Simulation of Maneuvering Control During Underway Replenishment

Samuel H. Brown* and Reidar Alvestad†
David W. Taylor Naval Ship Research and Development Center, Annapolis, Md.

In the work presented here, emphasis was placed on performing a sensitivity analysis of the maneuvering control parameters during underway replenishment (UNREP) control simulations. Some approximate nonlinear sea-state excitations acting on the ships' hulls due to a specific irregular sea were added to the simulation model. The mathematical model for both the nonlinear force and moment excitations was developed by using the Volterra series mathematical formalism. The forces and moments were represented during the simulation by time series. The sea state was defined in the UNREP simulation by the Pierson-Moskowitz spectra. Automatic controllers were used on each ship to eliminate human bias. The work indicated that the nonlinear sea-state excitations do not adversely affect the performance of the automatic controller on each ship during UNREP. The sensitivity studies revealed that measurement errors in the range of 3 to 5% in the maneuvering control variables were acceptable under the simulation condition. The good controllability of both ships when using automatic control during UNREP simulations indicated that automatic control should be considered for collision avoidance during UNREP. The results of the simulation sensitivity control variable analysis will be used for engineering judgments in developing a prototype sensing system for maneuvering control during UNREP.

Nomenclature

A = longitudinal separation distance measured between centers of mass of the two ships
B = lateral separation distance between the two ships (side-to-side distance), B_0 = nominal separation distance, $B-B_0=\Delta B$, and $\Delta\dot{B}=\dot{B}-\dot{B}_0=\dot{B}$, since $\dot{B}_0=0$
a_T = gain constant in integral feedback loop
$F^{(n)}$ = term n in functional series
g = gravitational constant
$H(\omega)$ = first-order (linear) transfer function
$H(\omega_1,\omega_2)$ = second-order transfer function
h = wave height (crest to trough) for regular wave
h_n = nth order impulse response function
I_z = moment of inertia about z axis
K_L = feedback gain vector for leading ship
K_T = feedback gain vector for tracking ship
L = ship length between perpendiculars (LBP)
m = mass of ship
n_1 = initial propeller speed (ahead straight-line motion)
Δn = $n-n_1$ (n = propeller speed, $n'=n/n_1$)
N = yawing moment about z axis, ($N'=N/\frac{1}{2}\rho L^3u_1^2$)
r = angular velocity of yaw ($r=\dot{\psi}, r'=rL/u_1$, $\dot{r}'=\dot{r}L^2/u_1^2$)
$S_X(\omega)$ = Pierson-Moskowitz spectrum
$t,\Delta t$ = time and time interval, respectively
u,v = velocity components of the origin of the body axes (longitudinal and transverse components, respectively, corresponding to surge and sway velocity components), ($u'=u/u_1$, $v'=v/u_1$)
u_1 = initial equilibrium velocity component (ahead straight-line motion at constant speed with rudder at amidships, ($u_1'=1$)
Δu = $u-u_1$
$\dot{u},\dot{v}$ = acceleration components of the origin of the body axes, ($\dot{v}'=\dot{v}L/u_1^2$)
V = velocity vector of the origin of the body axes
x,y,z = coordinate axes fixed in ship; origin of axes system need not be at the center of gravity of the ship (positive direction forward, starboard, and downward, respectively)
x_0,y_0,z_0 = coordinate system fixed with respect to the surface of the earth
$X(t)$ = free-surface elevation
X,Y = hydrodynamic force components on ship body (longitudinal and lateral components respectively, ($X'=X/\frac{1}{2}\rho L^2u_1^2$, $Y'=Y/\frac{1}{2}\rho L^2u_1^2$)
ζ = wave amplitude for regular wave
δ = angular displacement of the rudder, δ_0 = nominal rudder angle and $\Delta\delta$ = rudder perturbations about δ_0 (output from digital controller)
$\epsilon(\omega)$ = random phase angle
λ = wavelength of regular wave
ρ = water mass density
$\phi(\omega)$ = phase of first-order system
$\phi(\omega_1,\omega_2)$ = phase of second-order system
ψ = angle of yaw, (ψ_0 = nominal yaw angle, $\Delta\psi=\psi-\psi_0$, and $\Delta\dot{\psi}=\dot{\psi}-\dot{\psi}_0=\dot{\psi}$ since $\dot{\psi}_0=0$)
χ = ship-to-wave heading angle (measured clockwise from x axis in ship-to-wave direction)
ω = radian frequency
$(\ )'$ = nondimensional variable when used as a superscript on variable

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*Project Engineer and Research Physicist, Propulsion and Auxiliary Systems Dept.

†Project Engineer and Electronics Engineer, Naval Research Laboratory, Washington, D.C.

Introduction

THE operational procedure of replenishing ships at sea (UNREP) while steaming on parallel courses is used extensively by the Navy. An analysis of the replenishment operation could determine if alterations of the ship maneuvering and control system could reduce the collision hazard, increase the efficiency, and extend the operating conditions under which UNREP can be performed. Descriptions of fullscale UNREP operations have been published in the literature.[1-3]

The complex dynamic interaction between two ships maneuvering on close parallel courses is not completely understood. This interaction involves the maneuvering characteristics of each ship, the hydrodynamic interaction between both ships, and the skills of the helmsmen and conning officer of both ships.[1-3] Work is being performed by the authors to define and analyze the ship maneuvering control parameters to improve ship control during UNREP. A hybrid computer simulation[4-6] for underway replenishment maneuvering of two Mariner-type ships was developed. Control of rudder angle and propeller shaft speed was effected by human operators or automatic controllers. For each case, the important maneuvering control variables were determined to be heading angle, heading angle rate, longitudinal and lateral separation distance, lateral separation rate, propeller speed, and rudder angle.

