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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

RUDDER ROLL STABILIZATION

by

Pal Man Park

December 1986

Thesis Advisor George J. Thaler

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Rudder Roll Stabilization

by

Pal Man Park
Lieutenant, Republic of Korea Navy
B.S., R.O.K. Naval Academy, 1979

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requirements for the degree of

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December 1986

ABSTRACT

In recent years, the concept of using the rudder for roll stabilization of a ship in a seaway has been investigated with good results. Such designs have been used to solve the roll problem of a ship on steady course while compensating for yaw perturbations.

To complete a review of the possible design strategies to meet the specifications for this model, the effects of the feedback gains on rolling and yawing are studied in detail. Roll angle and roll rate feedback are used to control the rudder.

Roll stabilization with the rudder in various sinusoidal sea states is studied by simulation on the IBM digital computer. The model used is based on the data obtained from a typical naval ship. The Root Locus method is used to design the feedback gains. The computer simulation programs are written in Digital Simulation Language (DSL/VS), are plotted as data in DISSPLA and include the effects of rudder servo nonlinearities, which seriously restrict the ability of the rudder to reduce roll.

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I. INTRODUCTION

There is a need to reduce roll on various types of ships in order to increase the comfort of the passengers, to provide safe operation of container ships in bad weather and to provide stable platforms for helicopter operations.

Passive or active tanks, or stabilization fins are most commonly used at present to control roll. But both have disadvantages: tanks require a lot of space, fins introduce a considerable drag, are expensive, and also require space for the hydraulic actuators.

Recently there has been a considerable amount of interest in Roll Stabilization systems which use the rudder (RRS), since rudder motions not only affect a ship's heading but influence the roll motions as well. This resulted in the successful installation of a rudder roll stabilization system on some ships of the United States Coast Guard Cutter HAMILTON class (378 foot) as reported by references (1) and (2).

This thesis describes a simple mathematical model for the transfer between the rudder angle and the two outputs : Rate of turn (heading rate) and roll angle. Computer simulations demonstrate results of a design procedure for a combined controller for roll stabilization with the rudder. Models are also provided for the disturbances and the steering machine.

This thesis is organized as follows : Chapter II gives mathematical models of the ship, the disturbances and the steering machine. Chapter III deals with the controller design. Chapter IV gives results of computer simulation and Chapter V summarizes the results giving conclusions and recommendations for further research.

II. MATHEMATICAL MODELING

The motions of a ship in waves depend on

- The dynamics of the ship
- The disturbances and
- The controller output, which is influenced by the steering machine.

A. THE SHIP'S DYNAMICS

In van Amerongen and Van Cappelle, 1981 [Ref. 3: p. F2 1-3], the basic mathematical model was derived which describes the dynamics between the rudder as input signal and yaw and roll as output signals. The results will be summarized below.

The basic equation are :

$$Y = m(\dot{v} - ur). \tag{2.1}$$

$$K = I_x \ddot{\Phi}. \tag{2.2}$$

$$N = I_z \dot{r}. \tag{2.3}$$

where

m	is the mass of the ship, including the mass of the displaced water.
$U = u_i + v_j + w_k$:	Linear velocity vector with components along x, y, and z-axis.
u	is rate of surging.
v	is rate of swaying.
w	is rate of heaving.

$\mathbf{\Omega} = p_i + q_j + r_k$: Vector angular velocity with components about x, y, and z-axis respectively.

p	is rate of roll ($= \dot{\Phi}$).
q	is rate of pitch ($= \dot{\Theta}$).
r	is rate of yaw ($= \dot{\Psi}$).

$\mathbf{F} = x_i + y_j + z_k$: Vector force acting on the ship.

x	is hydrodynamic force along x-axis.
y	is hydrodynamic force along y-axis.
z	is hydrodynamic force along z-axis.

$\mathbf{M} = K_i + M_j + N_k$: Vector moment acting on the ship.

