Report 27-267 Computer Simulation of Ship Underway Replenishment, Feasibility Study

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20034

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COMPUTER SIMULATION OF SHIP UNDERWAY REPLENISHMENT, FEASIBILITY STUDY

By
Samuel H. Brown and Lanny J. Puckett

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Samuel H. Brown, et al

Naval Ship Research and Development Center
Annapolis, Maryland

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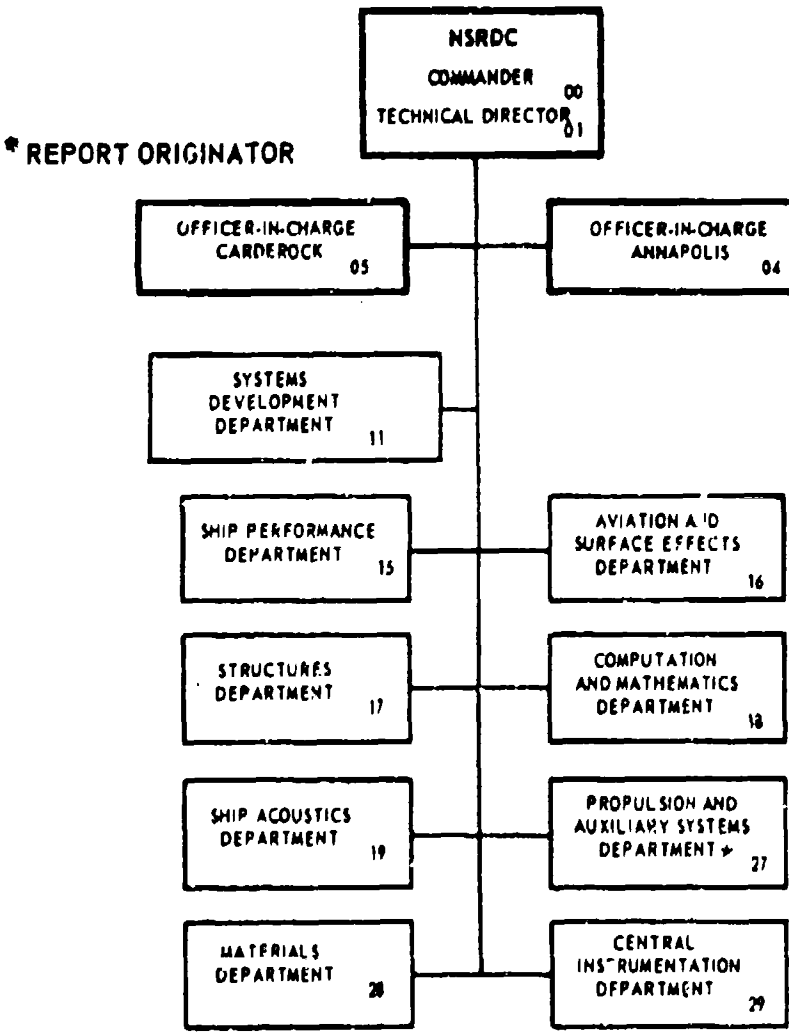

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13. ABSTRACT

This feasibility study concluded that a computer simulation of ship underway replenishment can be developed. A system of linear equations of motion for describing two ships maneuvering on essentially parallel courses was chosen as the basic equations for the mathematical model to be used in the computer simulation. The derivation of these linear equations is presented. A better representation using nonlinear equations of motion will be considered in a later phase of the study.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Underway replenishment						
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Maneuvering equations						
High lines						
Tracking						
Computer simulation						

TABLE OF CONTENTS

DEFINITIONS AND TERMINOLOGY

$\bar{o}$, $\bar{x}$, $\bar{y}$, $\bar{z}$	- Coordinate system which moves with the constant average velocity of the two ships.
o_1, x_1, y_1, z_1,	- Coordinate axes fixed in ship 1.
o_2, x_2, y_2, z_2	- Coordinate axes fixed in ship 2.
u, v	- Velocities along x and y, respectively.
Ψ	- Angle of yaw measured between coordinate axes $\bar{o}\bar{x}$ and ox.
M	- Mass of the body (ship).
I_z	- Moment of inertia of the ship about coordinate axis oz.
X, Y	- Force acting on the ship along coordinate axes ox and oy.
N	- Moment acting on ship about coordinate axis oz.

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INTRODUCTION

The operational procedure of replenishing ships at sea by steaming on parallel courses in close proximity[1,2] came into general use during World War II. This procedure is still used extensively by the Navy, although collisions have occurred during replenishment operations which have resulted in damage.

Analysis of the replenishment operations may provide a means of reducing the collision hazard by improved methods of ship maneuvering and ship control.

The dynamic interaction of two ships in close proximity maneuvering on parallel courses[1,2] involves the hydrodynamic interaction between the ships, the skills of the helmsmen, and the conning officer of both ships. This complex dynamic interaction is not completely understood and requires further analytical and experimental study.

This laboratory is currently engaged in an applied research program to define the parameters affecting ship control during underway replenishment (UNREP). Monitoring of these control parameters aboard ship may provide information for the conning officer and/or helmsmen which will reduce the collision hazard and also improve the efficiency of the UNREP operation.

This first phase report from the UNREP research program describes the background of the problem, derives the linearized equations of motion for two ships on essentially parallel courses, and discusses the computer simulation to be developed at NSRDC from these equations as the basis of the mathematical model.

Future work in the UNREP program will concentrate on the development of the computer simulation using the linear equations of motion, analysis of the computer simulation results, and refinement of the mathematical model to include nonlinear terms. It may be necessary to go directly to the nonlinear maneuvering equations if preliminary investigations indicate the presence of instabilities in the solutions of the linear equations.

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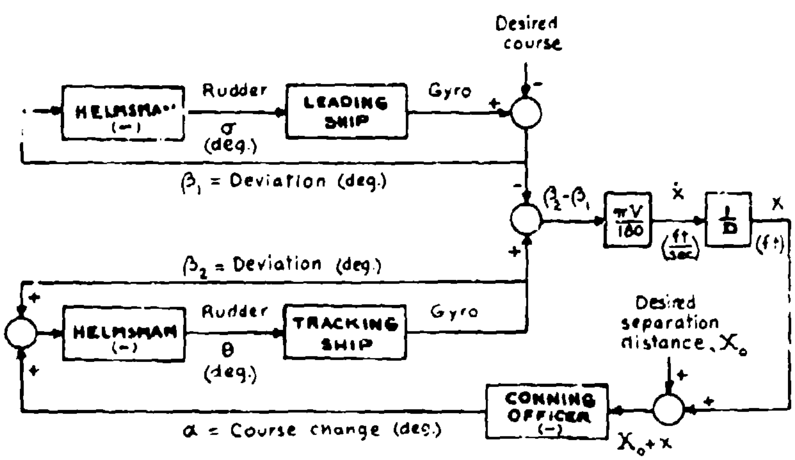
[1] Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

GENERAL DISCUSSION OF UNDERWAY REPLENISHMENT

Replenishment operations[1,2] are conducted at sea for the purpose of transferring stores between ships to extend the period of time that the ships can be operational at sea. Since the cargo must be guided and controlled during the transfer operation, a suitable physical connection must be maintained at all times between the ships moving essentially parallel to each other and at nearly identical speeds. This physical connection requires that the ships be close together; thus, there is the danger of collision. The tracking ship is usually assigned the task of avoiding collision and maintaining station relative to the leading ship. The leading ship must maintain a steady course and must keep oscillations about this course to a minimum.