The control work reported herein[7] emphasized the use of an automatic controller on each ship for sensitivity studies of maneuvering control variables. During UNREP maneuvering simulations, the leading ship sets a straight course at constant speed and the tracking ship tries to maintain station relative to the leading ship. Using an automatic controller on each ship was one technique of eliminating subjective results due to the skills of the human "operators" when using manual control. The primary objective of the work presented here was to determine the effects of nonlinear sea-state excitations (i.e., sway force and yaw moment acting on the ships' hulls) on the performance of the automatic controller on both ships during UNREP. Previous preliminary work[4-6] indicated that the performance of the automatic controller on each ship was not adversely affected by linear sea-state excitations on the ship's hull. This point will be treated in more detail in future work. The UNREP control simulation results[4-7] are being used for engineering judgments in designing a prototype sensing system for maneuvering control during UNREP.

It was necessary in this work to estimate the transfer functions associated with the nonlinear sway force and yaw moment excitations. Realistic data would be from an unrestrained Mariner moving at constant mean speed in oblique regular waves. The Mariner would also have the contraints of the hydrodynamic interaction effects of another Mariner and an automatic controller. These data do not exist. The only experimental data available to the authors at the time of this work were those taken by Chey[8] at the Stevens Institute of Technology for a single restrained model moving at constant speed in oblique regular waves. Theoretical data for an unrestrained Mariner were calculated by Salvesen[9] from potential theory. These data have not been verified by experiment however, and as a consequence were not used in this work.

Since the data used in determining the transfer functions in this work were from restrained model test data and do not meet some of the criteria mentioned earlier, it probably means that the sway force and yaw moment excitations are approximations. Hence, the amplitudes of the random excitation processes were changed several orders of magnitude and in sign in some of the simulation work to determine if this would significantly degrade the performance of the automatic controller. These changes in amplitude of the time series were made to compensate for the ship motion effects that were neglected in the nonlinear excitations. These simulated nonlinear excitations had the necessary characteristics of being slowly varying random processes with nonzero mean (dc offset). The authors realize that actual ship response to the nonlinear excitations may not be entirely realistic from a hydrodynamic point of view. However, it is concluded that this work gives a good indication of the performance of the automatic controller on each ship when both ships are subjected to nonlinear sea-state excitations, which is the objective of this work.

UNREP Simulation in Irregular Seas

The UNREP simulation incorporates some approximate nonlinear irregular sea-state excitations on the ships' hulls and the hydrodynamic interaction forces and moments acting on both the leading and tracking ships (see Fig. 1). The UNREP simulation is capable of controlling either the leading or tracking ship's rudder and propeller shaft speed "manually" or "automatically," but only automatic control is considered in this phase for lateral control. Longitudinal control was performed manually during the simulation.

Basic Mathematical Model

Since the object of UNREP maneuvering is to maintain a safe lateral and longitudinal separation between two ships traveling on essentially parallel courses, the sway and yaw degrees of freedom were considered most important. The roll and pitch motions were neglected in the UNREP simulation because they have insignificant effects on lateral separation distance and would have added unnecessary complexity to the simulation model.

The ship dynamics model for each of the two identical Mariners used in this study consists of a set of linearized equations in the horizontal plane (surge, sway, and yaw).[7] The nonlinear hydrodynamic interaction forces and moments and the nonlinear effects of the oblique irregular unidirectional sea (4 on Beaufort scale) are added to the model as additional forces and moments. The nonlinear equations for the leading ship are:

Surge Equation

$$(X'_{\dot{u}} - m')\dot{u}' + X'_u \Delta u' = -X'_n \Delta n' \tag{1a}$$

Sway Equation

$$(Y'_{\dot{v}} - m')\dot{v}' + Y'_v v' + (Y'_{\dot{r}} - m'x'_G)\dot{r}' + (Y'_r - m'u'_l)r' = -Y'_\delta \delta - Y'_n \Delta n' - Y'(A,B) - Y'_S(\chi) \tag{1b}$$

Yaw Equation

$$(N'_{\dot{v}} - m'x'_G)\dot{v}' + N'_v v' + (N'_{\dot{r}} - I'_z)\dot{r}' + (N'_r - m'x'_G u'_l)r' = -N'_\delta \delta - N'_n \Delta n' - N'(A,B) - N'_S(\chi) \tag{1c}$$

where

$Y'(A,B)$ = nondimensional hydrodynamic interaction force caused by tracking ship on the leading ship

$N'(A,B)$ = nondimensional hydrodynamic interaction moment caused by tracking ship on the leading ship

$Y'_S(\chi)$ = nondimensional slowly varying, second-order sway force due to sea state (ship-to-wave angle $\chi = 150$ deg)

$N'_S(\chi)$ = nondimensional slowly varying, second-order yaw moment due to sea state (ship-to-wave angle $\chi = 150$ deg)

$Y'(A,B)$ and $N'(A,B)$ depend on the longitudinal separation A, measured between centers of mass of two ships, and lateral side-to-side distance B, measured between two ships' centers of mass. Since the study ships are identical, the interaction force $Y'(A,B)$ and moment $N'(A,B)$ are changed to $-Y'(-A,B)$ and $-N'(-A,B)$ when applied to the tracking ship's maneuvering equations. A and B are constantly calculated and updated in the simulation. The steady-state interaction curves used in this study are for two Mariner ships traveling at 15 knots at different parallel positions (see Figs. 2 and 3 in Ref. 5 for actual curves used in this work). The data for the interaction curves were taken from Calvano.[10]

The basic Mariner study ship's characteristics are presented in Table 1. The hydrodynamic maneuvering coefficients used in this work were previously presented.[5] (The coefficients are taken from the averaging of hydrodynamic coefficients presented at the Twelfth International Towing Tank Conference.[11])

Simulation of Rudder Dynamics

The rate of change of the rudder angle[7] was assumed to be directly proportional to the error signal δ_e. The rate constant K was set equal to 0.50 s^{-1}. The mathematical model and analog computer diagram for the rudder dynamics were designed by C.L. Patterson of the David W. Taylor Naval Ship Research and Development Center.

