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WIND-TUNNEL TESTS TO DETERMINE AIR LOADS ON MULTIPLE-SHIP MOORINGS FOR DESTROYERS OF THE DD692 CLASS

by

Lt. (jg) M.E. Long, USNR

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Report R-332

PERSONNEL

The tests were conducted at the Aeromechanics Division of the David Taylor Model Basin by Lt. (jg) M.E. Long, USNR, with the assistance of R.H. Bresk and Milton Hawranek. The report is the work of Lieutenant (jg) Long.

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WIND-TUNNEL TESTS TO DETERMINE AIR LOADS ON MULTIPLE-SHIP MOORINGS FOR DESTROYERS OF THE DD692 CLASS

ABSTRACT

Wind-tunnel tests were conducted at the David Taylor Model Basin to determine the wind forces and moments on models of destroyers of the DD692 Class moored singly and in groups of two, four, and six abreast.

The models were built from the waterline up, like recognition models. The linear scale ratio was 1 to 73.8. Individual three-component balances supported the models above a ground board which was used to represent the water surface. Tests were conducted on the single model at wind speeds of 125, 100, and 75 knots, and on the groups of models at 125 knots for a 360-degree range of angles of yaw.

Results are given in the form of curves which show the lateral and the longitudinal forces in pounds, and the yawing moment in pound-feet, for the single model and for individual models in the groups, as functions of angle of yaw. Total forces and moments on the groups computed from the data on the individual models are also shown as functions of the yaw angle. Results of the tests on the single model at different wind speeds are expressed in coefficient form. Expressions for estimating the forces and moments on the full-scale destroyers and a method for extrapolating the test results to larger numbers of ships in line abreast are given.

INTRODUCTION

The disposal of ships, both merchant and combat, that have become surplus since the cessation of hostilities is a problem of greater magnitude than any similar one heretofore encountered. In order to keep in existence the more modern vessels that cannot be actually operated, extensive installations must be provided for tying up these ships. The magnitude of the problem makes it desirable to have reliable data on which the design of rational mooring installations can be based. Accordingly, the Bureau of Yards and Docks on 21 October 1944 requested (1)* the David Taylor Model Basin to conduct tests to determine the forces on moored ships due to winds and to water currents. Tests were requested on four classes of vessels: destroyers, submarines, escort carriers, and merchant ships. The present report gives results of wind-tunnel tests on six models of destroyers of the DD692 Class. Tests of the other three classes of vessels will be described in subsequent reports. In these tests, horizontal wind forces and yawing moments were measured on a

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* Numbers in parentheses indicate references on page 21 of this report.

single model and on individual models set up in groups of two, four, and six to represent typical line-abreast ship-mooring installations.

MODELS AND APPARATUS

The models were built to a linear scale of 1 to 73.8 to represent destroyers of the DD692 Class. Since only the wind loads on moored vessels were of interest in these tests, the model hulls were cut off at the waterline. Table 1 gives pertinent information about the ships and models.

TABLE 1

Principal Data on Destroyers of the DD692 Class and on 1:73.8-Scale Models for Wind-Tunnel Tests

Particulars	Full-Size Ship	1:73.8-Scale Model
Overall length	376.5 feet	5.10 feet
Beam	40.83 feet	0.54 foot
Standard displacement	2200 tons	
Design waterline	13.0 feet	0.18 foot
Displacement, moored	2100 tons	
Draft, moored	10.6 feet	0.14 foot
Projected broadside area, moored	10,100 square feet	1.80 square foot
Projected frontal area, moored	1420 square feet	0.25 square foot

The amount of detail reproduced on the models can be judged by the photographs, Figures 1 through 4. The rigging and radio antennas, the 20-mm guns, all radar antennas except the large fire-control radar antenna, and all lights except the 24- and 36-inch searchlights were omitted, as being of minor importance.

The models on which forces were measured were attached to individual three-component horizontal force balances, as shown in Figure 1. These balances consisted of two steel plates held in parallel planes by wire-end spacer rods. The motion of the top plate with respect to the base was restrained by three cantilever beams bolted solidly to the base plate. The ends of these beams were attached to the top plate by wire-end push-pull rods. Wire-resistance strain gages cemented in pairs to these beams made possible the measurement of the forces in the horizontal plane. The longitudinal force was measured by the central beam while the lateral or side force was measured by the two end beams; see Figure 1. These latter beams were located approximately 1/4 and 3/4 of the model length from the bow. The measurement of the lateral force at these two stations made possible the computation of the

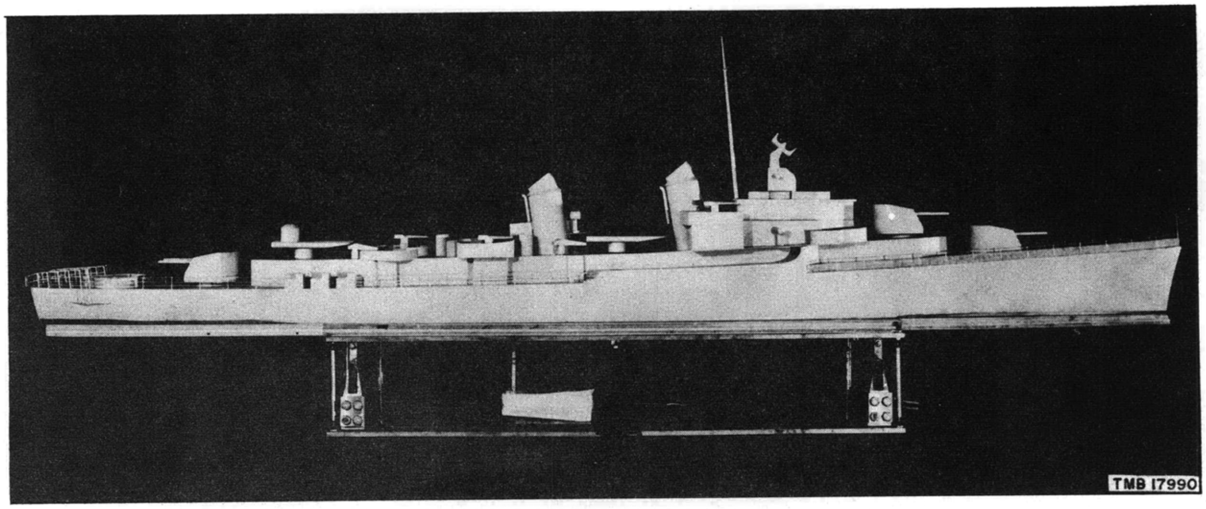

Figure 1 - Model Mounted on Three-Component Horizontal Force Balance

The lateral force and the yawing moment are measured by the two strain-gage beams near the ends of the balance; the longitudinal force is measured by the third beam near the center of the balance.

