0.0027
10	0.336	0.116	0.351	-0.056	0.066	-0.003	10	0.345	0.117	0.360	-0.055	0.068	-0.0218
15	0.518	0.192	0.550	-0.051	0.085	-0.053	15	0.514	0.193	0.456	-0.053	0.086	-0.0506
20	0.690	0.291	0.749	-0.037	0.096	-0.069	20	0.697	0.315	0.763	-0.047	0.102	-0.0889
25	0.844	0.428	0.946	-0.031	0.098	-0.139	25	0.859	0.460	0.972	-0.054	0.109	-0.1343
30	0.991	0.619	1.168	-0.040	0.114	-0.178	30	0.995	0.624	1.173	-0.042	0.111	-0.1821
35	1.069	0.788	1.327	-0.032	0.107	-0.225	35	1.070	0.793	1.332	-0.037	0.107	-0.2250
40	1.130	0.948	1.459	-0.013	0.102	-0.263	40	1.125	0.954	1.475	-0.008	0.101	-0.2677
41	1.105	0.972	1.472	-0.009	0.098	-0.270	41	1.109	1.010	1.498	-0.035	0.112	-0.2624
42	1.065	0.979	1.469	0.004	0.094	-0.274	42	1.079	1.019	1.482	-0.036	0.103	-0.2673
43	0.894	0.809	1.208	0.019	0.080	-0.212	43	0.832	0.790	1.148	-0.010	0.072	-0.2161
45	0.785	0.804	1.123	-0.013	0.082	-0.200	45	0.798	0.795	1.126	0.002	0.070	-0.2115
50	0.714	0.842	1.103	0.005	0.069	-0.207	50	0.731	0.844	1.117	0.017	0.065	-0.2144
55	0.624	0.884	1.082	0.004	0.083	-0.207	55	0.616	0.879	1.073	0.001	0.062	-0.2059
60	0.530	0.922	1.063	-0.003	0.061	-0.205	60	0.521	0.917	1.055	-0.006	0.054	-0.2097
70	0.338	0.946	1.005	-0.007	0.045	-0.206	70	0.342	0.942	1.002	-0.001	0.039	-0.2111
80	0.161	0.958	0.972	-0.008	0.023	-0.220	80	0.162	0.964	0.977	-0.008	0.023	-0.2214
90	0	0.998	0.998	0	0	-0.250	90	0	0.996	0.996	0	0.001	-0.2484

TABLE 18
Test Results for Square Plate $B/L = 0.07$

$Re = 0.56 \cdot 10^6$						$Re = 0.71 \cdot 10^6$					
α°	c_C	c_D	c_Y	c_X	$c_{M,x}$	α°	c_C	c_D	c_Y	c_X	$c_{M,x}$
-2	-0.062	0.071	-0.064	-0.069	0.006	0	0	0.074	0	-0.074	0.002
0	0	0.069	0	-0.069	0.003	2	0.065	0.077	0.068	-0.074	-0.001
2	0.062	0.071	0.064	-0.069	-0.002	5	0.160	0.086	0.167	-0.072	-0.006
5	0.156	0.080	0.163	-0.067	-0.006	10	0.323	0.132	0.341	-0.073	-0.018
10	0.315	0.125	0.332	-0.069	-0.020	15	0.485	0.206	0.521	-0.073	-0.047
15	0.482	0.189	0.517	-0.067	-0.048	20	0.654	0.311	0.721	-0.068	-0.085
20	0.648	0.305	0.712	-0.065	-0.093	25	0.788	0.442	0.901	-0.068	-0.142
25	0.783	0.440	0.895	-0.068	-0.140	30	0.915	0.593	1.089	-0.055	-0.187
30	0.908	0.586	1.079	-0.054	-0.184	35	0.988	0.738	1.232	-0.049	-0.222
35	0.969	0.728	1.238	-0.030	-0.213	40	1.000	0.873	1.327	-0.025	-0.247
40	1.024	0.869	1.356	-0.023	-0.247	41	1.003	0.901	1.348	-0.021	-0.255
41	1.010	0.889	1.346	-0.008	-0.247	42	0.788	0.788	1.108	-0.051	-0.215
42	0.823	0.754	1.116	-0.010	-0.205	45	0.757	0.749	1.066	-0.006	-0.202
45	0.738	0.738	1.044	0	-0.195	50	0.698	0.768	1.037	0.040	-0.199
50	0.681	0.761	1.021	0.033	-0.197	55	0.618	0.806	1.014	0.044	-0.200
55	0.601	0.792	0.994	0.039	-0.192	60	0.512	0.828	0.972	0.029	-0.198
60	0.497	0.818	0.957	0.021	-0.189	70	0.319	0.871	0.927	0.002	-0.202
70	0.315	0.856	0.912	0.003	-0.194	80	0.175	0.972	0.987	0.003	-0.238
80	0.173	0.975	0.990	0.001	-0.236	90	0.002	1.076	1.076	0.002	-0.279
90	0	1.071	1.071	0	-0.275						

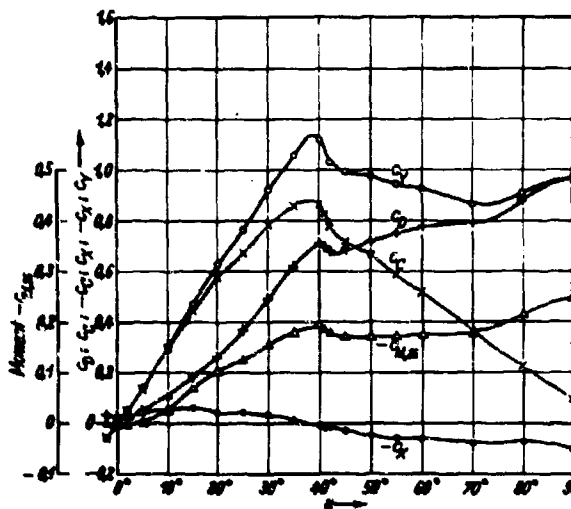


Figure 18 - Flow Forces on Rectangular Rudder TMB 075 075 15
 $A_R = 1$, $Re = 0.69 \cdot 10^6$, JfS wind
tunnel measurement, uncorrected,
 $A_R/A_S = 0.204$. (Numerical values in Table 4)

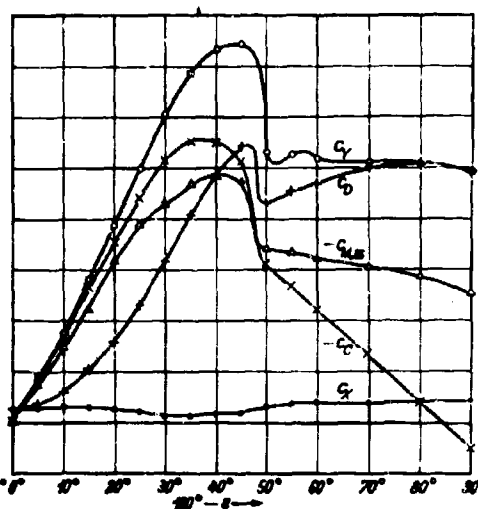


Figure 19 - Flow Forces on Rectangular Rudder TMB 075 075 15 in Astern Motion
 $A_R = 1$, $Re = 0.56 \cdot 10^6$, JfS wind
tunnel measurement, uncorrected,
 $A_R/A_S = 0.204$. (Numerical values in Table 4)

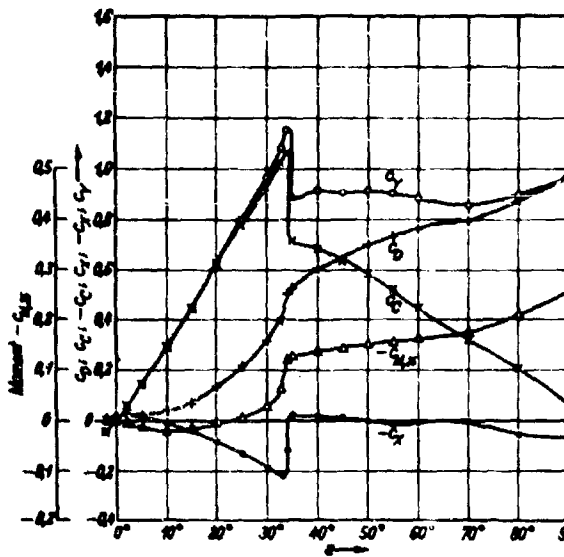


Figure 20 - Flow Forces on Rectangular Rudder NACA 0015
 $R = 1$, $Re = 0.79 \cdot 10^6$, JfS wind
 tunnel measurement, uncorrected,
 $A_R/A_S = 0.204$. (Numerical values in
 Table 5).