During UNREP operations both relative speed and separation distance of ships are monitored by the conning officer[2] on the tracking ship. A line with markers is used to measure the distance between the ships. One end of the line is secured to the leading ship; the other end is tended by men on the tracking ship who take up and pay out the line to keep it taut. The conning officer orders small course and small speed changes to maintain position. Figure 1 shows a control block diagram of the UNREP operation with the tracking ship on the starboard beam of the leading ship. This diagram is discussed in appendix A.



From Thal-Larsen.[2]

Figure 1 - Replenishment-At Sea Operation with Tracking Ship on Starboard Beam of Leading Ship

The constant tensioned wire highlines installed in the Navy's newly constructed UNREP ships and in UNREP ship conversions introduce another parameter to be considered. This parameter is a steady lateral pull due to constant tensioned wire highlines between the two ships which may affect the steering of both the leading ship (delivery ship) and tracking ship (receiving ship). However, in UNREP operations[3] the constant tensioned wire highlines did not introduce a significant problem. This area is discussed in appendix B.

REPLENISHMENT SIMULATION TO BE DEVELOPED

Pertinent literature relating to UNREP operations was reviewed to evaluate the feasibility of computer simulation of underway replenishment. The selected papers and reports from this literature search were studied from two aspects: their applicability to a good mathematical model of UNREP operation (e.g., assumptions made, the reasons for these assumptions, and the purpose of the papers and reports); and their applicability from the standpoint of simulating ship replenishment by computer (e.g., selection of the computer, the reasons for its selection, its capabilities and deficiencies, and its availability).

ANALYSIS OF PAST WORK

In the field of UNREP, the literature is scarce. Newton,[4] Silverstein,[5] and Taylor[6] report experimental and theoretical investigations of interaction forces between two ships maneuvering on parallel courses. The control problem involving the conning officer and helmsmen during an UNREP operation is not considered in these investigations.

Methods presented in these references may be helpful in determining the forces between the two ships during the UNREP computer simulation in this program.

The University of California[1,2] reported significant UNREP work done 10 years ago by a research group sponsored by NAVSHIPS. This group recorded incomplete statistical data during full-scale ship UNREP operations. The sea trials consisted of refueling a destroyer, USS HALSEY-POWELL (DD 686), by the USS ASHTABULA (AO 51) at 17 knots, and replenishing USS UHLMANN (DD 687) by the USS TICONDEROGA (CVA 14) at 25 knots. The project was terminated by the Navy, however, before all data for a complete statistical analysis could be obtained. Details of these sea trials and examples of these data appear in appendix C.

Figure 1 shows the control block diagram that was designed for the partially completed UNREP analog computer simulation at the University of California. This block diagram represents the UNREP operation with the tracking ship on the starboard beam of the leading ship. The incomplete sea trial UNREP data mentioned above were used to determine the transfer functions incorporated in the block diagram. A brief discussion of the determination of the transfer functions appears in appendix A.

This University of California work provides important background information useful in understanding the relationship between ship control and ship interaction during UNREP operations. However, the method of UNREP computer simulation considered by the University of California was not suitable for use in this program for the following reasons:

- Funds in excess of the amount presently allocated would be required to obtain complete statistical data for this simulation from extensive UNREP operations.

- If models tests are used to obtain UNREP data, the scaling problems involved with human operators in the control loops for these tests are extremely difficult to handle.

- This analog computer simulation using linear transfer functions is extremely hard to generalize to the nonlinear case.

Pauling and Wood[7], present the linear equations of motion for two ships maneuvering on essentially parallel courses. It was decided to use these equations as a basis for the mathematical model in the UNREP computer simulation to be developed for the following reasons:

- Costly hydrodynamic work can be eliminated because most of the hydrodynamic coefficients in the equations of motion can be estimated from theoretical considerations.

- Nonlinear terms can be added to the equations of motion in a later phase of the work if it is found necessary to consider nonlinear aspects of UNREP operations.

LINEAR EQUATIONS OF MOTION

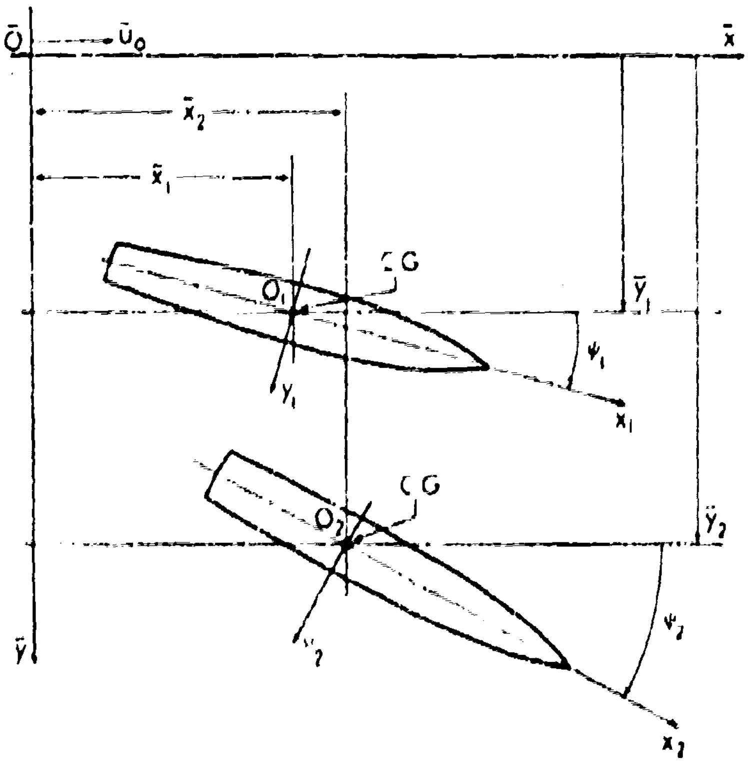
The following assumptions are made in developing the linear equations[7] of motion.

- The ships operate on nominal parallel courses; thus, the time average resultant velocity vectors are parallel.

- The average speed of both ships is constant and equal.

- The short-time deviations from the above conditions are small. Thus, the linear displacement from the average position of the ship is small compared to the ship dimensions; angular deviations are small; velocity disturbances are small compared to the average velocity; and accelerations corresponding to these disturbances result in moments and forces which are small compared to those already acting on the ship.

In order to describe the motion of the two ships it is necessary to use two sets of coordinate systems,[7] shown in figure 2.