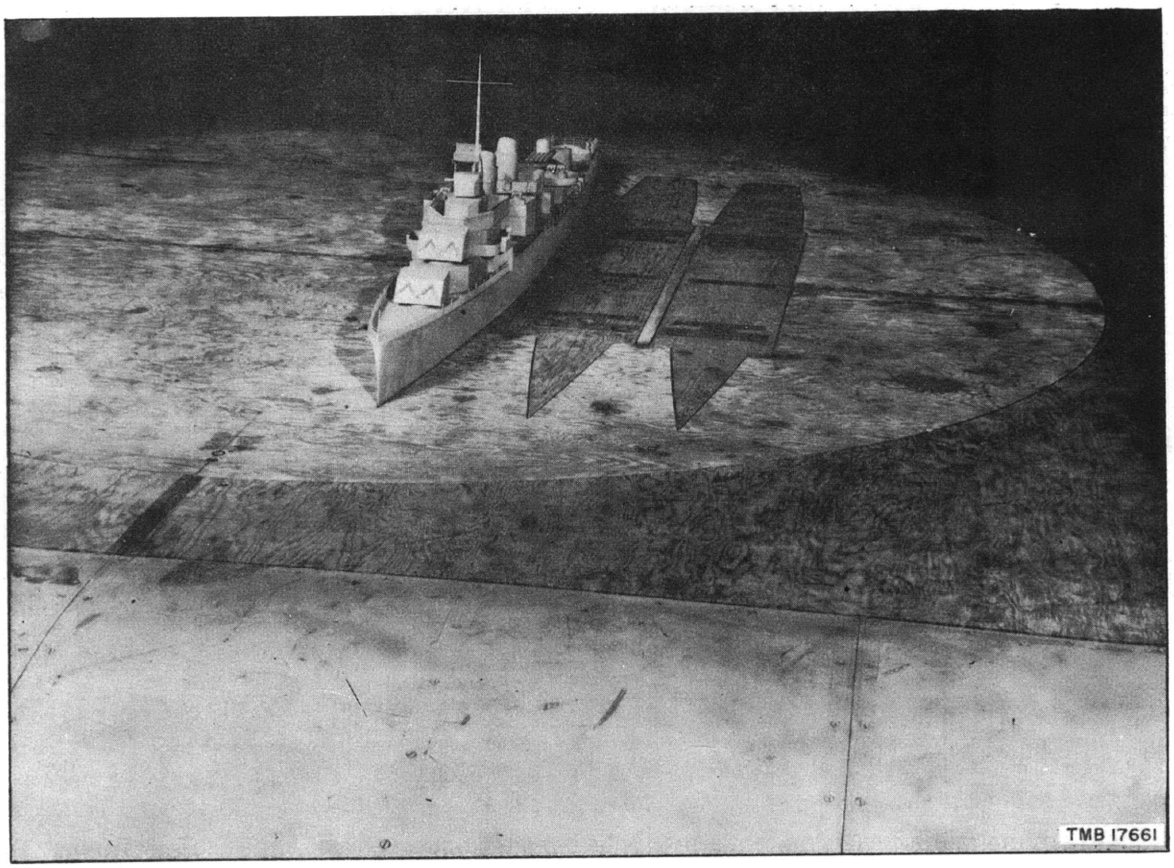

Figure 2 - Model Set Up on Ground Board in Wind Tunnel

The model is shown heading directly into the wind stream. The rounded sheet-metal leading edge is visible in the foreground, whereas the trailing edge slopes down to the tunnel floor in the background. The two filler pieces on the port side of the model cover the additional balances used in the tests of groups of models. The models are fastened directly on these filler pieces, the clearance between the pieces and the ground board allowing the necessary freedom of motion of the balance systems.

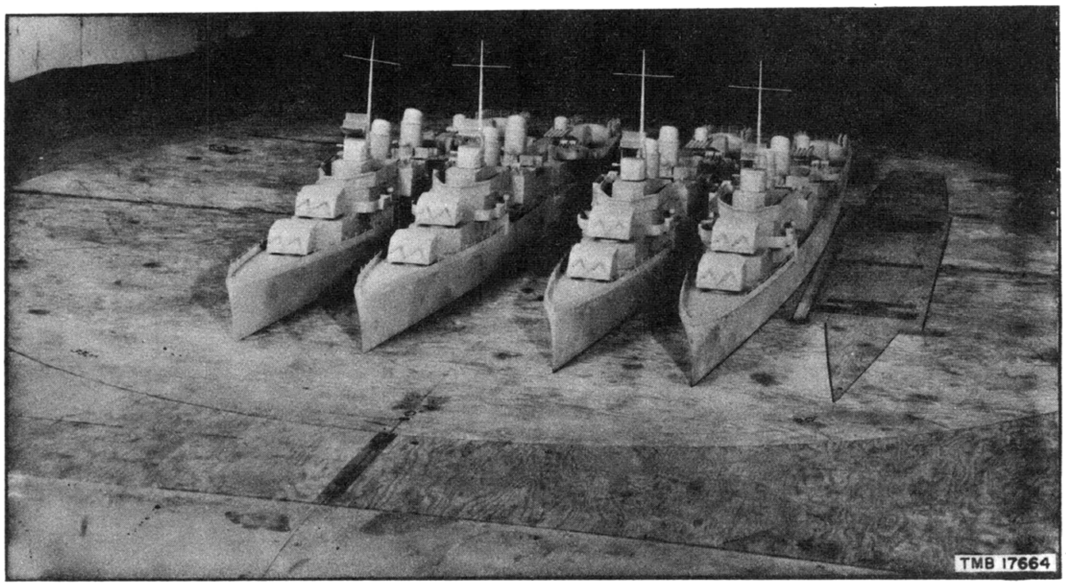

Figure 3 - Four Models Set Up on Ground Board in Wind Tunnel

The two starboard models are fastened directly to the ground board, while the two port models are mounted on three-component force balances.

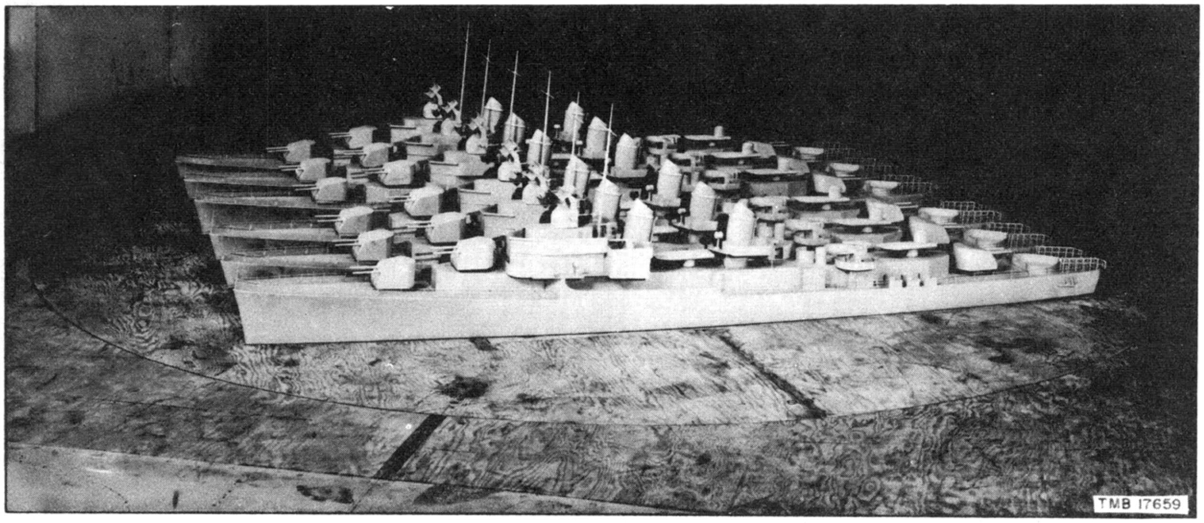

Figure 4 - Six Models Set Up on Ground Board in Wind Tunnel

The central turntable has been yawed so that the wind stream approaches the models from the port quarter.

yawing moment as well as the total lateral force. The three components obtained from the force balances were lateral force, yawing moment, and longitudinal force. The balances were calibrated by applying known forces at each strain-gage beam and noting the reaction of the entire system under these simple loads.

The models were set up in the wind tunnel on a false floor or ground board built up above the floor of the wind-tunnel test section. At the upstream end of the ground board a rounded sheet-metal leading edge extended down to the tunnel floor, whereas the trailing edge tapered down at a 1:8 slope. This construction gave a steady flow over the central level surface of the ground board. Sections of the ground board corresponding roughly to the waterline-plan form of the models were cut out, and the force balances were set below the surface of the ground board on a steel base plate. Plywood filler pieces shaped to fit inside these cut-outs were attached to the top plates of the force balances, and the models in turn were mounted on these plywood pieces; see Figure 1. Clearance was provided between the ground board proper and the filler pieces, to give the necessary freedom of motion for the balances. Figure 2 is a photograph showing a single model set up on the ground board, while Figure 3 is a similar photograph showing a group of four models set up on the ground board.

In order to obtain wind loads for different yaw angles, a circular section was cut out of the level surface of the ground board. This section carried the models and balances, and could be yawed to any desired angle with the wind stream. This circular section can be seen in Figures 2, 3, and 4. Figure 4 is a photograph showing a group of six models set up for test on the ground board and yawed at plus 60 degrees to the wind stream.

