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THE INTERACTION OF TWO VESSELS IN CLOSE PROXIMITY by Douglas E. Layne

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

THE INTERACTION OF TWO VESSELS IN CLOSE PROXIMITY

by

Douglas E. Layne

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SHIP PERFORMANCE DEPARTMENT

DEPARTMENTAL REPORT

December 1976 SPD 741-01

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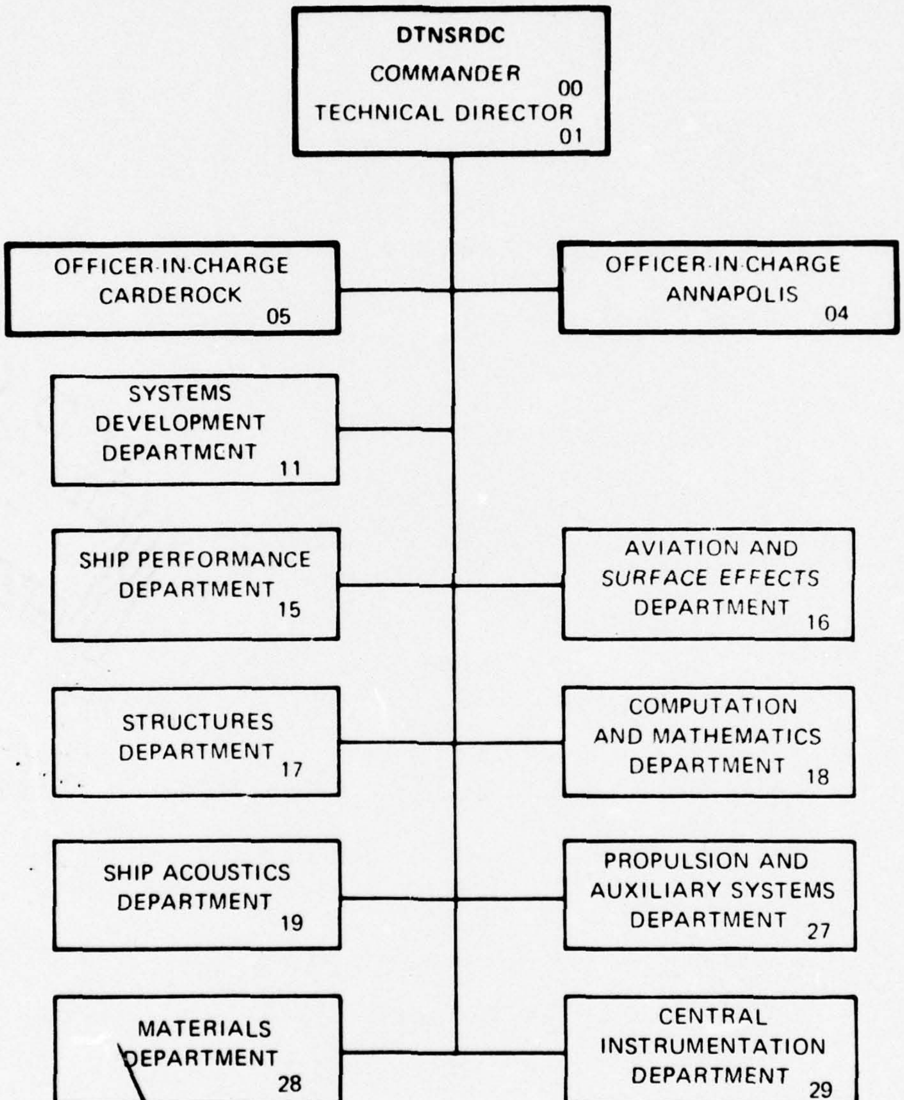

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Interaction effects examined in the NAVSHIPS-sponsored study concerned the relative heading and rudder angles required when one ship is approaching, running alongside, and pulling away from another ship. These effects are obtainable by measuring forces and moments during captive model investigations. More specifically, the study concerned two restrained models, one of which was positioned statically relative to the other. One model represented an aircraft carrier of the CVA-58 Class and the other, a fast combat support ship of the AOE-1 Class.

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The principal objective was to assess the interaction between these ships at various speeds and separations and thus determine the corresponding rudder and drift angles required to provide neutral forces and moments. Determination of drift angles (β) has been neglected in earlier experimental work. It was included here because even though these values are thought to be relatively small, they could alter tha amount of angle required of the rudder.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

BACKGROUND

Mention is often made of the interaction effects of ships in close proximity to each other, but relatively little is known about such effects, especially in open waters. The first significant awareness of the problem was evidenced by Taylor[1] who studied the relative reactions of vessels underway and close to one another. Taylor's investigation was shortly followed by that of Hislam[2] and after a period of more than three decades, by the work of Robb[3], Gawn[4], and Newton[5]. A theoretical study had been conducted by Silverstein[6] in 1957. Probably the most outstanding of the experimental contributions that followed Taylor was the study by Newton whose results exhibited the same trends as the theoretical results of Silverstein.

In September 1967 the Naval Ship Systems Command (NAVSHIPS) authorized the Naval Ship Research and Development Center (NSRDC) to investigate the effects of interactions between ships during replenishment-at-sea operations. The results were submitted to the sponsor but were not published formally. They are now placed in the open literature as of general interest to the scientific community. The loss of many lives during the recent collison of an aircraft carrier and a destroyer emphasizes once again the importance of additional and more detailed studies to determine the magnitude of forces attributable to ship interactions and the amount of rudder angle needed to overcome them.

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[1] Taylor, D. W., "Some Model Experiments on Suction of Vessels," Transactions, Society of Naval Architects and Marine Engineers (1909)

[2] Hislam, P. A., "The HAWKE-OLYMPIC Collision," Scientific American Supplement (12 February 1912)

[3] Robb, A. M., "Interaction between Ships," Transactions, Royal Institution of Naval Architects (1949)

[4] Gawn, R. W. L., "The Admiralty Experiment Works," Transactions, Royal Institution of Naval Architects (1955)

OBJECTIVE

Interaction effects examined in the NAVSHIPS-sponsored study concerned the relative heading and rudder angels required when one ship is approaching, running alongside, and pulling away from another ship. These effects are obtainable by measuring forces and moments during captive model investigations. More specifically, the study concerned two restrained models, one of which was positioned statically relative to the other. One model represented an aircraft carrier of the CVA-58 Class and the other represented a fast combat support ship of the AOE-1 Class.

The principal objective was to assess the interaction between these ships at various speeds and separations and thus determine the corresponding rudder and drift angles required to provide neutral forces and moments. Determination of drift angles (β) has been neglected in earlier experimental work. It was included here because even though these values are thought to be relatively small, they could alter the amount of angle required of the rudder.

DESCRIPTION OF THE INTERACTION MODELS

Model 4838 of the AOE was 4.89m (16.04 ft) long, and Model 4411-2 of the CVA was 6.28m (20.62 ft) long; each model had a linear ratio of 48 and was equipped with propulsion motors, propellers, bilge keels, and turning rudders. The principal particulars of the AOE and CVA designs are given in Table 1 for the prototypes and models. Figure 1 is a sketch of the fast attack support ship alongside and abreast of the aircraft carrier. Figure 2 presents details of the AOE model.

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[5] Newton, R. N., "Interaction Effects between Ships Close Aboard in Deep Water," David Taylor Model Basin Report 1461 (October 1960)

[6] Silverstein, B. L., "Linearized Theory of the Interaction of Ships," University of California, Institute of Engineering Research (May 1957)

TABLE 1

PRINCIPAL DIMENSIONS AND CHARACTERISTICS FOR FULL-SCALE AND MODEL CVA AND AOE

CHARACTERISTIC	CVA-59	MODEL 411-2	AOE-1	MODEL 4838
Length between Perpendiculars	301.75m (990.00 ft)	628m (20.62 ft)	234.70m (770.00 ft)	4.89m (16.04 ft)
Beam, Molded	39.41m (129.30 ft)	0.82m (2.69 ft)	32.61m (107.00 ft)	0.68m (2.23 ft)
Draft, Even Keel	10.26m (33.65 ft)	0.21m (0.70 ft)	11.58m (38.00 ft)	0.24m (0.79 ft)
Displacement, Tons	73155Mg (72,000 tons)	0.643Mg (0.633 tons)	52123Mg (51,300 tons)	0.458Mg (0.451 tons)
Number of Propellers	4	4	2	2
Number of Rudders	3	3	2	2
Center of Gravity Aft of STA. 10			1.17m (3.85 ft)	0.02m (0.08 ft)
Rudder Area				
Total	$113.8m^2$ ($1225 ft^2$) (3)†	$0.049m^2$ ($0.53 ft^2$) (3)	$5611.2m^2$ ($604 ft^2$)	$0.024m^2$ ($0.262 ft^2$)
Outboard	$91.04m^2$ ($980 ft^2$) (2)	$0.039m^2$ ($0.425 ft^2$) (2)	$28.06m^2$ ($302 ft^2$)	$0.012m^2$ ($0.131 ft^2$)
Centerline	$22.76m^2$ ($245 ft^2$) (1)	$0.010m^2$ ($0.106 ft^2$) (1)		
Rudder Area Coefficient:*				
Total	0.0368 (3)	0.0368 (3)	0.0206	0.0206
Outboard	0.0294 (2)	0.0294 (2)	0.0103	0.0103
Centerline	0.0074 (1)	0.0074 (1)		

*Area/(Length * Draft)

