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A METHOD FOR PREDICTING THE TORQUE OF SEMIBALANCED CENTERLINE RUDDERS ON MULTIPLE-SCREW SHIPS

by

S. C. Gover and C. R. Olson

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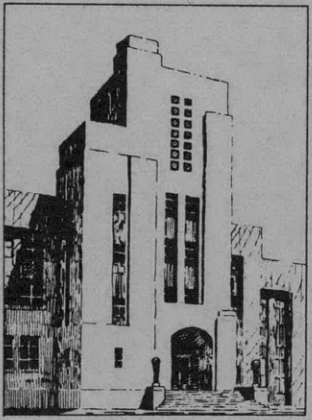

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Report 915

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ABSTRACT

An empirical method is presented for predicting the torque required for semibalanced rudders not directly in the propeller slipstream. An example of the method is given and theory, full-scale trials, and model test results are compared.

INTRODUCTION

The purpose of the rudder torque prediction project[1] is to develop methods whereby ship designers can estimate the torque to be overcome in turning rudders to given angles at given ship speeds. This report presents an empirical method for predicting the torque required for normal semibalanced rudders which are not directly in the propeller slipstream. The report explains the development of the method, shows an example of its use, and compares the predicted torque values for several rudders with the values as obtained from Joessel's formula,[2] full-scale trials, and model tests.

DESCRIPTION OF RUDDERS

The torque prediction method is intended to apply to normal semibalanced centerline rudders such as shown in Figure 1. The parameters of the various rudders are given in Table 1. The parameters used in Table 1 are defined in Table 2. The characteristics of a typical rudder with notations as used in later sample calculations are shown in Figure 2.

DEVELOPMENT OF METHOD

The method discussed in this report deals with the rudder torque to be overcome in initiating a free turn from a straight course. Although larger torques are sometimes found in zig-zag maneuvers, in restrained model tests, and in maneuvers going astern, the values of initial torque are the prime requisites in rudder design calculations.

The basis of the method is the effect of rudder shape on the location of the center of pressure and on the normal force coefficient. It was found in evaluating considerable model and full-scale rudder torque data that the most significant parameter was the height to chord ratio of the lower portion of the rudder. Curves for normal force coefficients and center of pressure for the whole rudder plotted against h_1/c_1 (height to chord ratio of lower portion of rudder) were derived from tests[3] of a systematic series of rudders which encompassed a wider range of parameters than shown in Table 2. The torque calculated from these curves was in reasonable agreement with measured values, indicating that other parameters such as section, aspect ratio of the upper portion, thickness, and percent balance or hull effects such

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[1] References are listed on page 5.

as wake, drift angle, and reduction in speed were either not critical or were implicitly taken into account in the analysis.

It was believed advisable, however, for estimating the effect of rudder modifications to take into consideration the shape of the upper portion of the rudder also. Therefore, it was assumed that the rudder may be considered as two relatively independent rudders consisting of the upper and lower portions whose principal parameters are height to chord ratios. The torque of each portion may be calculated from the coefficients for normal force and center of pressure given by the empirical curves of Figures 3 and 4. The curves were adjusted from those previously mentioned so that they could be applied to the individual portions of the rudder.

METHOD OF USING THE CURVES

The procedure followed in using this method for predicting rudder torque is first to determine the height to chord ratio of the upper and lower portions of the rudder. Then Figures 3 and 4 are entered with these values to obtain normal force coefficients and center of pressure values for various rudder angles.

The normal force values for each portion of the rudder are obtained by using the normal force coefficients in the formula

$$F_N = C_N\left(\frac{\rho}{2}\right) AU^2$$

where F_N is the normal force in pounds,
C_N is the normal force coefficient,
ρ is the mass density of water,
A is the projected area in square feet, and
U is the speed in feet per second.

The moment arm of the upper portion of the rudder expressed as a percent of the chord, is read directly from Figure 4. The moment arm of the lower portion is obtained by subtracting the distance of the rudder stock to the leading edge from the distance of the center of pressure to the leading edge. Multiplying the normal force values by the moment arms results in torque values for the two portions of the rudder. Adding these two values gives the total torque for the rudder. Slide-rule accuracy is sufficient for this work considering the design accuracy necessary and the lack of agreement between experimental results[4]. Likewise, when calculating the normal force, the value of the mass density term $\rho/2$ for sea water may be taken as unity. The method assumes also that torque varies as the square of the speed, a fact which has generally been found to be approximately true.

EXAMPLE OF TORQUE CALCULATION

Assume that the rudder torque for the USS ALASKA (CB1) is to be calculated for a speed of 31.4 knots. The principal dimensions of the rudder are shown in Figure 5. Using these dimensions and obtaining normal force and center pressure coefficients from Figures 3 and 4, the detailed calculations are carried out as in Table 3.

The example (Table 3) is carried further by comparing the calculated values with the results obtained from 20- and 30-foot free-turning models and from full-scale trials. The comparison, shown in Figure 6, indicates reasonably good agreement between the present method and the results of ship and model tests.

ACCURACY OF METHOD

The method is based on empirical curves derived from experimental results of both model and full-scale tests. To show the order of accuracy to be expected from the method, comparisons are made between the predicted values of torque and actual measured torques obtained from model and full-scale tests. Comparison with torque values from Joessel's formula are also made.

