UNITED STATES EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

THE POWER COST OF ROLL STABILIZATION ON THE CONTE DI SAVOIA

BY J. G. THEWS AND L. LANDWEBER

EXPERIMENTAL MODEL BASIN
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JANUARY 1937 REPORT NO. 430

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INTRODUCTION

This report is an approximate power cost evaluation of gyro-stabilization in terms of bilge keel size. Details for an exact evaluation are not available. A few experiments were also conducted with different sized bilge keels to determine their relative effectiveness in the damping of rolling motion. The form which was used for these tests, a six foot model of the U.S.S. Lexington, was one which was qualitatively similar to that of the Conte Di Savoia.

The power cost of the gyro-stabilizing plant is taken as the power required to operate the plant plus that required to carry its displacement. The power cost of bilge keels is the power required to move them through the water in the forward motion of the ship. Bilge keels, depending upon their design, will have negligible or neutral buoyancy and thus they may add nothing to the ship's displacement.

General data regarding the Conte di Savoia:

(a) Size

Length of ship	801	feet
Beam (max.)	95.7	feet

(b) Bilge keels

Length	164	feet
Depth	2.95	"
Wetted surface area	1936	sq.ft.

(c) Average conditions during an Atlantic crossing according to the recent paper by Santis and Russo:

Displacement	39,000	tons
Draft (mean)	30.2	feet
Metacentric height	2.07	"
Period (complete)	28	sec.

The following statements in regard to the stabilizers on the Conte di Savoia are from the "Souvenir number of the Shipbuilder and Marine Engine-Builder."

> "The stabilizer plant ... comprises three large gyroscopes. For its operation the plant requires fully 2000 H.P. Including all accessories, foundations, and associated structure, it has an aggregate weight of about 750 tons." (This appears to be a conservative estimate.)

The thrust horsepower curve, Figure 1, and the following figures were also obtained from this same source:

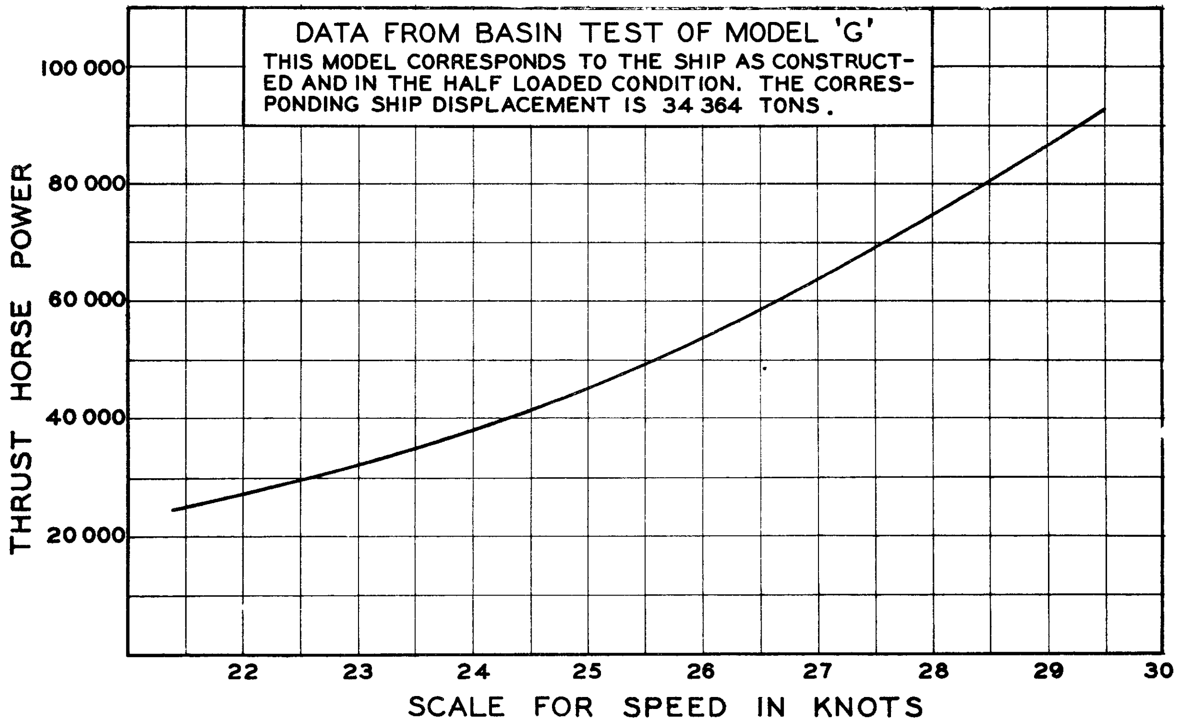


FIGURE 1. SPEED-POWER CURVE FOR THE CONTE DI SAVOIA

At an average speed of 29.5 knots on a nine hour trial the average shaft horsepower for the first six hours was 126,700 and for the last three 130,000. This would give an arithmetic time average of 127,900 S.H.P. for the nine hours.