In the tests of the groups of models, the centerline of the mooring for the group coincided with the zero-degree centerline of the circular section. Models on the port side of this centerline were all mounted on force balances, while models to the starboard were fastened directly to the ground board. However, since the groups were yawed through 360 degrees, the models on which forces were measured were in turn to windward (for example, at 90 degrees yaw) and to leeward (for example, at 270 degrees yaw) with respect to the fixed models.

TEST CONDITIONS

Tests were run in the David Taylor Model Basin 8- by 10-foot closed-throat atmospheric Wind Tunnel 1. Tests on the single model, shown in Figure 2, were run at dynamic pressures of 53.0, 33.9, and 19.1 pounds per square foot, corresponding to wind speeds of 125, 100, and 75 knots in standard air. Tests on the groups of two, four, and six models were run at a speed of 125 knots. In all tests the angle of yaw was varied from 0 degree to 360 degrees by increments of 30 degrees.

The models were placed so that the centerlines of models adjacent to the mooring were 5 3/8 inches from the centerline of the mooring, and the

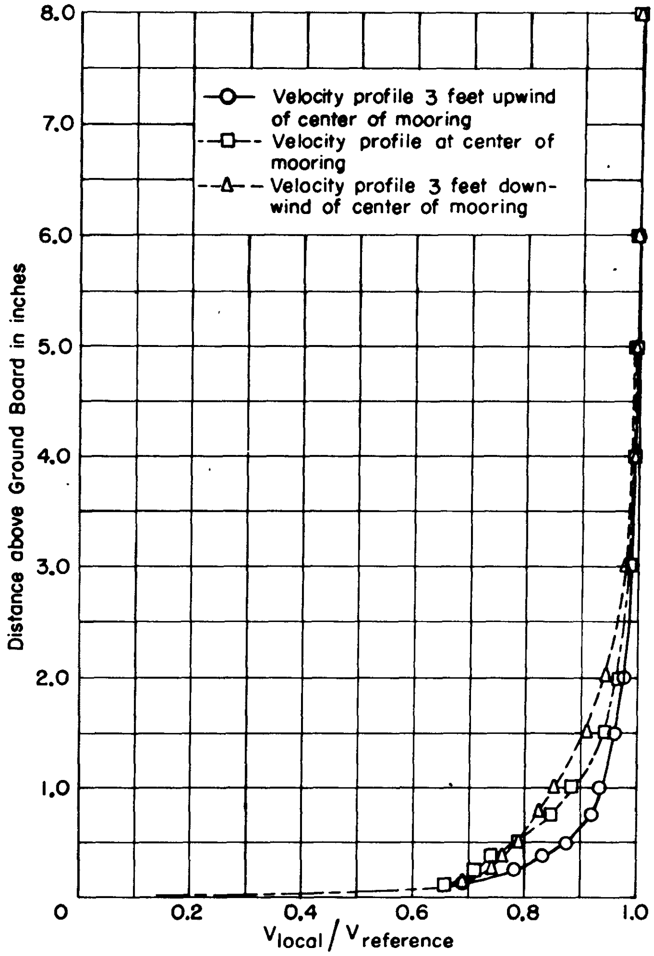

Figure 5 - Velocity Profiles Measured above Unobstructed Ground Board

centerlines of models on the same side of the mooring were 7 1/2 inches apart. This spacing corresponds to distances of 33 and 46 feet respectively for the prototype ships.

The reference test velocity was measured at a point 8 inches above the ground board, approximately at the level of the tops of the stacks of the models. The velocity profile between the ground board and this reference point was determined over the unobstructed ground board by a total-head survey, the static pressure being assumed constant from the reference point down to the ground board. Figure 5 shows the average velocity profiles measured at three different stations along the ground board, that is, at the farthest distance upstream to which any one of the models would extend, at the center of the groups of models, and at the farthest distance downstream to which any of the models would extend. Figure 6 shows these velocity profiles scaled up in the ratio 73.8 to 1, together with a wind gradient measured over flat, level country (2).

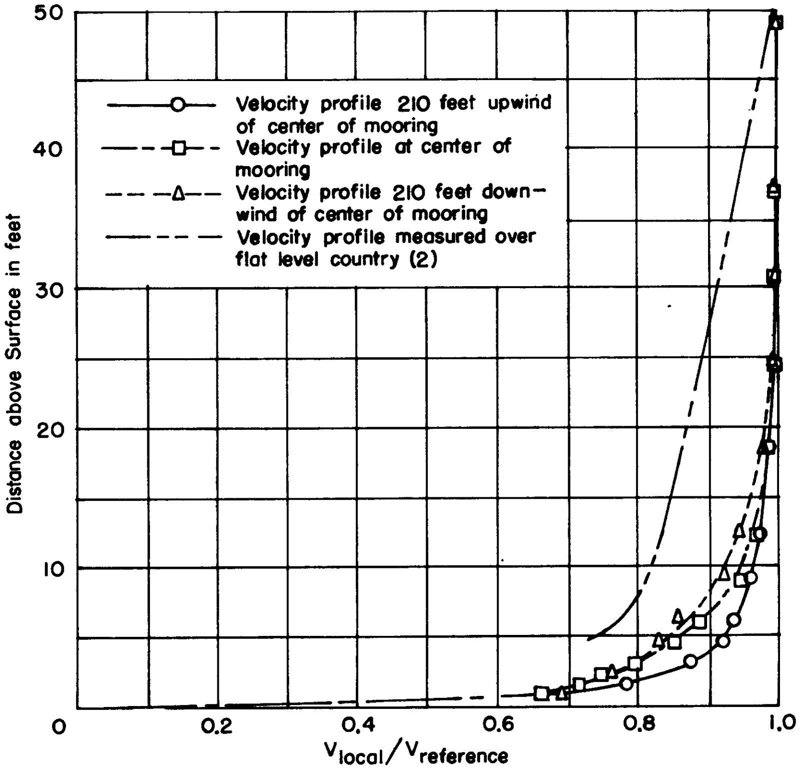

Figure 6 - Velocity Profiles Scaled Up to Full Size from Measurements over Unobstructed Ground Board

RESULTS

In this report the forces and moments measured on the models are given directly. The lateral force is taken positive toward the starboard, and the longitudinal force is taken positive toward the stern. A positive yawing moment is one that tends to turn the ship to starboard. The moment center for the individual models is taken at the center* of the model, whereas for the groups the center of moments is taken at the center of the mooring, which is the geometric center of the group. The forces are given in pounds, and the yawing moment is given in pound-feet.

Figure 7 shows the lateral force, longitudinal force, and yawing moment for a single model as a function of angle of yaw, for wind speeds of 125, 100, and 75 knots.

Figures 8, 9, and 10 give similar results for individual models in the groups of two, four, and six, for a wind speed of 125 knots.

In Figures 11, 12, and 13 the total lateral force, the total longitudinal force, and the total yawing moment about the center of the mooring are given for the three groups of models.

(Text continued on page 15)

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* The center of the model is taken as the midpoint between perpendiculars, which is 189.7 feet aft of the bow on the prototype ship.