K	is rolling moment about x-axis.
M	is pitching moment about y-axis.
N	is yawing moment about z-axis.

Angular moment $= I_x \dot{p}_i + I_y \dot{q}_j + I_z \dot{r}_k$.

I_x	is mass moment of inertia about x-axis.
I_y	is mass moment of inertia about y-axis.
I_z	is mass moment of inertia about z-axis.

The coordinate system where the above variables are defined is shown in Figure 2.1.

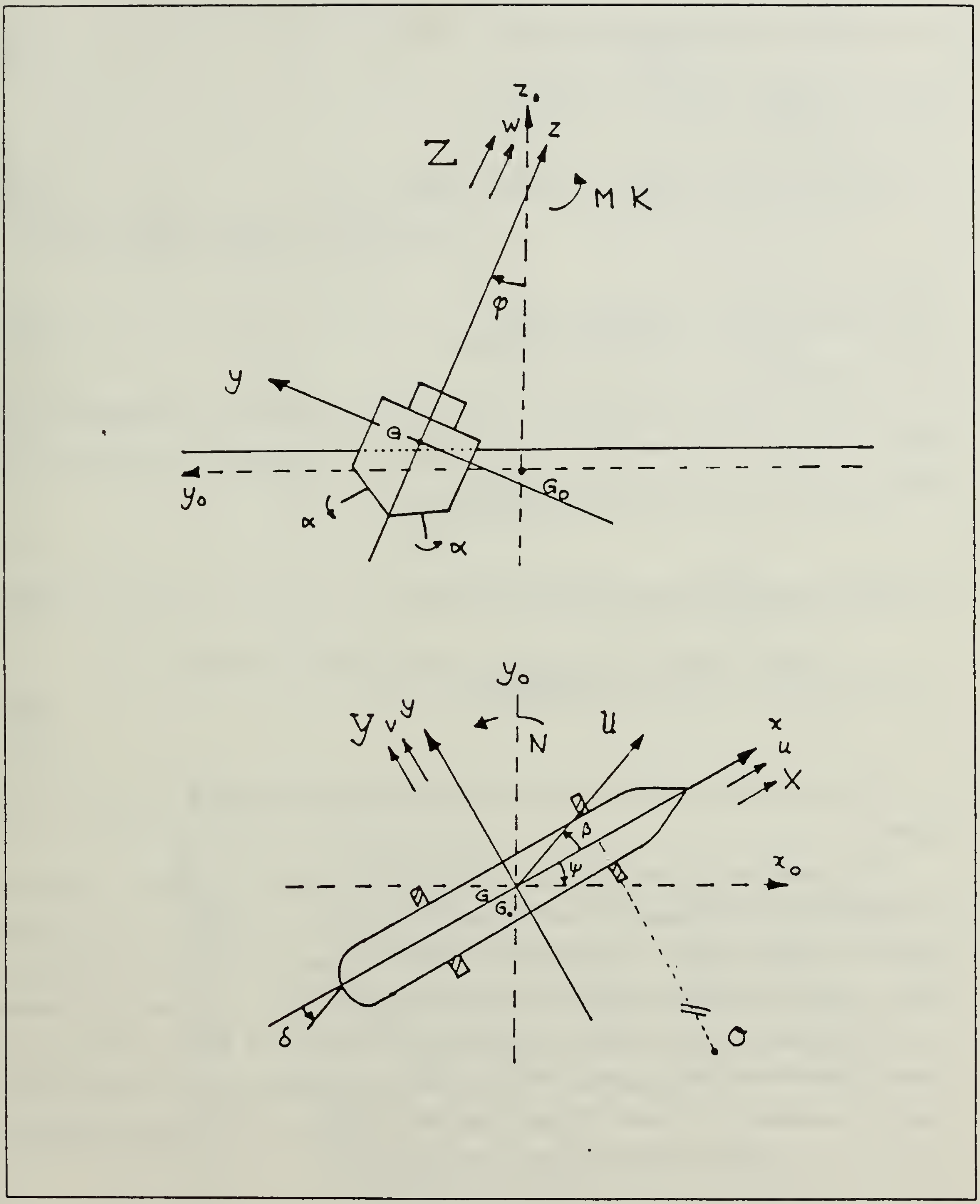

Figure 2.1 Coordinate System of the Ship.