Limitations of Mathematical Model

The following limitations and basic assumptions[7] apply in developing the UNREP mathematical model:

1) $Y_S(\chi)$ and $N_S(\chi)$ are assumed independent of v, $\dot{v}$, $\dot{u}$, $\dot{\psi}$, and $\ddot{\psi}$ since these variables are kept small by the automatic controller under the conditions of the simulation.

2) The effects of oblique irregular sea on the propeller (propeller loading) and power plant, which affect the ship's longitudinal control during maneuvering, are small. The reliability of X_n, Y_n, and N_n obtained from calculations by Calvano[10] in open seas are uncertain under the conditions of the simulation because the propeller performance in calm-water conditions and in a sea state can be somewhat different.

3) It is assumed that both ships are subjected to the same irregular wave system at any given instant of time.

4) Linear maneuvering equations are used as the basis of the UNREP mathematical model. Current UNREP control simulation work in calm water using nonlinear maneuvering equations as the basis for the mathematical model showed nearly the same results as for the model using linear maneuvering equations.

The major objective of this work is to get an indication of the performance of the automatic controller on both ships to nonlinear sea-state excitations. The automatic controller performance data are then used to determine the sensitivity of the maneuvering control variables. The simulation results presented here are being used for engineering judgments in designing and building a prototype sensor system for maneuvering control during UNREP.

Generation of Sway Force and Yaw Moment Induced on Ship Hull (Slowly Varying, Second-Order)

Background

The fundamental mathematical techniques of the Volterra series were used for generating the sway force and yaw moment time series acting on the ship hull in irregular waves, and have their engineering origins in the field of electrical engineering communication theory. The Volterra series was used so that the non-linear sea-state excitations could be related to the sea-state characteristics. The fundamental ideas used here were first expressed by Wiener[12] over 30 years ago. This work was applied much later to ship hydrodynamics by such authors as Vassilopoulos,[13] Tick,[14] and Hasselmann.[15]

Theory

The present application involves the hypothesis that the sway force and yaw moment acting on a ship hull in oblique irregular waves can be represented by an infinite functional power series[16] (the nonlinear system is assumed time invariant and the kernels thus depend only on time differences):

$$Y(t) = \sum_{n=0}^{\infty} F^{(n)}(t,x) \tag{2}$$

Table 1 Characteristics of Mariner-type study ship[a]

Length	527.8 ft	160.9 m
Beam	76.0 ft	23.2 m
Draft	29.75 ft	9.07 m
Displacement	16,800 tons	16.9×10^6 kg
Block coefficient, C_b	0.6	0.6

[a] The ship's coordinates are assumed to be at the ship's center of gravity (i.e., $x_G, y_G = 0$).

where $F^{(0)}(t,x) = h_0$ (a constant) and

$$F^{(n)}(t,x) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} h_n(\tau_1,\ldots,\tau_n) X(t-\tau_1)\ldots X(t-\tau_n)\,d\tau_1\ldots d\tau_n \qquad (n>0)$$

where

$h_n(\tau_1,\ldots,\tau_n)$ = kernel function (for analytic purposes, symmetric kernels may be assumed without loss of generality)

$X(t)$ = excitation which may be deterministic or stochastic

In application to physical problems the series is truncated after n terms to yield a functional polynomial. The response, $Y(t)$ for a finite number of terms will be mathematically meaningful if the input $X(t)$ is bounded and the kernels are each absolutely integrable. The Volterra series represents a causal physical system.

It is assumed for this work, that the series converges. We shall limit our analysis of the sway force and yaw moment to include excitation effects only through second order ($n=2$) where $X(t)$ in this case is the irregular wave free-surface elevation at a reference point. Equation (3) is the *fundamental mathematical model*[17] and is called a truncated functional power series or functional polynomial. This quadratic series can be used to analyze wave force or moment excitations on the ship hull that are proportional to the wave amplitude or the wave amplitude squared (system is assumed time invariant):

$$\begin{aligned} Y(t) &= Y^{(0)}(t) + Y^{(1)}(t) + Y^{(2)}(t) \\ &= h_0 + \int_{-\infty}^{\infty} h_1(t-t_1)X(t_1)\,dt_1 \\ &\quad + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_2(t-t_1,t-t_2)X(t_1)X(t_2)\,dt_1 dt_2 \\ &= h_0 + \int_{-\infty}^{\infty} h_1(\tau)X(t-\tau)\,d\tau \\ &\quad + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_2(\tau_1,\tau_2)X(t-\tau_1)X(t-\tau_2)\,d\tau_1 d\tau_2 \end{aligned} \tag{3}$$

Tick[14] has called Eq. (3) a time-invariant quadratic system, since it includes both a first-order and second-order term.

The term, h_0 in the truncated series was set equal to zero [see Eq. (3)]. The first-order term $Y^{(1)}(t)$, is the familiar convolution integral for linear, time-invariant systems and can be used to represent the first-order sway force or first-order yaw moment acting on the ship hull. The irregular first-order sway force (and moment) acting on the ship hull generally contain many high-frequency and low-frequency components, and are zero-mean process. These terms were not studied in this work because they were studied earlier[4-6] and considered not to cause a significant control problem under the conditions of the simulation. The primary objective of this phase of the work was to study the effects of the slowly varying, nonlinear sea-state excitations acting on the ship's hull on the automatic controller performance of each ship.