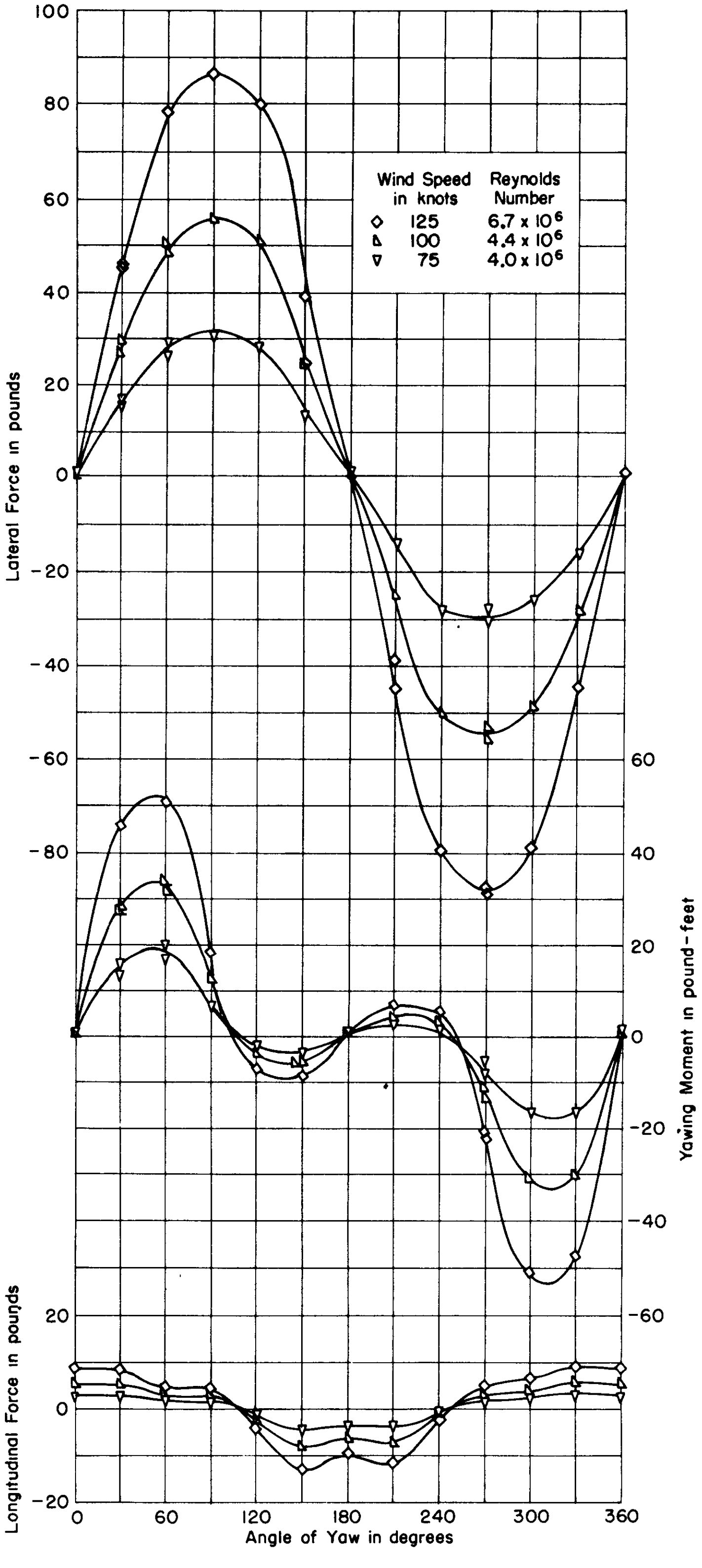

Figure 7 - Variation of Lateral Force, Yawing Moment, and Longitudinal Force with Angle of Yaw for One Model at Wind Speeds of 125, 100, and 75 Knots

The moment center is at the center of the model.

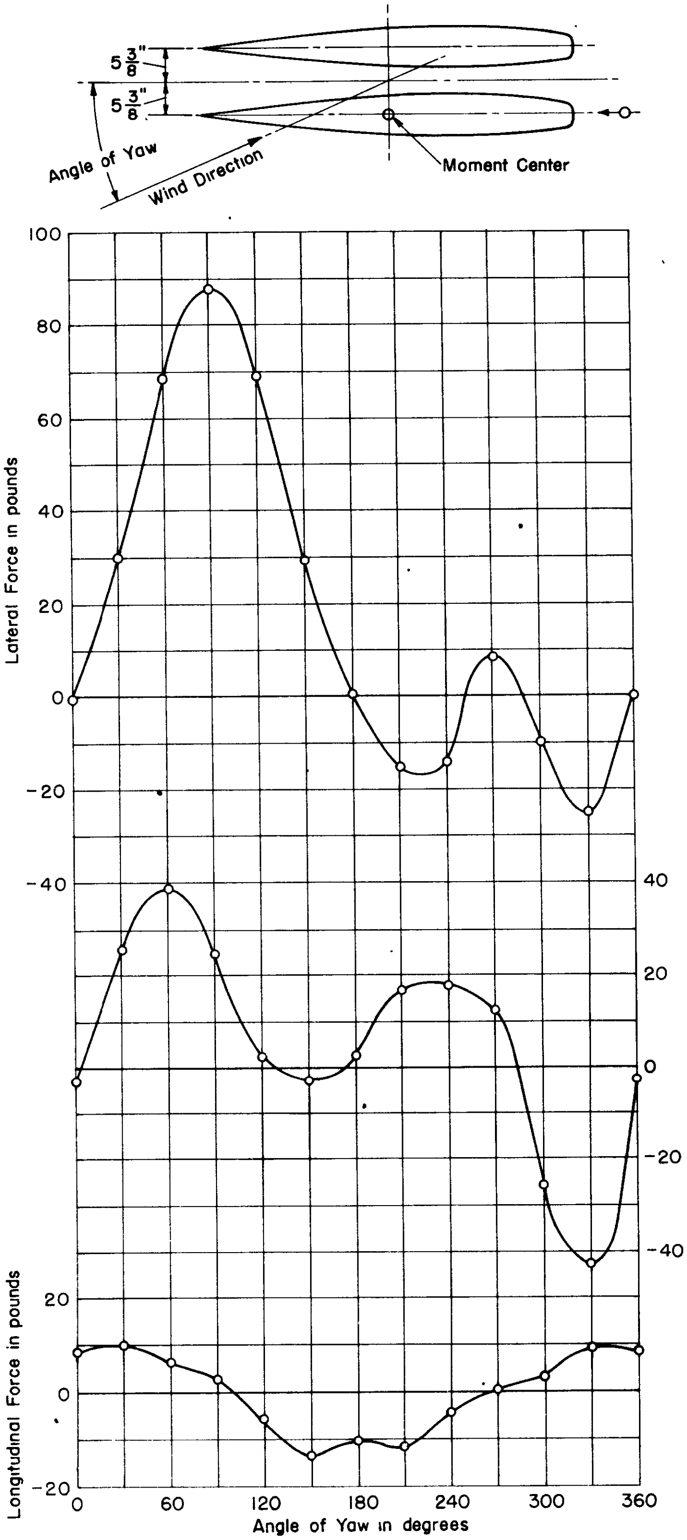

Figure 8 - Variation of Lateral Force, Yawing Moment, and Longitudinal Force with Angle of Yaw for One Model in Mooring Group of Two at a Wind Speed of 125 Knots

The moment center is at the center of the model.