The left-hand sides of equation (2.1) - (2.3) can be expanded into a Taylor series in which the higher - order terms are neglected :

$$Y = Y_v v + Y_r r + Y_\Phi \Phi + Y_\delta \delta \tag{2.4}$$

$$K = K_v v + K_r r + K_\Phi \Phi + K_{\dot\Phi} \dot\Phi + K_\delta \delta \tag{2.5}$$

$$N = N_v v + N_r r + N_\Phi \Phi + N_\delta \delta \tag{2.6}$$

Laplace transform of equations (2.1) - (2.6), substitution of equations (2.1) and (2.4) in (2.5) and (2.6) and substitution of equations (2.2) and (2.3) in (2.5) and (2.6) yield, under the assumption that $\dot v$ is small :

$$\Phi(s) = \frac{\omega_n^{\,2}}{s^2 + 2\zeta\omega_n s + \omega_n^{\,2}} \{K_\delta\ \delta(s) - K_r\ r(s)\}. \tag{2.7}$$

$$r(s) = \frac{1}{s\tau_r + 1} \{N_\delta\ \delta(s) - N_\Phi\ \Phi(s)\}. \tag{2.8}$$

These equations can be illustrated with the block diagrams of Figure 2.2 and Figure 2.3.

The model used in the subsequent analysis was "derived" as follows. First it was assumed that the influence of the rudder on heading rate would not be strongly influenced by roll angle. The conclusion of this assumption is that a heading rate model could be established using only rudder angle as input. The second assumption was that linear models would be sufficient to identify the major features of the dynamics that would be required. With the further assumptions that the roll dynamics could be modeled as a second order system with inputs of rudder and heading rate only, the trial model looks like equation (2.7) and (2.8).