From Pauling and Wood.[7]

Figure 2
Coordinate Systems

One coordinate system ($\bar{o}$, $\bar{x}$, $\bar{y}$, $\bar{z}$) moves with the constant average velocity of the two ships. $\bar{o}\bar{z}$ is directed vertically downward; the $\bar{x}\bar{y}$ plane coincides with the surface of the water; and $\bar{o}\bar{x}$ is parallel with the average velocity of the two ships. The second set of coordinates (o_1, x_1, y_1, z_1) and (o_2, x_2, y_2, z_2) is fixed in the two ships with o fixed at the ship's center of gravity, ox directed forward, oy to starboard, and oz downward. The plane oxz is the ship's plane of longitudinal symmetry. The plane oxy is parallel to the water surface when the ship floats at rest. It is assumed that the principal axes of inertia are ox, oy, and oz. This assumption is exactly correct for oy and nearly correct for ox and oz where ships of normal proportions and mass distributions are considered. The motion of the ship is restricted to the $\bar{x}\bar{y}$ plane; and thus, pitch, heave, and roll motions are neglected. The motion is described by velocities u_1, u_2, v_1, v_2, accelerations $\dot{u}_1$, $\dot{u}_2$, $\dot{v}_1$, $\dot{v}_2$ parallel to the x and y axes, and angular displacements Ψ_1, Ψ_2, velocities $\dot{\Psi}_1$, $\dot{\Psi}_2$, and accelerations $\ddot{\Psi}_1$, $\ddot{\Psi}_2$ about the z axis.

In the two coordinate systems fixed, respectively, in the two ships, the equations of motion are described as follows (the subscripts 1 and 2 refer to ships one and two, respectively):

$$M_1(\dot{u}_1 - \dot{\Psi}_1 v_1) = X_1 + T_1 + X_{R1}$$

$$M_1(\dot{v}_1 + \dot{\Psi}_1 u_1) = Y_1 + Y_{R1}$$

$$I_{z1}\ddot{\Psi}_1 = N_1 + N_{R1}$$

$$M_2(\dot{u}_2 - \dot{\Psi}_2 v_2) = X_2 + T_2 + X_{R2}$$

$$M_2(\dot{v}_2 + \dot{\Psi}_2 u_2) = Y_2 + Y_{R2}$$

$$I_{z2}\ddot{\Psi}_2 = N_2 + N_{R2} \quad , \qquad (1)$$

where

M = mass of the ship

I_z = moment of inertia

T = thrust of propellers

X_R, Y_R = rudder forces applied to the ship

N_R = rudder moment

X, Y = motion-dependent external hydrodynamic forces applied to the ship

N = motion-dependent external hydrodynamic moment applied to the ship.

It is assumed that the hydrodynamic variables[7] (X_1, X_2, Y_1, Y_2, N_1, N_2) depend on the following:

- Velocities u_1, u_2, v_1, v_2, $\dot{\psi}_1$, $\dot{\psi}_2$ for each ship.
- Accelerations $\dot{u}_1$, $\dot{u}_2$, $\dot{v}_1$, $\dot{v}_2$, $\ddot{\psi}_1$, $\ddot{\psi}_2$ for each ship.
- Relative positions for each ship $\bar{x}_2 - \bar{x}_1$ and $\bar{y}_2 - \bar{y}_1$.

Thus, the variable X_1 may be expressed as $X_1 = X_1(u_1, u_2, v_1, v_2, \dot{u}_1, \dot{u}_2, \dot{v}_1, \dot{v}_2, \dot{\psi}_1, \dot{\psi}_2, \ddot{\psi}_1, \ddot{\psi}_2, \bar{x}_2 - \bar{x}_1, \bar{y}_2 - \bar{y}_1)$ with similar expressions for X_2, Y_1, Y_2, N_1, N_2. Other external forces not mentioned might result from wind, waves, etc. All of these forces and moments are dependent on the geometry of the ship.

It is assumed here that the motion of each ship consists of small perturbations superimposed on an initial state of motion.[7] Thus, the perturbation of the u velocity, for example, is represented by

$$u(t) = u_o(t) + \delta u(t) \quad , \qquad (2)$$

where δu is a small quantity. Assuming the X_1 is an analytic function of the independent variables, X_1 is expanded in a Taylor's series about its value at the initial state of motion:

$$X_1 = X_1(u_{1o}, u_{2o}, \ldots, (\bar{y}_2 - \bar{y}_1)_o$$

$$+ \frac{\partial X_1}{\partial u_1} \delta u_1 + \frac{\partial X_1}{\partial u_2} \delta u_2 + \ldots + \frac{\partial X_1}{\partial (\bar{y}_2 - \bar{y}_1)} \delta (\bar{y}_2 - \bar{y}_1) \qquad (3)$$

$$+ \frac{1}{2} \frac{\partial^2 X_1}{\partial^2 u_1} (\delta u_1)^2 + \ldots .$$

Substituting equation (2), plus other equations representing the perturbations of its motion, and equation (3) into the first of equation (1) and retaining terms to the first power of δu_1 etc results in the equation for the initial state of motion,[7]

$$M_1(\dot{u}_{1o} - \dot{\Psi}_{1o} v_{1o}) = X_1(u_{1o}, u_{2o}, \ldots, (\bar{y}_2 - \bar{y}_1)_o) + T_{1o} + X_{R1o} \qquad (4)$$

plus the equation for perturbed motion

$$M_1(\delta\dot{u}_1 + \dot{\Psi}_{1o}\delta v_1 - \delta\dot{\Psi}_1 v_{1o})$$

$$= \frac{\partial X_1}{\partial u_1} \delta u_1 + \frac{\partial X_1}{\partial u_2} \delta u_2 + \ldots \frac{\partial X_1}{\partial (\bar{y}_2 - \bar{y}_1)} \delta (\bar{y}_2 - \bar{y}_1) + \delta T_1 + \delta X_{R1} , \qquad (5)$$

where the nonlinear terms are dropped;

$$\left(\text{example } \frac{1}{2} \frac{\partial^2 X_1}{\partial^2 u_1} (\delta u_1)^2\right) .$$

These nonlinear terms will be considered in future work.

It should be noted that the partial derivatives $\partial X_1/\partial u_1$ etc are evaluated[7] at the initial state of motion ($u_1 = u_{10}$, $u_2 = u_{20}$, $\bar{y}_2 - \bar{y}_1 = (\bar{y}_2 - \bar{y}_1)_o$. The changes in thrust and rudder force, δT and $\delta X_{\Omega 1}$ are considered to depend on the motion or to be independent variable quantities. However, it is required that they be small quantities.

It is also necessary to introduce the assumption of constant average velocity, $\bar{u}_o$, of both ships parallel to $\bar{o}\bar{x}$. The resultant velocities in the ox and oy directions are given in terms of the velocities parallel to $\bar{o}\bar{x}$ and $\bar{o}\bar{y}$ for either ship as follows:[7]

$$u = \bar{u}\cos\Psi + \bar{v}\sin\Psi$$

$$v = -\bar{u}\sin\Psi + \bar{v}\cos\Psi \quad , \tag{6}$$

where the subscripts denoting either ship have been dropped.