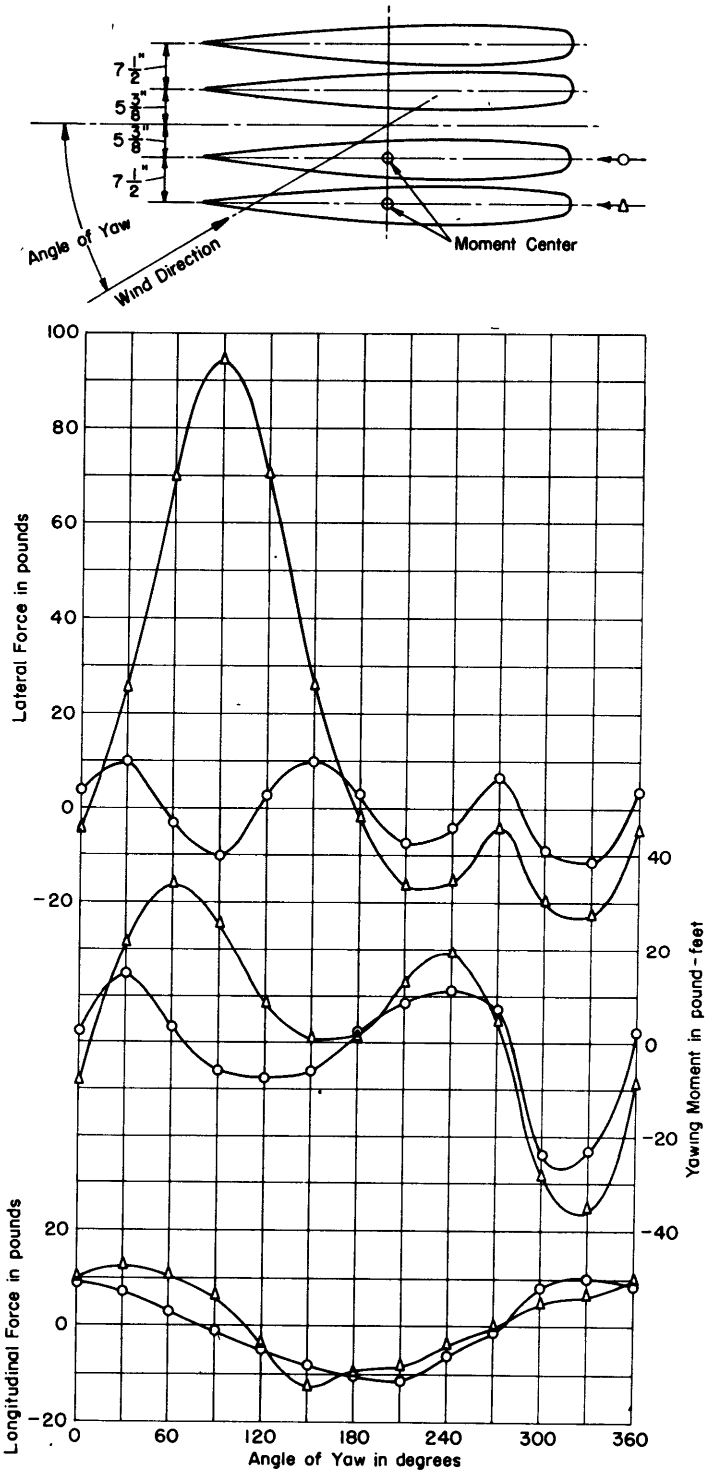

Figure 9 - Variation of Lateral Force, Yawing Moment, and Longitudinal Force with Angle of Yaw for Two Models in Mooring Group of Four at a Wind Speed of 125 Knots

The moment centers are at the centers of the models.

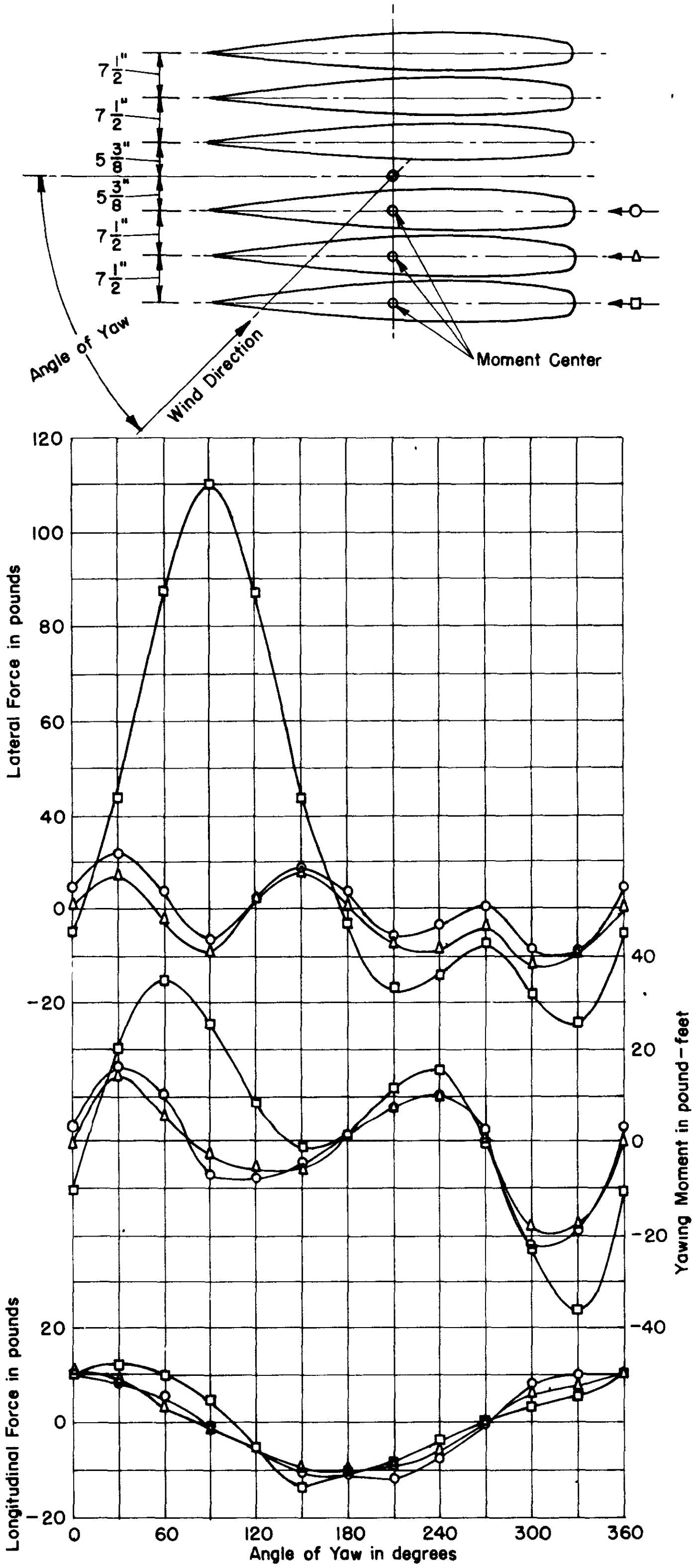

Figure 10 - Variation of Lateral Force, Yawing Moment, and Longitudinal Force with Angle of Yaw for Three Models in Mooring Group of Six at a Wind Speed of 125 Knots

The moment centers are at the centers of the models.

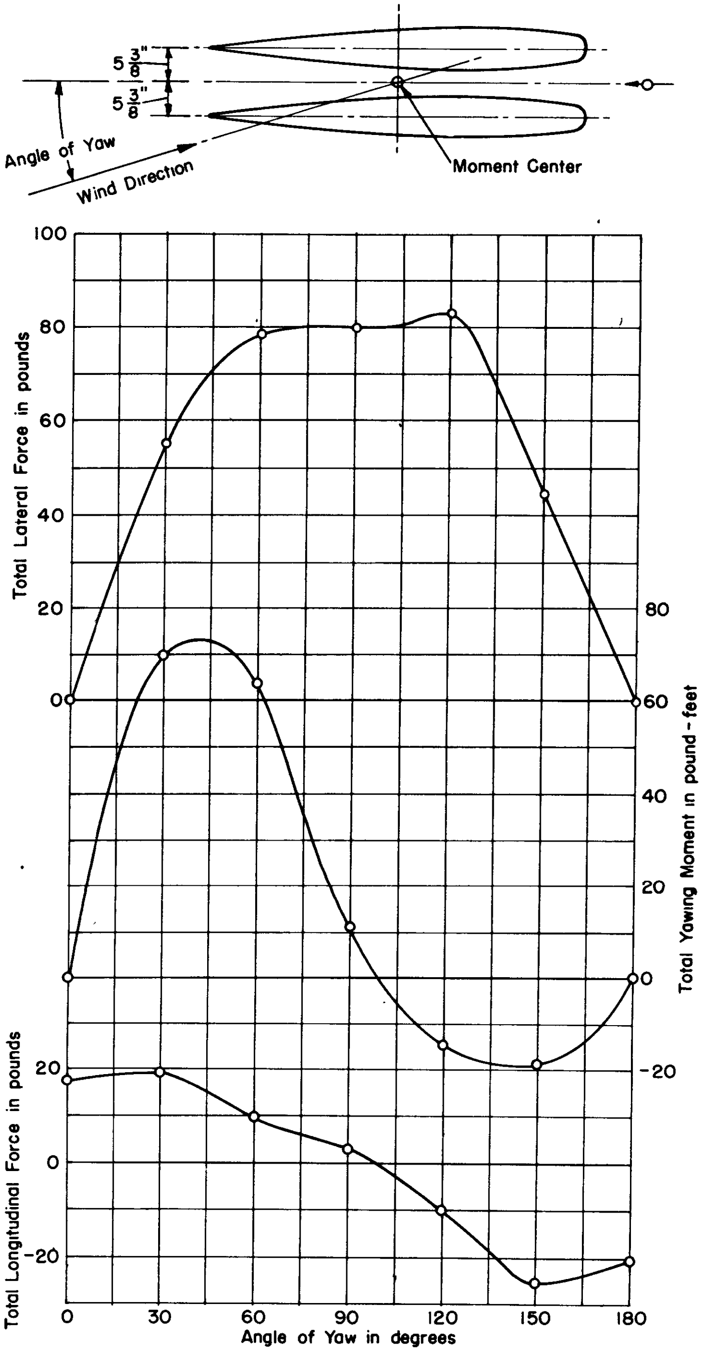

Figure 11 - Variation of Total Lateral Force, Total Yawing Moment, and Total Longitudinal Force with Angle of Yaw for Two Models at a Wind Speed of 125 Knots

The moment center is at the center of the mooring.