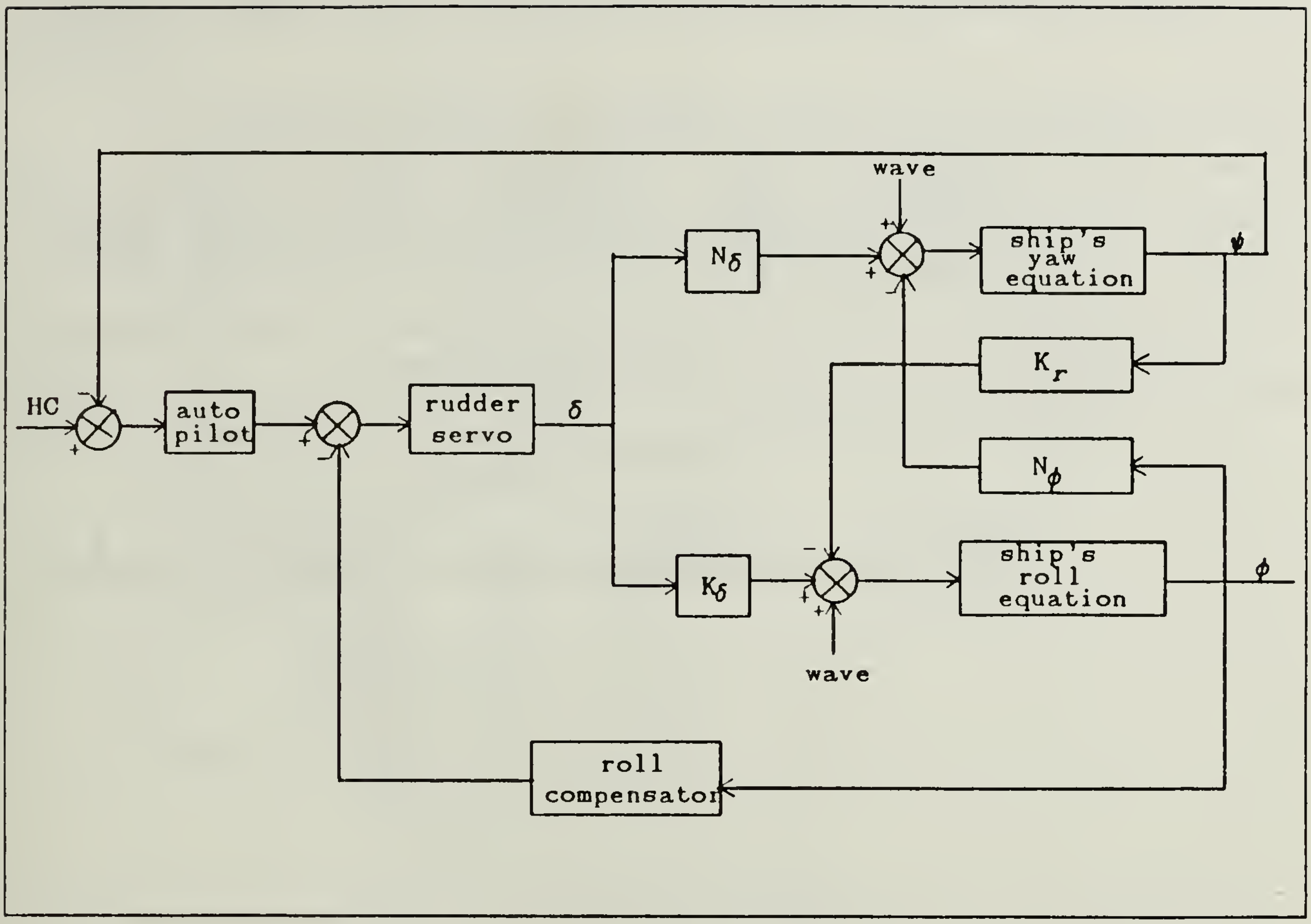

Figure 2.2 Block Diagram for Ship and Control System (With Compensator).

where

Φ	is rolling angle.
r.	is heading rate.
δ	is rudder angle.
N_δ	is a constant relating rudder angle to heading rate.
K_δ	is a constant relating rudder angle to rolling.
K_r	is a constant relating heading rate to rolling.
N_Φ	is a constant relating rolling rate to heading rate.
τ_r	is the time constant of the heading rate system.
S.	is the Laplace transform variable (= d/dt).
ζ	is the damping ratio of the roll dynamics.
ω_n	is the natural frequency of the roll dynamics.

The parameter values of this model have been estimated from full-scale trials with a naval ship. Table 1 gives some results [Ref. 4: p. 44]. Note that N_Φ has been assumed to be zero.