By substituting the equations

$$u = u_o + \delta u$$

$$v = v_o + \delta v$$

$$\bar{u} = \bar{u}_o + \delta\bar{u}$$

$$\bar{v} = \delta\bar{v}$$

$$\Psi = \Psi_o + \delta\Psi \tag{7}$$

into equation (6), the following two equations[7] are obtained:

$$u_o + \delta u = (\bar{u}_o + \delta\bar{u})\cos(\Psi_o + \delta\Psi) + \delta\bar{v}\sin(\Psi_o + \delta\Psi)$$

$$v_o + \delta v = -(\bar{u}_o + \delta\bar{u})\sin(\Psi_o + \delta\Psi) + \delta\bar{v}\cos(\Psi_o + \delta\Psi) \quad . \tag{8}$$

It is assumed here that the average yaw (Ψ) angle of the ship is small[7] so that the following approximations may be made

$$\cos \Psi_o \cong 1$$

$$\sin \Psi_o \cong \Psi_o \quad . \tag{9}$$

Then substituting these approximations (equation (9)) into equation (8) results in the equations,

$$u_o + \delta u = \bar{u}_o + (\delta\bar{u} + \Psi_o \delta\bar{v})$$

$$v_o + \delta v = -\Psi_o \bar{u}_o \quad -\bar{u}_o \delta\Psi + \delta\bar{v} \quad . \tag{10}$$

Thus, to the first order approximation[7]

$$u_o = \bar{u}_o$$

$$v_o = -\Psi_o \bar{u}_o \tag{11}$$

where $\bar{u}_o$ is the constant average velocity of both ships and Ψ_o the appropriate average angle of yaw for the ship in question. Since Ψ_o has been assumed to be small, terms of the form $\Psi_o \delta u$, etc, can be neglected.

The equations of perturbed motion[7] about an initial steady-state motion for the two ships are ($\bar{u}_o$ = constant, $\bar{v}_o$ = constant):

$$M_1\dot{u}_1 = \frac{\partial X_1}{\partial u_1}\,\delta u_1 + \frac{\partial X_1}{\partial u_2}\,\delta u_2 + \dots + \frac{\partial X_1}{\partial(\bar{y}_2 - \bar{y}_1)}\,\delta(\bar{y}_2 - \bar{y}_1) + \delta T_1 + \delta X_{R1}$$

$$M_1(\dot{v}_1 + \dot{\psi}_1\,\bar{u}_o) = \frac{\partial Y_1}{\partial u_1}\,\delta u_1 + \frac{\partial Y_1}{\partial u_2}\,\delta u_2$$

$$+ \dots\dots + \frac{\partial Y_1}{\partial(\bar{y}_2 - \bar{y}_1)}\,\delta(\bar{y}_2 - \bar{y}_1) + \delta Y_{R1}$$

$$I_{z1}\ddot{\psi}_1 = \frac{\partial N_1}{\partial u_1}\,\delta u_1 + \dots + \frac{\partial N_1}{\partial(\bar{y}_2 - \bar{y}_1)}\,\delta(\bar{y}_2 - \bar{y}_1)$$

$$M_2\dot{u}_2 = \frac{\partial X_2}{\partial u_1}\,\delta u_1 + \frac{\partial X_2}{\partial u_2}\,\delta u_2 + \dots \frac{\partial X_2}{\partial(\bar{y}_2 - \bar{y}_1)}\,\delta(\bar{y}_2 - \bar{y}_1)$$

$$+ \delta T_2 + \delta X_{R2}$$

$$M_2(\dot{v}_2 + \dot{\psi}_2\bar{u}_o) = \frac{\partial Y_2}{\partial u_1}\,\delta u_1 + \frac{\partial Y_2}{u_2}\,\delta u_2$$

$$+ \dots \frac{\partial Y_2}{\partial(\bar{y}_2 - \bar{y}_1)}\,\delta(\bar{y}_2 - \bar{y}_1) + \delta Y_{R2}$$

$$I_{z2}\ddot{\Psi}_2 = \frac{\partial N_2}{\partial u_1}\,\delta u_1 + \ldots + \frac{\partial N_2}{\partial(\bar{y}_2 - \bar{y}_1)}\,\delta(\bar{y}_2 - \bar{y}_1) \quad . \tag{12}$$

The retention of only the first order hydrodynamic force terms of equation (12)[7] implies that these forces can be expressed by terms proportional to the first powers of perturbation displacements, velocities, and accelerations. However, Wehausen[8] and Cummins[9] showed that the hydrodynamic forces on a body moving at a free surface can be expressed by the first order perturbation terms only in special cases. One such case[10] is that of small amplitude periodic motion, for example, that of ship motion in regular waves where the amplitudes of the motion are small. The present problem will not necessarily be confined to the case of periodic motion. Thus, it is uncertain that the retention of only linear terms sufficiently describes the hydrodynamic forces involved.

Accordingly the computer simulation using the linear maneuvering equations may exhibit unstable solutions thus making it necessary to go directly to the nonlinear maneuvering equations. The nonlinear equations will be obtained by adding the perturbed higher order force terms to the linear equations.

COMPUTER FACILITY

The computer simulation for the UNREP project must allow for a man-in-the-loop. To obtain this man-machine interface the simulation must operate in real time, thus implying that the simulation be done on an analog computer. This laboratory presently has an analog computing capability which should be sufficient for the simulation. This capability includes the interface to a mock-up of a surface ship bridge. This facility is being enlarged to include a complete hybrid computing capability which will allow the simulation to run in real-time while providing the programing flexibility of a digital computer.

DISCUSSION

There is very little quantitative data on the two-ship hydrodynamic coefficients available; therefore, it will be necessary to estimate these hydrodynamic coefficients for a general ship situation in the maneuvering equations. The use of estimated coefficients is justified to some extent because the study is not directed toward specific ships but toward general results applicable to a variety of ship types. These coefficients will be estimated for the most part from unpublished work from the hydrodynamics facility of NSRDC. Every effort will be made to use hydrodynamic coefficients which specifically refer to the two-ship situation. When these coefficients are not available, the single-ship hydrodynamic coefficients will be used.

The first studies made by exercising the UNREP simulation will attempt to determine the minimum number of maneuvering parameters necessary for use by the conning officers and/or helmsmen for station keeping during steady-state UNREP operations. The maneuvering parameters for steady-state operation may not be sufficient for accurate station keeping during non-steady-state operations.

These first studies will also include determining the display characteristics of the maneuvering parameters and investigating the accuracies needed for the sensors measuring these parameters aboard ship.

After implementing the UNREP computer program on the hybrid computer the results will be compared with the limited available unpublished and published UNREP data from sea trials and model tests. This validation procedure will also include parametric studies of the general hydrodynamic sensitivities. As a result of these sensitivity studies, it may be found necessary to determine some hydrodynamic coefficients more accurately by model tests at NSRDC.

Other areas of future investigation include:

- The adaption of the UNREP computer simulation to the ship approach situation at the beginning of the UNREP maneuvers.

- Modification of the UNREP computer simulation to ir [illegible]de sea state, roll, pitch, etc.

- Collision course avoidance and the display of maneuvering parameters to warn the conning officer and/or helmsmen of the collision situation and provide information to reduce the hazard.

CONCLUSIONS

From the limited references[1-7] available on underway replenishment, it was determined that the best basis for a mathematical model for the simulation of underway replenishment was the line[illegible] equations developed by Pauling and Wood which can be general[illegible]ed to the nonlinear case.

Some of the general ship hydrodynamic coefficients in the equations of motion may have to be determined by model tests.