†Numbers in parentheses indicate number of rudders

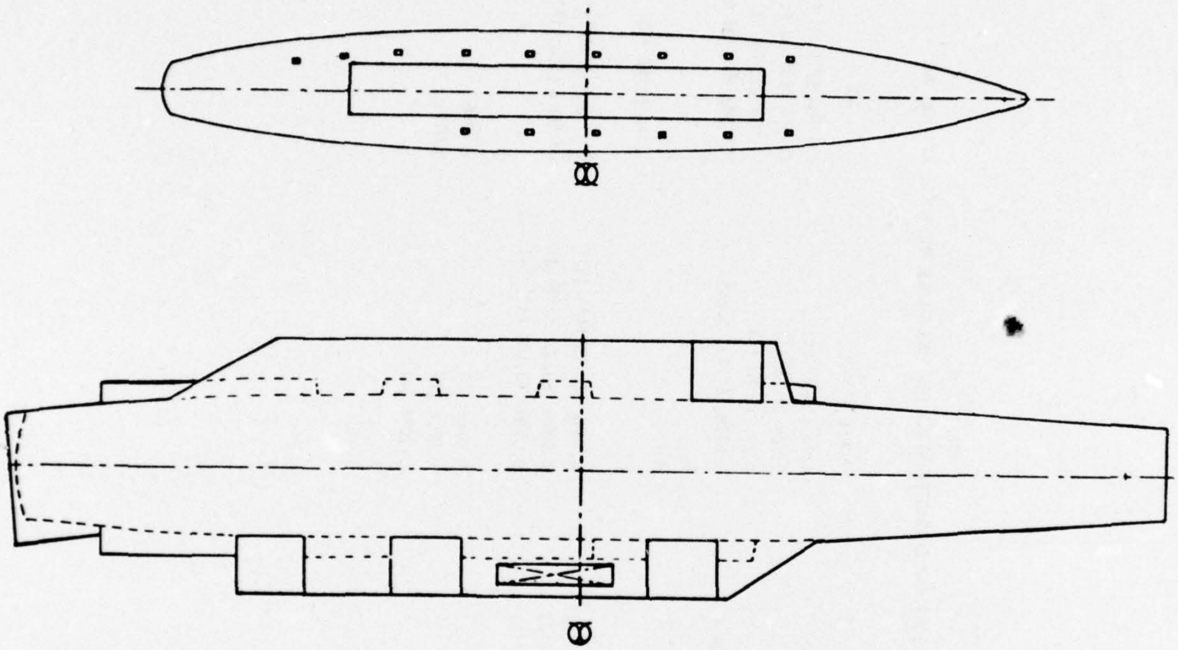
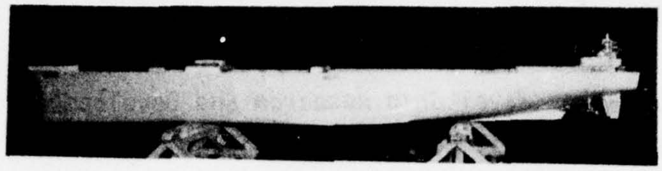
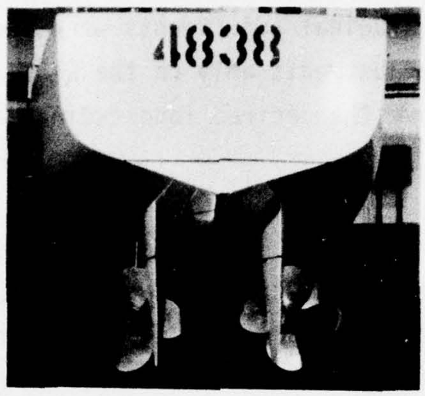


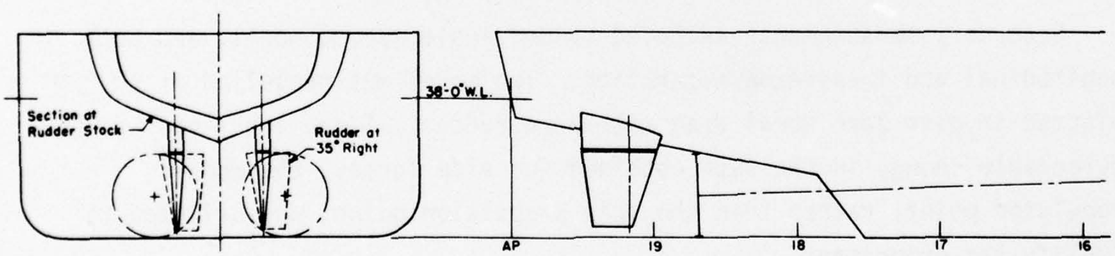
Figure 1 - The Fast Attack Support Ship with the Aircraft Carrier Alongside and Abreast Amidships



Profile View



Stern View



Sketch of Stern and Profile

Figure 2 - Profile and Stern Views of AOE as Represented by Model 4838

TEST APPARATUS

The David W. Taylor Naval Ship Research and Development Center's (DTNSRDC) Carriage 1 was utilized with the towing arrangement shown in Figure 3. The AOE model was located in the center of the basin and attached to the main girder, and the CVA model was located on the south-side of the basin centerline under an auxiliary carriage. The models were rigidly connected to the girders and were allowed motion only in the vertical direction. Longitudinal adjustments were available on both the CVA and AOE and lateral adjustments only on the CVA. Thus the models could be positioned to give the desired longitudinal and lateral separation.

Primary measurements on the AOE model consisted of two components of transverse forces and two of longitudinal forces. These were acquired through the use of four modular force gages located equidistant, 0.322 times length of model, fore and aft of the center of gravity (CG). The fore and aft lateral gages were used to determine side forces and moments, and the longitudinal gages were used to monitor the propulsion point from the standpoint of model drag. Located at each tow point was one lateral and one longitudinal gage. Figures 4 and 5 illustrate the method of attachment to the forward and rear towpoints of the AOE model.

Secondary measurements included rudder angle, speed, model, and both longitudinal and transverse separation. The model was propelled at an RPM selected to give zero model drag with zero rudder. Since there was no appreciable change in the data obtained for side forces, the model propulsion point, rather than the ship propulsion point, was utilized to simplify the experiment.

The models were self-propelled and equipped with scaled propellers. Propulsion was regulated with the assistance of revolution counters and the longitudinal force gages to determine the model propulsion point. A rudder-turning apparatus was developed to remotely vary the angels in