Assuming that the trials and model data apply for the same conditions of loading the propulsive coefficient is estimated as follows:

At 29.5 knots (from curve), the thrust horsepower,

$$T.H.P. = 92{,}000.$$

Using 12% for thrust deduction (t)

$$E.H.P. = (1 - t) \times T.H.P.$$

$$= 92{,}000 \times 0.88 = 80{,}900.$$

Therefore the propulsive coefficient, E.H.P./S.H.P., is

$$80{,}900 / 127{,}900 = 0.63$$

This coefficient will, in this analysis, be taken as constant at the two speeds for which the following computations apply.

Estimated increase of ship resistance (E.H.P.) due to the added displacement of the gyro plant:

For the speeds selected it is assumed that the resistance increment varies as 70% of the displacement increment. Thrust deduction is, as above, 12%.

The displacement increment is

750 / 34,364 or 2.18%

The speeds selected are the designed speed of 25.75 knots and a reasonable higher speed of 28.5 knots. By Figure 1, the thrust horsepowers at these speeds are respectively 51,000 and 80,000 or, in terms of E.H.P.,

51,000 (1 – 0.12) = 44,900 E.H.P., and
80,000 (1 – 0.12) = 70,400

The increased resistance due to carrying the gyro plant is thus:

(a) At 25.75 knots

70% x 2.18% x 44,900 E.H.P. = 685 E.H.P.

(b) At 28.5 knots

70% x 2.18% x 70,400 E.H.P. = 1075 E.H.P.

Cost of running the stabilizer plant in terms of E.H.P. on the main turbines of the ship's propellers.

The Shipbuilder states, as noted above, that the plant requires fully 2000 H.P. This is electrical power from the turbo dynamos and presumably includes the losses in the motor-generator sets since these are listed as part of the stabilizer plant.

The small (850 KW) turbo generators use steam at 698°F., and at 400 pounds per sq. in.

The large main turbines (Parson's latest type) use steam (according to figures on boiler design) at 450 pounds and 250°F. superheat.

For lack of specific data the relative efficiencies of these turbines, the small and the main, will be taken as 60 and 80 respectively. On this basis the 2000 H.P. required by the stabilizer plant are equivalent to

2000 x (80 / 60) or 2670 S.H.P., or
(2670 x 0.63) = 1680 E.H.P.

Bilge keel resistance:

Assuming that bilge keel resistance is frictional and that the coefficient c_f is given by Schoenherr's equation

$$\frac{0.242}{\sqrt{c_f}} = \log_{10}(R' c_f)$$

the following constants are used in computing bilge keel resistance:

Temp. of sea water 55°F.
Kinematic viscosity 1.39×10^{-5} F.P.S. Units
Density of sea water 1.023
Reynold's number R' at 25.75 knots is

$$25.75 \times 1.689 \times 800 / 1.39 \times 10^{-5} = 2.5 \times 10^9$$

Reynold's number at 28.5 knots is

$$28.5 \times 1.689 \times 800 / 1.39 \times 10^{-5} = 2.77 \times 10^9$$

Since c_f does not vary rapidly with R' at this speed, a mean value of R' = 2.6 x 10^9 is taken. For this value of R', $c_f = 0.00137$. As far as is known no data are available on c_f for a rolling ship under way. The calculations are for a non-rolling ship. The roughness factor on the bilge keels is taken as 10%.

Resistance of the bilge keels on the Conte di Savoia:

c_f = 0.00137 (average for the speed range)
ρ = 1.99
A = 1936 sq.ft.
V_1 = 25.75 knots or 43.5 ft./sec.
V_2 = 28.5 knots or 48.1 ft./sec.
R (resistance) = $1.10 (c_f \times \rho/2 \times A \times v^2)$
R at 25.75 knots = 5500 pounds, or 436 E.H.P.
R at 28.5 knots = 6730 pounds, or 590 E.H.P.

Total power cost of carrying present roll damping equipment on the Conte di Savoia:

At 25.75 knots

Gyro plant consumption	1680 E.H.P.
Cost of added displacement	685 E.H.P.
Cost of present bilge keels	436 E.H.P.
Total	2801 E.H.P.

At 28.5 knots

Gyro plant consumption	1680 E.H.P.
Cost of added displacement	1075 E.H.P.
Cost of present bilge keels	590 E.H.P.
Total	3345 E.H.P.

These total powers could be used to drive bilge keels of the following estimated sizes:

At 25.75 knots, 2801 E.H.P., will drive bilge keels of

Surface area

2801 x 1936/436 = 12,500 sq.ft., or

Bilge keels

84 inches deep and 447 feet long.

At 28.5 knots, 3345 E.H.P., will drive bilge keels of

Surface area

3345 x 1936/590 = 11,000 sq.ft., or

Bilge keels

84 inches deep and 393 feet long.

The action of deep bilge keels on the Conte di Savoia is a matter of conjecture. Bilge keels of the above sizes should provide exceptionally heavy damping, certainly more than the gyro stabilizers do at all except the smaller angles. The lengths are, however, unpractical on this ship.

According to diagrams in the Shipbuilder's Souvenir Number for this ship an efficient length would be about 275 feet extending approximately from frame 109 to frame 198. Bilge keels of this length and 84 inches deep would require an estimated 1730 E.H.P. at 25.75 knots and 2340 E.H.P. at 28.5 knots. These values are 62% and 70% respectively of the powers required to carry and operate the present gyro stabilizing plant and to carry the present small bilge keels.