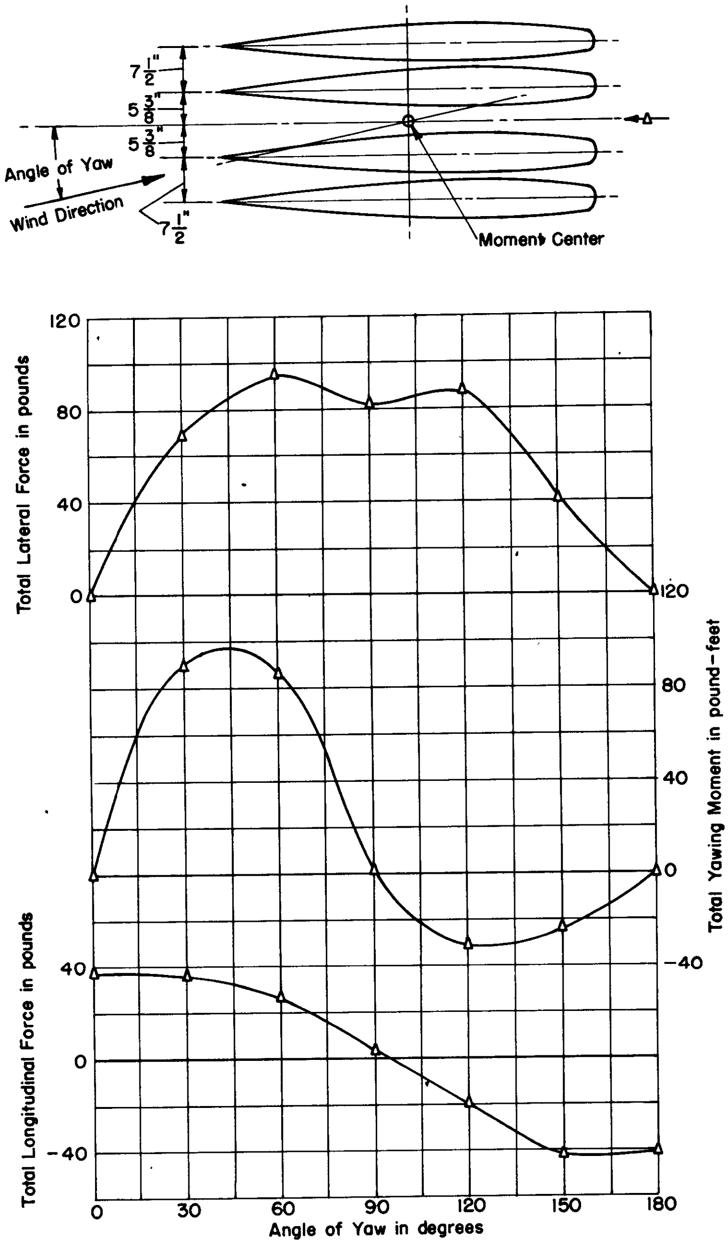

Figure 12 - Variation of Total Lateral Force, Total Yawing Moment, and Total Longitudinal Force with Angle of Yaw for Four Models at a Wind Speed of 125 Knots

The moment center is at the center of the mooring.

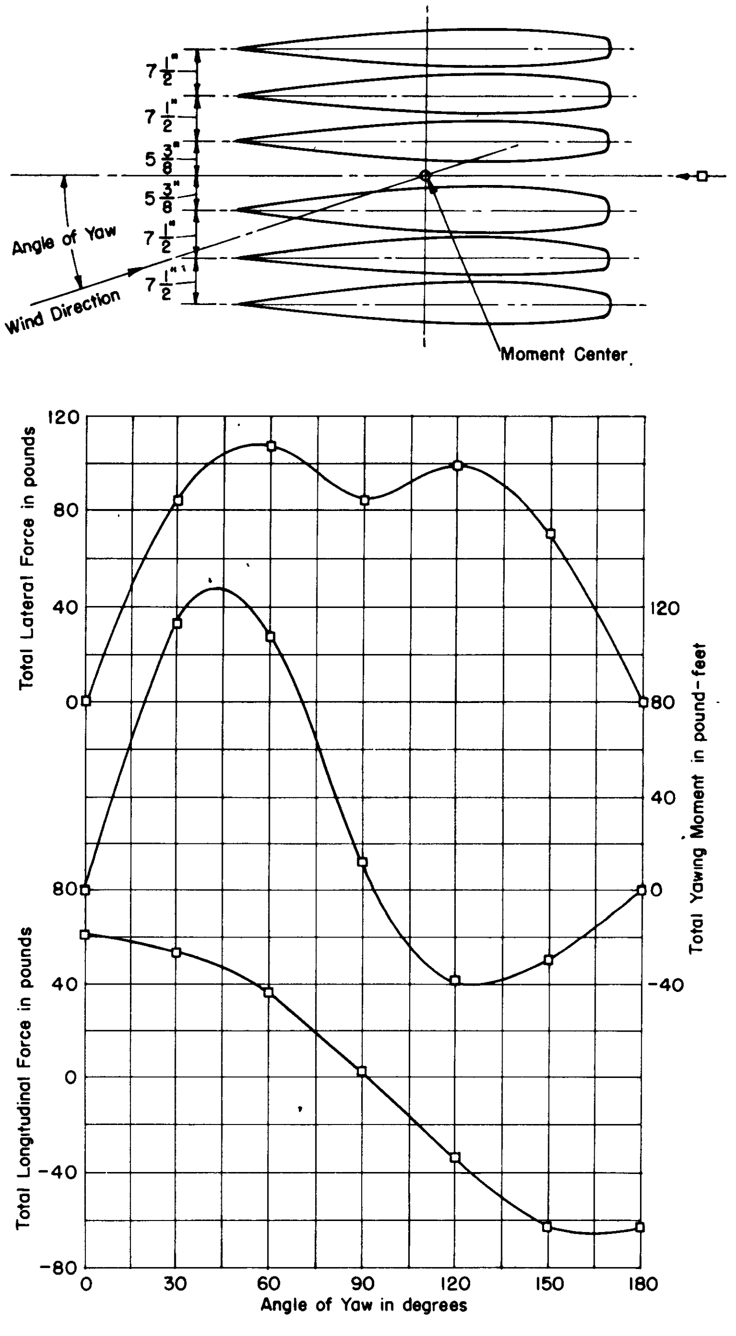

Figure 13 - Variation of Total Lateral Force, Total Yawing Moment, and Total Longitudinal Force with Angle of Yaw for Six Models at a Wind Speed of 125 Knots

The moment center is at the center of the mooring.

The precision of the results for the individual models is believed to be plus or minus 3 pounds for the lateral force, plus or minus 1.5 pound for the longitudinal force, and plus or minus 3.4 pound-feet for the yawing moment.

The range of Reynolds numbers covered by these tests is 4.1×10^6 to 6.9×10^6, the Reynolds number being given by

$$\mathfrak{R} = \frac{VL}{\nu}$$

where V is the wind speed in feet per second,

L is the overall length (5.10 feet), and

ν is the kinematic viscosity of air (1.568×10^{-4} square foot per second at standard conditions).