COMPARISON WITH MODEL AND SHIP RESULTS

Rudder torque was calculated for eight vessels for which model and full-scale data were available for comparison.[4] The results are plotted in Figure 6. In most cases, the predicted values agree fairly well with both the model and ship values. The full-scale results for the CA69, CL80, and CVL28 were doubtful because the trials were run during wartime under unfavorable conditions and the indicated variations may not be true. The one case where predicted values do not agree either with the model or ship results is for the DD644. The indications are that the predicted torques for single-rudder destroyers may be too small. Further tests are needed on destroyer models to evaluate the effect of hull response or drift angle on the rudder torque so that allowances can be made for this type of vessel.

COMPARISON WITH JOESSEL'S FORMULA

For years, Joessel's formula has been the standard method of computing rudder torque[2]. However, this formula is based on a series of experiments which were conducted on the Loire River in 1873, and were made with a flat plate set at fixed angles. The formula does not allow for variations in aspect ratio or the effect of swinging the rudder. Reference 4 indicates that the rudder torque values from tests with fixed rudder angles on a restrained model do not approximate full-scale ship torque as well as do tests made with a swinging rudder on a free-turning model.

Figure 6 shows that Joessel's torque values at the smaller rudder angles indicate much greater overbalance than the full-scale, model, or predicted values. At the larger rudder angles, Joessel's values are usually much larger than the experimental values.

In general, Joessel's curves have larger negative and positive torque values than the others because the normal force coefficients used in Joessel's formula are usually more than twice as large as those found from experiments with free-turning models. The torque curves from the prediction method tend to cross over from overbalance to underbalance at smaller angles than those from Joessel's formula for rudders of aspect ratio less than one and at larger angles for aspect ratios greater than one. This is because the center of pressure shifts forward with increasing aspect ratio in the experimental curves but is neglected in Joessel's formula. Therefore the differences at all rudder angles cannot be compensated for with a single correction factor.

An alternative procedure, which may serve as a check on the foregoing method, is to apply an empirical correction factor to the values given by Joessel's formula for specific rudder angles if the design rudder is quite similar to other rudders for which torque data are available. A graph of such correction factors, commonly called coefficients of reduction, for various rudders at 30-degrees rudder angle is shown in Figure 7. The coefficients are shown as functions of the aspect ratio of the movable portions of the rudders. A similar curve could be derived for 35-degrees rudder angle assuming that there was no flow breakdown or that suitable experimental data were available. However, it would be impractical to use correction factors for rudder angles of 20 degrees or less because of large variations in the coefficient which occur when one of the torque values approaches zero.

DISCUSSION

Comparison of model and ship rudder torque results is complicated by the lack of agreement in full-scale trial data. Unknown errors are present even under the best of trial conditions. All of the full-scale data cited in the report were derived from measurement of pressures in the hydraulic rams of the steering gear. In addition to errors in measuring the rapidly fluctuating pressure changes, there are unknown friction losses in the crosshead and variations in the rudder rate, which often makes it difficult to secure reliable data. Likewise, the predicted values do not allow for variations in local velocity or effective angle of attack caused by the turning characteristics of the ship. The effect of propeller race at large rudder angles is another factor which is disregarded. In most cases the propellers of single-rudder multiple-screw ships are spaced far enough apart so that only a small portion at the trailing edge of the rudder might overlap the propeller slipstream when the rudder is hard over. In rare cases where the leading edge of the rudder overlaps the slipstream the effect on rudder torque may be considerable.

Model and full-scale tests of a single-rudder DD445-Class destroyer resulted in larger torque values than for a similar rudder on a cruiser model. This was probably due to a larger angle of attack on the destroyer rudder because of straighter flow in the vicinity of the rudder. The predicted values for the torque of destroyer rudders should be used with caution until further tests are made to determine whether correction factors are needed for this type of vessel. Rudder torques predicted by the foregoing method have been compared successfully with both American and British results of model tests for twin-screw submarines having semi-balanced centerline rudders.

CONCLUSIONS

1. The proposed method of predicting rudder torques for semibalanced centerline rudders on multiple-screw ships appears to give fairly reliable design data.

2. Further tests are needed on single-rudder destroyers to determine what correction factors are necessary to make this method more accurate for this type of vessel.

3. The rudder torque values predicted by this method agree much closer with actual measured torques than do values obtained with Joessel's formula.

REFERENCES

1. Bureau of Ships letter S22-(3) (442-440-330) of 17 May 1948 to David Taylor Model Basin.

2. Rossell and Chapman, "Principles of Naval Architecture," Society of Naval Archetects and Marine Engineers Vol. 2, page 203 (1939).

3. Hagen, G.R., "Hydrodynamics Characteristics of Twenty-three Rudders," David Taylor Model Basin Report C-398 (in preparation).

4. Hagen, G.R., "Comparison of Rudder Torques from Model Tests and Ship Trials of Single-Rudder Multiple-Screw Ships," David Taylor Model Basin Report C-373 (August 1951).

TABLE 1

Shape Parameters of Various Rudders

All dimensions are in feet and square feet.