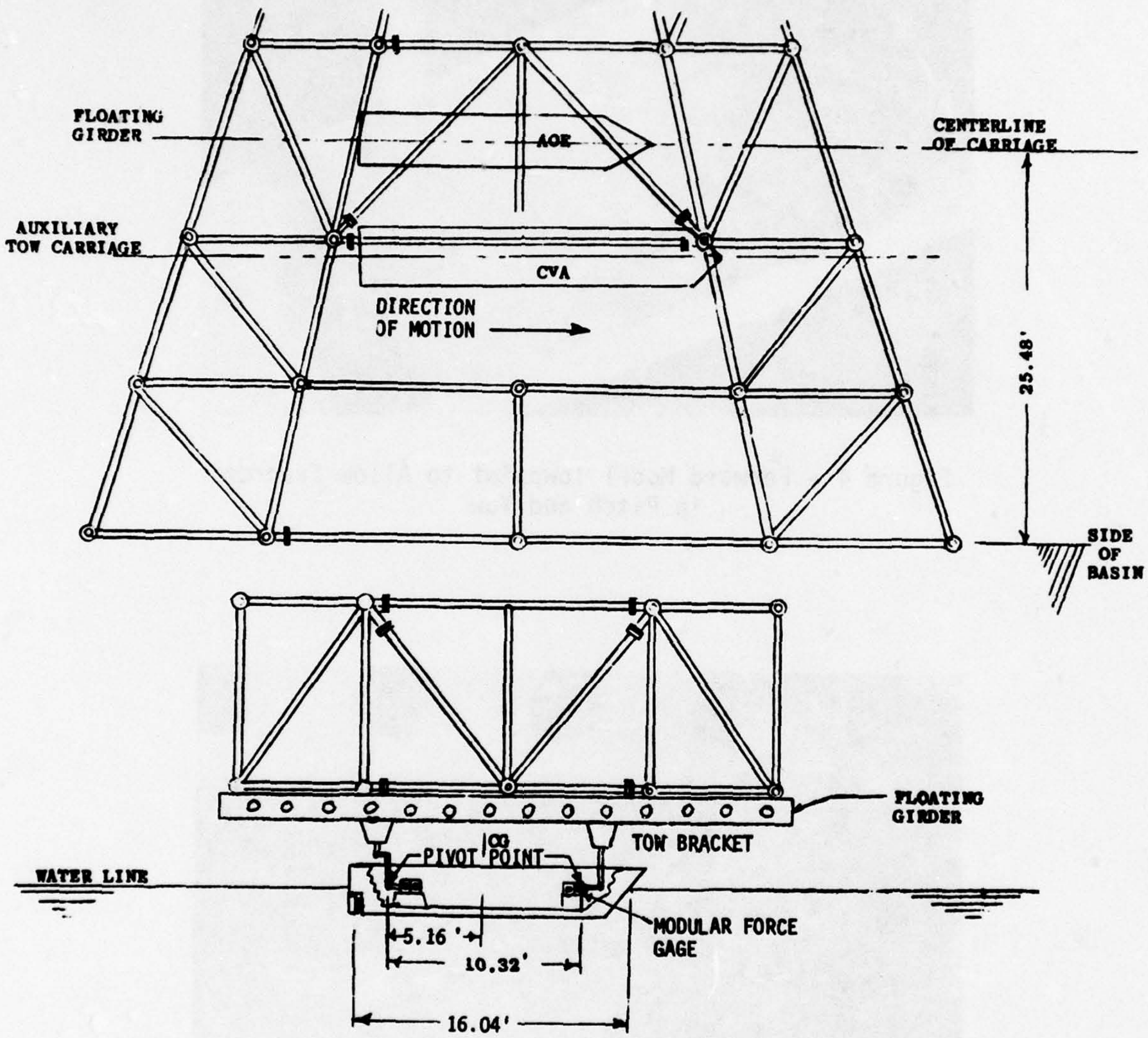


Figure 3 - Towing Arrangement with AOE Mounted Under Carriage

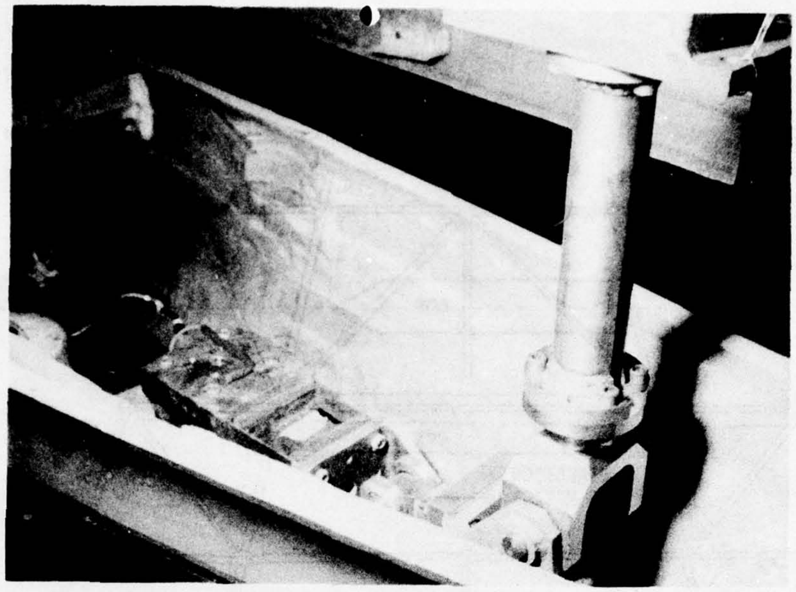


Figure 4 - Forward Model Towpoint to Allow Freedom in Pitch and Yaw

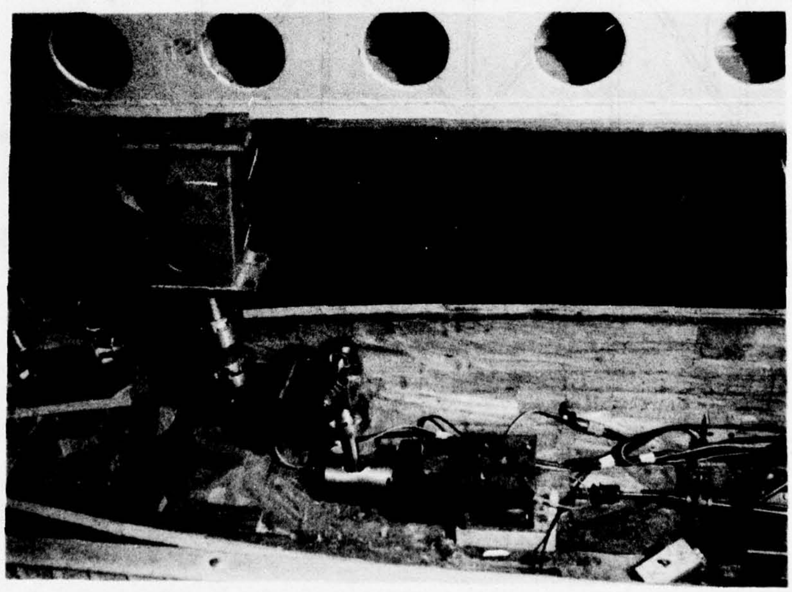


Figure 5 - After Model Towpoint to Allow Freedom in Pitch, Roll and Yaw

5-degree increments, making it possible to obtain seven data points in a single pass in the basin.

Data obtained from the experiment were converted to digital form and printed on paper tape. The input pulse was attenuated according to a calibration factor through a David Taylor Model Basin (DTMB) control unit. This, in turn, was passed through intergrating digital voltmeters and from there, to the digital printer.

Most of the interaction experiment was concerned with force measurements due to variations caused by different rudder angles at various longitudinal and transverse separations. Figure 6 is a photograph of the models as evaluated.

The analysis of the data also required information relative to side forces at various drift angles with zero rudder. For these measurements, the yaw table was mounted on the forward end of the towing carriage to enable variation of drift angle (see Figure 7).

TEST PROCEDURE

The CVA was positioned relative to the AOE at various transverse and longitudinal positions. The models were then run on parallel courses under the carriage while the interaction forces and moments on the AOE model were measured.

The longitudinal separation covered a range corresponding to $\pm$304.8m ($\pm$1000 ft) full-scale with Station 10, amidships, as a zero point. In terms of beam-to-beam distances, the transverse separation covered the area from 15.24m to 76.20m (50 to 250 ft) full scale. The experiment also covered speeds corresponding to full-scale speeds of 15, 20, and 25 knots. For each position, measurements were obtained for a range of rudder angles (δ_r).

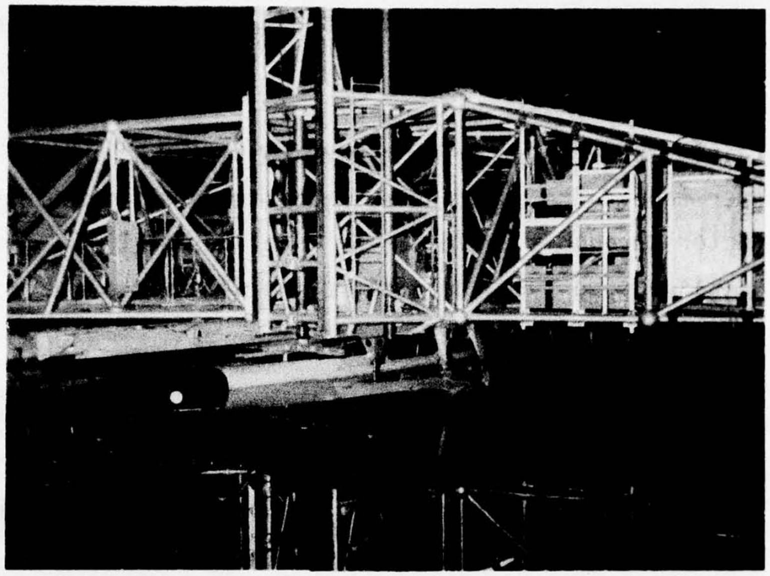


Figure 6 - Models Setup for Interaction Measurements

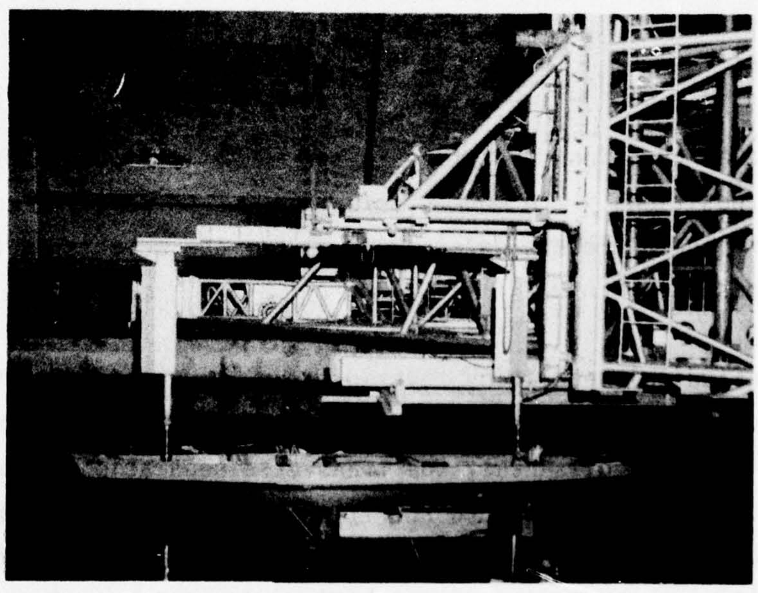


Figure 7 - Model Setup for Determining Side Forces Due to Drift Angle

The normal procedure for the experiment was to position the models at the desired transverse and longitudinal positions and obtain force data versus changing rudder angle at a specific speed. This resulted in over 1300 data points with 7 bits of primary and secondary data at each point.

EQUATIONS OF MOTION FOR INTERACTION

The force and moments acting on the vessels when in a steady, straight-line motion are shown by the diagram in Figure 8. For a given speed, the magnitude of the lateral force Y depends on the angle of drift, β, the shape of the hull, the angular displacement of the rudders, δ_r, and the interaction between the ships. The lateral force may be expressed nondimensionally as the lateral force coefficient Y'. For small changes of β and δ_r as follows:

$$Y' = [Y_*' + Y_{\delta_r}' \delta_r + Y_\beta' \beta]$$

$$Y = [Y_*' + Y_{\delta_r} \delta_r + Y_\beta \beta] \frac{\rho}{2} \ell^2 u^2 = Y_* + Y_{\delta_r} \delta_r + Y_\beta \beta$$

where Y_* = the value of Y when β and δ_r are zero and the ship is in open water,

Y_{δ_r} and Y_β = derivatives of Y with respect to δ_r and β, respectively,

ρ = fluid mass density,

ℓ = length between perpendiculars of the vessel

u = resultant linear velocity of the ship.