In the above, the gyro plant has been charged with the maximum power requirements for full time. According to the paper by Santis and Russo the gyro was used only 16% of the time at sea. In considering this value it is to be remembered that the Conte di Savoia has her route in comparatively quiet water. This favors the minimum use of the stabilizing plant.

To charge the gyro plant with only 16% of its full power requirements still gives the following results in terms of bilge keel size:

(a) At 25.75 knots.

Gyro plant consumption (16% of 1680)	269	E.H.P.
Same cost of added displacement	685	"
Same cost of present bilge keels	436	"
Total	1390	E.H.P.

(b) At 28.5 knots

Gyro plant consumption	269	E.H.P.
Same cost of added displacement	1075	"
Same cost of present bilge keels	590	"
Total	1934	E.H.P.

In case (a) it is estimated that 1390 E.H.P. at 25.75 knots will drive a bilge keel surface area of 6170 sq. ft. This would give a pair of keels each 275 feet long and 5.6 feet deep.

Similarly for (b) 1934 E.H.P. at 28.5 knots will drive a bilge keel surface area of 6340 square feet, or a pair of keels each 275 feet long and 5.8 feet deep.

From the above it would be fair to say that a pair of keels 275 feet long and about 68 inches deep can be carried by the Conte di Savoia for the same average power cost of her present total roll stabilizing equipment. This would provide her with bilge keels of area about 3.25 times that of her present ones.

To obtain some information on how effective bilge keels of different sizes might be on the Conte di Savoia a few tests were made using a six foot model of the aircraft carrier Lexington.

The normal characteristics of the two ships considered as 801 foot ships compare as follows:

Characteristic	Lexington		Conte di Savoia
Length	801 ft.		801 ft.
Beam	98.8 "		95.7 "
Draft	26.5 "	(+ 14%=)	30.2 "
Displacement	32,750 T	(+ 19%=)	39,000 T

The Lexington model was loaded for the tests to have a displacement corresponding to that of the Conte di Savoia. The drafts would thus also correspond very nearly. With the correction for displacement, it is noted that the two ships compare favorably in the above listed characteristics.

The model was tested for the following cases:

I Bare hull with half rudder

II Equipped with bilge keels similar to those on the Conte di Savoia

III Equipped with bilge keels 275 feet long and 68 inches deep. (The size estimated as capable of being carried for the same power requirements as now required to carry the gyro plant, to operate it 16% of the time, and to carry the present small bilge keels.)

IV Equipped with bilge keels 275 feet long and seven feet deep. (These, as noted above, it is estimated could be carried for about 65% of the present total power requirements to carry and operate the gyro plant and the present small bilge keels.)

The model in each case was loaded to have a period in rolling corresponding to 28 seconds for the Conte di Savoia. The GM was made as nearly the same as possible, the comparison being:

Conte di Savoia	2.07 to 2.2	feet
Lexington	2.3	feet

The results of these tests are given in figures 2 and 3. Figure 2 gives the comparative declining angle curves. Figure 3 shows the damping effects in terms of angular damping and a comparison with available data for the Conte di Savoia unstabilized but equipped with the 160 ft. by 35.5 inch bilge keels. Both of the larger sized keels provide more bilge keel damping than is known to exist on any other existing bilge keel dampened ship. The 275 ft. x 68 inch keels are about twice as effective as the small 160 ft. x 35.5 in. keels and the hull with appendages combined. How effective they are compared with that of the gyro plant cannot be stated because of lack of gyro information. In any case they should be more uniformly effective at all times.