Parameters	CVL 48 CA 69	CA 139	CB 1	CVL 28 CL 80	CL 145	DD 644
A_1	194.8	208.5	309.6	206.1	194.9	69.2
h_1	8.69	8.00	10.67	8.67	8.25	6.42
c_1	22.42	26.07	29.02	23.77	23.62	10.78
d	8.67	10.48	10.69	8.83	8.79	3.90
h_1/c_1	0.388	0.307	0.368	0.365	0.349	0.596
d/c_1	0.387	0.402	0.368	0.371	0.372	0.362
A_2	107.8	128.5	185.9	80.8	125.2	30.8
h_2	7.14	7.08	8.83	4.54	7.33	4.16
c_2	13.75	15.58	18.33	14.94	14.83	6.88
h_2/c_2	0.519	0.454	0.482	0.304	0.494	0.605
$h_1 + h_2$	15.83	15.08	19.50	13.21	15.58	10.58
$(h_1 + h_2)^2$	250.6	227.4	380.3	174.5	242.7	111.9
$A_1 + A_2$	302.6	337.0	495.5	286.9	320.1	100.0
$\frac{(h_1 + h_2)^2}{A_1 + A_2}$	0.828	0.675	0.768	0.609	0.758	1.119
$\frac{A_2}{A_1 + A_2}$	0.356	0.381	0.375	0.282	0.391	0.308
$\frac{dh_1}{A_1 + A_2}$	0.249	0.249	0.230	0.265	0.227	0.248

TABLE 2

Definition of Parameters

A_1	Projected area of lower portion of semibalanced rudder
A_2	Projected area of upper portion of semibalanced rudder
c_1	Mean chord of lower portion of rudder
c_2	Mean chord of upper portion of rudder (taken to centerline of rudder stock)
C_N	Normal force coefficient, where $C_N = C_L \cos\delta + C_D \sin\delta$
d	Length from leading edge of lower portion to centerline of rudder stock, measured along mean chord
F_1	Normal force on lower portion of rudder
F_2	Normal force on upper portion of rudder
h_1	Span of lower portion of rudder
h_2	Span of upper portion of rudder (measured at rudder stock)
Q	Torque of rudder about rudder stock
U	Velocity of ship in feet per second
v	Velocity of ship in knots
x_1	Distance measured along c_1 for location of center of pressure of lower portion from leading edge
x_2	Distance measured along c_2 for location of center of pressure from centerline of rudder stock
δ	Rudder angle
ρ	Mass density of water

TABLE 3

Rudder Torque Calculations, USS ALASKA (CB1)

Torque of Lower Portion		
v = 31.5 knots U = 53.0 ft/sec h_1 = 10.67 ft	c_1 = 29.02 ft h_1/c_1 = 0.368 d = 10.69 ft	d/c_1 = 0.368 A_1 = 309.6 sq ft $F_1 = C_n A_1 U^2$ lb $Q_1 = F_1 (x_1 - d)$ lb-in.

δ deg	C_N	F_1 lb	x_1/c_1	$x_1/c_1 - d/c_1$	$x_1 - d$ in.	Q_1* lb-in.
5	0.079	68,700	0.278	- 0.090	- 31.6	- 2,170,000
10	0.167	145,400	0.298	- 0.070	- 24.4	- 3,550,000
15	0.268	233,000	0.319	- 0.049	- 17.1	- 3,980,000
20	0.375	326,000	0.339	- 0.029	- 10.1	- 3,290,000
25	0.492	428,000	0.356	- 0.012	- 4.2	- 1,790,000
30	0.612	532,000	0.369	+ 0.001	+ 0.3	+ 160,000
35	0.739	643,000	0.378	+ 0.010	+ 3.5	+ 2,250,000

Torque of Upper Portion			
v = 31.4 knots U = 53.0 ft/sec	h_2 = 8.83 ft c_2 = 18.33 ft	h_2/c_2 = 0.482 A_2 = 185.9 sq ft	$F_2 = C_N A_2 U^2$ lb $Q_2 = F_2 x_2$ lb-in.

δ deg	C_N	F_2 lb	x_2/c_2	x_2 in.	Q_2 lb-in
5	0.090	47,000	0.245	53.9	2,530,000
10	0.187	97,600	0.266	58.5	5,710,000
15	0.291	152,000	0.287	63.2	9,600,000
20	0.416	217,000	0.306	67.3	14,600,000
25	0.528	275,500	0.323	71.1	19,570,000
30	0.649	338,500	0.336	73.9	25,000,000
35	0.777	405,500	0.345	75.9	30,800,000

Torque of Whole Rudder at 31.4 Knots

δ deg	Q_1 lb-in	Q_2 lb-in	Q (Total) lb-in
5	- 2,170,000	2,530,000	360,000
10	- 3,550,000	5,710,000	2,160,000
15	- 3,980,000	9,600,000	5,620,000
20	- 3,290,000	14,600,000	11,310,000
25	- 1,790,000	19,570,000	17,780,000
30	160,000	25,000,000	25,160,000
35	2,250,000	30,800,000	33,050,000

*Negative torque values indicate that center of pressure is forward of rudder stock.