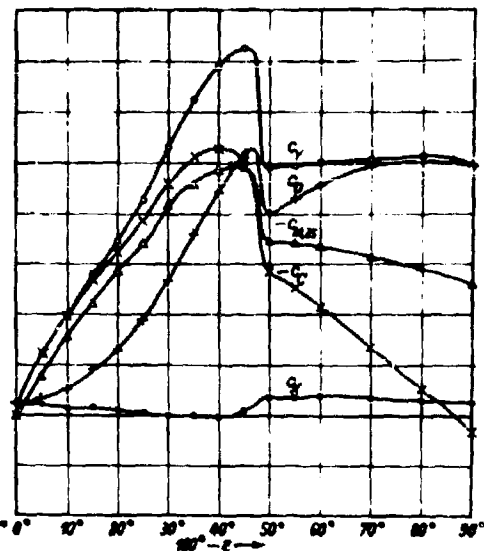


Figure 21 - Flow Forces on Rectangular Rudder NACA 0015 in Astern Motion

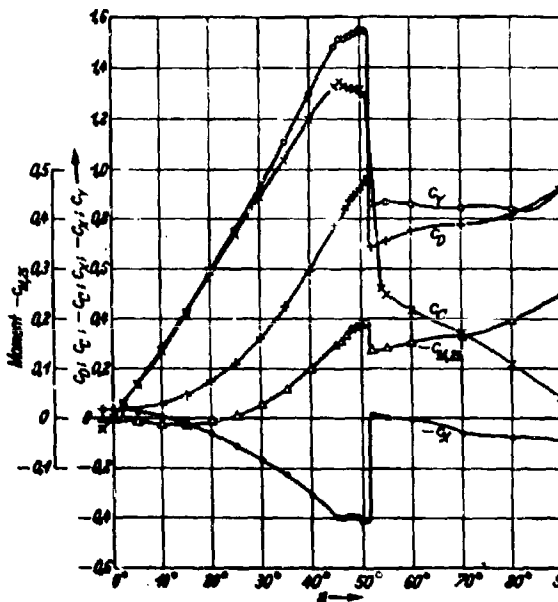


Figure 22 - Flow Forces on Rectangular Rudder NACA 0025

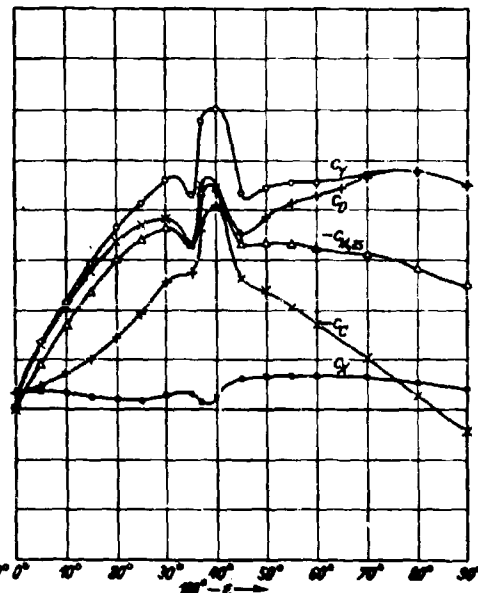


Figure 23 - Flow Forces on Rectangular Rudder NACA 0025 in Astern Motion

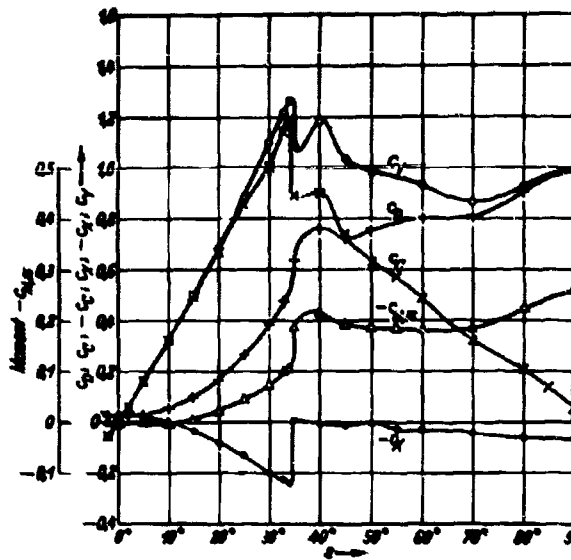


Figure 24 - Flow Forces on Rectangular Rudder JfS 58 TR 15

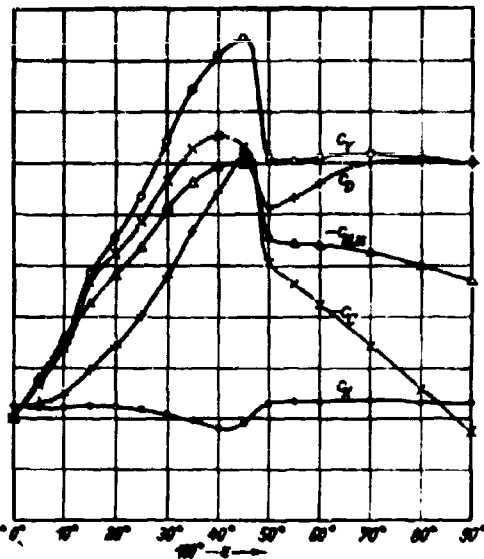


Figure 25 - Flow Forces on Rectangular Rudder JfS 58 TR 15 in Astern Motion

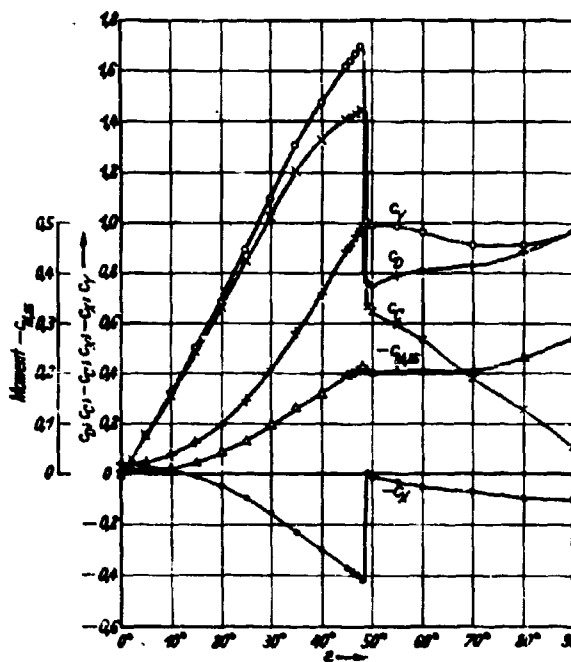


Figure 26 - Flow Forces on Rectangular Rudder JfS 58 TR 25

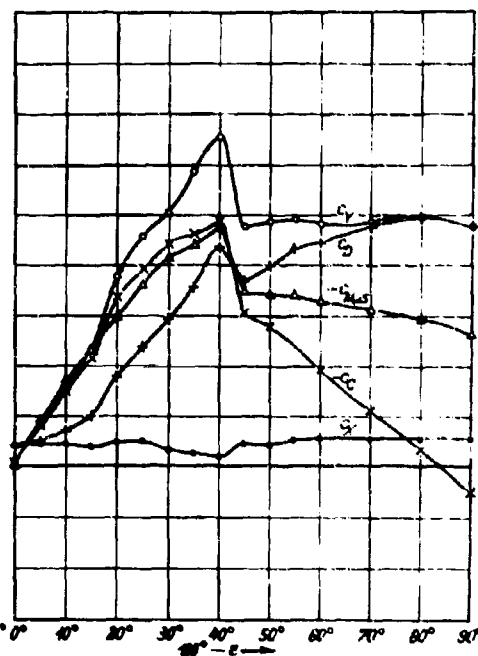


Figure 27 - Flow Forces on Rectangular Rudder JfS 58 TR 25 in Astern Motion

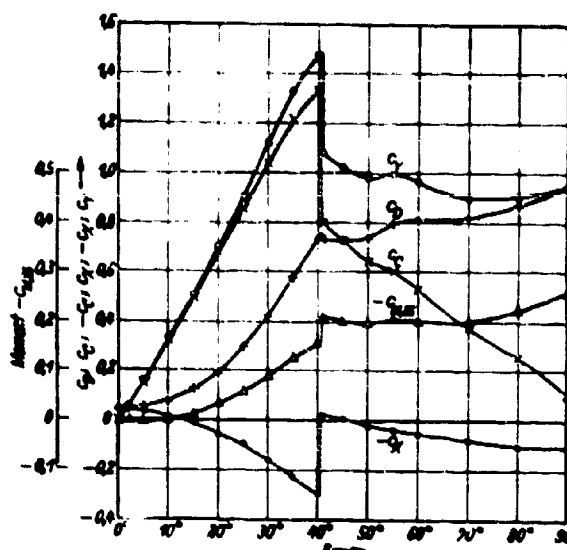