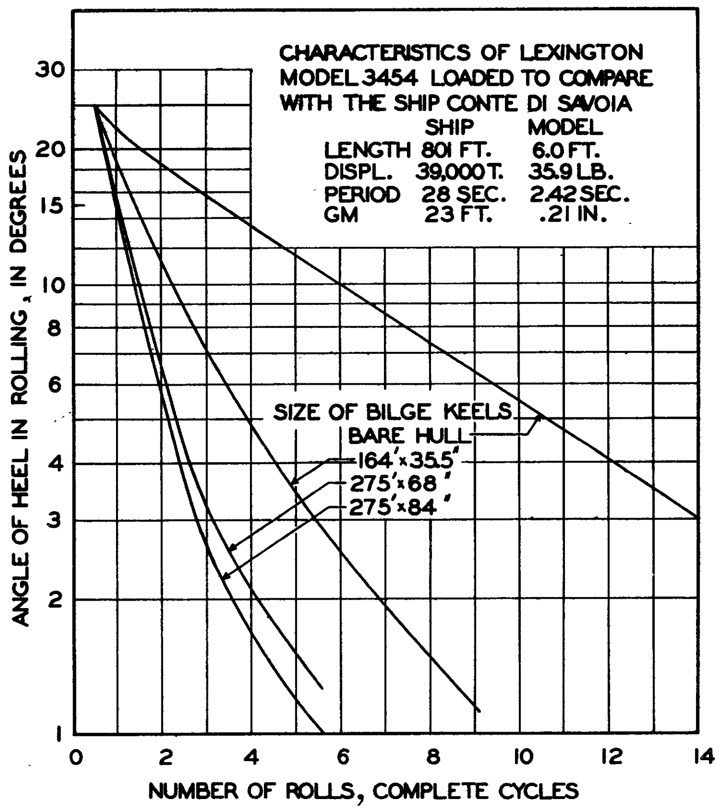


FIG. 2 DECLINING ANGLE CURVES OF U.S.S. LEXINGTON MODEL

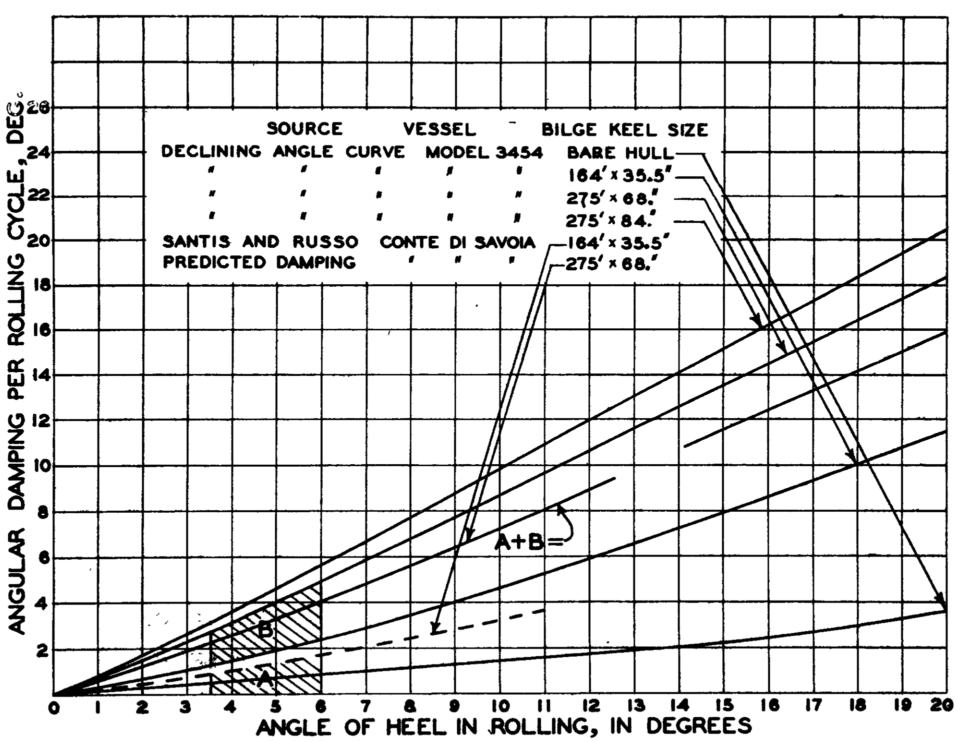


FIG. 3 ANGULAR DAMPING CURVES OF U.S.S. LEXINGTON MODEL

Figure 4 gives some comparative information regarding various ships on roll damping. $d\theta/dN$ is the loss of angle due to damping per roll, i.e., per complete rolling cycle.

Figures 5 and 6 give curves showing the conditions of ship speed and heading at which synchronism exists between ship and wave period. They show that regardless of whether the ship's period is 28 or 20 seconds and the speed 20 or 30 knots that it is practically impossible not to be in a synchronous sea when the sea is in the wide neighborhood of either quarter. It will be noted that it is quite probable that two and even three wave systems making up a confused sea can be in synchronism with the ship simultaneously.

Exact synchronism need not exist in order to produce heavy rolling. The relative wave period may differ from the ship's period by plus or minus 10% and, other conditions being favorable, heavy rolling is very probable. Figures 7 and 8 contain curves similar to those in Figures 5 and 6 but show regions of probable heavy rolling for the indicated periods and speeds of the ship. The bounding edges of these regions represent the plus or minus 10% variation from exact synchronism.

According to the above it should not appear surprising that a large ship can be made to roll heavily in comparatively short waves. Also, it indicates that an impracticably large gyro plant is required to take care of these conditions, assuming that it can be made to do so for various combinations of yawing, pitching, and rolling.

Figure 9 is a generalized chart of synchronous conditions for any ship. It may be noted that if the values of the contours and of the abscissae are multiplied by the period and the square of the period respectively of any ship, then the contour values will give the ship's speed in knots and the abscissae will be lengths of waves in feet for synchronism.

That the Conte di Savoia's gyro-stabilizers are none too effective is shown by the following table from the recent paper by Santis and Russo.

TABLE 1

Rolling of The Conte di Savoia at Ship Speeds of 26.5 Knots

Angles are measured from the vertical.
Trials are for fifteen minute intervals.

	Mean Rolling in Degrees	
	Free	Stabilized
1	4.38	3.05
2	6.6	1.85
3	4.88	2.04
4	5.24	2.88
4	6.2	3.05
5	6.6	2.39
6	8.72	5.83
6	9.64	6.91
7	12.3	10.5
7	8.86	7.1
7	12.9	8.7
8	11.8	4.4
8	11.7	4.5
8	8.1	4.5
9	12.1	5.4
9	12.1	6.9
9	12.9	5.45
10	6.7	2.4
11	7.97	4.8
12	9.93	7.57
12	9.93	6.49
12	13.24	6.41
13	12.9	8.5
13	11.6	8.05
14	6.92	2.7
Grand Average	9.37	5.30

That fair sized bilge keels are effective in preventing rolling is evidenced by the following model rolling data in Table 2. The average depths and lengths of the keels are, for the examples listed, approximately 13% and 31% of the ships' drafts and lengths.