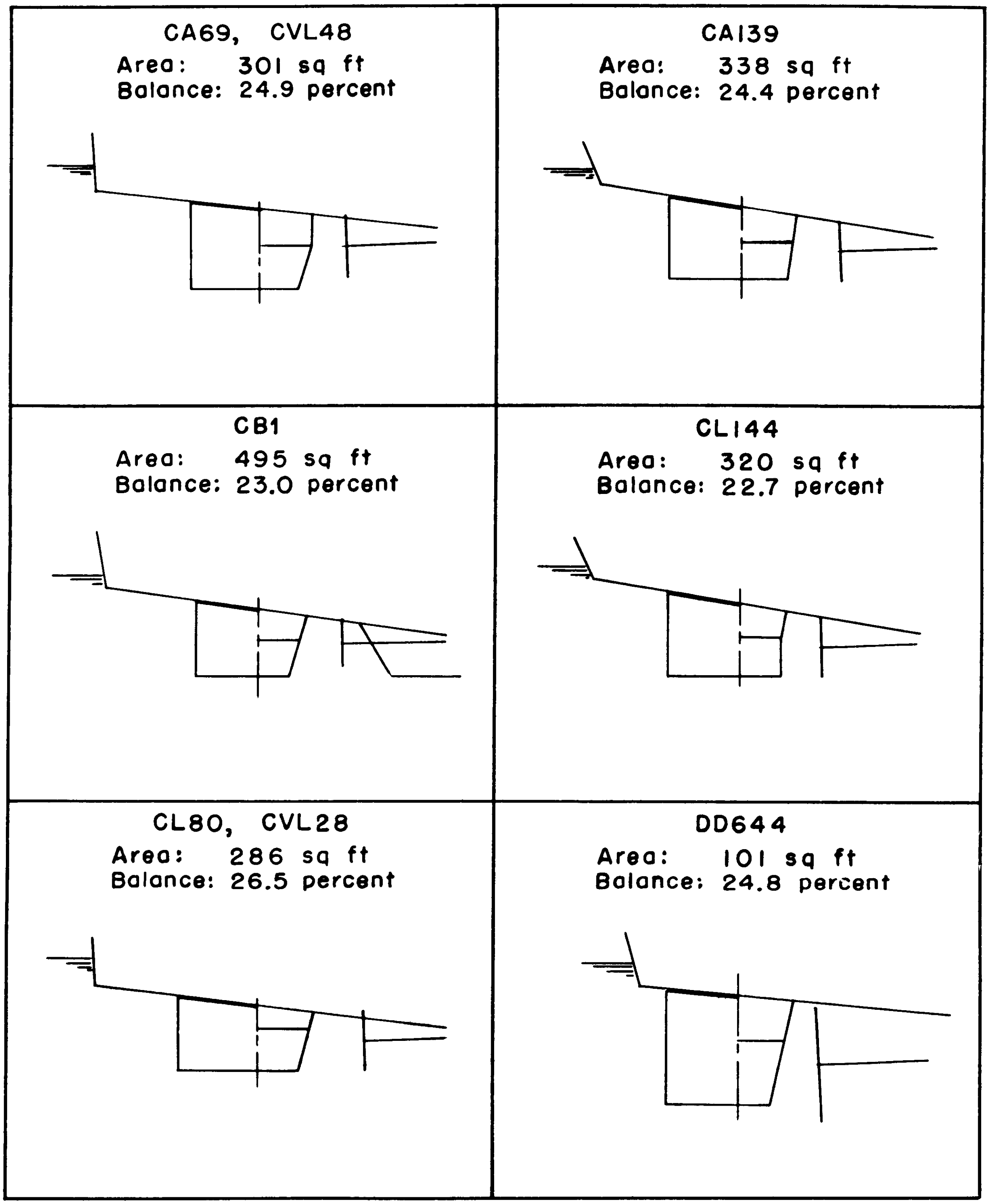


Figure 1 - Sketches of Referenced Rudders

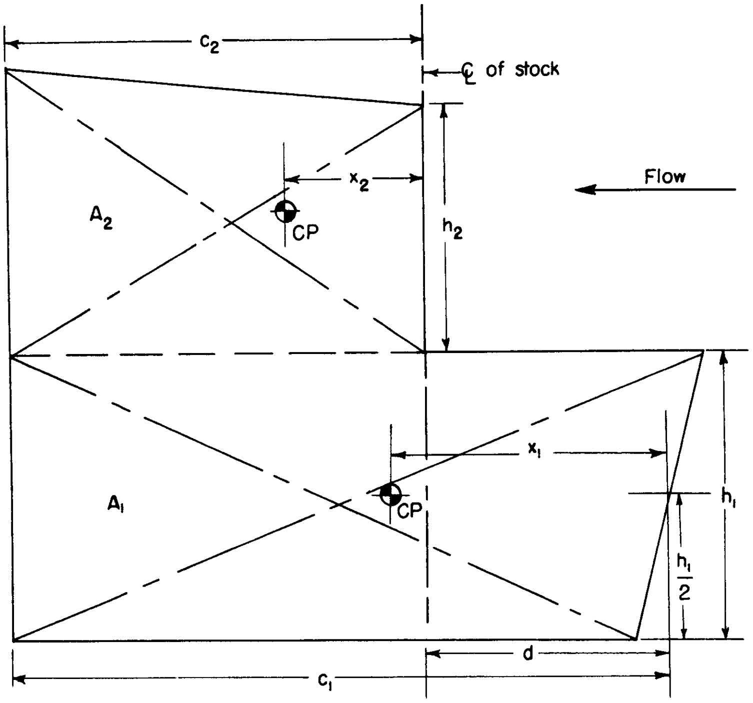


Figure 2 - Typical Rudder with Notations

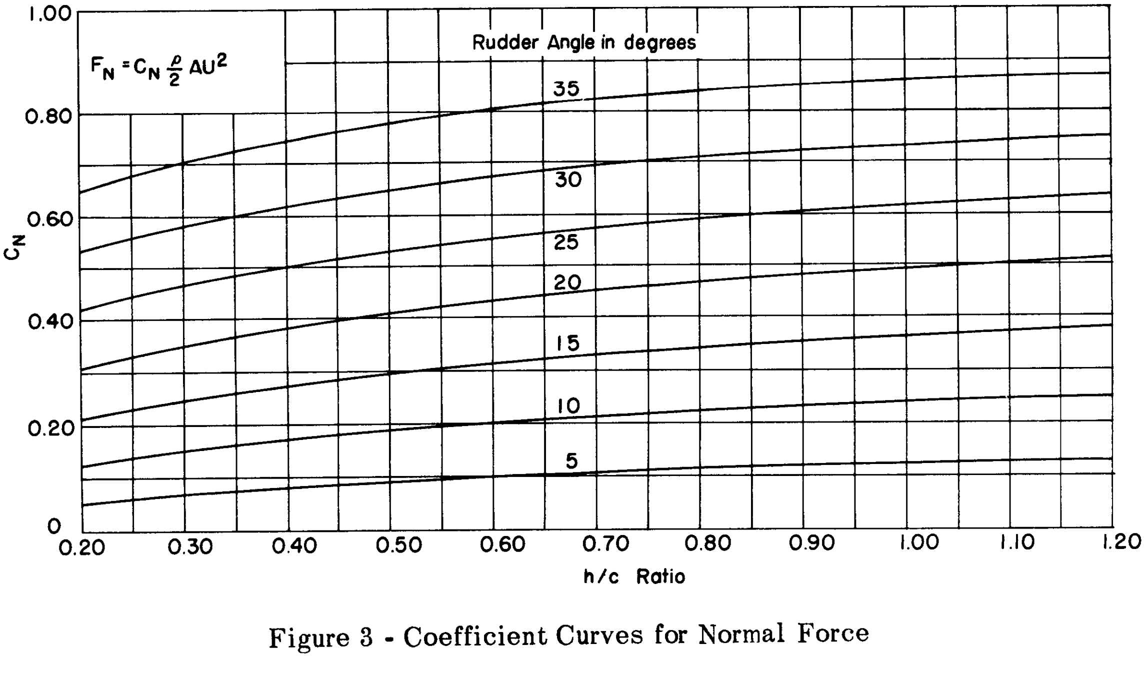