Similarly, the hydrodynamic yawing moment acting on the vessel may be given by:

$$N = N_* + N_{\delta_r} \delta_r + N_\beta' \beta$$

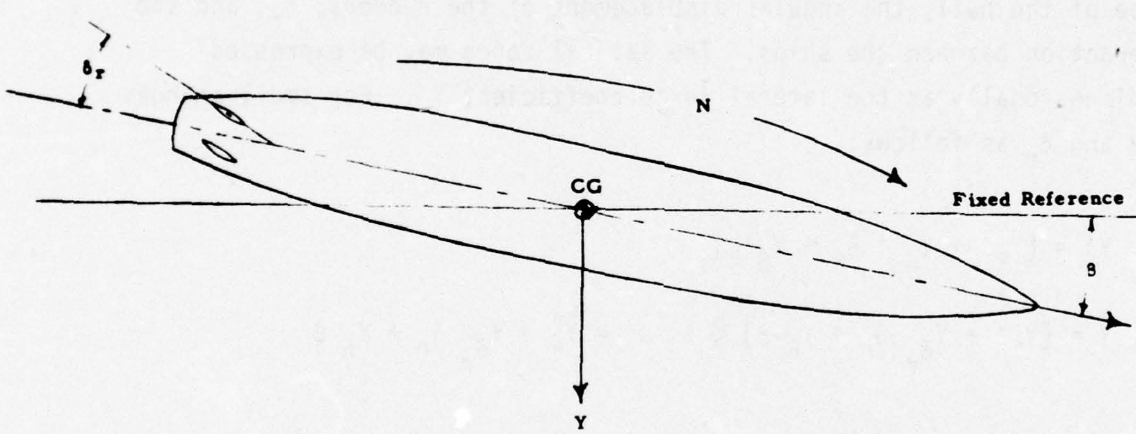


Figure 8 - Positive Directions of Axes, Angles, Forces, and Moments

when N_* is the value of the yawing moment when δ_r and β are zero and the ship is in open water and N_{δ_r} and N_β are the derivatives of N with respect to δ_r and β, respectively.

The equations can be amplified to include additional effects which occur during actual ship operations:

1. A term defined by the subscript I to account for interaction between two objects not physically attached. In this instance, the term applied to actions due to two vessels operating in close proximity to one another, but it could also pertain to a vessel operating in a restricted waterway or canal.

2. A term defined by the subscript c to account for interaction due to a physical connection, such as replenishment lines, between two ships. With these additional terms, the equations of motion may be written as

$$Y = Y_* + Y_I + Y_c + Y_{\delta_r} \delta_r + Y_\beta \beta$$

and

$$N = N_* + N_I + N_c + N_{\delta_r} \delta_r + N_\beta \beta$$

where Y_I is the value of Y when β, δ_r, and Y_* are zero and the vessel is in close proximity to another object whether fixed or moving and where Y_c is the value of Y when β, δ_r, Y_*, and Y_I are zero and the vessels are physically connected with replenishment lines or cables, etc. The same relationship is true to N_I and N_c.

REDUCTION AND PRESENTATION OF DATA

The method used to reduce the data for the interaction evaluation are considered to be reasonably representative of current Center practice for captive-model stability and control tests for surface ships. The procedural steps are as follows:

1. The Y-force measured as reactions at the centers of attachment by each of the modular force gages are added vectorially to obtain the total model Y-force. The center of attachment for the forward gages was located at the swivel forward of the gages, and the center of attachment for the after gages was located at the center of the ball joint aft of the aft gages.

2. The same two Y-forces are subtracted vectorially and the vector difference is multiplied by the longitudinal distance from one center of attachment to the reference point (CG) to obtain the model N-moment. The centers are located equidistant from the CG.

3. The values of the measured model Y-force and N-moment are converted to nondimensional coefficients in accordance with ITTC standard nomenclature.

In applying the equations of motion for interaction, the values for Y_c and N_c are zero since there is no physical connection between the vessels. The Y_* and N_* terms are forced to be zero by so orienting the model that these terms disappear. The remaining terms, then, are those due to the interaction effects, the δ_r terms and the β term.

Typical data obtained from the interaction experiment are shown by the reference curves presented in Figures 9 and 10. Figure 9 shows the variation of the hydrodynamic forces (Y') and moment (N') with β as derived from experiments with a single model using the apparatus of Figure 7. The slopes of the Y' and N' are the values Y'_β and N'_β,

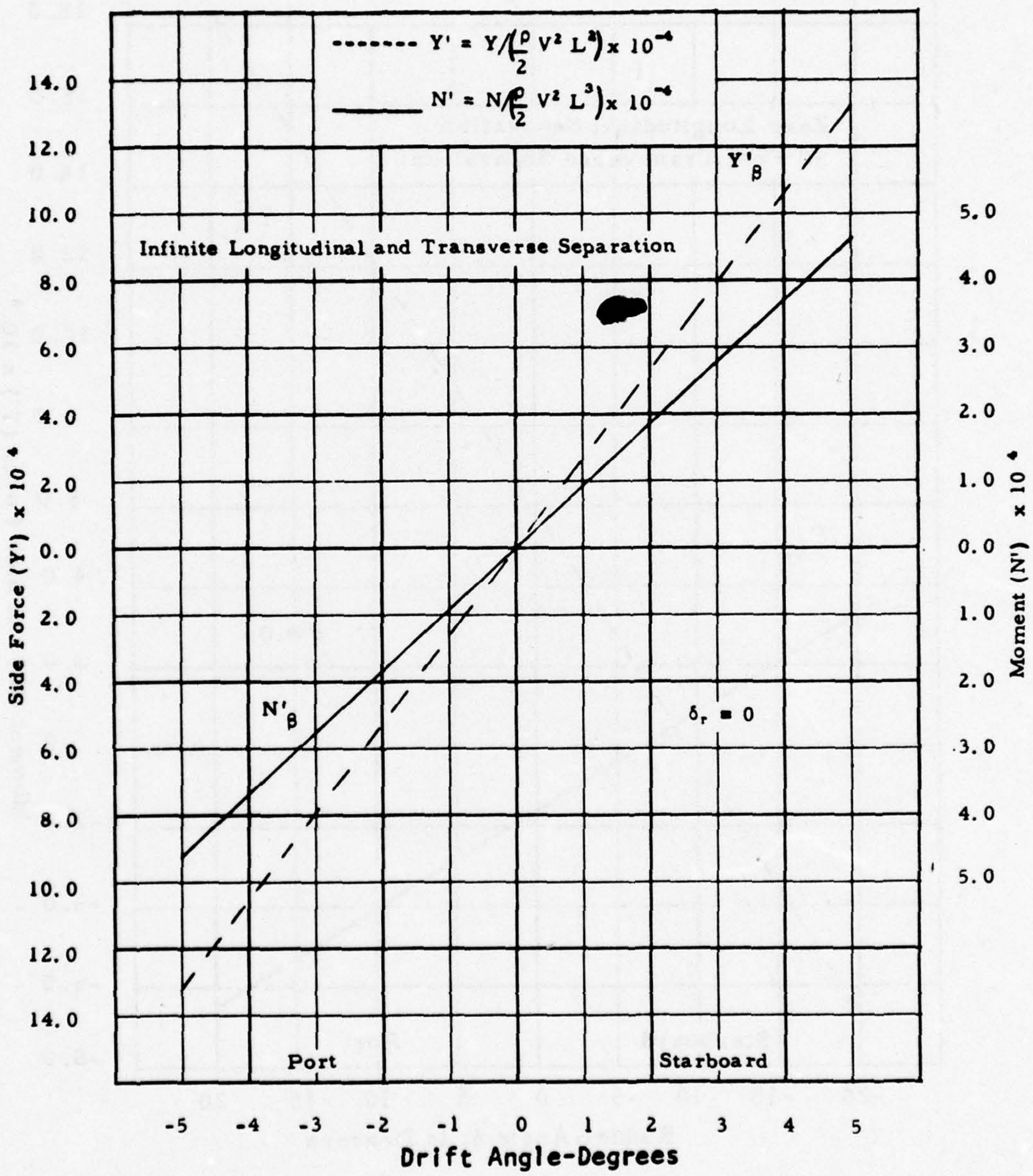


Figure 9 - Variation of Hydrodynamic Force(Y) and Moment(N) with Drift Angle β (15-Knot Speed)