TABLE 2.

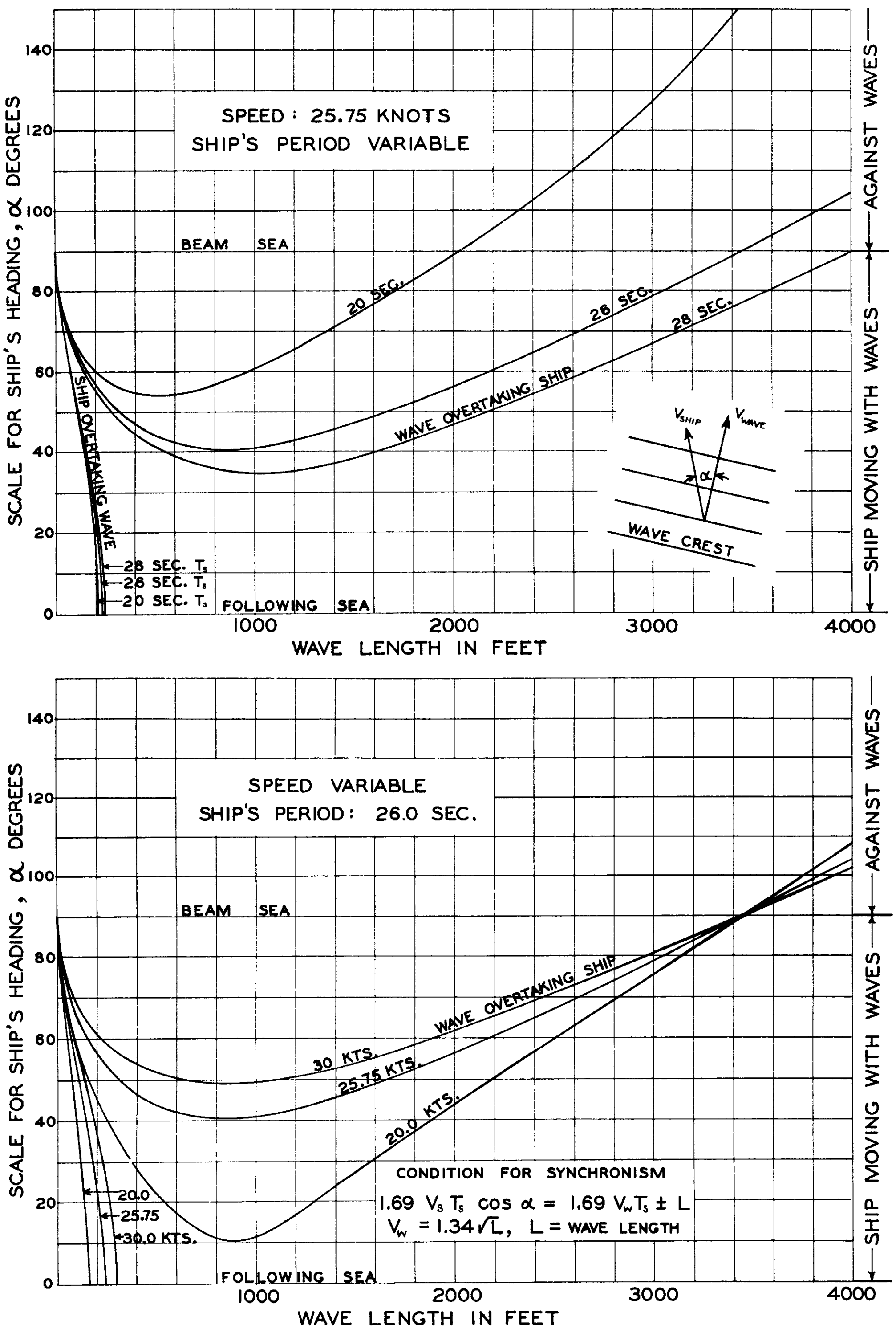
Model	Amplitude of roll in degrees from the vertical	
	Without Bilge Keels	With Bilge Keels
U.S.S. Ranger model	15	7
Cruiser model 2697	12	5
Battleship model 3366	15	8
		For the comb. Bilge and Docking keels.
Tanker model 3336	15	8
U.S.S. Lexington model loaded as Conte di Savoia	15	3.5
		(275' x 68" B.K.)

This report is not intended as a complete discussion of the subject. Clearly, other factors such as initial capital invested, depreciation, and the consistent reliability of the roll damping characteristics of the devices must be considered.