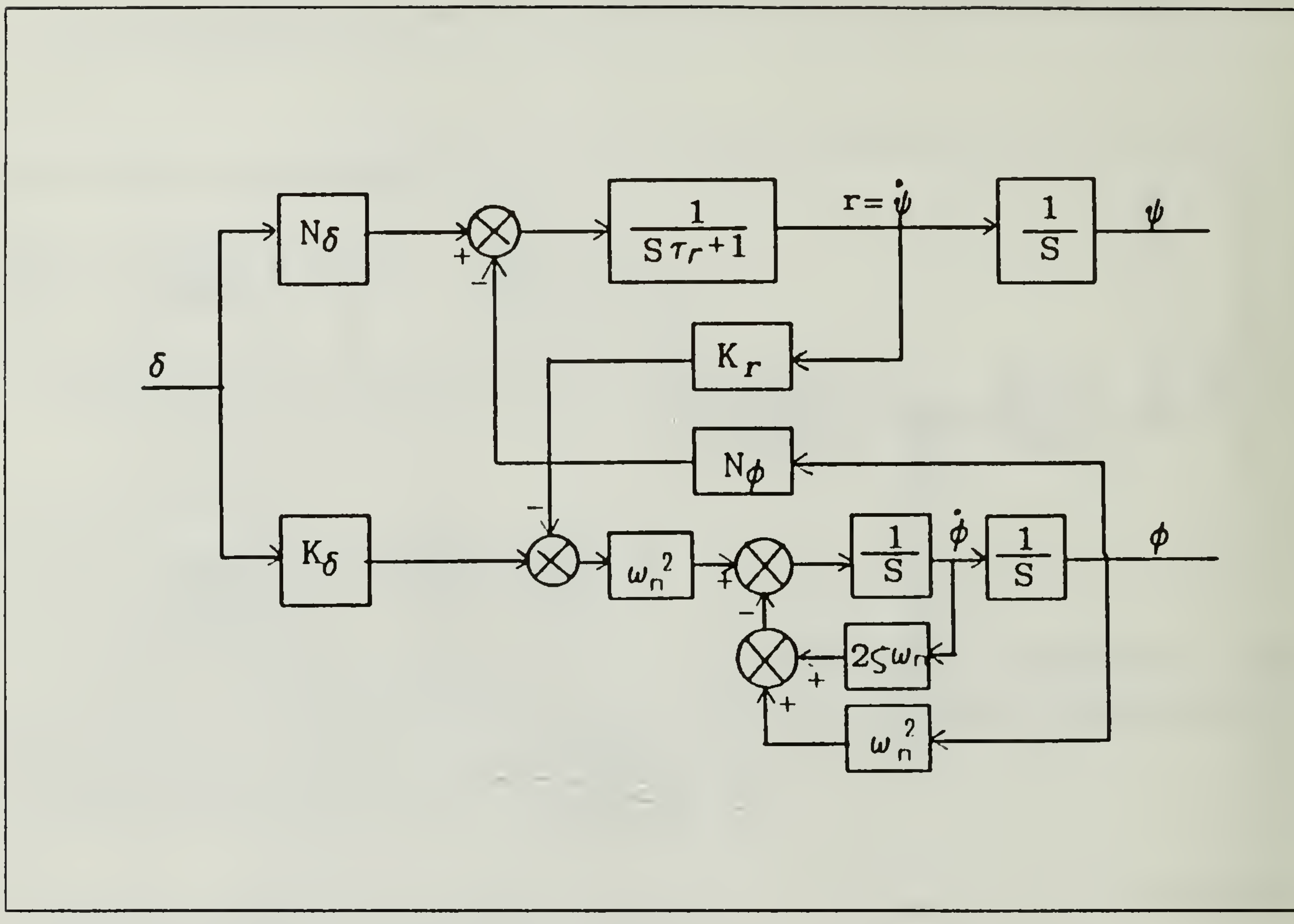

Figure 2.3 Block Diagram of the Dynamics between Rudder and Yaw and Roll (Without Compensator).

TABLE 1

PARAMETERS FOR A NAVAL SHIP

	at 13 knots	at 17.5 knots	at 20.5 knots
N_δ	0.050	0.077	0.087
K_δ	0.13	0.20	0.25
K_r	4.2	4.9	5.3
τ_r	6.8	6.7	5.9
ζ	0.18	0.18	0.22
ω_n	0.59	0.59	0.58

(Note : All the above coefficients assume that the basic unit of time is the second. The basic unit of angular displacement can be either radians or degrees without altering the coefficients. However, for convenience, in the remainder of this thesis all angles will be in degrees.)

It is interesting to compare the coefficients obtained for the naval ship in Table 1 [Ref. 4: p. 44], with those of a ship for which a Rudder-Roll-Stabilization has apparently been successfully implemented. The comparison data contained in Table 2 was obtained for the CONFIDENCE from John R. Ware [Ref. 1: p.11]. There is a remarkable similarity in most of the parameters, there is a slight difference in the coefficient relating rudder angle to turn rate. Clearly, the CONFIDENCE will turn much more rapidly, with a consequent reversal of the rudder induced roll.