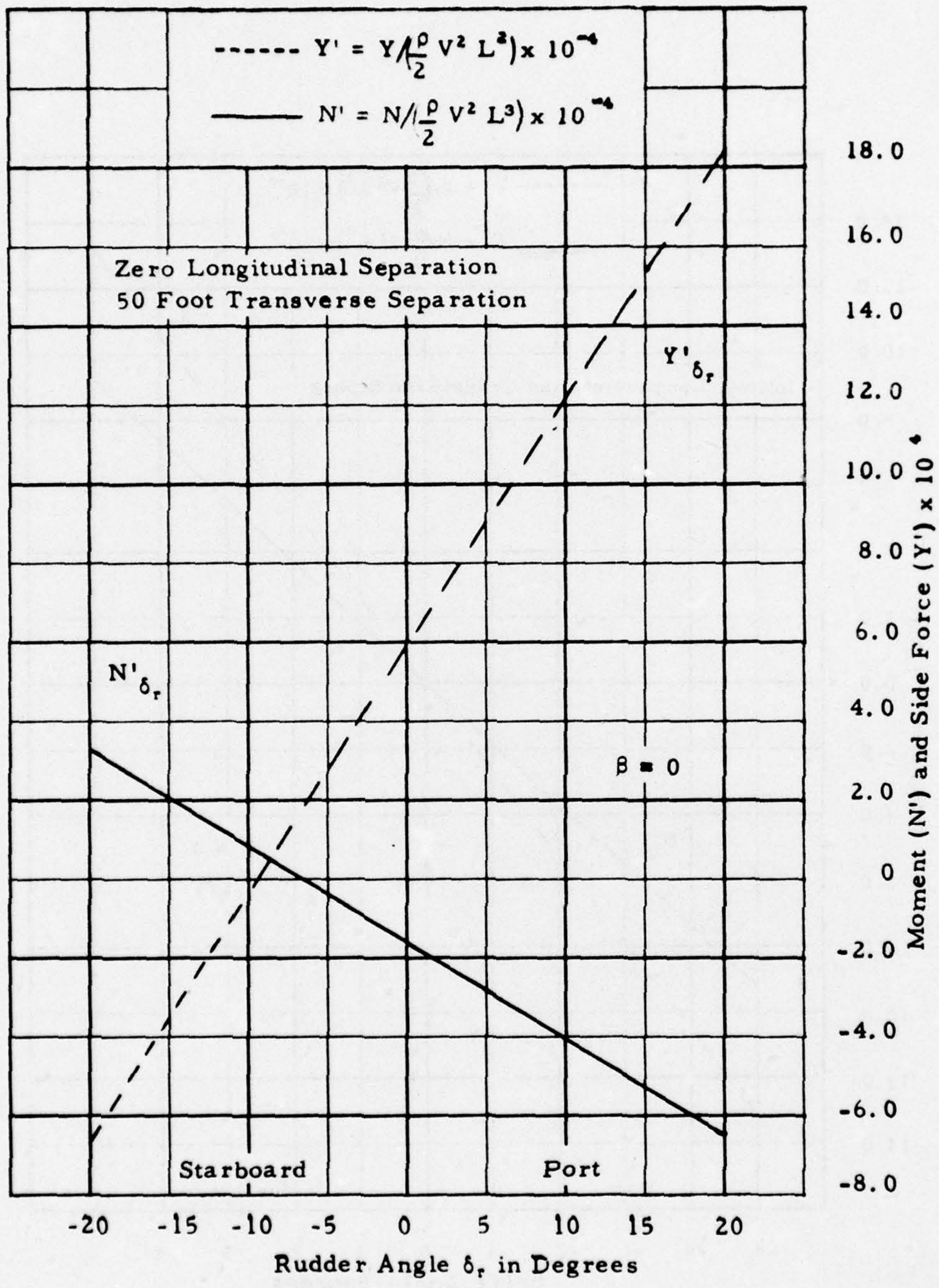


Figure 10 - Variation of Hydrodynamic Force(Y) and Moment(N) with Rudder Angle(δ_r)

respectively. Figure 10 shows the variation of the hydrodynamic force (Y') and moment (N') with δ_r as derived from interaction experiments using the setup shown in Figure 6 and the conditions described under test procedure. The slopes of the Y' and N' curves in Figure 10 are the values Y'_{δ_r} and N'_{δ_r} respectively.

The interaction term Y_I is derived from intercept data for values of Y versus δ_r or Y versus β. Values for N_I are determined in a similar way using data for N versus δ_r. Photographs of the models as evaluated to determine the Y_I and N_I terms are presented in Figures 11 and 12.

The curves in Figures 13, 14, and 15 present faired values of non-dimensional coefficients of N and Y under conditions of zero rudder and yaw for speeds of 15, 20, and 25 knots, respectively, at various longi tudinal and transverse separations. That is, the curves present the force and moment Y_I' and N_I'. This method of presentation is similar to that of Newton[5].

The amount of rudder required and the resulting yaw angle required to counterbalance the interaction effect for any given separation of the ships is found by setting the Y and N terms on the left-hand side of the equations of motion equal to zero and solving simultaneously for δ_r and β. The results of these calculations are presented in the form of curves in Figures 16, 17, and 18. These data have been faired and crossfaired graphically. Words in parentheses on the ordinates of Figures 13 through 18 pertain to an imaginary centerline between the two models. Inward and outward has the meaning of toward and away from the imaginary line. For example, inboard rudder is defined as the direction toward the opposing model. Use of the notation in parentheses eliminates the need to transpose values when the models are reversed from port-starboard to starboard-port.