Figure 3 - Coefficient Curves for Normal Force

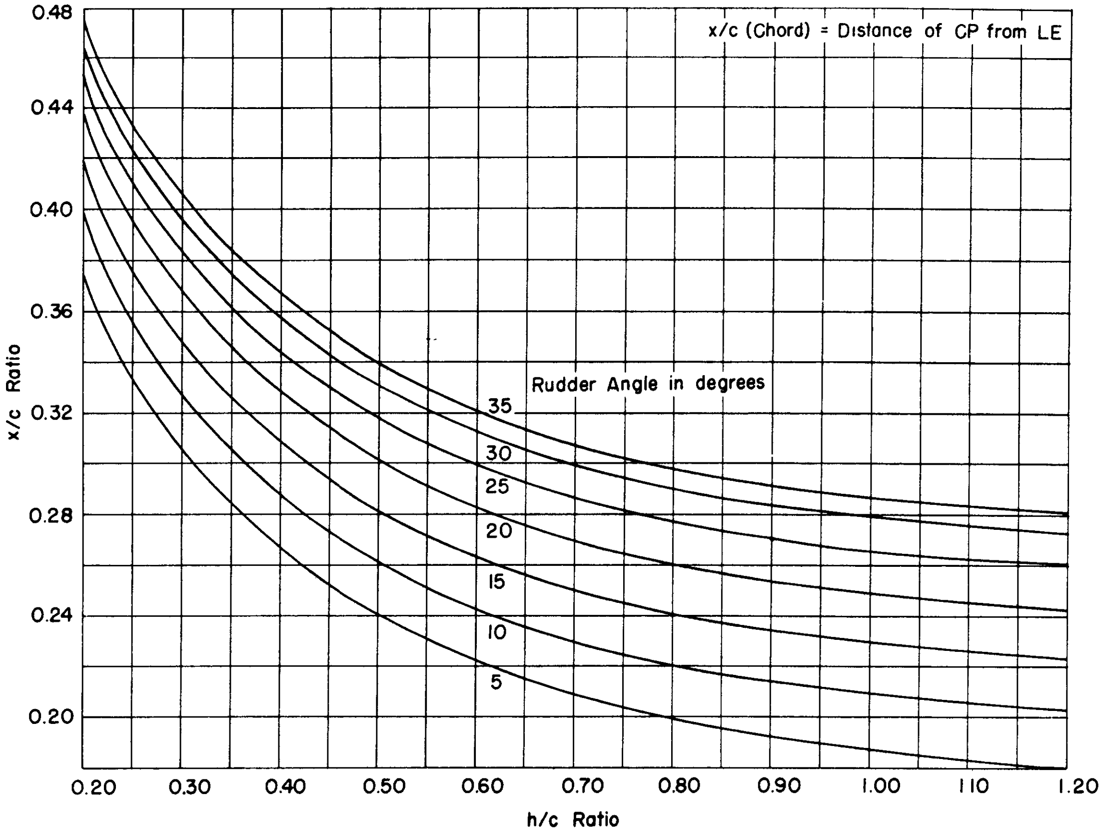
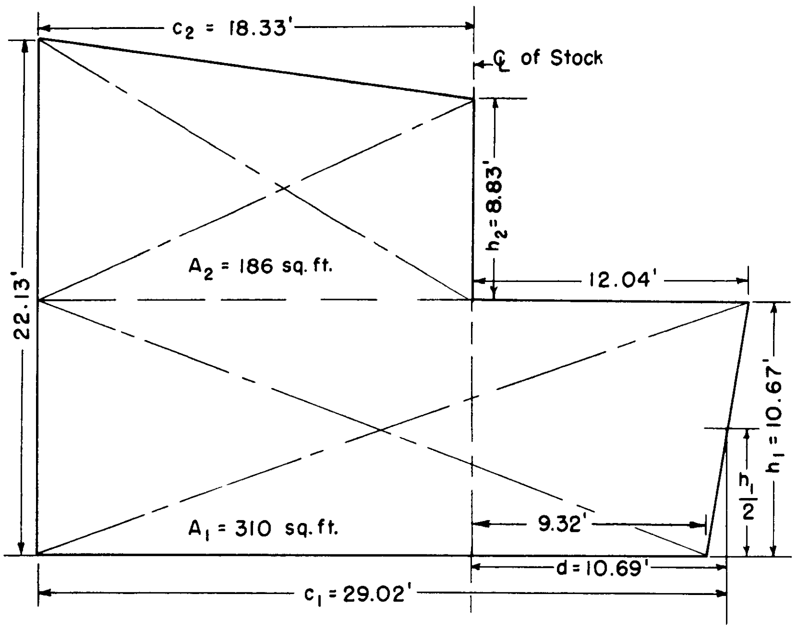


Figure 4 - Center of Pressure Curves



Area = 496 sq. ft.