Figure 28 - Flow Forces on Rectangular Rudder JfS 61 TR 25

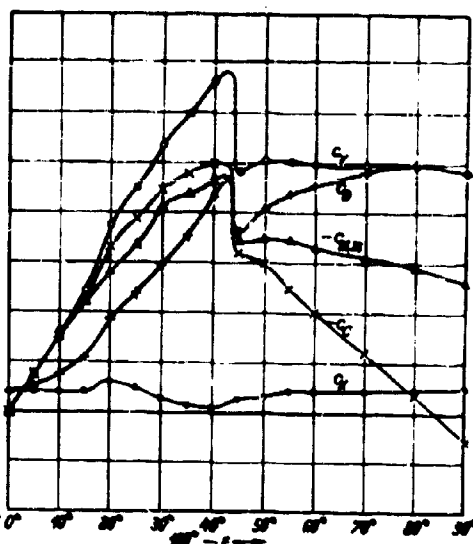


Figure 29 - Flow Forces on Rectangular Rudder JfS 61 TR 25 in Astern Motion

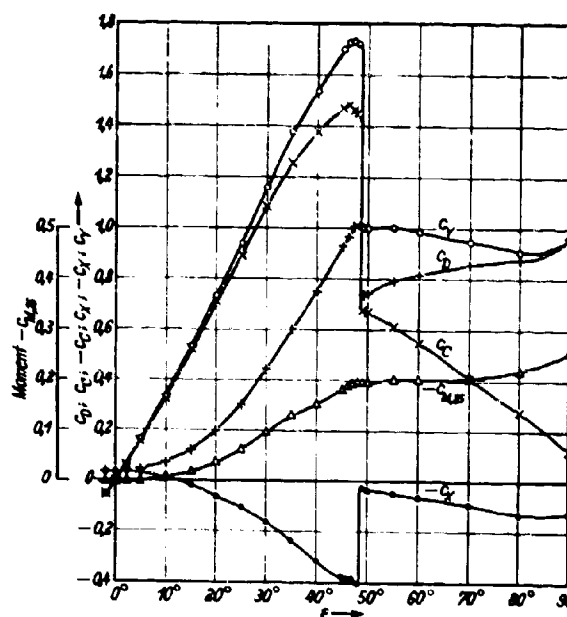


Figure 30 - Flow Forces on Rectangular Rudder JfS 62 TR 25

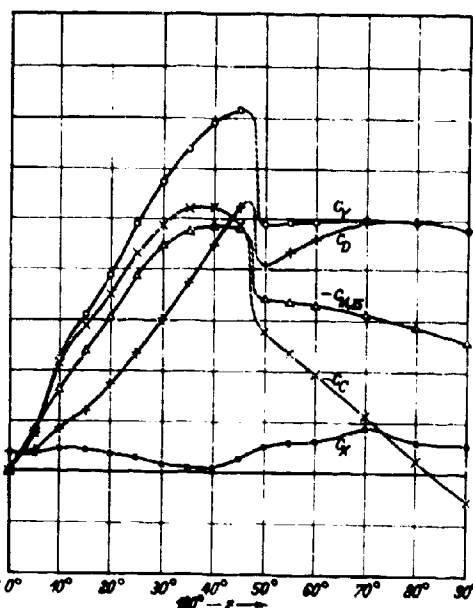


Figure 31 - Flow Forces on Rectangular Rudder JfS 62 TR 25 in Astern Motion

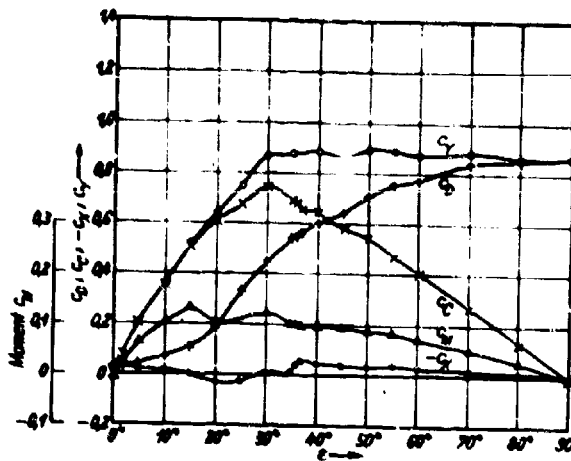


Figure 32 - Flow Forces on Rectangular Bow Rudder JfS 55 BR 15

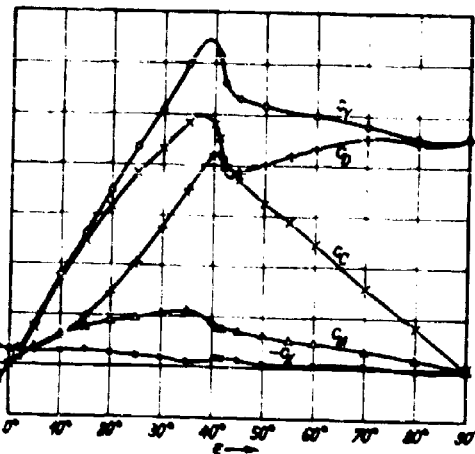


Figure 33 - Flow Forces on Rectangular Bow Rudder JfS 54 BR 15

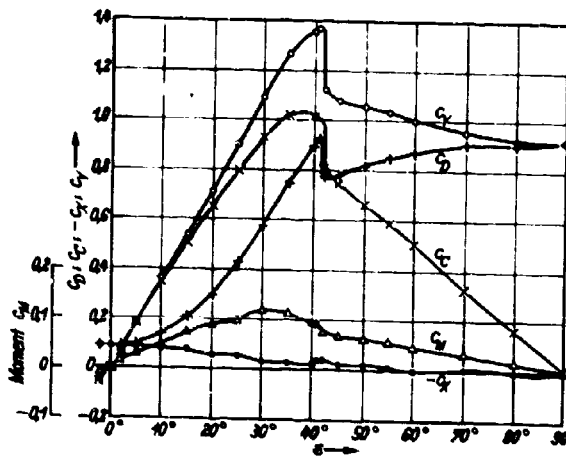


Figure 34 - Flow Forces on Rectangular Bow Rudder JfS 59 BR 15

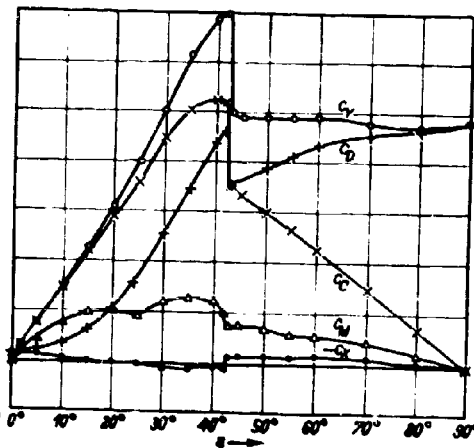


Figure 35 - Flow Forces on Rectangular Bow Rudder JfS 57 BR 15