The second-order term $Y^{(2)}(t)$ with the second-order impulse response, is the basic mathematical term that will be used to study the second-order force (and moment) wave excitations throughout this work. The second-order sway force (and yaw moment) each consist of two components: 1) the rapidly varying (high-frequency) second-order component and, 2) the slowly varying second-order component. The rapidly varying sway force (and yaw moment) are a zero-mean process and are neglected in this work. It is the slowly varying component of the sway force (and yaw moment) each containing a (dc offset) nonzero mean, which are believed to cause the ship's large surface excursions, that must be controlled by the rudder.

Slowly Varying Second-Order Wave Excitations

The Gaussian stochastic integral representation[17] will be used to represent the irregular sea:

$$X(t)=\int_0^\infty \cos(\omega t-\epsilon(\omega))\sqrt{2S_x(\omega)\mathrm{d}\omega} \tag{4}$$

where

$S_x(\omega)$ = one-sided wave energy spectrum for irregular sea state (Pierson-Moskowitz wave energy spectrum)
$\epsilon(\omega)$ = uniformly distributed random phase angles from 0 to 2π

Substituting $X(t)$ [Eq. (4)] into the second-order term $Y^{(2)}(t)$ [Eq. (3)] results in the following expression:

$$\begin{aligned}Y_2^{(2)}(t)\cong&\int_0^\infty\int_0^\infty \cos[(\omega_1-\omega_2)t-(\epsilon(\omega_1)-\epsilon(\omega_2))\\&+\phi(\omega_1,\omega_2)]\sqrt{|H(\omega_1,\omega_2)|^2S_x(\omega_1)S_x(\omega_2)\mathrm{d}\omega_1\mathrm{d}\omega_2}\\&+\int_0^\infty\int_0^\infty \cos[(\omega_1-\omega_2)t-(\epsilon(\omega_1)-\epsilon(\omega_2))+\phi(\omega_1,-\omega_2)]\\&\times\sqrt{|H(\omega_1,-\omega_2)|^2S_x(\omega_1)S_x(\omega_2)\mathrm{d}\omega_1\mathrm{d}\omega_2}\end{aligned} \tag{5}$$

where $H(\omega_1,\omega_2)$ is called the second-order transfer function and is defined as

$$H(\omega_1,\omega_2)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(\tau_1,\tau_2)e^{-i[\omega_1\tau_1+\omega_2\tau_2]}\mathrm{d}\tau_1\mathrm{d}\tau_2 \tag{6}$$

The transfer function can be written in terms of the amplitude and phase components as

$$H(\omega_1,\omega_2)=|H(\omega_1,\omega_2)|e^{i\phi(\omega_1,\omega_2)} \tag{7}$$

The first term in Eq. (5) can be used to represent the contribution of the wave frequency pair sums to the second-order wave forces (or moment) excitation. The second term in Eq. (5) will be used to represent the contribution of wave frequency pair sum differences to the second-order wave force (or moment excitations). Following past investigations, we shall call the first term the *rapidly varying second-order term* and the second term the *slowly varying second-order term*.

Estimation of the Transfer Functions

In 1970, Lee[18] calculated the second-order transfer function for forced oscillations of two-dimensional cylinders floating on the free surface. However, a general practical theory does not appear available at this time for determining the general second-order transfer function for an arbitrary ship wave system.

A very general approach using cross bi-spectral analysis for determination of the second-order transfer function $H(\omega_1,\omega_2)$ for ship problems has been discussed by Tick[14] and Hasselmann.[15] This method has the drawback that expensive experimental records from model testing must be taken. From these records, a third-order moment must be determined,[17] and complex mathematical manipulation and computer techniques must be used to determine the transfer function. This method was not used in this work primarily because of the cost.

The synthesis used here, however, deals with the slowly varying nature of the important nonlinear forces (or moments) which can be estimated by an approximate method developed by Newman.[19] This method disregards the rapidly varying second-order forces (and moments) which are not considered to be important in the problem being studied here.

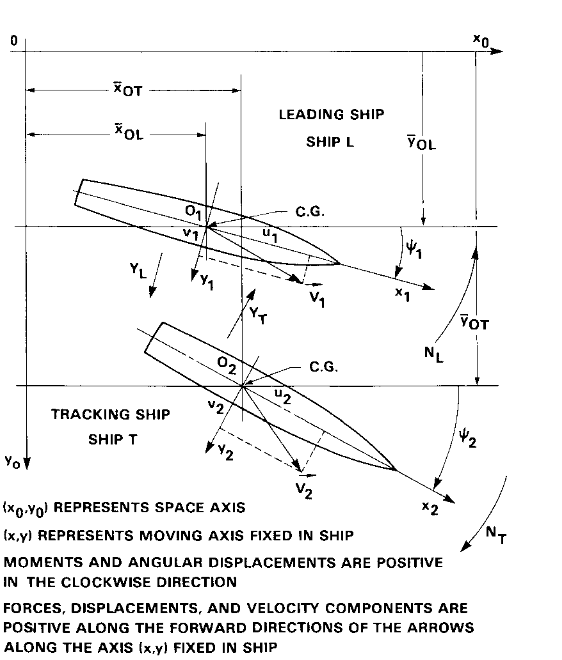
Newman[19] approximates the slowly varying transfer function $H(\omega_m,-\omega_n)$ (which is real for symmetric transfer functions) by approximating the function in the bifrequency plane by its diagonal value $H(\omega_n,-\omega_n)$. These diagonal values can be obtained by model testing involving monochromatic (regular) waves or theoretical calculations involving complex hydrodynamic potential calculations.

In general, however, the error resulting from this approximation cannot rigorously be determined.[19] However, for practical engineering purposes, as in the work presented here, this approximation offers the only possibility for analysis of the slowly varying forces (or moments).

Discussion of Chey's Experimental Data

Completely realistic data would be from an unrestrained Mariner moving at constant mean speed in oblique regular waves. The Mariner would also have the constraints of hydrodynamic interaction effects of another Mariner and an automatic controller. These data do not exist.