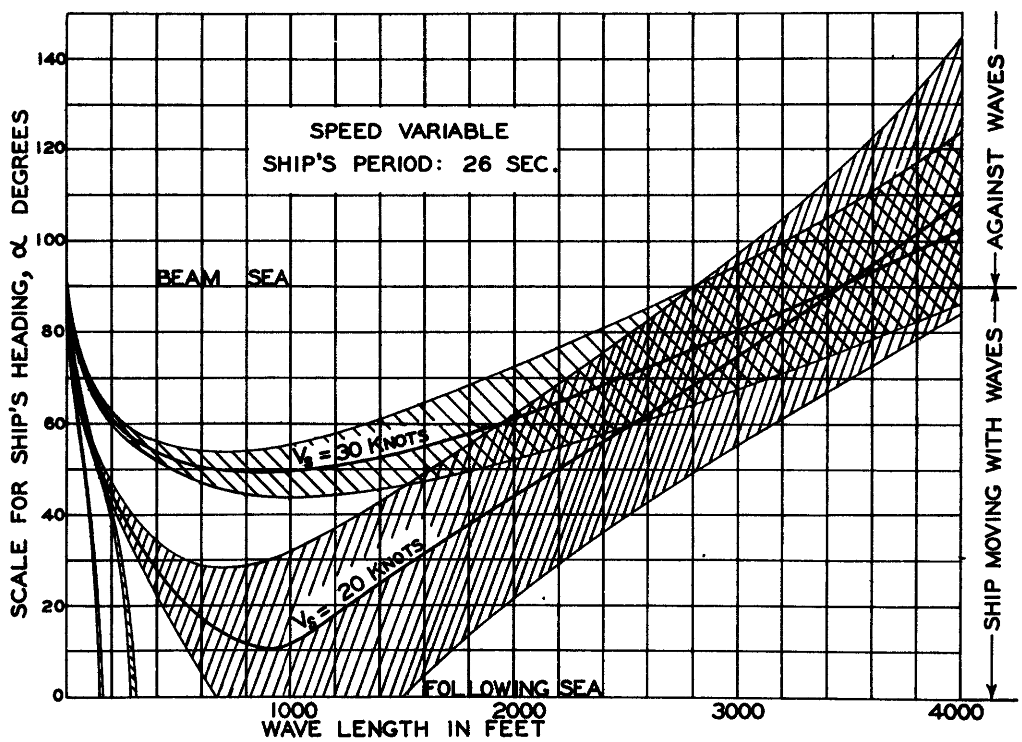
SHIP OR MODEL	DISPLACEMENT TONS	LENGTH FEET	BEAM FEET	DRAFT FEET	GM INCHES	PERIOD SECONDS	$\frac{d\theta}{dN}$ IN DEG. WHEN ANGLE OF HEEL IN ROLLING IS:						REMARKS
							3°	6°	8°	10°	12°	15°	
U.S.S. OREGON (SHIP)	9810	348		23.3	36	15.2	.12	.28	.44	.62	.85	1.31	NO BILGE KEELS
" " "	9790	"		"	"	15.7	.68	2.20	3.62	5.50	7.70	11.70	BILGE KEELS – DEPTH 14" TO 34", LENGTH = 207.5'
H.M.S. REVENGE (1898)	5260						.10	.32	.51	.74	1.01	1.5	DEEP OR HEAVY, NO BILGE KEELS
" "	"						.65	2.0	3.2	4.7	6.5	9.6	HEAVY, WITH BILGE KEELS
H.M.S. DEVASTATION (1898)	9157	285					.7	1.9	3.1	4.4	6.1	8.9	WITH BILGE KEELS
H.M.S. NARCISSUS	8548						.4	1.0	1.6	2.3	3.2	4.7	" " "
H.M.S. VOLAGE	3078	270					.3	.86	1.38	2.0	2.8	4.1	" " "
H.M.S. SULTAN	9286	325					.2	.4	.6	.9	1.1	1.5	" " "
U.S.S. LANGLEY (MODEL DATA)	11,000	520	65	18.9	46	16.7	.12	.29	.56	.78	1.0	—	NO BILGE KEELS
" " " "	"	"	"	"	"	17.2	.50	2.4	3.5	4.4	—	—	WITH BILGE KEELS, 15" × 180'
U.S.S. RANGER (MODEL DATA)	15,740	730	80.2	20.7	61	17.2	.18	.45	.70	1.10	1.55	2.3	NO BILGE KEELS
" " " "	"	"	"	"	"	17.5	.60	1.9	3.0	4.1	5.3	9.0	WITH BILGE KEELS, 42" × 176'
U.S.S MARYLAND (MODEL)	33,000	600	97.3	30.6	60	16.8	.40	1.3	2.1	3.0	4.2	6.2	BILGE KEELS; 2 SEGMENTS/SIDE ; 45" × 184' PER SIDE
CRUISER MODEL NO. 2697	11,512	600	64.4	19.7	67	12.2	.10	.35	.50	.85	1.2	—	BARE HULL
" " "	"	"	"	"	"	"	.6	1.4	1.9	2.5	3.5	—	BILGE KEELS, 36" × 200'
BATTLESHIP MODEL NO. 3366	40,000	720	106	30	72	17.8	.2	.45	.80	1.3	2.2	4.1	NO BILGE KEELS
" " "	"	"	"	"	"	18.1	.7	2.2	4.1	6.2	8.1	11.4	WITH COMBINATION BILGE AND DOCKING KEELS
" " "	"	"	"	"	"	"	.84	2.7	4.9	7.6	9.7	13.7	WITH 36" BILGE KEELS, 180 FEET LONG
ROYAL SOVEREIGN (UNBULGED)	30,600	614	102.5	33	41	19	.1	.2	.25	.28	.3	.5	NO BILGE KEELS
" " "	"	"	"	"	"	"	.6	1.25	1.9	2.8	3.9	4.9	B.KS., DEPTH 3'-4', LENGTH 350'
ROYAL OAK (BULGED)	33,240	"	"	31.5	62	16	.1	.3	.5	.73	1.1	1.65	NO BILGE KEELS
" " "	"	"	"	"	"	"	.5	1.2	1.9	2.9	4.0	5.9	B.KS., DEPTH 3'-3½', LENGTH 200'
REVENGE (BULGED)	32,000	"	"	31.5	62	16	.1	.4	.7	1.0	1.4	1.85	NO BILGE KEELS
" "	"	"	"	"	"	"	.4	1.1	1.75	2.5	3.5	5.1	B.KS., DEPTH 5½', LENGTH 200'
MERCHANT SHIP MODEL	11,600	430	55	23.6	36.4	14.0	1.3	1.5	1.7	1.9	2.1	2.3	ALL APPENDAGES (B.KS, RUDDER, BOSSINGS), NO TANKS ON
" " "	"	"	"	"	"	"	1.9	2.5	2.7	2.9	3.0	3.2	" " ONE TANK ON
" " "	"	"	"	"	"	"	3.1	4.4	5.0	—	—	—	" " TWO TANKS ON
CONTE DI SAVOIA (MODEL)	38,000	801	95.7	28.0	27.6	28.0	0.71	1.68	2.41	3.18	—	—	BILGE KEELS 35½" × 164'
MODEL OF RESOR 1935 TANKER MODEL 3336	16,200	435	66.5	27.1	66	9.37	.13	.35	.56	.78	1.08	1.6	NO BILGE KEELS
" "	"	"	"	"	"	9.50	.33	.92	1.50	2.25	3.23	5.4	BILGE KEELS 18" × 182.5'
" "	"	"	"	"	"	9.74	.80	2.7	4.1	5.5	6.9	9.1	BILGE KEELS 36" × 182.5'
MODEL OF A LIGHTSHIP	332	100	24	9.4	18.5	4.02	0.11	.29	.46	.65	.88	1.3	NO BILGE KEELS
" "	"	"	"	"	28.4	4.17	0.43	1.6	2.9	4.6	6.8	10.6	BILGE KEELS LENGTH 59½', DEPTH – 2'6"
" "	"	"	"	"	28.4	4.24	0.31	1.0	1.7	2.6	3.6	5.0	" " " " " 1'9"
" "	"	"	"	"	28.4	4.27	0.30	.78	1.2	1.7	2.3	3.3	" " " " " 1'0"
" "	"	"	"	"	46.9	3.39	0.87	1.4	2.4	3.7	5.3	8.3	" " " " " 2'6"
" "	"	"	"	"	13.4	6.36	0.42	1.6	2.8	4.3	6.3	9.6	" " " " " "
* U.S.S. LEXINGTON (6' MODEL)	39,000	801	95.7	30.2	25	28.	2.0	4.2	5.7	7.3	9.0	11.6	BILGE KEELS 275' × 68"