Aspect Ratio, $\frac{(h_1 + h_2)^2}{A_1 + A_2} = 0.768$ $\frac{h_1}{c_1} = 0.368$ $\frac{h_2}{c_2} = 0.482$ Balance = 23 percent

Figure 5 - Principal Dimensions of CB 1 Rudder

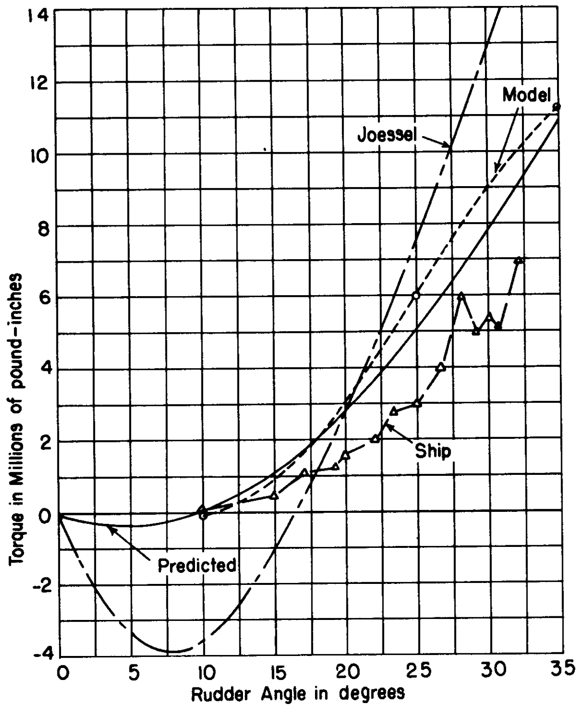


Figure 6a - CA 69 Rudder
Torque at 30 KTS

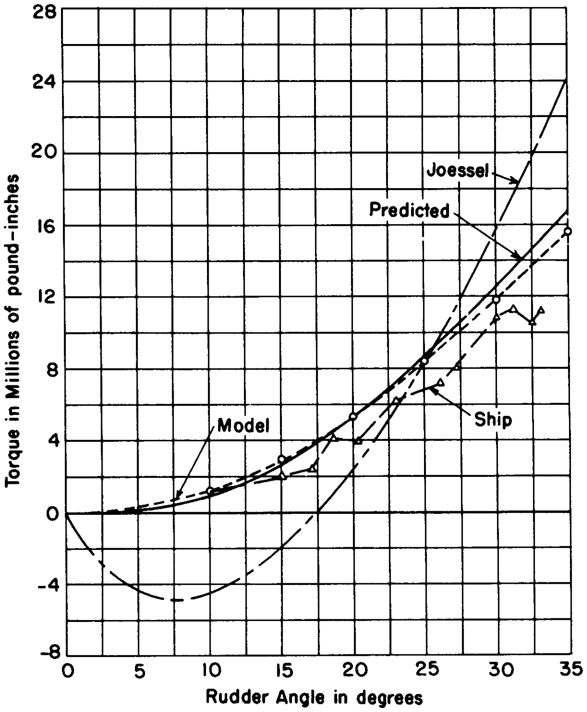


Figure 6b - CA 139 Rudder
Torque at 30.0 KTS