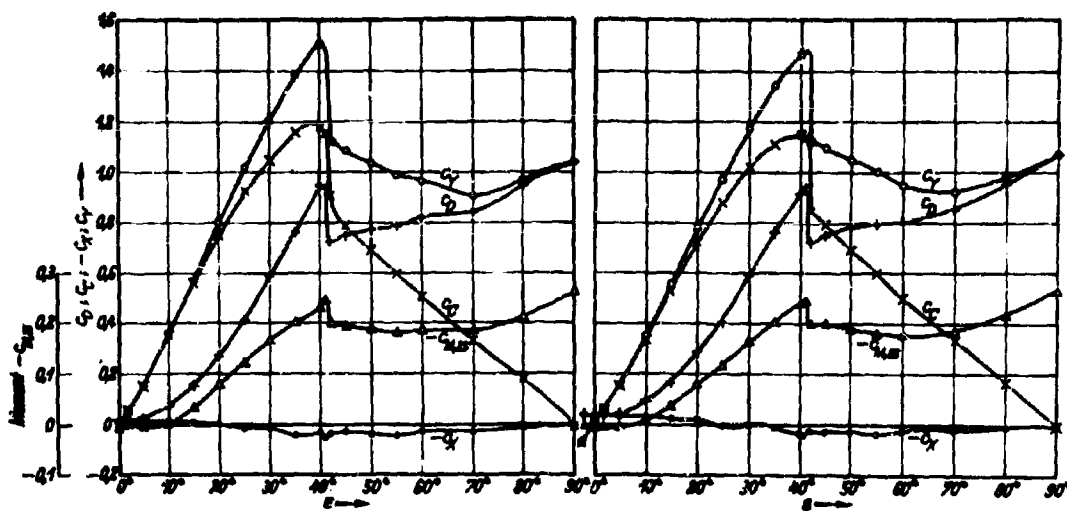


Figure 36 - Flow Forces on Square Plate $B/L = 0.015$

Figure 37 - Flow Forces on Square Plate $B/L = 0.03$

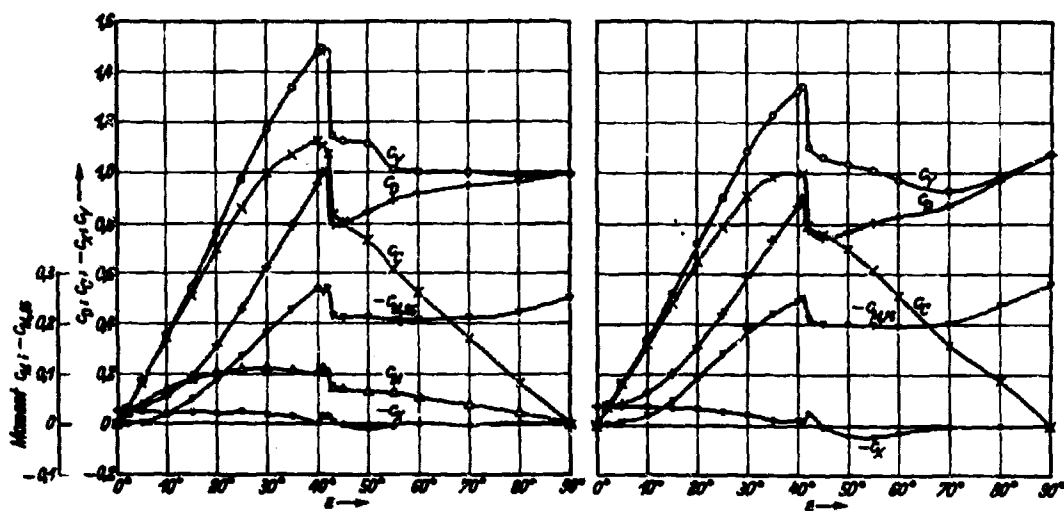


Figure 38 - Flow Forces on Square Plate $B/L = 0.05$

Figure 39 - Flow Forces on Square Plate $B/L = 0.07$

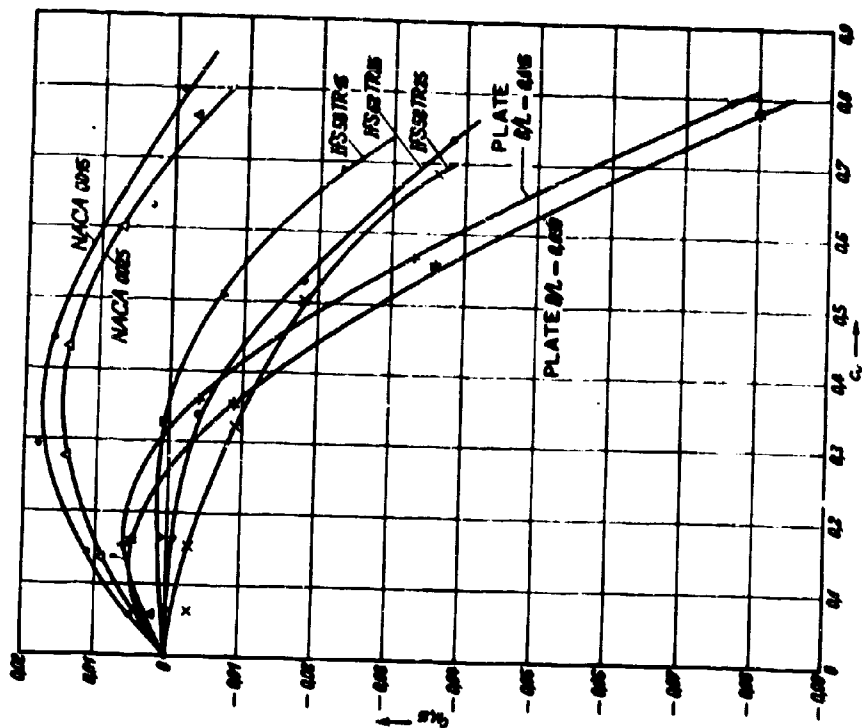


Figure 41 - Comparison of the Rudder Moment Curve which Determines the Choice of the Location of the Turning Axis, for Various Rudder Profiles at Small Rudder Angles in Straight-Ahead Motion

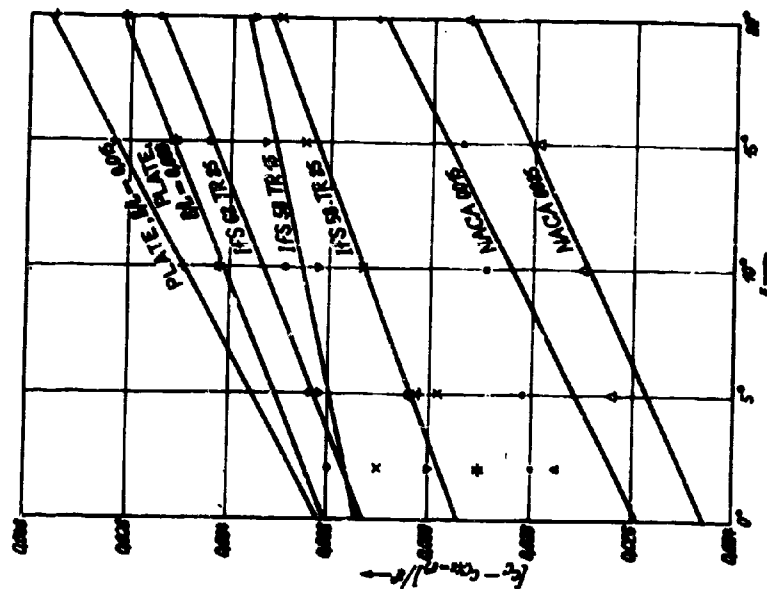


Figure 40 - Efficiency of Various Rudder Profiles at Small Rudder Angles in Straight-Ahead Motion

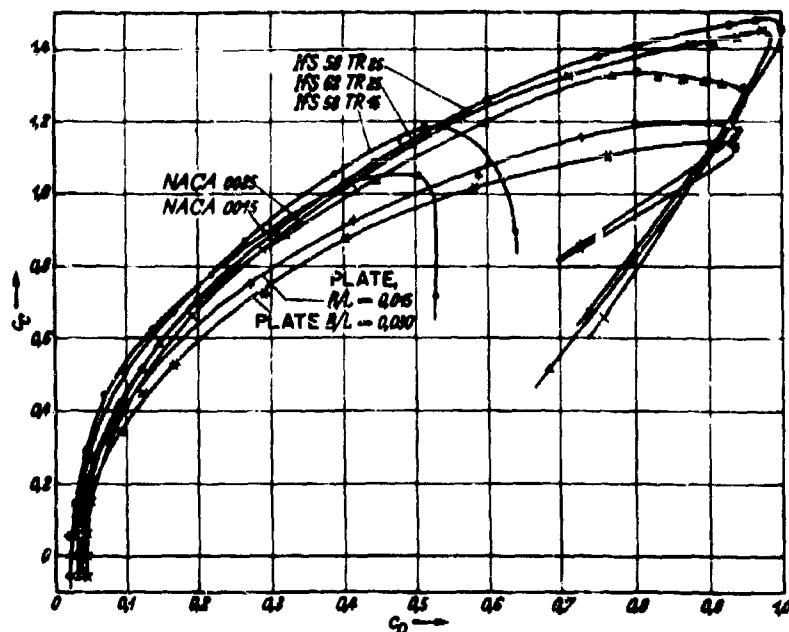


Figure 42 - Drag Power Requirement of Various Rudder Profiles at Rudder Angle in Straight-Ahead Motion