TABLE 2

PARAMETERS FOR CONFIDENCE MODEL

	at 16 knots
N_δ	0.175
K_δ	0.17
K_r	4.57
τ_r	8.0
ζ	0.195
ω_n	0.565

B. THE DISTURBANCES

Waves are the most important disturbance with respect to roll. They can be described by means of a frequency spectrum, for instance the Bretschneider Spectrum [Ref. 5], or the Pierson-Moskowitz Spectrum [Ref. 6]. However, these models of the sea state are not conveniently used for the design of a roll stabilizing compensator. In this thesis the wave disturbance used is a single frequency sinusoid, with ω = 0.5 rad/sec which is the natural frequency of the ship in roll. This disturbance is used to cause roll motion, and the compensator is adjusted to provide maximum reduction in roll amplitude.

Two methods are used to verify the behavior of the system over the range of frequencies in a normal sea state. These were

(1) A number of single frequency sinusoids, of different frequencies and properly adjusted amplitudes were used individually to determine the spectral response as in Figures 4.21 through 4.25.

(2) To approximate a real sea, eight sine waves of appropriate frequencies and amplitudes were added and the resulting wave used to check the roll suppression, as shown in Figures 4.3 through 4.12.

C. THE STEERING MACHINE

In order to reduce the roll motion of a ship using its rudder, the steering system must meet certain economic, hydrodynamic and machinery criteria. These criteria can be met by using as much of the existing expensive steering system machinery as possible, thus voiding most of the capital and maintenance costs associated with conventional roll stabilizers.

When the rudder is going to be used for reduction of roll motions it should be able to follow frequencies near the natural roll frequency, ω_n, without a noticeable phase lag. The steering machine used can be described by the simplified block diagram of Figure 2.4a, and autopilot can be described by the block diagram of Figure 2.4b.