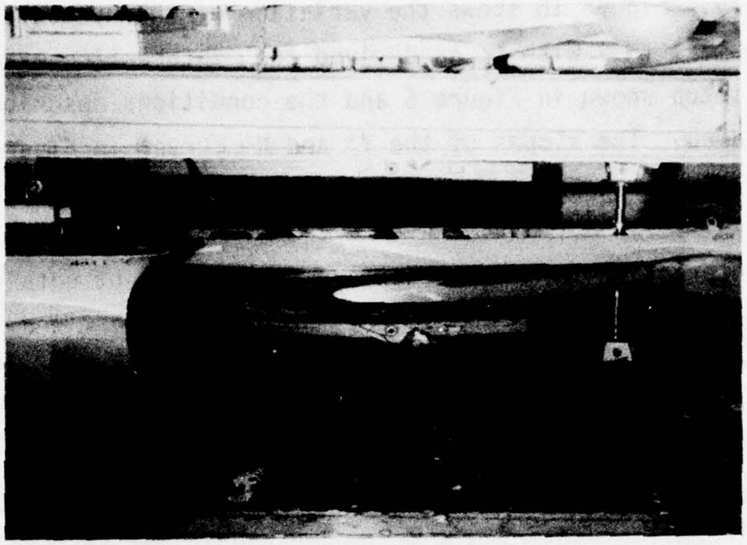


Figure 11 - Profile View of AOE Ahead of CVA

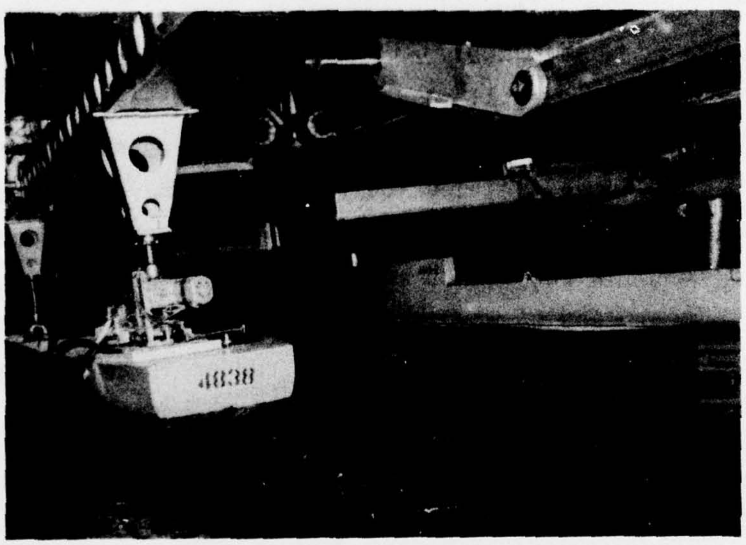


Figure 12 - Stern View of AOE Ahead of CVA

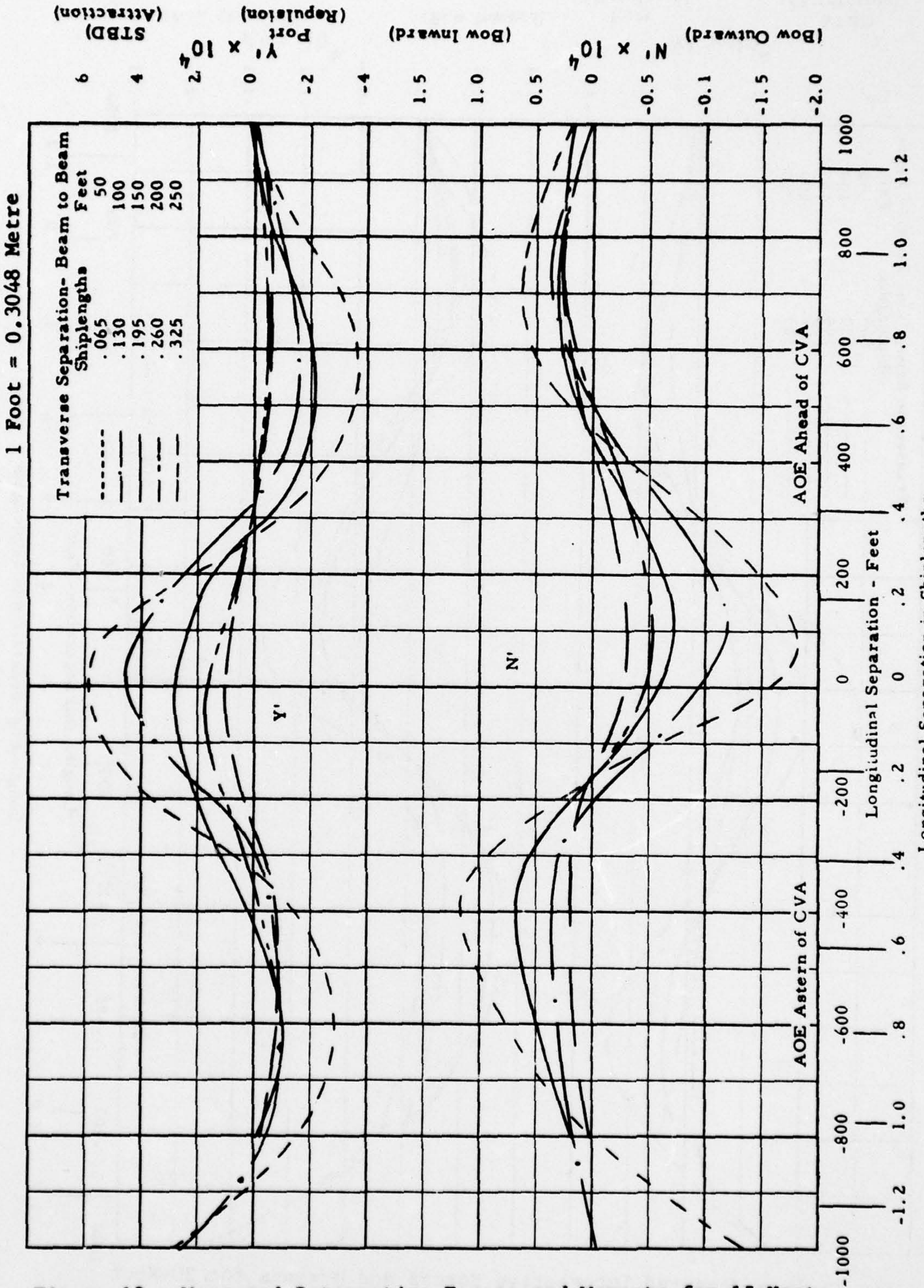


Figure 13 - Measured Interactive Forces and Moments for 15-Knot Condition

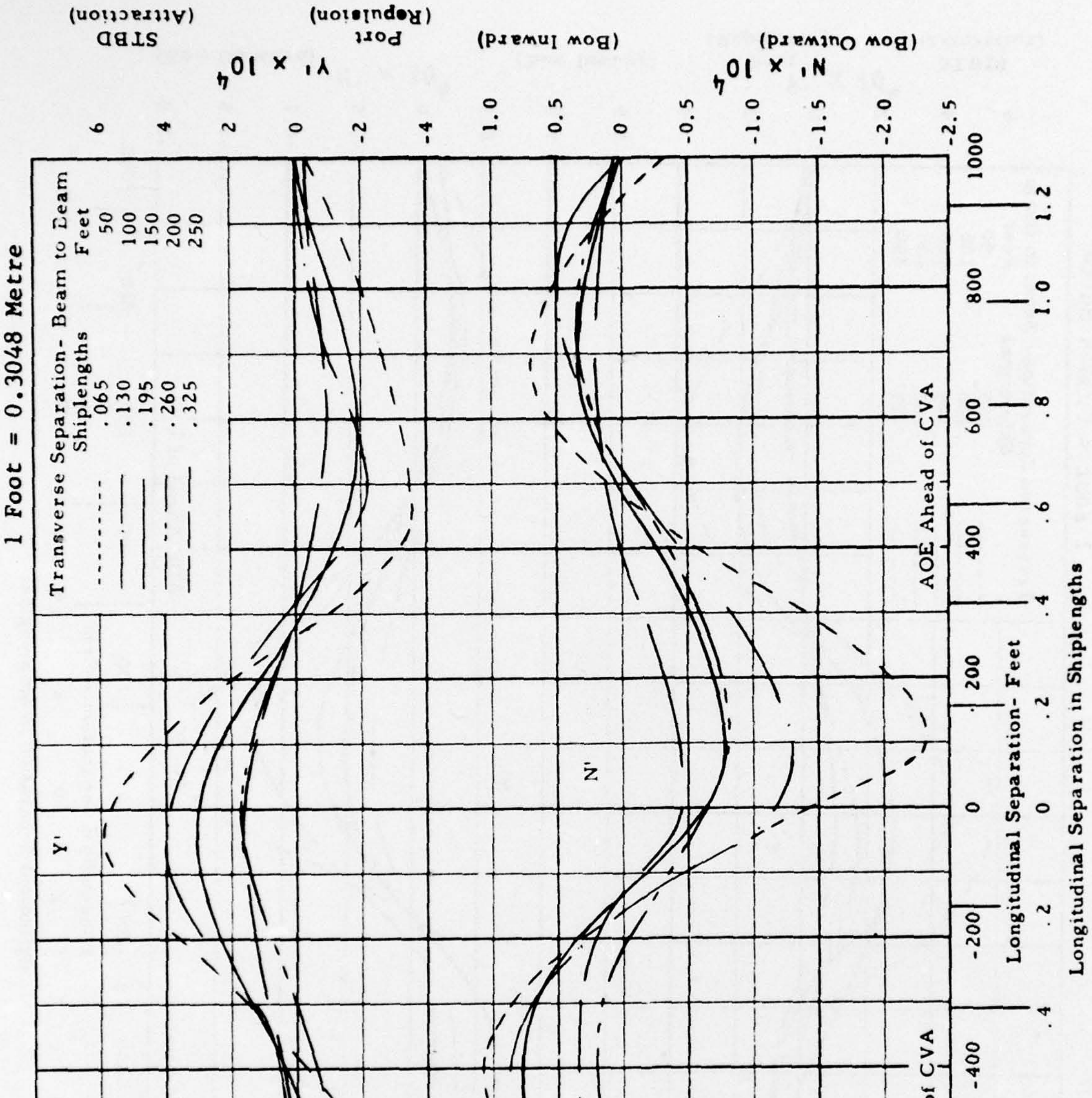


Figure 14 - Measured Interactive Forces and Moments for 20-Knot Condition

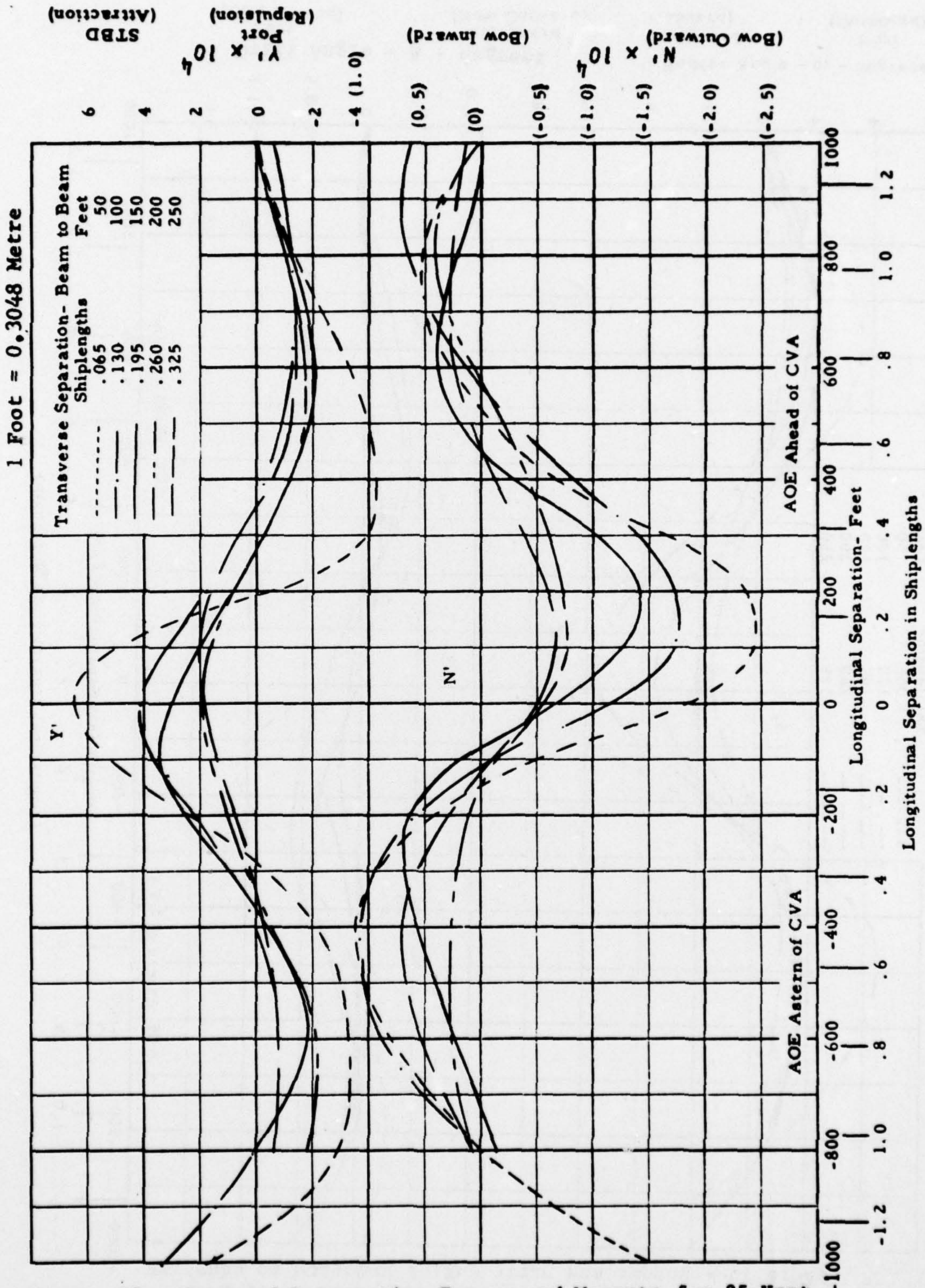