TABLE 19
Rudder Efficiency and Drag Power Requirements of the Profiles Investigated

PROFILE	$\frac{11c}{10^\circ}$	MOTION ALONG THE TURNING CIRCLE RUDDER ANGLE $\delta_R = -35^\circ$			
		STRAIGHT-AHEAD MOTION		$L_L/R_L = 0.5$	
		$C_{T/R} = C_C$	$C_{N/R} = C_D$	$C_{T/R}$	$C_{N/R}$
		CONTROL FORCE	DRAG POWER REQUIREMENT	CONTROL FORCE	DRAG POWER REQUIREMENT
NACA 0015.....	0.79	-0.922	0.135	-0.675	0.062
0025.....	0.78	-0.586	0.145	-0.637	0.060
J18 58 TR 15	0.78	-0.670	0.166	-0.714	0.087
*) 25	0.78	-0.660	0.191	-0.698	0.115
J18 58 TR 35	0.78	-0.708	0.199	-0.742	0.116

*) SEE ALSO FIGURE 43.

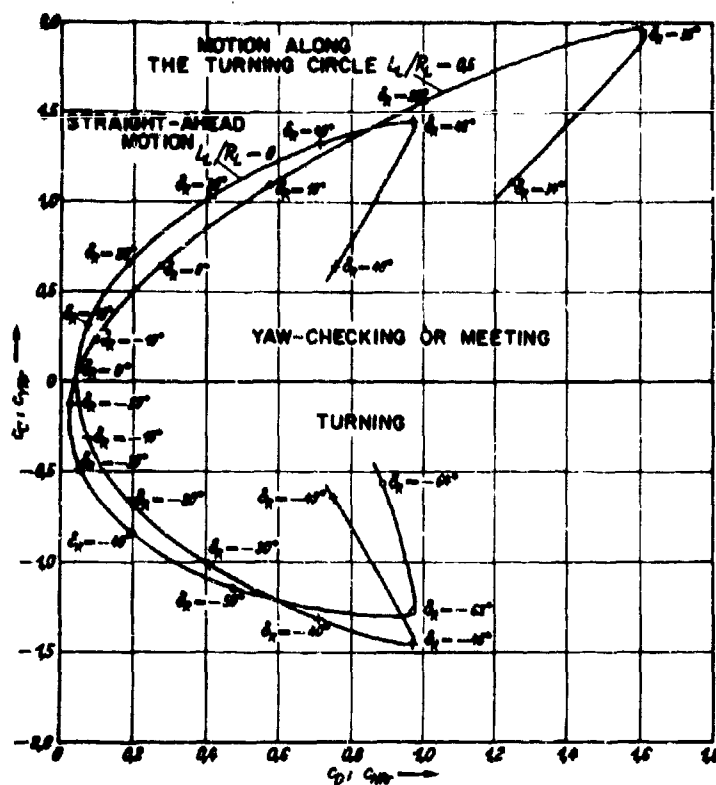


Figure 43 - Drag Power Requirement and Efficiency of Profile JfS 58 TR 25 for Straight-Ahead Motion and for Motion along the Turning Circle $L_L/R = 0.5$

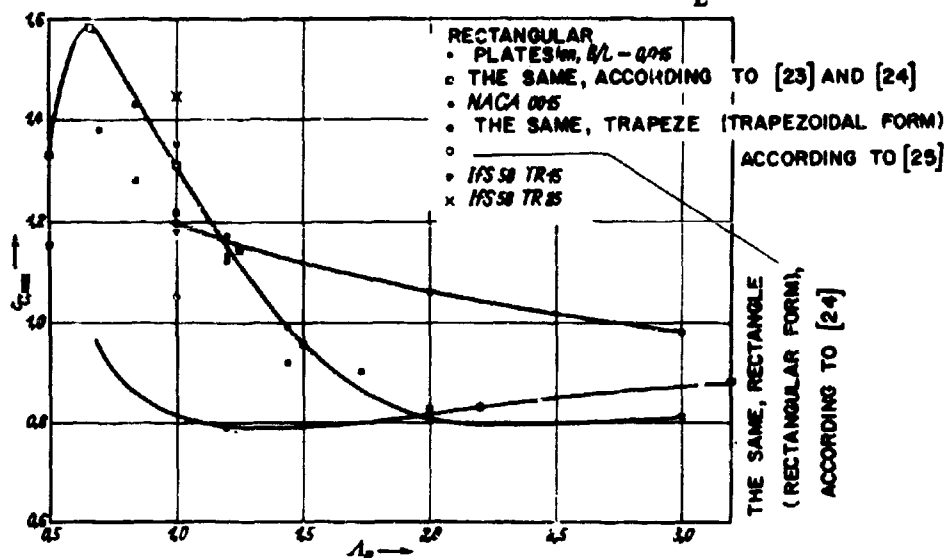


Figure 44 - Influence of Aspect Ratio on the Transverse-Force Coefficient for Various Rudders

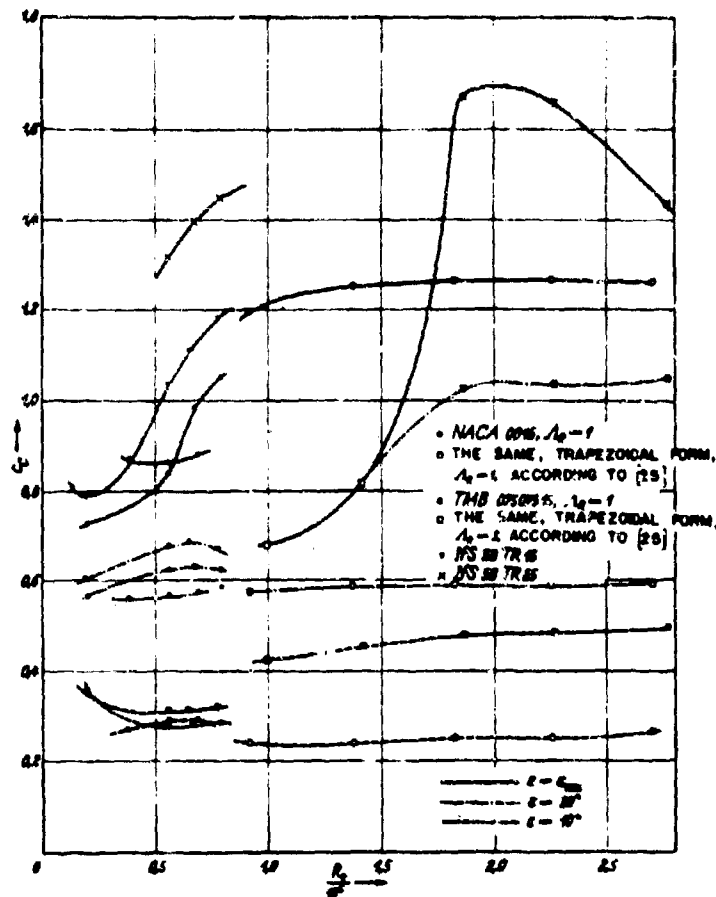


Figure 45 - Influence of the Reynolds Number on the Transverse-Force Coefficient for Various Rudders

G. MEASURES FOR SUBSEQUENT ALTERATION OF RUDDER CHARACTERISTICS

This catch word was adopted after the last war in order to resume research work on the problems concerning ship rudders. Even today there arises again and again the problem of improving the qualities and the efficiency of a rudder, with the aid of limited means in most cases.