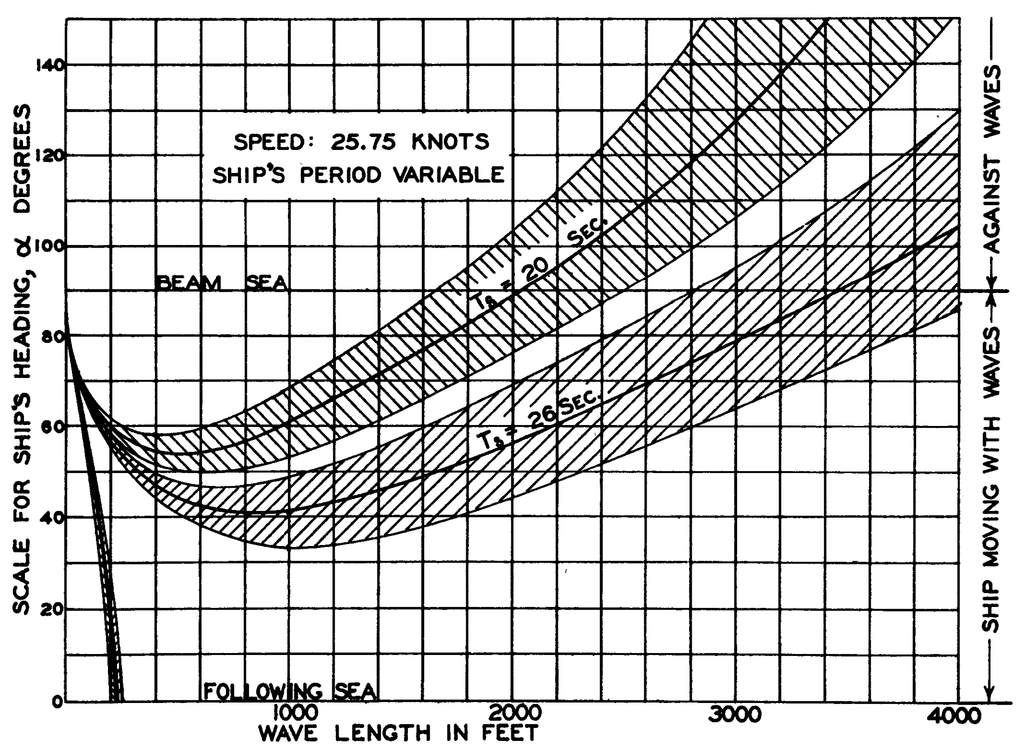
* LOADED AS THE CONTE DI SAVOIA

FIGURE 4. COMPARATIVE DAMPING OF SHIPS IN ROLLING.