These data for estimating the transfer functions associated with the slowly varying sway force (and moment) were obtained from work by Chey[8] and plotted by the authors (see Figs. 2 and 3). Chey presents experimental measurements of the forces and moments acting on a *restrained* series 60 ($C_b=0.60$) ship model (propeller without a driving motor) preceeding in oblique regular waves.



NOTE: The tracking ship is nearly abeam of the leading ship, and both ship's speeds are approximately 15 knots.

Fig. 1 Orientation of leading and tracking ships during UNREP.

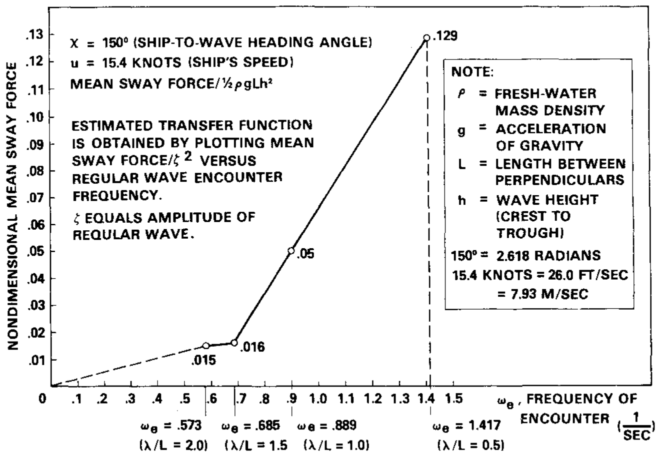


Fig. 2 Nondimensional mean sway force vs oblique regular wave encounter frequency.

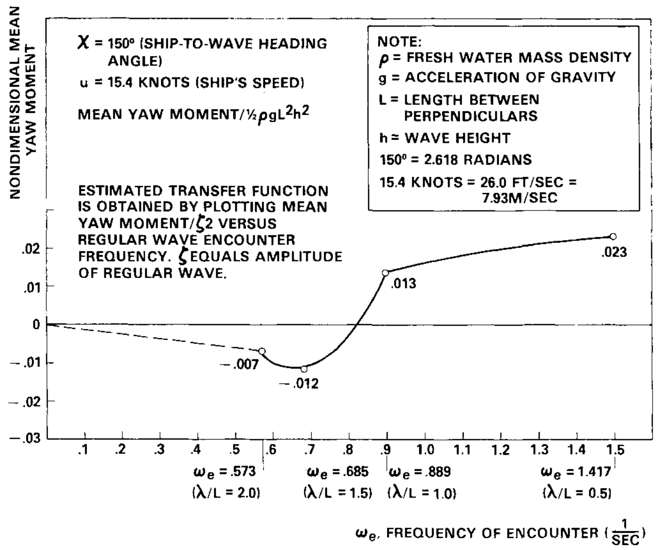


Fig. 3 Nondimensional mean yaw moment vs oblique regular wave encounter frequency.

The experimental results from a restrained ship model were used because they were the only experimental data available to the authors at the time of the work. Lalangas[20] reports that for a ship in beam seas at zero speed, the drift force on a model which is free to move is different from the drift force on a restrained hull.[21,22] Thus, it appears that it would have been more realistic for this work to have experimental data from partially restrained model testing. These data do not meet all the criteria mentioned earlier and are only an approximation also. Experimental partially restrained model data for a single ship were not available to the authors at the time of this work.

Salvesen[9] has calculated the drift force for a Mariner hull at 15 knots with a ship-to-wave angle of 150 deg. Salvensen's calculation uses complex potential-flow-type computer calculations where the model was unrestrained except for surge. Salvesen's data were not used in this work because his theory has not been verified against experimental data. Salvesen's results show that the peak of the drift force occurs at $\lambda/L=1.0$. Chey's data[8] do not show this trend. The difference, however, may be related to the fact that Chey's model test data are for a restrained model and the data are limited.

The limitations in the transfer functions used in this work, however, should not have a large effect on the performance of the automatic controller during the simulation, which is of

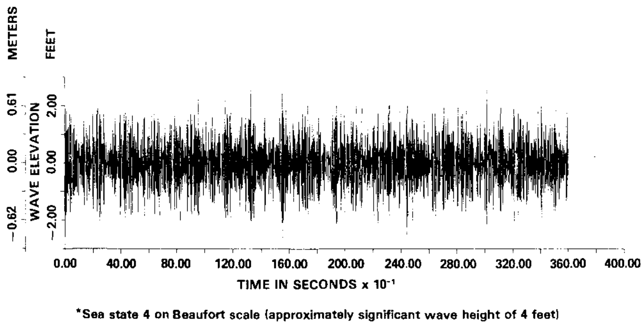


Fig. 4 Stationary seaway represented by waveheight time series.

primary concern in this work. Simulation results discussed later show that the controller is relatively insensitive (several orders of magnitude) to large changes in the amplitude and sign changes of the amplitude in the slowly varying sway force (and yaw moment) excitations.

Sway Force and Yaw Moment Time Series

Digital computer simulation programs developed by Neal[17] by using the second term of Eq. (5) as the basis for the mathematical model, were used to generate the time series of the nonlinear sway force and the nonlinear yaw moment acting on the Mariner study ship where $H(\omega_1,-\omega_1)$ is assumed to approximately equal $H(\omega_1,-\omega_2)$ which is Newman's approximation [see Eq. (7)]:

$$Y_2^{(2)}(t) \cong \int_0^\infty \int_0^\infty \cos[(\omega_1-\omega_2)t-(\epsilon(\omega_1)-\epsilon(\omega_2)) + \phi(\omega_1,-\omega_2)] \times \sqrt{|H(\omega_1,-\omega_1)|^2 S_X(\omega_1) S_X(\omega_2)}\, d\omega_1 d\omega_2 \tag{8}$$

In the computer calculation ω_1 and ω_2 are the encounter frequencies. The computer input required to generate the time series consists of a wave energy spectrum $S_X(\omega)$, and the approximation to the transfer function associated with the slowly varying sway force (or moment).