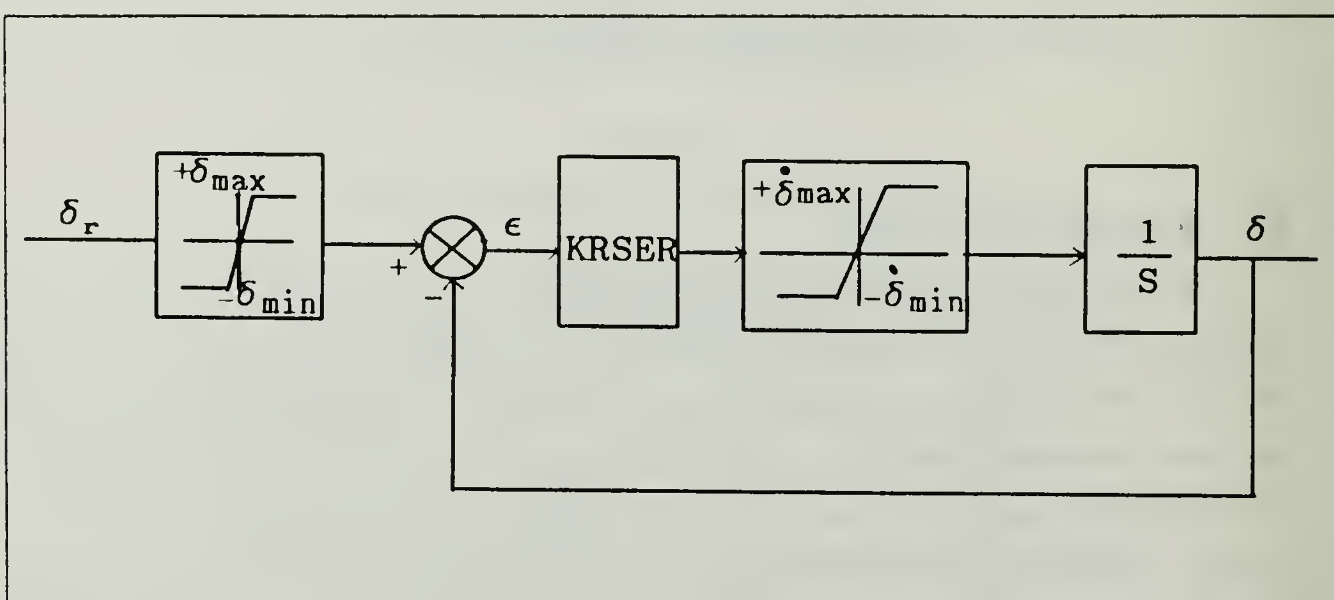

Figure 2.4a Block Diagram of the Steering Machine
KRSER = 10.0.

A positioning system is used to position the rudder for small signal operation. Its bandwidth should be much larger than that of the ship. In order to prevent a phase lag, the angle of rotation and the angle rate have limits.

The rudder angle limit is determined either by the mechanical construction of the steering machine or is set by the autopilot. The rudder rate limit is determined by the construction of the steering machine and by the number of hydraulic pumps which are in operation.

In the design of the controller care must be taken to ensure that the derivative of the output signal of the controller is less than the maximum rudder rate in order to prevent phase lag.

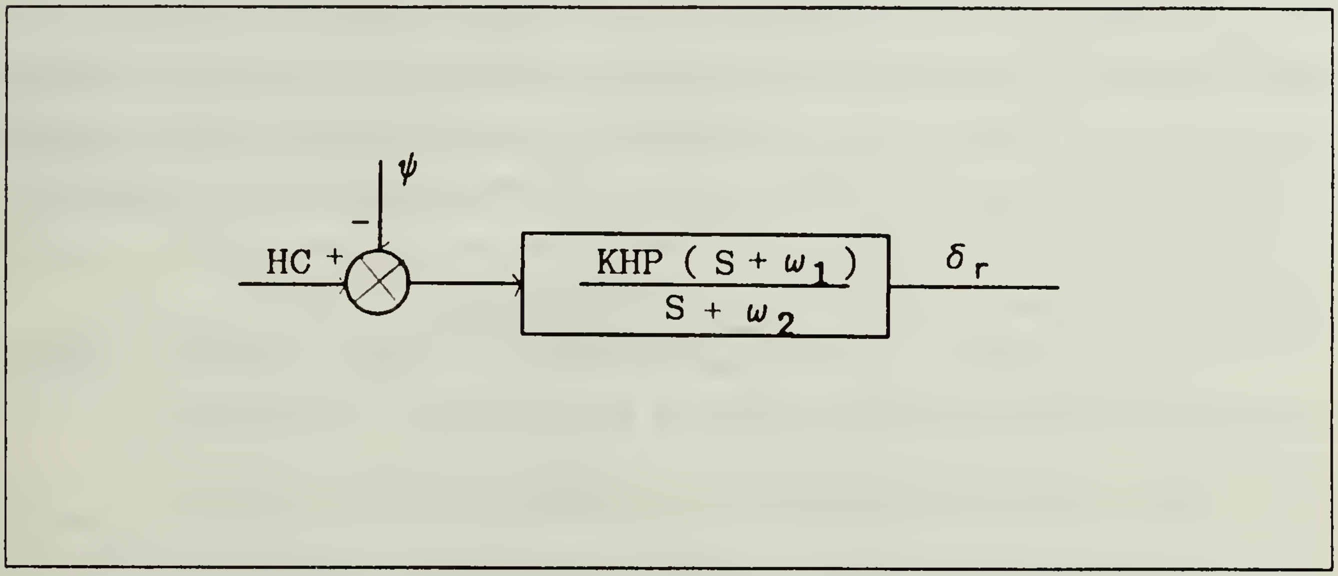

Figure 2.4b Block Diagram of the Autopilot
KHP = 40000.0, ω1 = 0.025, ω2 = 1000.0.