Frequently, an improvement in directional stability is what is desired. The most inexpensive means to achieve this is by the so-called rudder wedge arrangement.* Figure 46 shows an example taken from the extensive investigation by Thiemann.³⁰ Figures 46a, b, and c indicate,

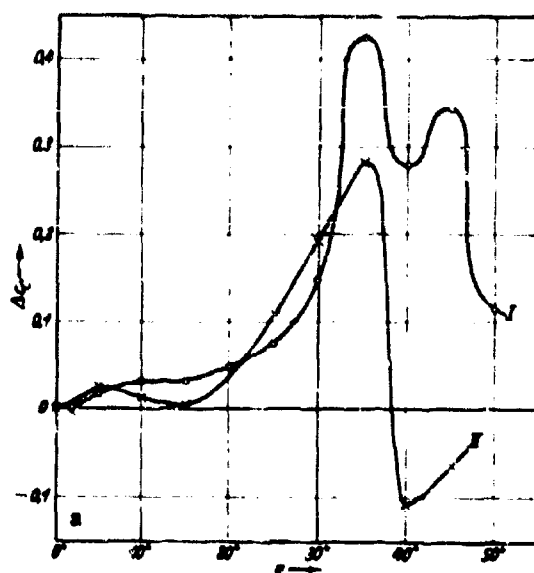
*Translator's note: Stankeil - "stagnation" wedge.

moreover, how this brings about a change in transverse force, resistance, and moment. Of course, the improvement of the transverse force and directional stability entails a certain additional resistance and a higher rudder moment. Moreover, it must be borne in mind that the effect of the wedge arrangement is all the greater, the poorer the design of the initial profile which is to be improved. That is a unique disadvantage of the more recent profiles; they can no longer be improved so easily later on by fitting a wedge on the profile.

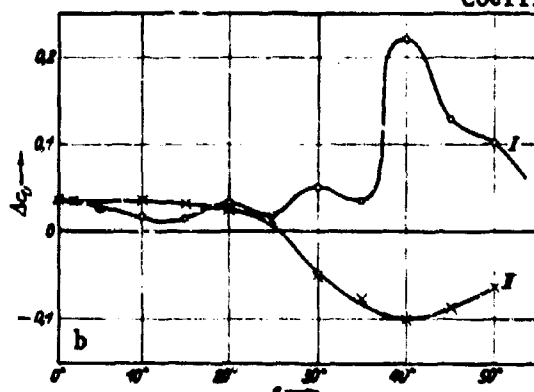
The development of the wedges fitted on the trailing edge of rudders will hardly be clarified entirely by the statements made here. After the last war it was a prestige question at one time whether this procedure originated in the model basin or in the shipyards building coastal vessels. It must be admitted, however, that evolutionally the procedure of the model basin was based on the trailing-edge control mechanism developed a number of years before for missiles by Herbert Wagner which makes this procedure about 20 years old now. Meanwhile, however, the author following a friendly suggestion was able to ascertain that even as early as 1934 the Howaldt Co. of Hamburg (Howaldt Shipyard at Hamburg) had fitted the seaside resort ship KÖNIGIN LUISE with a kind of alternately step-like rudder wedge to compensate for a reduction of the rudder area.

In the meantime, the shape of the rudder wedge has undergone a considerable evolution. First, the combination of a shortening of the profile at the trailing edge and the simultaneous fitting of a wedge at the new trailing edge, as shown in Form II in Figure 46, was successfully used in actual practice and later investigated experimentally. Thereby it is possible by the skillful application of these measures not only to increase the transverse force in the entire angular range, but also to reduce the rudder moment at the same time, as seen again in Figures 46a, b, and c.

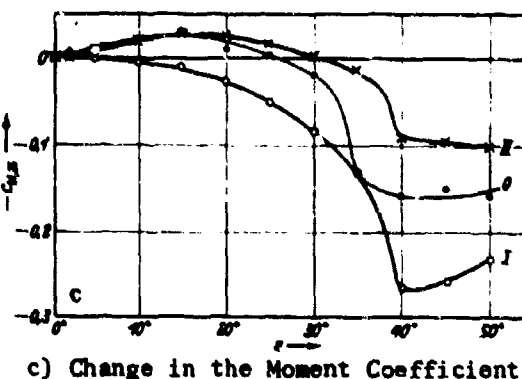
It should be pointed out nevertheless that the astern characteristics are affected somewhat adversely by the wedge arrangement. On the other hand, steering ability in astern motion depends less on the form of the rudder than on the rudder arrangement. In the case of a narrow propeller aperture or a twin-screw single rudder immediately behind the deadwood, shortening the deadwood helps more than changing the rudder profile.



a) Change in the Transverse-Force Coefficient



b) Change in the Resistance Coefficient



c) Change in the Moment Coefficient

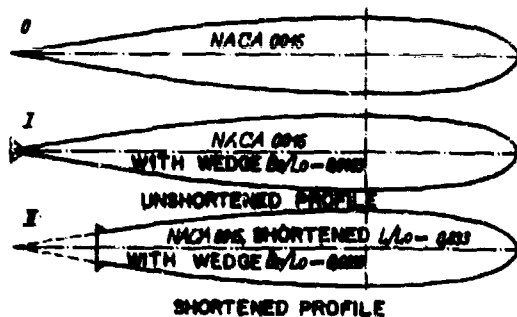


Figure 46 - Effect of Rudder Wedge Arrangement with and without Profile Shortening on Flow Forces Acting on Rectangular Rudder NACA 0015

We might mention in this connection one other inexpensive and already proven method of changing the rudder, that is, the use of end disks. In any event, this increases the contribution of the rudder to directional stability although it produces some additional resistance, especially for larger aspect ratios. At smaller aspect ratios, say, at 1.0 or even below that, the resistance increase is small in relation to the increase in the transverse force; in that case, however, the maximum rudder effect decreases so that we must count on a decrease in the maximum turning ability.

H. FUTURE TRENDS IN RUDDER FORMS

The optimum which was approximately obtained for balanced-rudder profiles with such forms as IfS 58 TR 25 and IfS 62 TR 25 will have to be investigated further in view of the influence of structural desires for a thick trailing edge and possibly for even greater profile thicknesses. In this connection, the danger of cavitation or air penetration, when rudders operate near the surface will have to be considered as the Froude number increases.

A parallel development for guide head rudders and semi-balanced rudders may be based on these results. In the case of the guide head rudders, a certain measure of balancing is urgently desirable as a particular goal of the development; thus far, this has been obtained in the highest degree with the HSVA form according to Figure 74.

In view of the bow-rudder development and the control of the stern motion with normal stern rudders, it is not enough to continue the development of the bow-rudder forms now begun. The effect of the deadwood in front of the stern rudder and of the ship hull behind the bow rudder warrants investigation. In both cases, a certain interspace must remain in order that the cross flow in the wake of the rudder does not react upon the hull with full force.

The above-mentioned fundamental influence exerted on the rudder forces by the turning of the ship which deforms the entire rudder polar curve must be investigated still further, especially in view of the maximum rudder effect, since possibly the simple conversion process used here does not encompass the overall improvement which might be obtained.

A special objective for model tests at particularly small Reynolds numbers, on one hand, and for certain types of ships, on the other, consists in the development of rudders which, for structural reasons, must have adequate shaft thickness while acting supposedly like thin plate rudders. Rudder IfS 57 TR 15 investigated here has not yet proved to be satisfactory in this sense; it still remains at a disadvantage compared to the plates of equal or even greater edge thickness.

It goes without saying, that additional effects due to the influence of the propeller slipstream, a greater Reynolds number, and natural roughness must be kept in mind for all further developments. In this connection the question becomes interesting as to the extent to which a partial flow separation may be quickly compensated for by giving a limited amount of rudder angle if the maximum transverse force is exceeded. If adequate safety can be provided in this area, the operational performance of rudders can also be increased in a simple manner by stepping up appreciably the permissible hard-over position of the rudder.

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APPENDIX
DISCUSSION BY OTHER INVESTIGATORS

Dr. Eng. Dr. Aschenbach, Frankfort (expanded in writing)

In 1943, I was engaged in experiments on new types of rudders on the basis of two German Reich patents; these experiments were altogether different from those discussed in the present paper.

One of the patents dealt with perforated and staggered rudder surfaces and the other with a 'spreading rudder' (German 'Spreizruder') which served as an anti-roll stabilizer.

The tests with the slotted rudder were undertaken at the request of the Reich Ministry of Transport and were carried out by the Hamburg Model Basin (HSVA).