It is assumed that the oblique irregular seaway in the UNREP simulation is unidirectional and long-crested. The seaway is statistically represented in this work by a Pierson-Moskowitz wave energy spectrum representing a sea-state 4 on the Beaufort Scale. The wave height time series that corresponds to the Pierson-Moskowitz wave energy spectrum[23] is shown in Fig. 4. A digital approximation to the random phase model [see Eq. (4)] was used to generate the wave surfaces with Gaussian distribution properties.

The digital-computer-generated slowly varying hydrodynamic sway force, and the slowly varying hydrodynamic yaw moment acting on the Mariner study ship at 15 knots in a 150-deg (0.524-rad) bow irregular sea (approximate significant wave height of 4 ft), are plotted versus time in Figs. 5 and 6, respectively. The results show that the simulated sway force and yaw moment time series generally appear to have the correct statistics. Both have a dc offset and the frequency is lower than the frequency of the wave height time series (Fig. 4). There are no experimental data available, or known to the authors, with which to compare these results. However, the simulated results seem to indicate that there is some validity in Newman's approximation for estimating the transfer functions.

The Automatic Controller

The automatic feedback control algorithms required for this phase of the project were primarily developed in earlier work.[6] During UNREP maneuvers at sea, the leading ship is charged with maintaining a constant heading while the

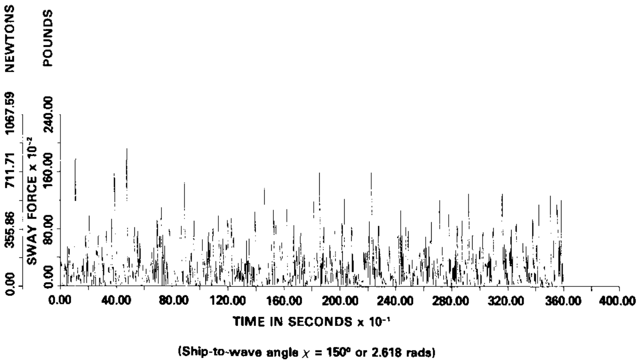


Fig. 5 Hydrodynamic slowly varying second-order sway force vs time for Mariner study ship at 15 knots in oblique irregular waves ($\chi = 150$ deg).

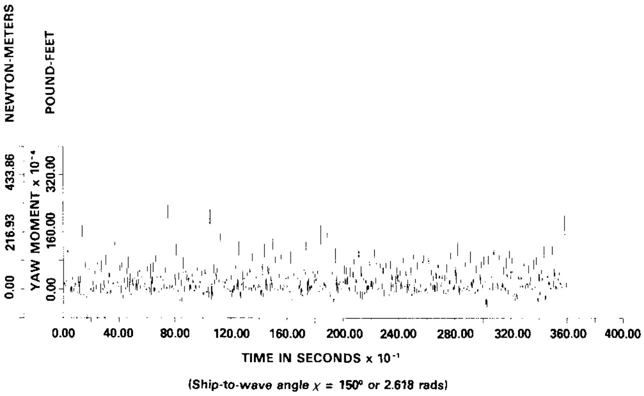


Fig. 6 Hydrodynamic slowly varying second-order yaw moment vs time for Mariner study ship at 15 knots in oblique irregular waves ($\chi = 150$ deg).

tracking ship is responsible for maintaining a constant separation distance. In the hybrid computer simulation, the algorithms for the two ships are adjusted to reflect their different control functions.

The main control law for the digital automatic controller on each ship is as follows:

$$\delta^* = \delta_0 + \Delta\delta \tag{9a}$$

$$\Delta\delta = K_1 \Delta\psi + K_2 \dot{\psi} + K_3 \Delta B + K_4 \dot{B} + a_T \int (\Delta B)\, dt \tag{9b}$$

Integral control was added to the tracking ship to improve the control characteristics, but was not needed for the leading ship. The gains K_L and K_T area as follows:

$$K_L = [20.0 \quad 40.0 \quad 0.0 \quad 0.0] \qquad a_T = 0.0 \tag{10a}$$

$$K_T = [10.0 \quad 35.0 \quad 0.6 \quad 3.0] \qquad a_T = 0.03 \tag{10b}$$

$$\hat{z} = \begin{bmatrix} \Delta\psi \\ \dot{\psi} \\ \Delta B \\ \dot{B} \end{bmatrix} \tag{10c}$$

where L and T represent leading and tracking ship, respectively. It must be kept in mind that all motion variables are actually perturbation variables about the nominal condition. Thus, ΔB represents the actual distance minus the desired distance.

For passing maneuvers, the tracking ship feedback vector was changed to

$$K_T = [20.0 \quad 40.0 \quad 3.0 \quad 14.0] \tag{11}$$

to improve the steady-state error characteristics.

Simulation Results

The simulation results for the irregular sea condition are shown in Figs. 7-10 where both ships' speeds are approximately 15 knots. The interaction data limits the range in side-to-side separation distance from 50 (15.24 m) to 140 (45.72 m) ft. Allowable rudder commands are limited to ± 20 deg. Each of the two ships has a separate automatic controller. On the leading ship, the controller maintains a constant heading, while on the tracking ship the controller's function is to maintain the lateral separation distance at the desired value (100 ft). The controllers are not directly coupled. The maneuvers simulated include stationkeeping, changing lateral station, and the approach and breakaway of the tracking ship. In all subsequent figures, the subscripts L and T denote the leading and tracking ships, respectively.