The method to simulate underway replenishment using classical control theory as partially developed by the University of California is not suited to this work because of the expense in obtaining statistical data used in the simulation and because the nonlinear aspects of the control problem are extremely difficult to include.

The computer program to be developed will provide important control parameters for display aboard ship. These displays will aid the conning officer and/or helmsmen in ship control and should reduce the risk of collisions during underway replenishment operations.

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APPENDIX A

STATISTICAL ANALYSIS OF SHIP REPLENISHMENT DATA

REFERENCES

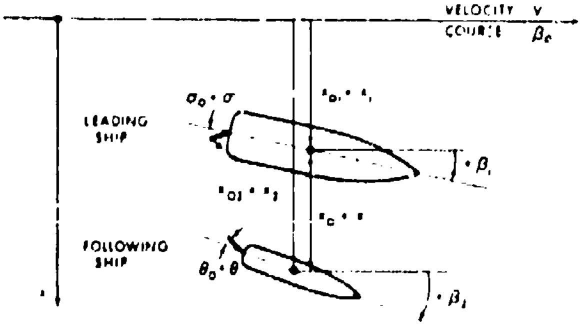
(a) Tichvinsky, L. M., and H. Thal-Larsen, "Replenishment at Sea, Experiments and Comments," 1st tech rept issued under the project "Replenishment at Sea," Univ. of California, Berkeley, Inst. of Engr. Research (now Office of Research Services), Rept 154, Issue 1 (1 June 1960)

(b) Thal-Larsen, H., "Manual Steering of Two Ships in Close Proximity During Replenishment-at-Sea Exercises," contributed by the Automatic Control Div. of ASME for presentaion at ASME winter annual meeting, Los Angeles, Cal. (16-20 Nov 1969)

This appendix presents a review of the analysis of the ship replenishment data, references (a) and (b), summarized in appendix C and carried out by the University of California.

The block diagram (figure 1 of the text) shows the six variables that are of most interest. These variables on the leading ship are defined as σ = rudder angle and β_1 = deviation of gyro angle from the desired course. On the tracking ship, θ = rudder angle, β_2 = deviation of gyro angle from the desired value, x = deviation from the desired separation distance of the two ships, and α = the ordered change in course of the tracking ship. In addition to these variables, also recorded during the full-scale ship trials were the helm angles on both the leading and tracking ships.

The following sign conventions were established for the variables (figure 1-A).



From Tichvinsky and Thal-Larsen (reference (a)).

Figure 1-A - Two Ships Abeam

Since compass readings increase in magnitude when a ship turns to the right, the gyro-angle variables β_1 and β_2 are considered to be positive for a ship turning to the right. The rudder-angle variables σ and θ are assigned positive values for the right-rudder deflections. An increase in separation between the two ships, x, is taken as being in the positive direction. The conning officer and helmsmen produce negative feedback corrections. Thus, α will be negative when x is positive.

Analysis of the data (appendix C, figures 1-C and 2-C was carried out to determine the linear transfer functions (figure 1 of the text).

The 17-knot data (appendix C, figure 1-C) were analyzed first. Figure 1-C shows the approximate phase relationship between the rudder and gyro oscillations for the oiler (AO), USS ASHTABULA, the leading ship. The gyro was approximately 180 degrees out of phase with the rudder. It was determined that the transfer function is nearly equal to

$$\frac{4}{D^2(0.5D + 1)} \quad \text{(gyro degree/min}^{2*}\text{)/rudder degree,} \qquad \text{(A-1)}$$

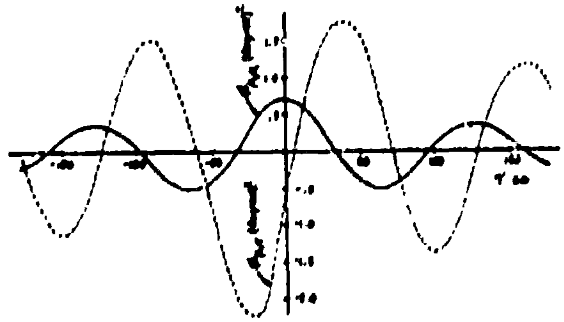
where D = d/dt is the differential operator.

Square-wave-rudder tests, at different frequencies, applied to the ship operating alone, confirmed the K_1/D^2 form of equation (A-1). The additional time constant in equation (A-1) is possibly caused by the destroyer on the starboard beam (references (a) and (b)).

For the helmsman on the oiler (AO) it is necessary to find a transfer function relating the AO gyro curve as input to the AO rudder curve as output. The inverse of the previously determined transfer function, equation (A-1), would quite accurately satisfy the mathematical relationship; the resulting third order derivative, however, would not be physically descriptive of the helmsman.

*Abbreviations used in this text are from the GPO Style Manual, 1967, unless otherwise noted.

A statistical description of the helmsman is provided by the correlation functions in figure 2-A.



From Thal-Larsen (reference (b)).

Figure 2-A
Statistical Input-Output Relationship
for the Helmsman plus Rudder Servo
on the Leading Ship (AO 51) at 17 Knots

The smoothing action of the statistical process involved in calculating these curves produced simple curves. The method by which these curves were computed and their interpretation as equivalent input-output functions is discussed in reference (b). It is sufficient to state here that the solid curves in figure 2-A can be considered as the input angle to the helmsman and the dashed curve the helmsman's response.

From figure 2-A, it is noted that when the ship swings from maximum velocity from one side to the other, the helmsman applies maximum rudder correction to stop that swing. This type of response is termed derivative response. Actually the helmsman is about 10 seconds late, which is about the time it takes him by watching the gyro repeater to estimate when maximum velocity has been reached. Thus, the proposed transfer function model for the helmsman and rudder servo combination becomes

$$-K_2 D e^{-L_1 D} \quad \text{rudder degree/gyro degree} \qquad \text{(A-2)}$$

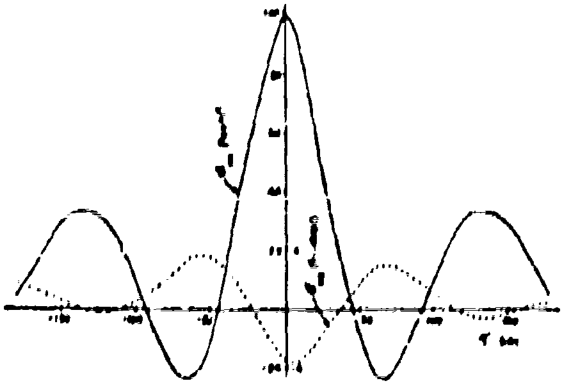
where

K_2 = 1 minute

L_1 = 1/6 minute or 10 seconds.

The minus sign accounts for the rudder action being applied to oppose the swing of the ship.

The statistical curves in figure 3-A may be regarded as input and output curves for the conning officer on the tracking ship.



From Thal-Larsen (reference (b)).

Figure 3-A
Statistical Input-Output Relationship for the Conning Officer on the Tracking Ship (DD 686) at 17 Knots

It was determined that his transfer function is approximately

$$-K_3 e^{-L_2 D} \quad \text{degree course change/feet separation distance change} \qquad (A-3)$$

where

K_3 = 0.04 degree/feet

L_2 = 1/12 minute or 5 seconds.