FIGS. 5 & 6. HEADING OF SHIP FOR SYNCHRONISM





FIGURES 7 & 8. SPEED & HEADING OF SHIP FOR SYNCHRONISM. SHADED AREAS GIVE THE REGIONS WITHIN WHICH THE RELATIVE WAVE PERIOD IS WITHIN PLUS OR MINUS 10 % OF THE SHIP'S NATURAL ROLLING PERIOD.

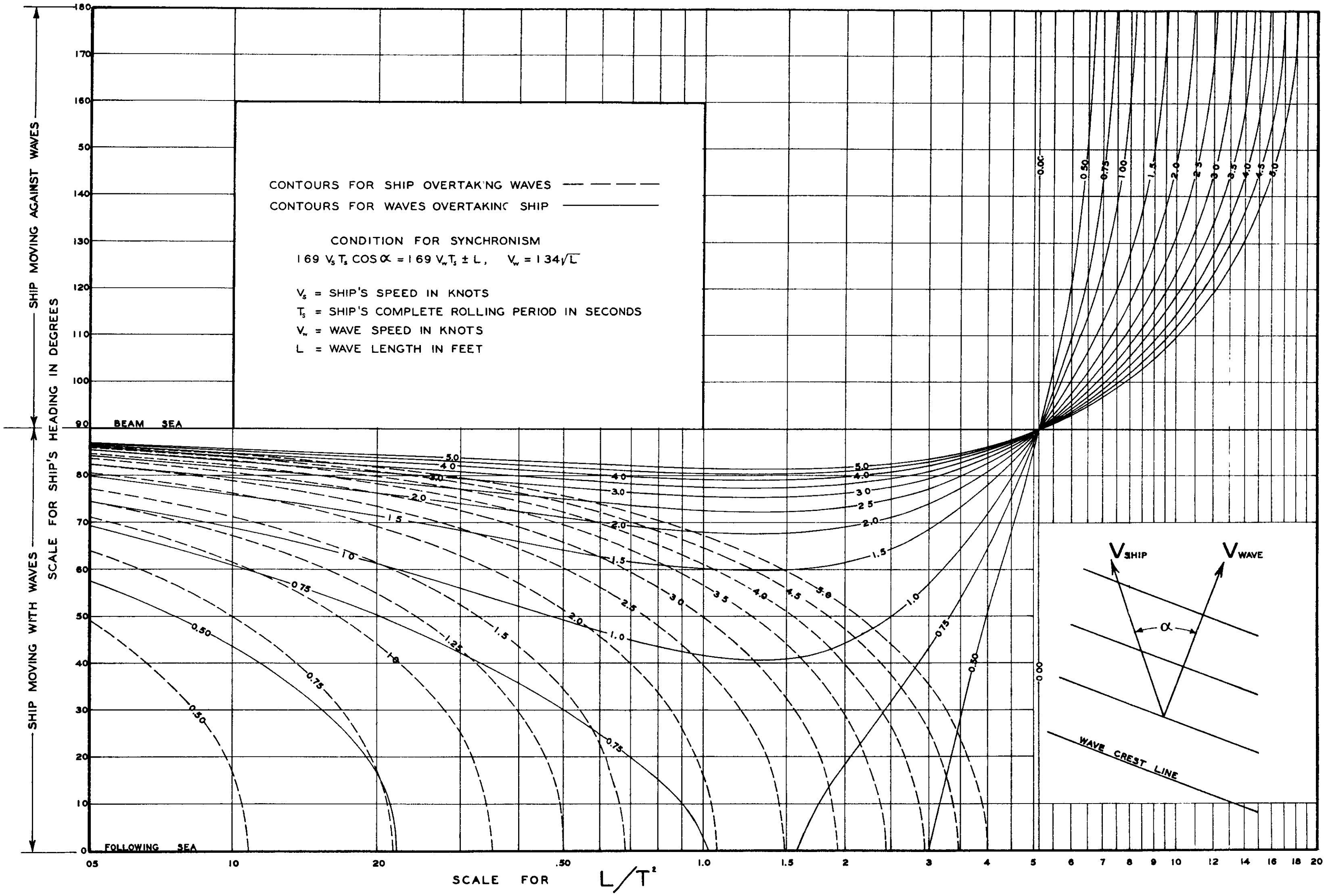


FIGURE 9. CONTOURS OF V_s/T_s FOR THE HEADING OF A SHIP FOR SYNCHRONISM BETWEEN THE SHIP'S COMPLETE ROLLING PERIOD AND THE RELATIVE PERIOD OF THE WAVES