DISCUSSION

In scaling the model results shown in Figures 7 through 13 up to the prototype ships, it is sufficient to assume that the forces are proportional to the areas, or proportional to the square of the linear scale. The yawing moment, the product of a force by a distance, can be assumed proportional to the cube of the linear scale. Accordingly, for any velocity the forces F and moments M on the full-size ship or group of ships can be estimated by the expressions

$$F_{fs} = 73.8^2 \left(\frac{V_k}{125}\right)^2 F_{125}$$

$$= 0.349\, V_k^2\, F_{125}, \text{ which may be taken as}$$

$$F_{fs} = 0.35\, V_k^2\, F_{125} \text{ to practical limits of accuracy}$$

and

$$N_{fs} = 73.8^3 \left(\frac{V_k}{125}\right)^2 N_{125}$$

$$= 25.7\, V_k^2\, N_{125}, \text{ which again for practical purposes may be taken as}$$

$$N_{fs} = 26\, V_k^2\, N_{125}$$

where F_{fs} is the force in pounds, lateral or longitudinal, on the full-scale ship or group of ships,

F_{125} is the force in pounds, lateral or longitudinal, measured on the model or group of models at a wind speed of 125 knots,

N_{fs} is the yawing moment in pound-feet on the full-scale ship or group of ships,

N_{125} is the yawing moment in pound-feet measured on the model or group of models at a wind speed of 125 knots, and

V_k is the wind speed in knots for which the forces and moments are desired.

Thus in Figure 13 the maximum total lateral force measured on the group of six models in a 125-knot wind is 108 pounds, occurring at approximately 55 degrees angle of yaw. Six full-size ships of the DD692 Class moored together would develop a maximum total lateral force in a 60-knot wind at 55 degrees angle of yaw of $0.35 \times 60^2 \times 108$, or 136,000 pounds. The maximum total longitudinal force on such a group would occur with a different wind direction, at about 165 degrees angle of yaw, and would amount to $0.35 \times 60^2 \times 66$, or 83,000 pounds. The maximum total yawing moment for this group and wind velocity would occur with the wind from 45 degrees angle of yaw, and would amount to $26 \times 60^2 \times 127$, or 11,900,000 pound-feet.

In Figure 14, the absolute values of the maximum total forces and moments measured for the single model and computed for the groups of models

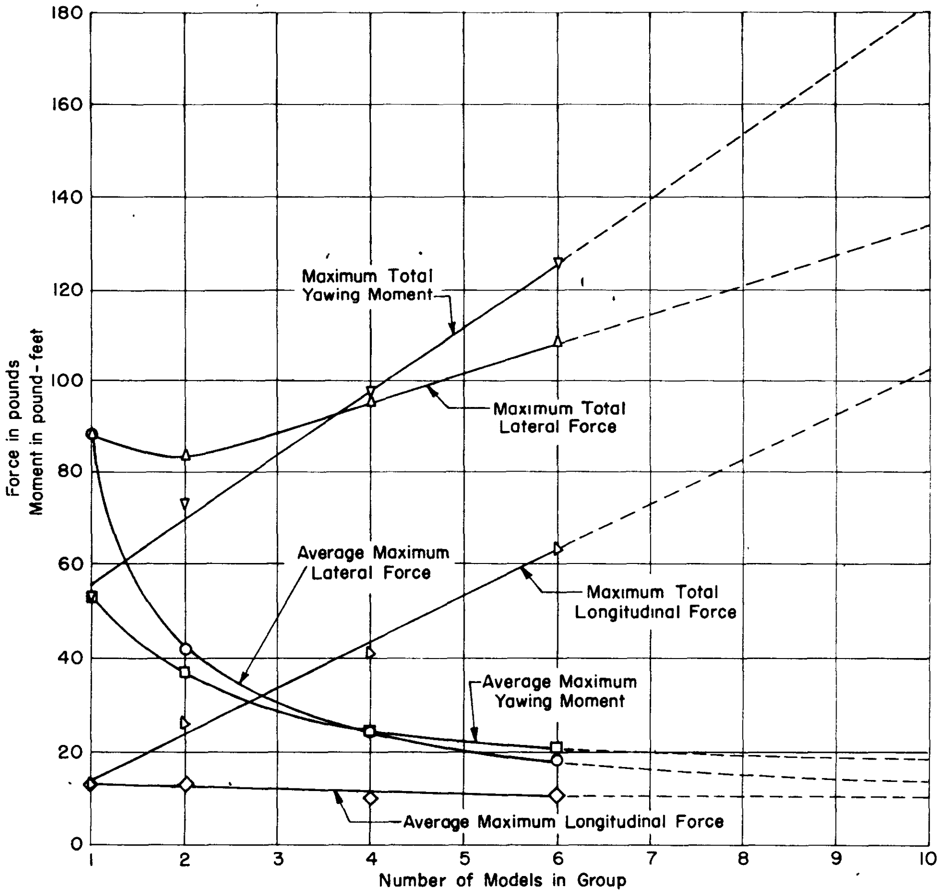

Figure 14 - Maximum Total Lateral Force, Yawing Moment, and Longitudinal Force Computed for Each Group of Models, Together with Average Values of These Maximum Total Forces and Moments per Model, Plotted against Number of Models in the Group

are plotted against the number of models in the group. In the same figure, the average per model of the maximum total forces and of the maximum total moments are also plotted against the number of models in the mooring group. The experimental curves are then extrapolated, so that the maximum total forces and moments on any number of models up to ten lined up abreast can be estimated.

In Figure 15 the absolute values of the maximum forces and moments measured on an individual ship in the different groups are plotted against the number of models in the group. Here again, these curves are extrapolated to ten models lined up abreast. For all practical purposes these can be used as maximum values for both positive and negative forces and moments.

The curves of average maximum total force and moment per model given in Figure 14 show the advantage gained by mooring ships in groups. However, these curves should not be used for design purposes. The maximum total forces and moments of Figure 14 and the maximum individual forces and moments in Figure 15 taken together form the basis for the design of a mooring. In each group the windward model receives the maximum lateral force and the leeward model receives the maximum yawing moment. However, the maximum longitudinal force is practically constant for all models in all the groups tested.

In order to have a basis for comparing forces on different types of ships, it seems desirable to reduce the data to some form of dimensionless coefficient. The coefficients chosen are defined as follows:

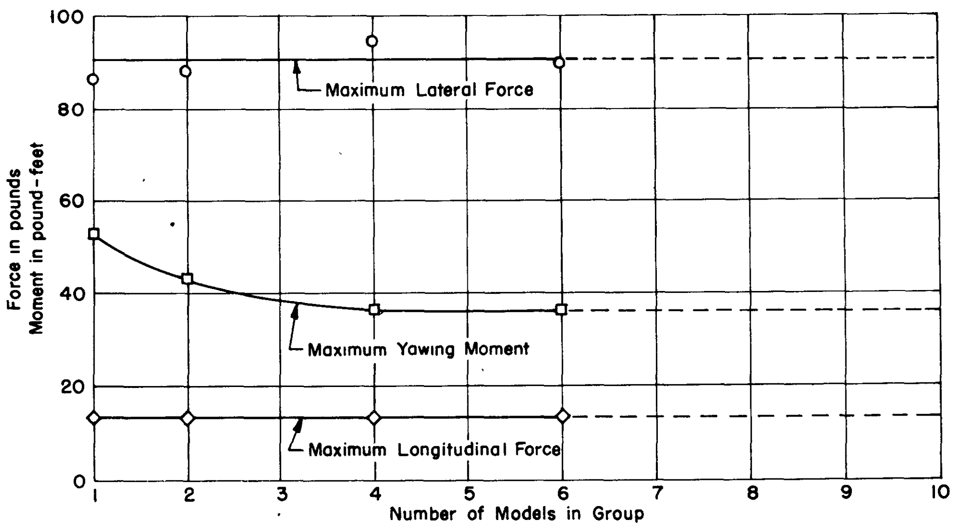

Figure 15 - Maximum Lateral Force, Yawing Moment, and Longitudinal Force Measured on Individual Models of Different Model Groups Plotted against Number of Models in the Group

In each group the windward model or the leeward model receives the maximum lateral force and yawing moment.