K_3 was estimated by taking the ratio of the two central peaks of the curves in figure 3-A.

Unfortunately, incomplete data allowed only rough estimates to be made of the transfer functions for the conning officer and the helmsman of the tracking ship. For simplicity it was assumed that the helmsman on the DD, together with the rudder servo, were represented by

$$-K_4 \text{ rudder degree/gyro degree} \quad \text{(A-4)}$$

where K_4 equals approximately two in the frequency range of interest displayed in figure 1-C of appendix C. Evidence from reference (a) and from laboratory tests (reference (b)) indicated a transfer function for the tracking ship (DD) of the form:

$$\frac{K_5 e^{-L_3 D}}{D(TD + 1)} \text{ (gyro degree/min)/rudder degree} \quad \text{(A-5)}$$

where

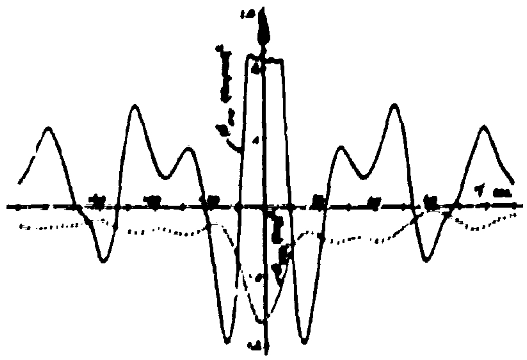
$T \cong$ 1/12 minute or 5 seconds

$L_3 \cong$ 1/15 minute or 4 seconds

$K_5 \cong$ 6 minutes^{-1}

The 25-knot data in figure 2-C were analyzed. It is evident that the helmsman operates the rudder at a more rapid rate compared to the 17-knot case. These statistical curves are used for determining the characteristic properties of the dynamic system.

Figure 4-A shows the statistical input-output curves for the leading ship, an aircraft carrier (CVA).



From Thal-Larsen (reference (b)).

Figure 4-A
Statistical Input-Output Relationship
for the Leading Ship (CVA 14)
at 25 Knots

The two curves are approximately 180 degrees out of phase. It was assumed that a linear transfer function is

$$\frac{K_6}{D^2} \text{ gyro degree/rudder degree} \qquad \text{(A-6)}$$

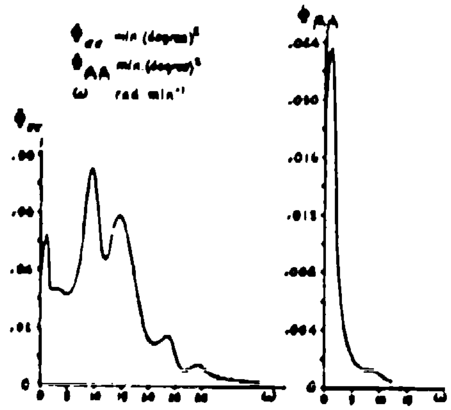
where K_6 is approximately 0.14 (gyro degree/minute^2)/rudder degree.

The helmsman does not have much time to estimate angular velocities of the gyro at the higher speed. It was assumed that the transfer function of the helmsman together with the rudder servo to be approximately

$$-K_7 \text{ rudder degree/gyro degree} \qquad \text{(A-7)}$$

where k_7 varies between 1.4 and 7. Thus, it is possible for the helmsman to compensate for the sensitivity of the ship. This sensitivity decreases with the square of the frequency.

Figure 5-A shows the self spectral density curves for the rudder and the gyro on the leading ship (CVA 14) at 25 knots.



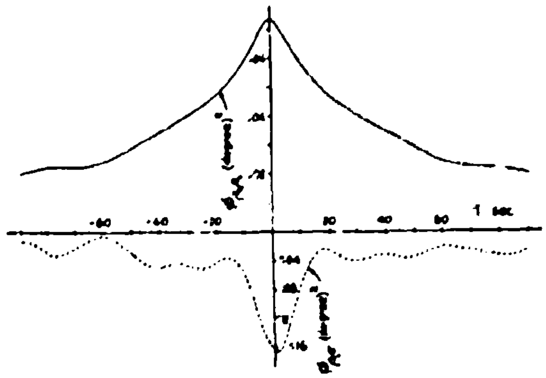
From Thal-Larsen (reference (b)).

Figure 5-A
Self-Spectral Density Curves for the Rudder and the Gyro on the Leading Ship (CVA 14) at 25 Knots

This figure shows that the aircraft carrier is insensitive to relatively high-frequency rudder perturbations. While the spectral density curve for the rudder shows a number of peaks at frequencies above $\omega = 1$ radian/min, no such peaks are seen in the spectral density curve for the gyro in figure 5-A.

The source of the strong spectral density peaks of the CVA rudder at circular frequencies of about 10 and 15 radians/min (corresponding to periods of approximately 40 and 26 seconds, respectively) is not clear. These frequencies are evident in the solid curve in figure 4-A. Also the rudder spectral density curve has small peaks corresponding to frequencies of 15 and 13 seconds, respectively. The 40- and 26-second periods are possibly induced by the action of the sea and the wind. The 15- and 13-second periods are possibly due to the rapid and continuous swinging back and forth of the rudder which gives the helmsman a "feel" for the ship.

The characteristics of the helmsman on the CVA are provided by figure 6-A.



From Thal-Larsen (reference (b)).

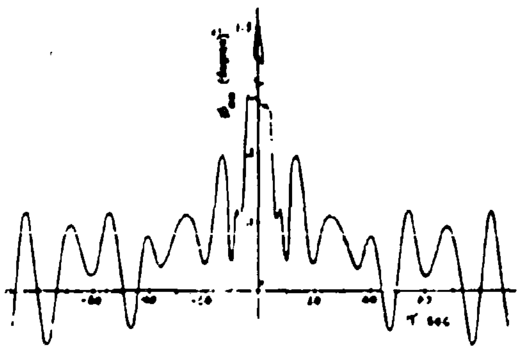
Figure 6-A
Statistical Input-Output Relationship for the Helmsman plus Rudder Servo on the Leading Ship (CVA 14) at 25 Knots

The solid curve, representing the gyro, does not extend enough to display the 6-minute period of continuous oscillation. If the solid curve is regarded as input to the helmsman, the helmsman's response has a gain factor of two. This is more than the 1.4 from equation (A-7) and represents a deviation in the correct direction because of the higher frequency involved in figure 6-A.

It was assumed that the transfer function of the tracking ship (DD) would probably be in the form

$$\frac{K_8}{D^2} \text{ gyro degree/rudder degree} \qquad \text{(A-8)}$$

where K_8 is probably less than 200 (see figure 7-A).



From Thal-Larsen (reference (b)).