In these tests, the slotted rudder was investigated in comparison to a conventional rudder of a barge; the former had only 89 percent of the area of the conventional rudder. The greatest profile thickness of the conventional rudder amounted to $1/30$ while that of the slotted rudder amounted to $1/11$ of the rudder length; in both cases it was located in the turning axis which was arranged approximately 17.5 percent of the length behind the leading edge of the rudder.

The balancing surface was equally large for both rudders; however, the slotted rudder exhibited a greater equilibration due to the slot and to the pressure increase in the forward zone of the flow which occurs in the case of streamlined profiles. The body plan of the barge and the two rudders are represented in Figure 1.

Two series of tests were carried out. First, the steering moments and the rudder turning moments were measured for various rudder angles with the model running straight ahead and then Z-maneuvers were carried out.

The curve of the steering moments are presented in Figure 2, and a curve of the rudder turning moments for both types of rudders is shown in Figure 3. From these, the energy expended in shifting the rudder was computed and is represented graphically for both types of rudders in

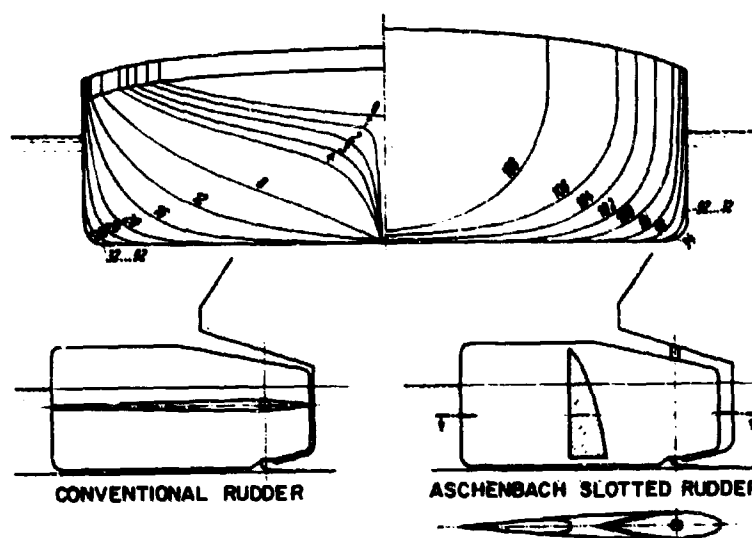


Figure 1 - Body Plan of the Barge and of the Two Rudders

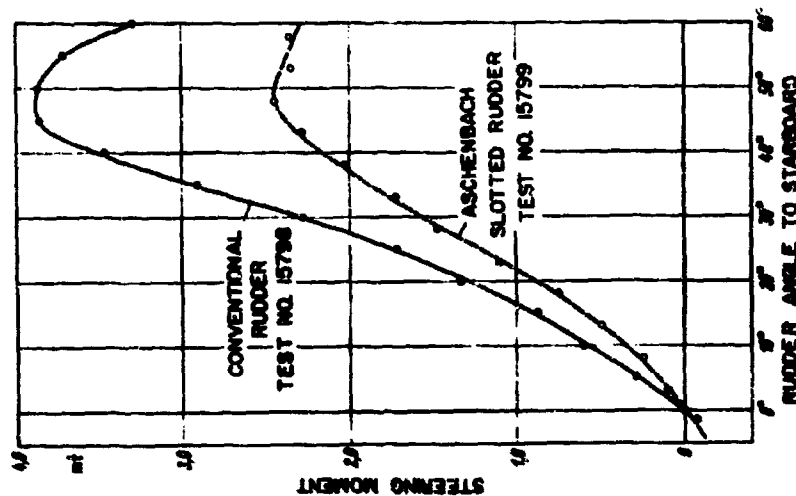


Figure 2 - Curves of the Steering Moments

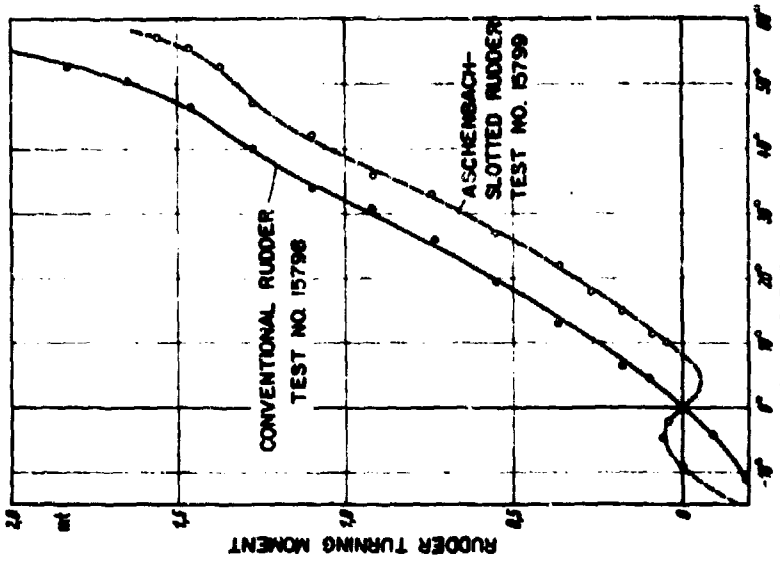


Figure 3 - Curve of the Turning Moments of the Rudder

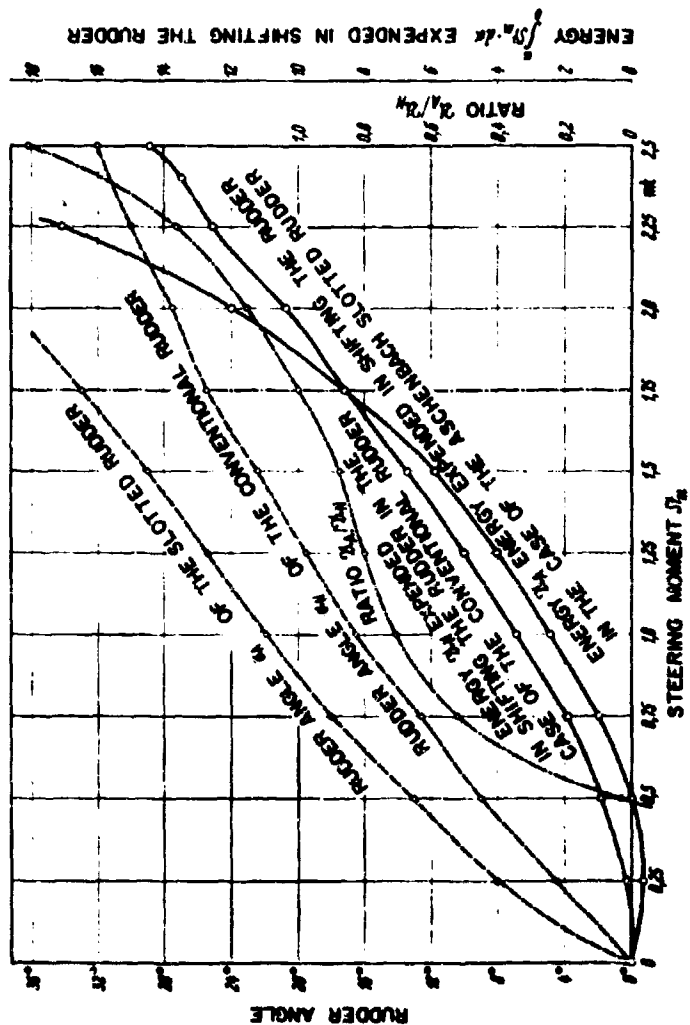


Figure 4 - Energy Expended in Shifting the Rudder for both Rudder Types

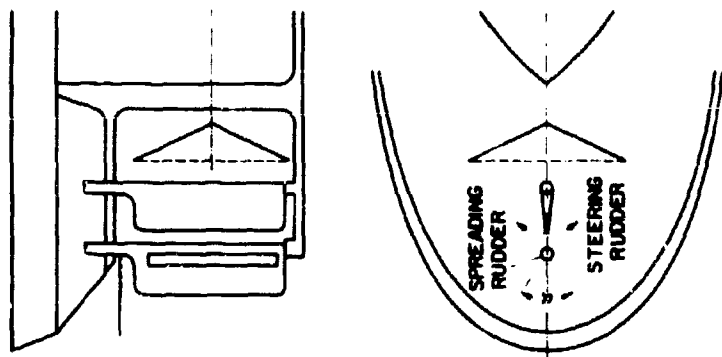


Figure 5 - Sketch of Rudder Arrangement

Figure 4. It will be seen that up to a rudder angle of 20 deg, the Aschenbach-slotted rudder can be shifted more easily with equal rudder efficiency.