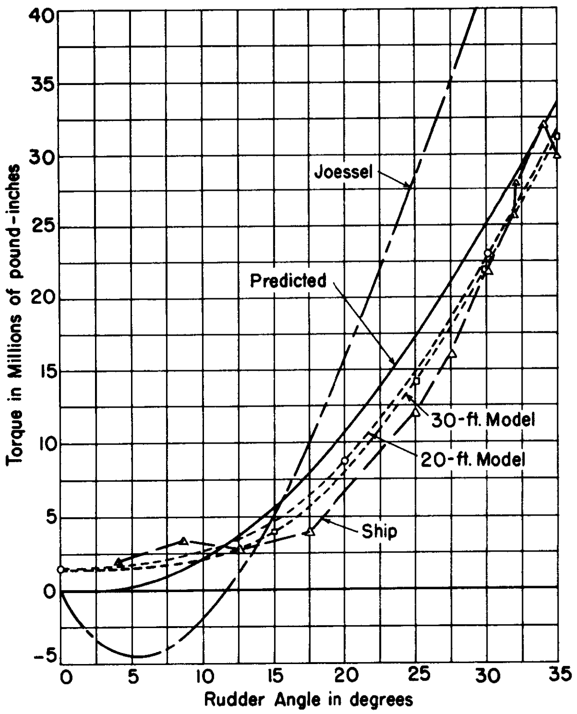


Figure 6c - CB 1 Rudder
Torque at 31.4 KTS

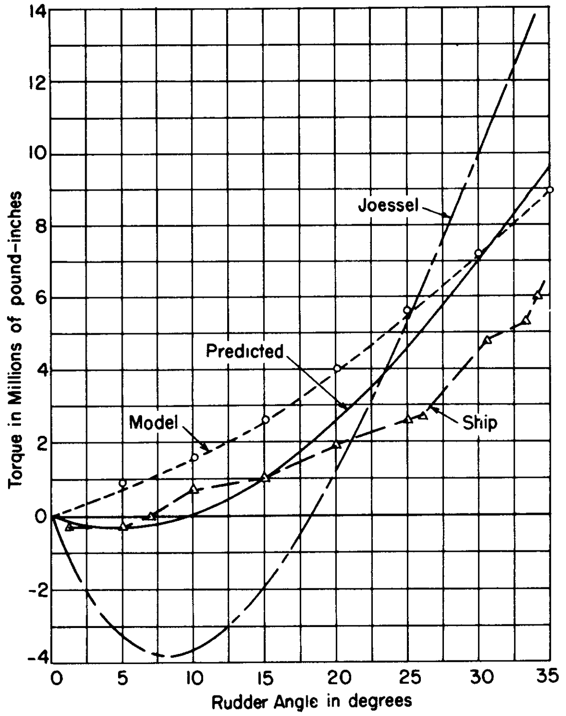


Figure 6d - CL 80 Rudder
Torque at 27.6 KTS

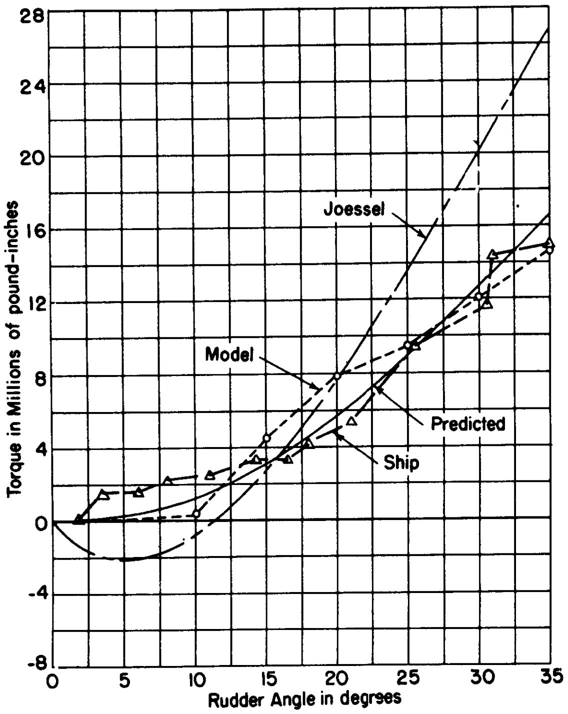


Figure 6e - CL 145 Rudder
Torque at 30.0 KTS

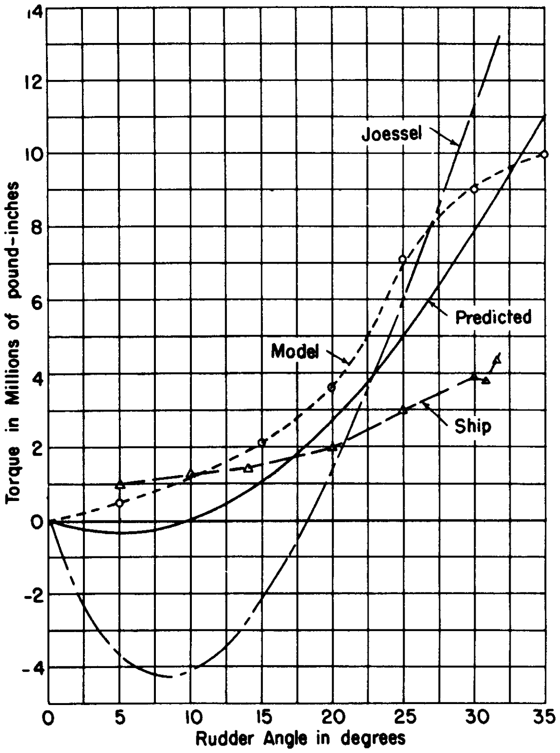


Figure 6f - CVL 28 Rudder
Torque at 29.2 KTS

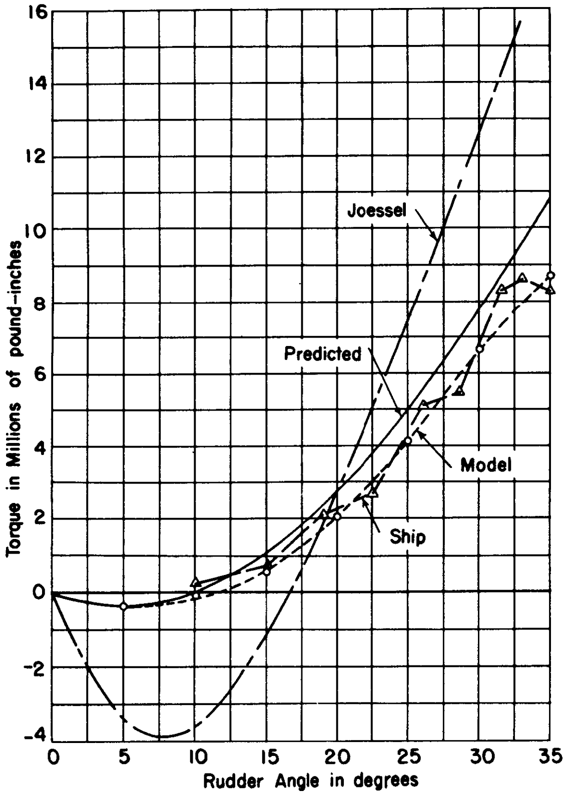