Figure 7-A
Statistical Curve for the Rudd[illegible] of the
Tracking Ship (DD 687) at 25 [illegible]ots

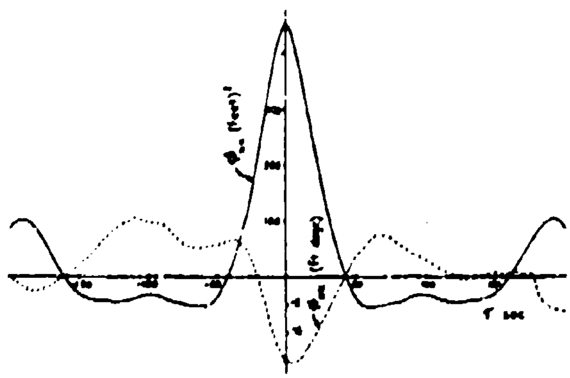
Lack of ship trial test data prevented a more accurate estimate of equation (A-8) as it does for equation (A-9) for the helmsman on the tracking ship.

$$K_9 \text{ rudder degree/gyro degree.} \qquad \text{(A-9)}$$

It was determined from figure 8-A that the transfer function for the conning officer is essentially

$$-K_{10}e^{-L_4 D} \quad \text{degree course change/feet separation distance} \tag{A-10}$$

which is the same form as equation (A-3) for the 17-knot test. K_{10} was found to be approximately 0.01 degree/feet and L_4 nearly equal to 1/12 minute.



From Thal-Larsen (reference (b)).

Figure 8-A
Statistical Input-Output Relationship for the Conning Officer on the Tracking Ship (DD 687) at 25 Knots

As a result of this project being discontinued by the Navy, only incomplete sea trial data were available for this analysis. Nevertheless, the statistically reduced data obtained may be of use to investigators in future work.

APPENDIX B

MODERN UNDERWAY REPLENISHMENT OPERATIONS

This appendix gives a summary of the study made by Captain Lienhard (USN), Commanding Officer of the USS SYLVANIA (AFS 2)* on the effects of constant tensioned wire highlines used during modern underway replenishment operations.

When transferring operations are conducted by conventional wire highline, housefall, or Burtoners, there is a transient effect on steering as the load passes between the two ships. Normally loads transferred by this method do not exceed 3,500 pounds. The maximum line pull will not greatly exceed this amount if a proper catenary is maintained. However, in constant tensioned transfer, the ram tensioner may be set to apply the maximum line pull of 12,500 pounds in the stores ship (AFS), 14,000 pounds in the oiler (AO), or 18,000 pounds in the ammunition ship (AE), for cargo, fueling, or missile transfer station rigs respectively.

The Commanding Officer of the USS SYLVANIA (AFS 2) conducted a survey of the effects of constant tensioned lines on steering over an 18-month period on a variety of different types of customer ships. The Commanding Officer of each customer ship was then asked the effects on his ship's steering. The results are summarized as follows:

- Use of constant-tensioned wire highline produces no greater problem to safe ship handling than conventional wire highline, housefall, or Burtoning.

- Possibly, the hazard may be less for the constant-tensioned wire highline because the tensioned pull is a constant parameter.

In the opinion of the author the principle elements of this new parameter which may cause a steering problem for the leading (delivering) and tracking (receiving) ship are:

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*Lienhard, B. A. (Capt, USN). "Shiphandling in Modern Underway Replenishment," NAVSHIPS Tech News, Vol. 21, No. 4 NAVSHIPS 0900 000 2085 (Apr 1972)

- Amount of pulled tension.

- Location of the attachment points of the rigs in relation to the location of the ship's pivotal points.

- Draft and trim of the ships.

There were also important safety considerations which were mentioned by Captain Lienhard:

- The tracking ship's conning officer can hasten the initial hookup and improve maneuvering safety by coming alongside of the leading ship at no greater than normal replenishment ship separation distance when the lines and rigs are being passed between the ships. Then the conning officer should move the tracking ship out to a greater separation as the tension is applied in the correct amount. The tracking ship can adjust the lateral separation to suit the present situation of speed, wind, and sea, and amount of rudder being carried.

- Once tension is applied on the lines, the conning officers of both ships should be alert to advise each other immediately of a developing situation which might require an emergency breakaway. For personnel safety and elimination of potential ship equipment damage, the leading ship should detension the rig before the tracking ship attempts to release the pelican hook or unshackle and cast off the rig.

APPENDIX C

FULL-SCALE UNDERWAY REPLENISHMENT SEA TRIALS

REFERENCES

(a) Tichvinsky, L. M., and H. Thal-Larsen, "Replenishment at Sea, Experiments and Comments," 1st tech rept issued under the project "Replenishment at Sea," Univ. of California, Berkeley, Inst. of Engrg. Research (now Office of Research Services), Rept 154, Issue 1 (1 June 1960)

(b) Thal-Larsen, H., "Manual Steering of two Ships in Close Proximity During Replenishment-at-Sea Exercises," contributed by the Automatic Control Div. of ASME for presentation at ASME winter annual meeting, Los Angeles, Cal. (16-20) Nov 1969)

The University of California (reference (a) and (b)) carried out full-scale sea trials on underway replenishment. These studies were not complete because the contract was terminated before complete statistical data could be taken. The sea trials consisted of refueling a destroyer USS HALSEY-POWELL (DD 686) by the USS ASHTABULA (AO 51) at 17 knots and replenishing USS UHLMANN (DD 687) by the USS TICONDERGA (CVA 14) at 25 knots. This appendix summarizes the methods used for studying the replenishment operations and gives examples of data from these trials.

During the trials helm angle, rudder angle, and gyro compass heading for both ships were recorded as a function of the time for the exercise while the two ships were abeam. Course commands by the conning officer of the tracking ship and the separation distance of the ships during the exercises were also recorded (See figures 1-C and 2-C.) These eight variables were used for auto- and cross-correlation.

Statistical analysis of the data yielded information on the dynamic response lags at different speeds and of factors affecting human behavior. In addition to the variables mentioned above, the following were found to be significant:

- Automatic pilot data.
- Propeller rpm of both ships.
- Pitch and roll angles of both ships.
- Environmental conditions: weather, sea state, wind, etc.

After analysis of the above mentioned data from the replenishment sea trials, the following summarized conclusions were made:

- The problem of primary importance is station keeping with cargo transfer of secondary importance. Improvements in the station-keeping and cargo handling technique are needed.

- The dynamic interaction between the conning officer and the helmsman is the primary reason for variations in separation distance between the two ships.

- The dynamic interaction between the helmsman and the ship and the hydrodynamic interaction between the two ships must both receive consideration.

- The increase of sensitivity with speed in the man-ship feedback loop results in the rapid increase in perturbation frequency and the corresponding decrease in amplitude with increased speeds.

- The mean rudder angles required by each ship results from the hydrodynamic interaction between the two ships.

- The hydrodynamic interaction between two ships abeam produces an additional lag in the response of the ship to the rudder which makes steering more difficult.

- The lack of knowledge by the helmsman of the hydrodynamic interaction between the ships result in large separation distances at higher replenishment speeds.