Figure 15 - Measured Interaction Forces and Moments for 25-Knot Condition

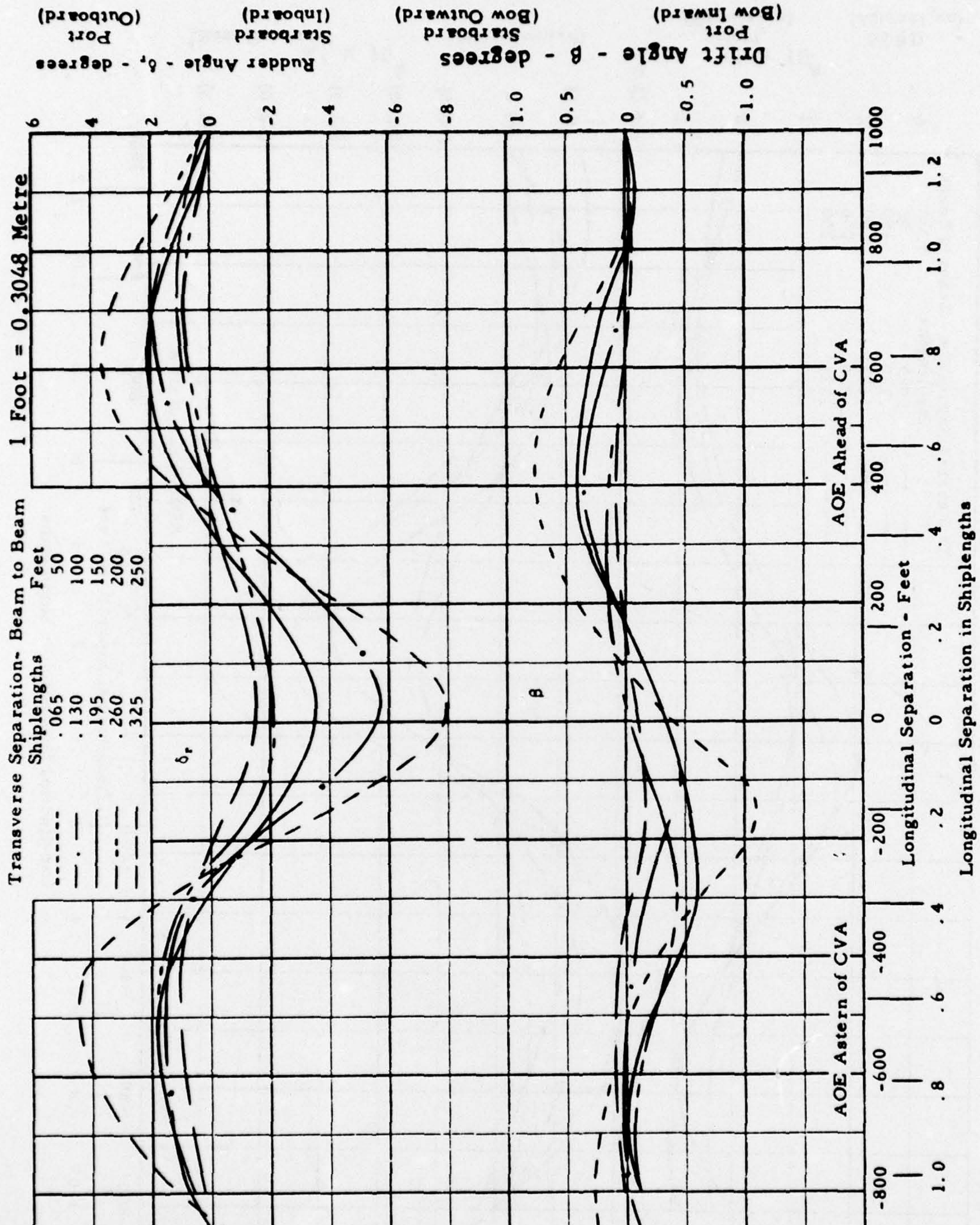


Figure 16 - Rudder and Drift Angles Required to Equalize Interaction Forces and Moments at 15 Knots

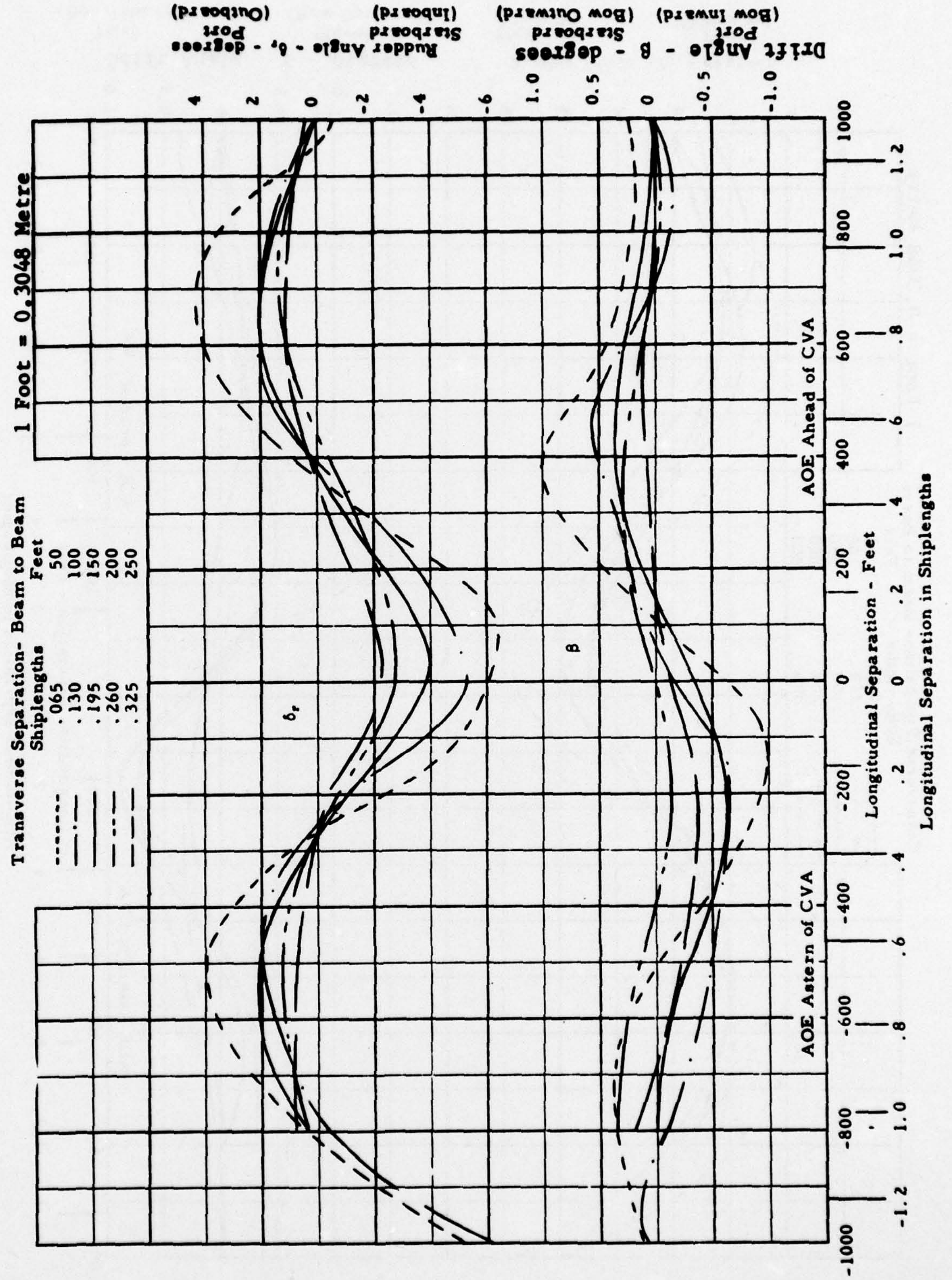


Figure 17 - Rudder and Drift Angles Required to Equalize Interaction Forces and Moments at 20 Knots

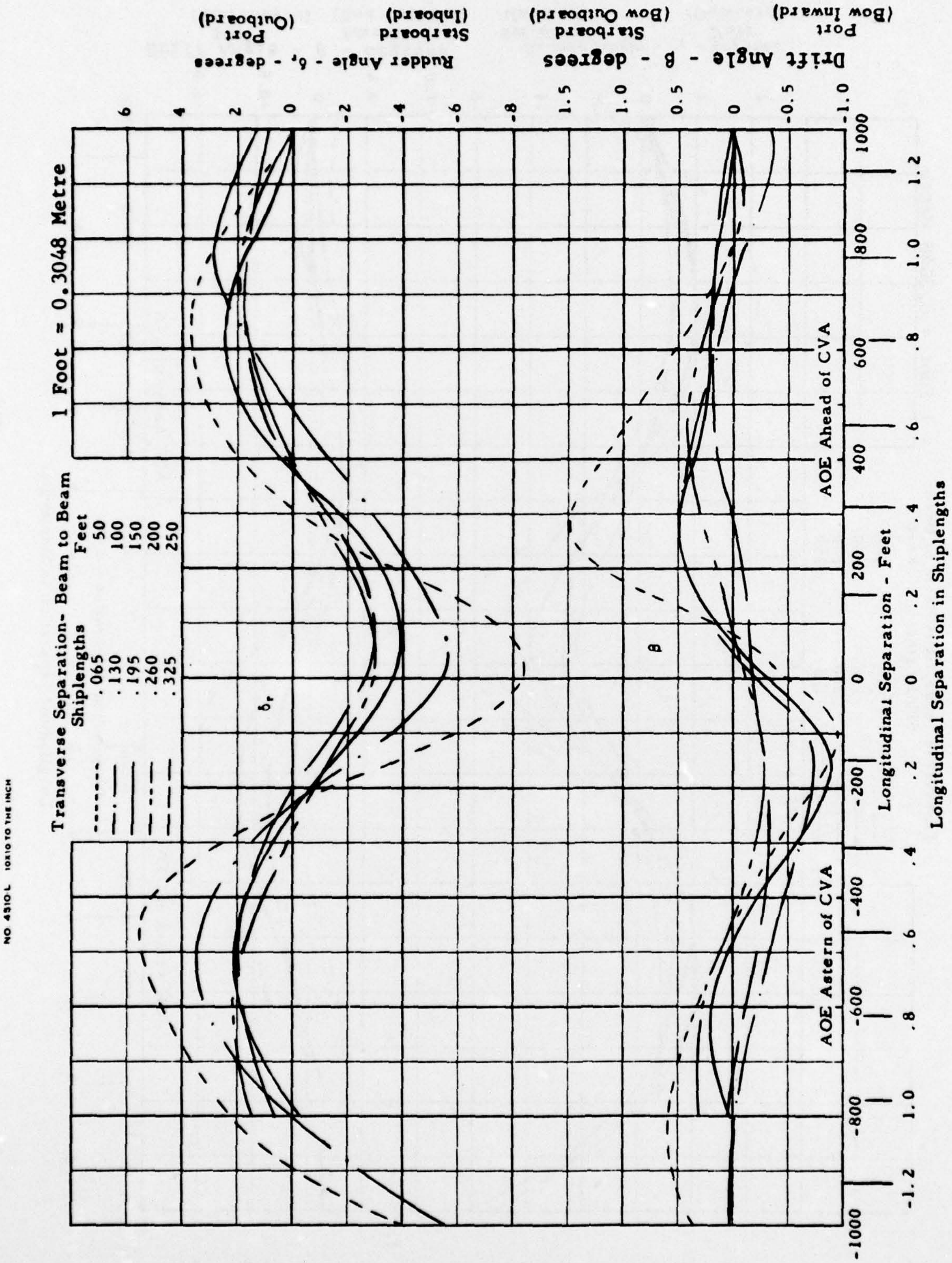
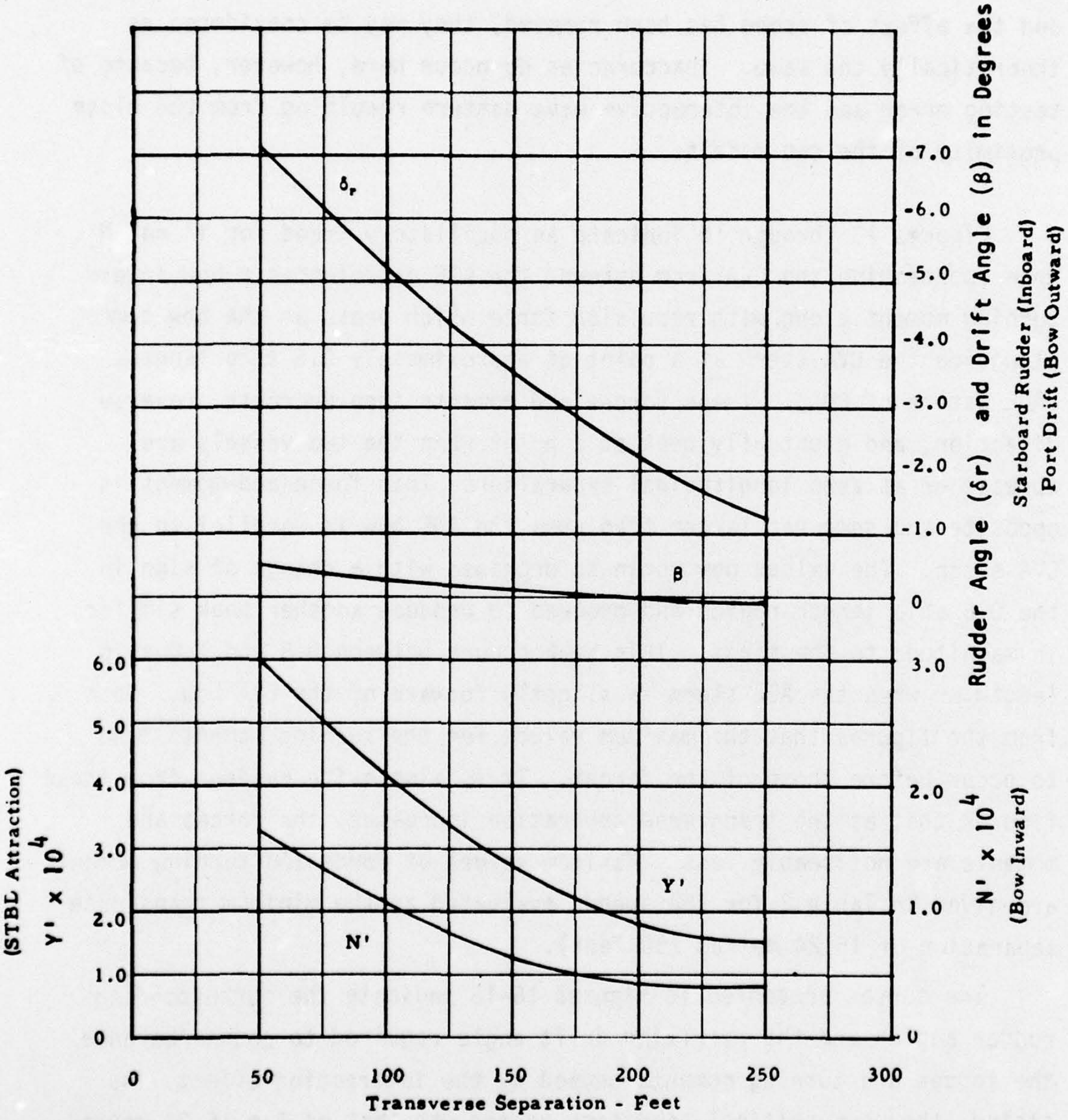