Figure 6g - CVL 48 Rudder
Torque at 30 KTS

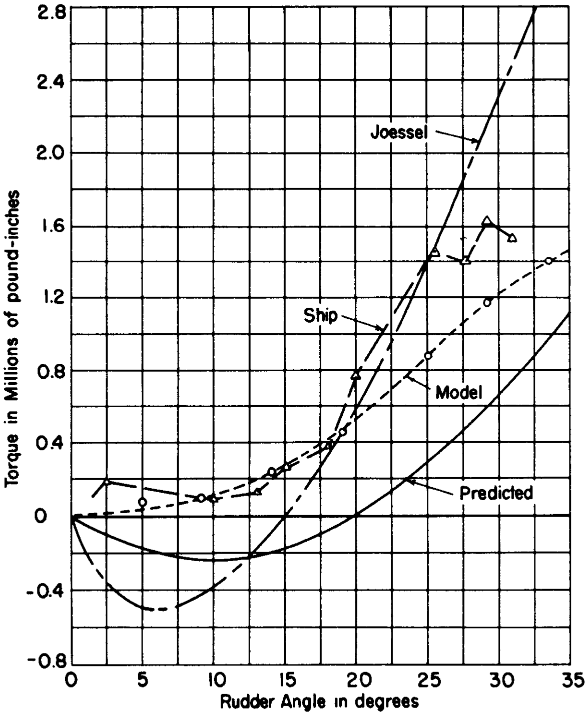


Figure 6h - DD 644 Rudder
Torque at 30 KTS

Figure 6 - Comparison of Rudder Torques

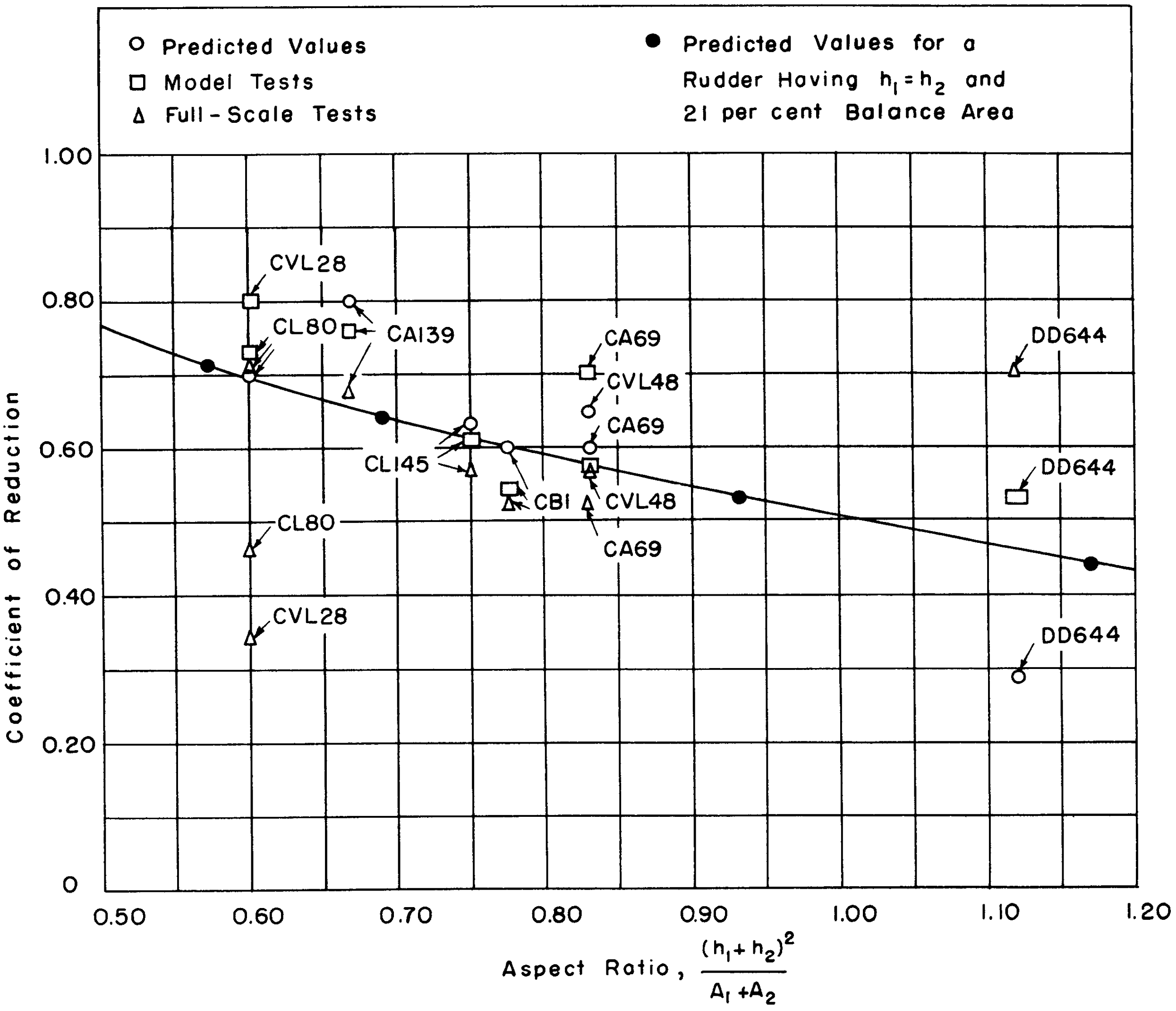


Figure 7 - Coefficients of Reduction for Various Rudders at 30 Degrees Rudder Angle

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