Figure 7 shows stationkeeping when the ships are abeam of each other ($A = 0$). The slowly varying sway force $Y_s(\chi)$ and slowly varying yaw moment $N_s(\chi)$ induced by the irregular sea on the ship hull are stored on the digital portion of the hybrid simulation as 20-min time series which are input to the ships' dynamic model as forcing functions at half-second intervals. These components are shown on channels 7 and 8 of the figures. The nonlinear interaction forces are also input to the ships' dynamic model, but are now shown on the graph recordings. Figure 7 shows that the automatic controller on each ship performs well in the station keeping mode under the conditions of the simulation (approximately 4 on the Beaufort scale).

Controller performance for a lateral station change command is shown in Fig. 8. The command was made to change separation distance B from (30.48 m) to 125 ft (38.10 m) in 10 s. The controller increases the separation distance to the desired value.

The time series components $Y_s(\chi)$ and $N_s(\chi)$ acting on the ship hull are caused by a fully developed wind-driven (approximately 11-16 knots) sea state (4 on Beaufort scale). To simulate a more severe sea condition, the component force and moment magnitudes were increased by a factor of 3. The resulting simulated maneuver is shown in Fig. 9. Adequate control is maintained, although perturbations on several variables are noticeable. The component force and moment magnitudes are also multiplied by -3 and adequate control was maintained. A sample of these runs were not shown to conserve space.

Figure 10 shows a complete passing maneuver where the longitudinal separation A changes from -550 ft (-167.64 m) to $+550$ ft ($+167.64$ m) in approximately 9 min. A maximum change of about 6 ft (1.83 m) in the lateral separation distance is experienced during the maneuver. The mutual lateral drift reaches approximately 90 ft (27.43 m) during the 20-min run. Since UNREP is generally performed in open water, lateral drift does not present a problem. Even so, lateral drift can be counteracted by adequate course changes on the leading ship.

The simulation results imply that the automatic control device performances are not adversely affected by the slowly varying force and slowly varying moment resulting from the nonlinear frequency interactions of the waves. Accordingly, an increase of three times the slowly varying sway force and slowly varying yaw moment does not appreciably affect the lateral separation distance between the two ships. This in turn suggests that an appreciable error in the evaluation of the nonlinear sway force and moment can be tolerated on the simulation of UNREP operation.

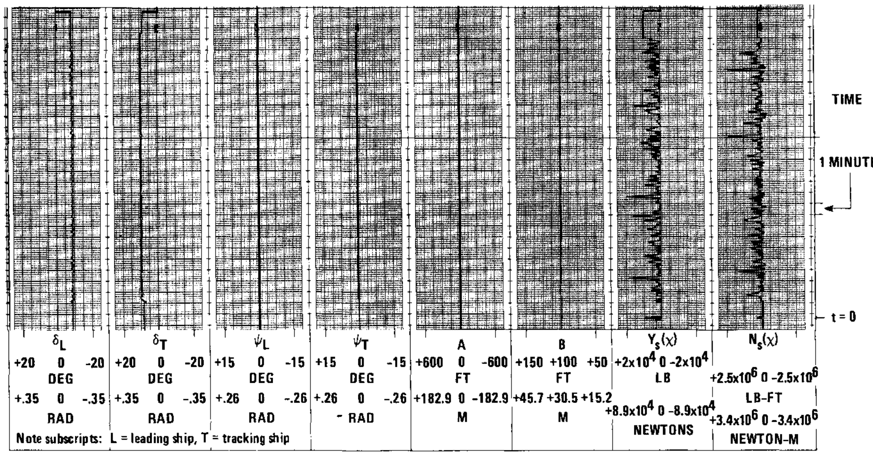


Fig. 7 Stationkeeping with longitudinal separation of $A = 0$ ft.

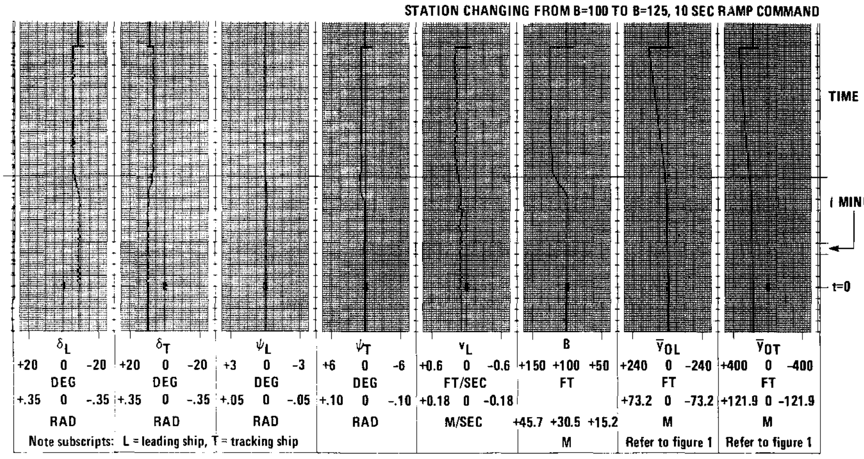


Fig. 8 Stationkeeping ($A = 0$) with change in separation distance (10-s ramp).

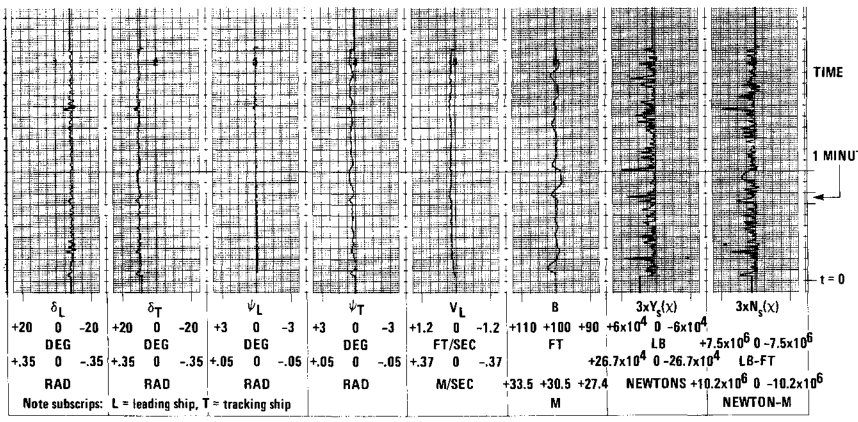


Fig. 9 Stationkeeping ($A = 0$) in high irregular sea.