Figure 18 - Rudder and Drift Angles Required to Equalize Interaction Forces and Moments at 25 Knots

Figure 19 shows the effect of transverse separation on the interaction forces and moments, and upon the combination of rudder angle and drift angle required to maintain separation. Curves are based on values of Y' and N' at the three speeds employed; since these data are nondimensionalized and the effect of speed has been removed, they may be considered as theoretically the same. Inaccuracies do occur here, however, because of testing error and the interactive wave pattern resulting from the close proximity of the two models.

Figures 13 through 15 indicate an oscillatory trend for Y' and N'. When approaching the CVA from astern, the AOE experiences a bow inward turning moment along with repulsion force which peaks as the bow comes alongside the CVA stern at a point of approximately 0.6 ship lengths (AOE astern of CVA). These forces and moments then decrease, reverse direction, and eventually peak at a point when the two vessels are abreast or at zero longitudinal separation. This force-and-moment is opposite and somewhat larger than when the AOE bow is parallel to the CVA stern. The values now begin to decrease with a change of sign in the 0.5 ship length region and proceed to produce another peak similar in magnitude to the first. This peak occurs between 0.8 and 1.0 ship length or when the AOE stern is slightly forward of the CVA bow. Note from the figures that the maximum values for the turning moments tend to occur before those of the forces. It is also quite evident from these figures that as the transverse separation increases, the forces and moments are noticeably less. Maximum values of force and turning moment are given in Table 2 for the speeds evaluated at the minimum transverse separation of 15.24 metres (50 feet).

The curves presented in Figures 16-18 indicate the corresponding rudder angles and the resulting drift angle required to counterbalance the forces and turning moments caused by the interaction effect. As stated, the most critical condition tested was that of the 15.24 metres (50-foot) transverse separation. The resulting rudder angles for this spacing are representative of any speed.



1 Foot = 0.3048 Metre

Figure 19 - Variation of Interaction Forces and Moments and Resultant Rudder and Drift Angles with Transverse Separation

TABLE 2

AOE Maximum Side Forces and Turning Moments

SPEED	SIDE FORCE		TURNING MOMENT	
Knots	Repulsion Mg (Tons)	Attraction Mg (Tons)	Bow Out MN.M(Ton-Feet)	Bow in MN.M(Ton-Feet)
15	-64 (-63)	102 (100)	-72.6 (-23,900)	46.8(15,400)
20	-111 (-109)	182 (179)	-164.3 (-54,100)	76.5 (25,200)
25	-207 (-204)	313 (308)	-272.4 (-89,700)	123.0 (40,500)

DISCUSSION

The primary difference between these data and prior information is the method whereby the experiments were conducted and results analyzed. Previous tests were concerned with collecting data (presented in the form of Figures 13-15) to be used for calculating the necessary opposing rudder force required to counteract the interaction force and turning moment. For this experiment rudder effects have been determined experimentally in conjunction with the interaction forces and turing moments.

As mentioned, experiments to determine the terms of Y_β and N_β were conducted on the AOE model alone in open water. These consisted of towing the model at various drift angles and measuring the resulting side forces and yawing moments. Preliminary investigative experiments conducted on the interaction models indicated only a slight error in the resultant β and δ_r values when Y_β and N_β were determined without considering the effect of interaction. This error was in the range of ±0.1 degree for the β angle and ±0.25 degree for the δ_r angle. The same does not apply, however, to the Y_{δ_r} and N_{δ_r} term; in that case, the error again amounts to ±0.1 degree for but increases to ±1.0 degrees for δ_r. By eliminating the need for determining Y_β and N_β for each condition evaluated, it was possible to include a larger range of longitudinal and transverse separations in the trials program.

The data of Figures 13-15 ranged from 8.2-degree starboard to a 5.6-degree port rudder, as shown in Figure 18. Probably the most important result from these experiments is the indication that the rudder position should be moved from outboard to inboard to outboard as the AOE overtakes and passes the CVA. With the AOE bow parallel to the CVA stern, a 5.5-degree port rudder was required (Figure 18). This changed to an 8.2-degree starboard rudder, or inboard, as the two ships came abreast. It then reverted back to a port rudder of approximately 3.8 degrees as the AOE stern passed the CVA bow. Although the drift angle cannot be controlled by the veseel as can the rudder, it is felt that its effect or magnitude should be realized. Again from Figures 16 through 18, this oscillatory motion was apparent, varying from approximately 1 degree port to 1 degree starboard in some cases.

The information presented in Figure 19 is based on the average of data from Figures 13-15 at a point of zero longitudinal separation. This figure merely shows that the values decrease as the transverse separation increases.

CONCLUSIONS AND RECOMMENDATIONS

When the AOE and CVA are in close proximity and on a more or less parallel course, the sequence for corrective rudder action appears to be outward as the AOE beings to approach, the CVA, inwards as the AOE comes abreast of the CVA, and then outward again as the AOE overtakes the CVA.

One very interesting result of this sequence is that when corrective rudder is applied to prevent the AOE from crossing the course of the CVA, an attractive force is produced. This corrective action takes place in the 0.8 to 1.0 ship length region when an outward rudder is required to maintain equilibrium.

The primary conclusion to be drawn from these experiments is that there is a definite need to be more knowledgeable concerning the effects of ship interactions. This need may be realized through extensive testing not only with the two ships evaluated here, but also with other ships that are associated with replenishment operations. The preliminary evaluation is better accomplished on models rather than full scale for such obvious reasons as economy, availability, and controlled environment. However, model results should be substantiated by full-scale data. This is one aspect of full-scale trials for which very little data are available.

As noted, the data presented herein were taken under static conditions, i.e., the models were stationary relative to each other. Further trials are necessary to confirm these results through measurements while one model is changing longitudinal position dynamically with respect to the other. This would provide continuous data rather than discrete points.

The information presented herein on ship interactions as well as that in previous studies represent only a small fraction of what is needed. A systematic study of various shapes and forms could lead to some very interesting conclusions and possibly to the development of techniques for estimating interaction effects for a given ship. Experiments of this nature and scope would, however, involve considerable time and expense to properly execute.

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