$C_X = \frac{X}{qA_x}$ is the longitudinal-force coefficient,

$C_Y = \frac{Y}{qA_y}$ is the lateral-force coefficient, and

$C_n = \frac{N}{qA_yL}$ is the yawing-moment coefficient,

where $q = \frac{\rho V^2}{2}$,

X is the longitudinal force in pounds,
Y is the lateral force in pounds,
N is the yawing moment in pound-feet,
A_x is the projected frontal area in square feet,
A_y is the projected broadside area in square feet,
L is the overall model length in feet,
V is the reference wind speed in feet per second, and
ρ is the density of air (0.002378 slug per cubic foot at standard conditions).

The use of different areas in defining C_X and C_Y was governed by the desire to compare the maximum values of both coefficients with flat-plate-drag coefficients, and to make both independent of the length-to-beam ratio of the ship. In comparing C_X and C_Y with flat-plate-drag data, the aspect ratio of A_x and A_y, the projected areas, must be determined. Let AR_x and AR_y be these two aspect ratios; then

$$AR_x = \frac{B^2}{2A_x} = 0.58$$

and

$$AR_y = \frac{L^2}{2A_y} = 7.2$$

where B is the beam in feet. The factor 1/2 is introduced because the ground board cuts off the flow around one boundary and makes the conditions analogous to those of a model of the same beam (or length) but double the area, formed of right- and left-hand duplications of the original model placed adjacent to and symmetrical about the plane of the ground-board surface. The maximum values of C_X and C_Y can now be compared with flat-plate-drag data (3), as shown in Table 2.

The maximum values of both C_X and C_Y measured in these tests are less than the corresponding flat-plate-drag coefficients. This is entirely reasonable, when the velocity deficiency in the boundary layer over the ground board is taken into consideration.

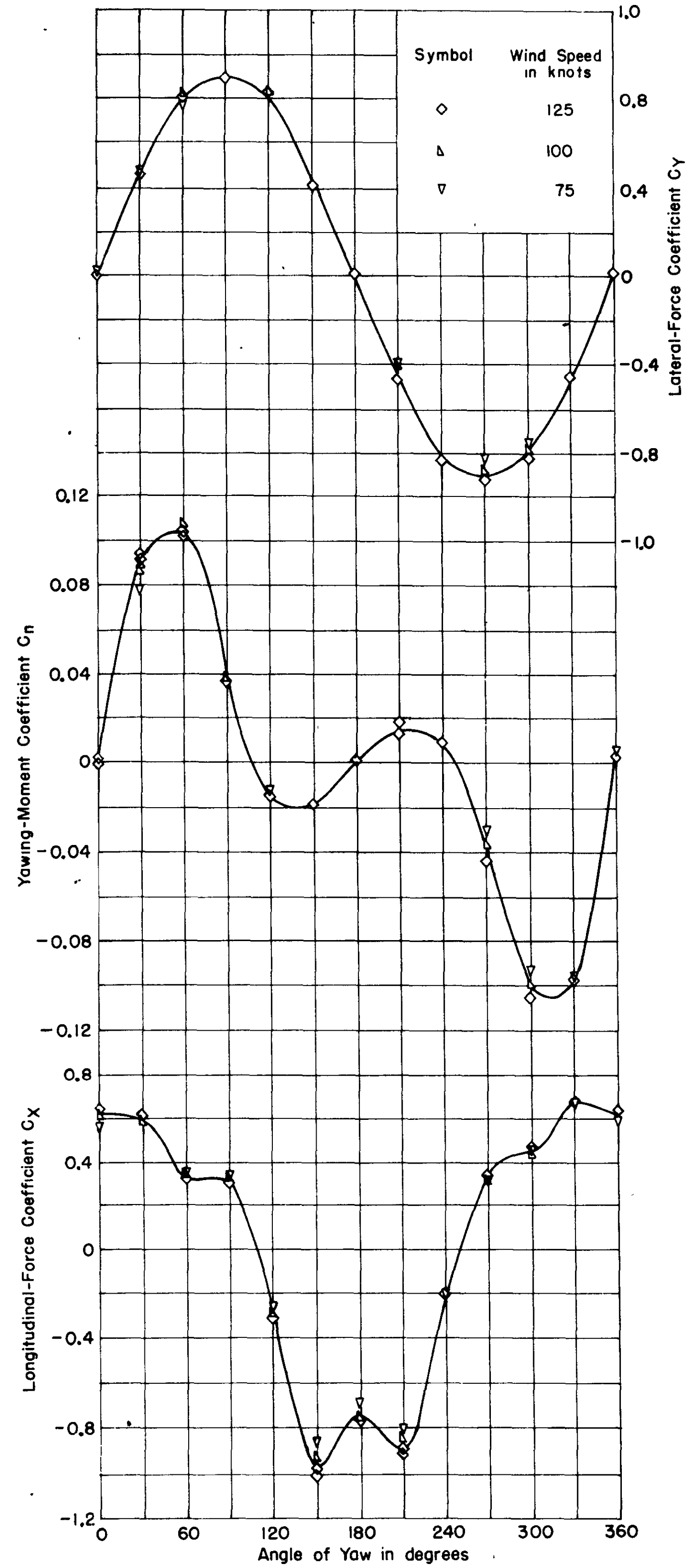

Figure 16 - Variation of Lateral-Force, Yawing-Moment, and Longitudinal-Force Coefficients with Angle of Yaw for a Single Model

TABLE 2

Maximum Longitudinal- and Lateral-Force Coefficients C_X and C_Y Compared with Flat-Plate-Drag Coefficients at the Appropriate Aspect Ratio

Coefficient	Area Exposed to Wind Stream	Aspect Ratio	Maximum Value of Coefficient	Flat-Plate-Drag Coefficient
C_X	Frontal Area	0.58	0.95	1.13
C_Y	Broadside Area	7.2	0.90	1.23

Figure 16 shows the variation of C_X, C_Y, and C_n with angle of yaw for three different test velocities. In general, the difference in the values of the coefficients for a given angle of yaw is of the same order of magnitude as the experimental scatter of the points, while at many yaw angles, for example, 60 degrees and 240 degrees, the coefficients computed for the different test velocities are practically identical. Since from the definitions of the coefficients the forces and yawing moment can be written as

$$X = C_X q A_x = C_X \frac{1}{2} \rho V^2 A_x$$

$$Y = C_Y q A_y = C_Y \frac{1}{2} \rho V^2 A_y$$

and

$$N = C_n q L A_y = C_n \frac{1}{2} \rho V^2 L A_y$$

and since C_X, C_Y, and C_n for a given yaw angle are constant for different wind speeds, it follows that within the limits of the test accuracy, the forces and yawing moment may be considered as directly proportional to the square of the wind speed.

The accuracy of the reproduction in the test setup of the velocity gradient above a water surface is open to question. Few data are available on the wind gradient immediately above a water surface. In general, however, since the experimental setup gives a more severe condition than that found experimentally over flat, level ground (2), it seems probable that it would approximate actual conditions reasonably well for estimating maximum forces and moments.

CONCLUSIONS

For the 1:73.8-scale models of destroyers of the DD692 Class, the following conclusions may be drawn within the limits of the test conditions:

1. The scale effect over the range of wind speeds used is within the experimental accuracy of the tests.

2. If the individual models are considered in groups abreast, the maximum lateral force occurs on the windward model, is much greater than the maximum lateral force on other models in the group, and is equal to the maximum lateral force on a model moored singly.

3. The maximum longitudinal force on an individual model is independent of the number of models in the group.

4. The maximum individual yawing moment occurs on the leeward model of a group and up to a certain point decreases with the number of models, thereafter remaining constant.

5. The lateral and longitudinal forces on a single model are less than would be predicted from the projected flat-plate area exposed to a uniform wind speed.

REFERENCES

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