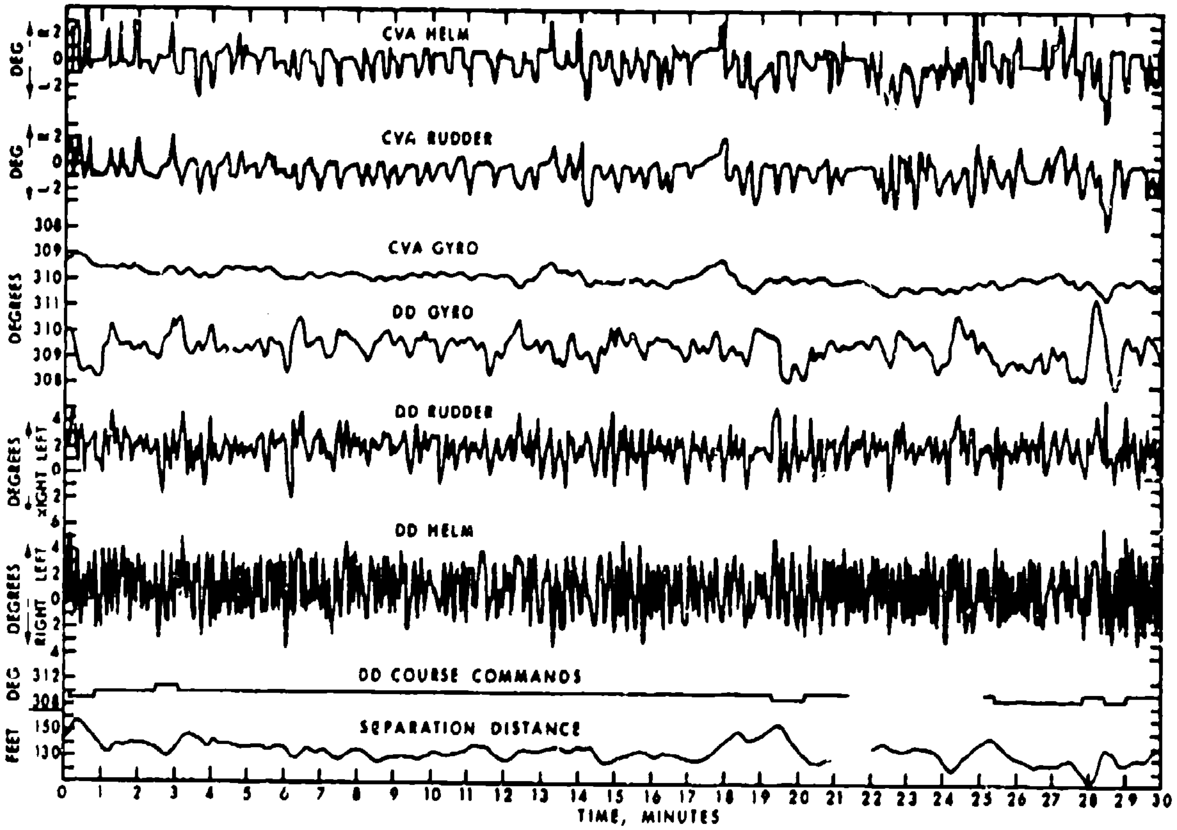
- A mathematical description on a statistical basis of the dynamics of two ships and the helmsmen of the two ships and the conning officer of the tracking ship involved in ship replenishment can be derived.

The following recommendations were offered:

- A means should be developed for instantaneous indication of the relative positions of the two ships at close proximity. This would enable the conning officer to see at once if the two ships are on convergent or divergent courses.

- Further study of the station-keeping problem.

- Experimental and theoretical determination of the hydrodynamic interaction between two ships.

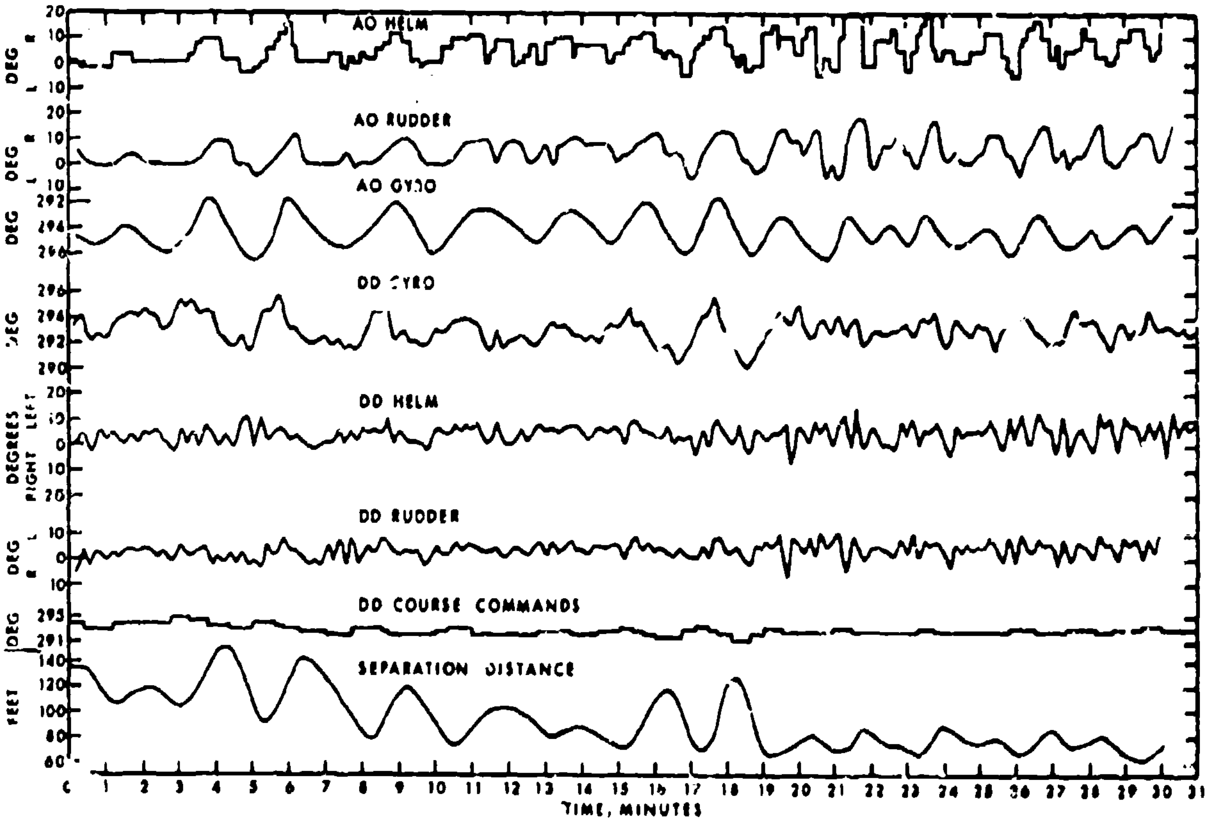


From Thal-Larsen (reference (b)).

Figure 2-C
25-Knot Test Data Abeam
(Leading Ship: USS TICONDEROGA (CVA 14);
Tracking Ship: USS UHLMANN (DD 687))

- Study of the control characteristics at high speeds of two ships during replenishment.

- Investigate the use of strip-chart recorders for helping the helmsman during station keeping.



From Thal-Larsen (reference (b)).

Figure 1-C
17-Knot Test Data Abeam
(Leading Ship: USS ASHTABULA (AO 51);
Tracking Ship: USS HALSEY-POWELL (DD 686))