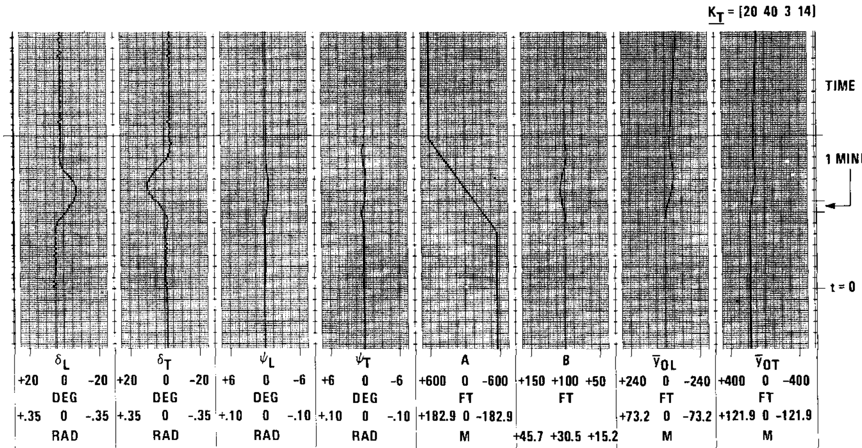


Fig. 10 Passing maneuver where A changes from -550 ft to $+550$ ft

Sensitivity Analysis

A preliminary analysis of controller sensitivity to errors in measurements of the feedback variables was performed in earlier work.[6] However, in the current work,[7] the controller design has been modified with the addition of integral feedback, and some approximately nonlinear irregular sea state excitations. Therefore, sensitivity is again considered, with the following modifications:

1) Since the frequency response cutoff point for the control loop is approximately 1 Hz, only low-frequency drift and dc errors are important.

2) Errors in separation distance were measured in response to a step error (dc) in each feedback variable. This is considered the worst case.

The absolute initial allowable controller error due to step errors in the feedback variables was determined. In each case, the maximum allowable variable error is approximately 5% of the expected maximum value. (The expected maximum value allowed in the simulation are as follows: $\psi_{\max.} = 15$ deg, $\dot{\psi}_{\max.} = 2$ deg/s, $B_{\max.} = 150$ ft, $\dot{B}_{\max.} = 10$ ft/s.) Errors in the maximum value of the control variables much in excess of 5% tend to cause the automatic control to become unstable. The controller functions well with errors up to 5% in the maximum variable value under the simulation conditions.

Since measurement of heading ψ and heading rate $\dot{\psi}$ by current techniques aboard ship seldom leads to step errors, the error in separation distance caused by errors in these variables will generally be less than that determined by the simulation. However, depending on the measurement device, electronic sensor or manual, errors in B and $\dot{B}$ may be discrete, thus possibly leading to step errors. The good performance of the automatic controller on each ship under the conditions of the UNREP simulation are demonstrated since the controllers do not appear to be sensitive to small errors in sensor measurement.

Discussion and Conclusion

Early phases[4-6] of the simulated UNREP control work by the authors revealed that the maneuvering control variables required for display include heading angle, heading angle rate, longitudinal and lateral separation distance, lateral separation rate, propeller shaft speed, and rudder angle. In the underway replenishment work presented in this paper,[7] a sensitivity study of control parameters was performed during simulated UNREP control using an automatic controller on each ship. Nonlinear sea-state excitations acting on each ship's hull were also simulated in this work. The Volterra series formalism was used as the basis for the mathematical model to generate the nonlinear sway force and nonlinear moment excitations. The nonlinear excitations were represented during UNREP control simulations by time series. Newman's approximation was used to estimate the transfer functions associated with the nonlinear sea-state excitations.

Past work[4-6] indicated that linear sea-state excitations were not a control problem under the simulated UNREP conditions. It is planned to study linear sea-state effects in more detail in future work.

The simulated UNREP control gave a good indication that the performance of the automatic controllers would not be adversely affected by nonlinear sea-state excitation under the simulation conditions. The sensitivity analysis of the maneuvering control variables indicated that the sensor noise and measurement errors of 3 to 5% were acceptable under the simulation conditions.

The good ship control performance of automatic control during UNREP simulations was demonstrated. Thus automatic control should be considered for collision avoidance during UNREP. The results of the simulated UNREP control work are being used to aid engineering judgements in designing a prototype sensing system for UNREP.

There are some limitations in the UNREP simulation model.[7] First, nonlinear terms containing the nonlinear maneuvering coefficients were not used in the maneuvering equations that form the basis for the mathematical model in the UNREP simulations. Second, the data used for estimating the transfer functions associated with the slowly varying sway force (and yaw moment) excitations were limited in scope and accuracy. Also, the validity of Newman's approximation has not been rigorously determined. Thus, the authors realize that actual ship response to the nonlinear excitation may not be entirely realistic from a hydrodynamic point of view. However, it is considered that this work gives a good indication of the performance of automatic controllers on each ship when both ships are subjected to nonlinear sea-state excitation, which was the objective of this work. The UNREP simulation technique presented here can easily be adapted to conventional naval surface ships provided that the appropriate hydrodynamic characteristics are available.

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