It should be pointed out that these tests with elements were not intended to determine optimum rudder arrangements but only to compare the conventional rudder with a slotted rudder designed on the spur of the moment. The slotted rudder should have been adapted to the hull. This is proved by my design for concrete tankers whose rudders were adapted to the form of the ship and as a result, exhibited a comparatively smaller head resistance both in the experimental tank at the Berlin Research Institute for Hydraulic Engineering and Shipbuilding and on the river Danube.

During the test runs along a sinuous course, the rudder is shifted to zero, whereupon it is shifted to port or starboard by means of a steering engine and the sheering of the model out of course is observed. Once the model has reached a course angle of 10 deg, the rudder is shifted to the opposite course and the measuring process is repeated. By carrying out this maneuver several times, we obtain the Z-maneuver for 10-, 20-, and 30-deg rudder angle. If the rudder is shifted in intervals from one hard-over position to the other (from full-right to full-left rudder), a turbulent flow is produced about the rudder which does not calm down very quickly; in the case of the moving ship, on the other hand, an almost laminar flow occurs since the rudder is shifted slowly with the result that the streamlining of the rudder stands out more prominently compared to the unstreamlined conventional rudder just as the existence of a slot becomes more prominent, too.

Although these tests demonstrated a certain superiority of the slotted rudder, it would nevertheless be a good idea if the author of the paper would extend his investigations to include this type of rudder also since in wartime not all of my proposals, objections, and modifications could be taken into consideration.

The other patent referred to concerned a twin 'spreading rudder' ('Spreizdoppelruder,' "spreading double rudder") which is to serve the purpose of roll quenching. According to the intensity of the seaway, the angle of spread (or flare) α is adjusted, and by means of the twin rudder, that half of the rudder which is effective in a given case can reduce the

yawing of the ship and thus the rolling as well since the yawing and rolling motions are coupled with one another through the path of the center of gravity; the result is that steering the ship along a straight course must also have the effect of damping the rolling of the ship, at least the rolling oscillations, at the same time.

The steering rudder does not participate in this; the spreading rudder, however, which may be installed fore or aft of the steering rudder is controlled by a gyroscope which shifts it accordingly. In a calm sea, the angle α may be set at zero.

Figure 5 shows a sketch of the arrangement. It has not been executed as yet. However, since it is simpler than other stabilizers, I should like to recommend that the author include this rudder arrangement in future tests.

Prof. G. Weinblum, Dr. Eng., Dr. Eng. h.c., Hamburg
(Word of appreciation).

Although the somewhat unfortunate time history may have tired you perhaps, you have nevertheless gained the impression how much work may be accomplished in this field, already regarded as classical, and how much has actually been accomplished by Mr. Thieme. The latter now resembles a sponge which is sucked full of useful information; hence, we may expect a number of interesting results from him in the course of the next few years. I believe that I speak for all present when I say that we are very grateful to Mr. Thieme for his fundamental and practically interesting presentation; thus we conclude the present lecture (Lively applause).

Dr. J. Richter, Dr. Eng., Berlin (submitted in writing).

First of all, I wish to express my appreciation to Mr. Thieme for his report. He may be certain that not only naval architects but also marine engineers and electrical engineers are keenly interested in this work.

I was particularly interested in the difference in the turning ability of the small ship model in comparison to the full-scale ship if the rudder is dimensioned according to scale and if one is governed by Froude's law when determining the model speed. In one individual case, I have

ascertained that for a scale of length of 1:75, the turning ability of the model fell 16 percent below the turning ability of the full-scale ship. I am sure that the author can furnish information as to the size of the model rudder required in order to predict the actual turning ability of a full-scale ship from steering tests with models.

Dipl.-Ing. H. Thieme (Written reply)

The two proposals made by Dr. Aschenbach—slotted rudder and spreading rudder—had not previously come to my attention nor presumably to many in this audience; hence, this presentation of his proposals will contribute to many additional lines of reasoning in the rudder development. What is common to both proposals from the hydrodynamic standpoint is that they concern the problem of the tandem rudder. Inasmuch as few data exist on this subject, I had already taken this project into consideration for further programs. Thus, the recommendation of Dr. Aschenbach falls on somewhat prepared ground.

I should like to point out, however, that I do not expect any advantage can be gained by using a slotted rudder. The superiority of this form as obtained in the rudder moment for equal efficiency in the lower angle range is based less on the superior quality of this arrangement than on the arbitrary underbalancing of the barge rudder used for comparison.

I have some reservations on accepting the conjecture regarding the dynamically obtained flow condition on the model rudder and the laminar condition on the ship rudder.

In conclusion, I wish to express my keen appreciation to Dr. Aschenbach for sharing his experiences with us and for his suggestions.

The question raised by Dr. Richter with regard to the methods of accounting for scale effect on the rudder efficiency broadens the scope of the subject in a natural and welcome manner. Hence, I am doubly grateful to him for his observation.

Let me first turn to Dr. Richter's statement that in one case he observed that the turning ability of the model amounted to only 84 percent of the turning ability of the ship. In a study of 11 ships of all possible types and various rudder angles, Suarez and Strumpf (Davidson Laboratory

Note No. 548) determined the ratios of the turning ability between model and ship to be between 0.7 and 1.14, in which case the values below 1 are altogether preponderant. Hence, Dr. Richter's observation lies within the range of statistically normal expectation.

The following scale effects may have an effect on the magnitude of the force to be expected on the rudder:

1. Apart from undesirable and extreme laminar effects, the wake on the rudder is generally greater for the model than for the ship.

2. For rudders in the propeller slipstream, we must always assume a greater velocity increment for the free-running models than for the ship. This effect is thus the opposite of the one referred to under 1. Hence, the final result may lie in both directions.

3. In the case of similar flow conditions, the smooth model rudder with a smaller Reynolds number normally shows smaller force coefficients in all cases than the rougher ship rudder with a greater Reynolds number; from this, too, we may therefore expect a contribution in terms of a reduction of the ratio of the turning ability.

In the normal case, no suitably computed corrections are made in model tests because of the considerable difficulties encountered in estimating these effects in advance. In case of given advance estimation the ratio of the turning ability to be expected under 1. may be guarded against by a dissimilar enlargement of the rudder area on the model or—in case one is restricted to fairly moderate rudder deflections—by replacing the streamline model rudder by a plate model rudder.

Although this goes somewhat beyond the question raised by Dr. Richter, but I want to avoid having the reader jump to any oversimplified analogy conclusions. Hence, I wish to add immediately that theoretically the change in the course stability as well as in the yaw-checking ability may be expected to amount to no more than approximately one-half the magnitude owing to the scale between model and ship in view of 1. and 2.; This result is obtained if consideration is given to the change of the flow angles on the rudder which is brought about by the scale effects.

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11 SUPPLEMENTARY NOTES		12 SPONSORING MILITARY ACTIVITY
13 ABSTRACT		
Starting from present day criteria for the choice of the size and arrangement of rudders, this paper discusses the suitable streamlining of guiding-head and balanced rudders. In addition to a purely visual comparison of conventional (usual) and newly developed profiles, the report includes profile offsets that have not been published previously and contrasts the form parameters of various rudder profiles which are based on a familiar mathematical method of profile representation. Comparative studies of several familiar foreign rudder profiles and of rudder profiles which have been developed in the Shipbuilding Institute in recent years indicate that the modern profiles definitely improve rudder efficiency, both when the ship is moving astern and ahead; this also applies to bow rudder profiles. The influence of the thickness ratio (proportion of thickness to length) in the case of plate rudders--which has not been established experimentally in publications thus far--is indicated in all additional test series. To illustrate the possibilities of subsequently improving the rudder profile either in efficiency or balancing, the use of a rudder wedge arrangement, with and without profile shortening, is discussed and examples are given from a special experimental investigation.		

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Rudder Arrangement						
Structural Design						
Hydromechanic Aspects						
Comparison of Profile Forms						
Wind-Tunnel Tests						
Alteration of Rudder Characteristics						
Guiding head rudder						

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