III. CONTROLLER DESIGN

A. INTRODUCTION

The primary objective of this chapter is to present procedures for the design and compensation of the wave input to roll output control system. Compensation is the adjustment of the system in order to limit the maximum roll magnitude.

The approaches to control system analysis and compensation used in this thesis are the Root-locus approach and the frequency-response (Bode) approach. The system was tested in 2 phases. In the first phase, the uncompensated system is tested by adjusting the frequency of the wave input. The wave function was generated as a sinusoidal input. Since both roll angle and roll rate are easily measured on ship, it was proposed that these be fed back to provide roll damping.

The system which may be designed by a trial-and-error approach is checked to see whether the designed system satisfies a desired maximum roll magnitude.

B. ROOT-LOCUS APPROACH TO CONTROL SYSTEM DESIGN

The Root-Locus method is a graphical method for determining the locations of all closed loop poles from knowledge of the location of the open loop poles and zeros as some parameter (usually the gain) is varied from zero to infinity.

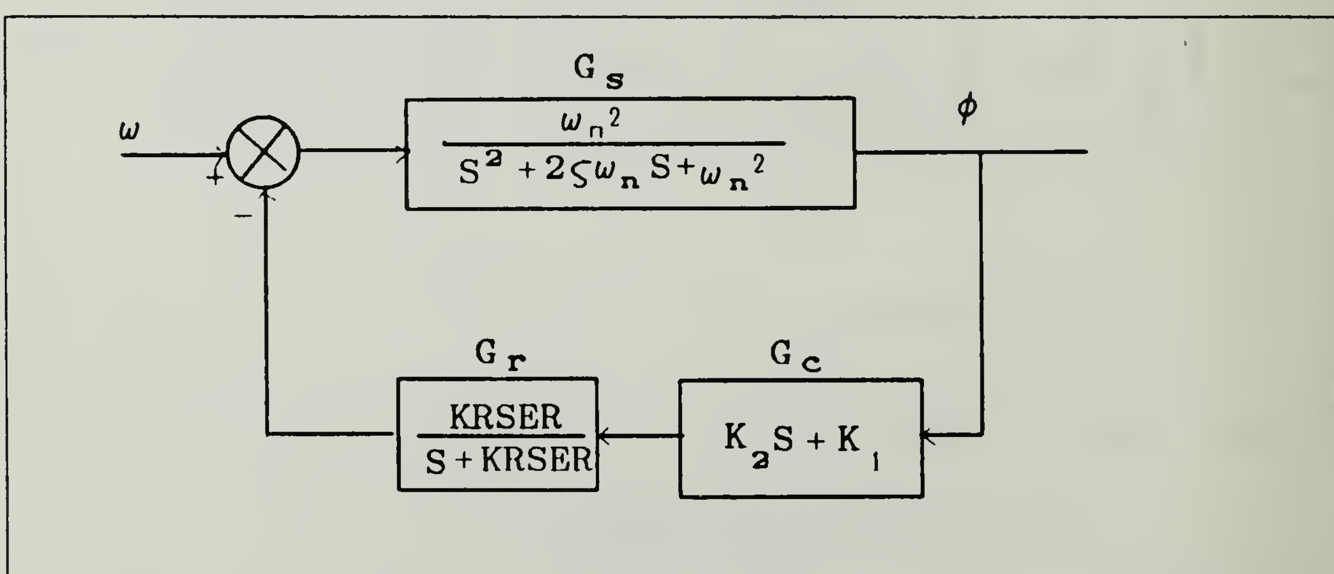

Figure 3.1 Block Diagram Manipulation for Root Locus Method (Wave Input to Roll Output).

In Figure 3.1

$$\omega_n = 0.59$$

$$\zeta = 0.18$$

$$KRSER = 10.0$$

In Figure 3.1, the transfer function of the roll compensator, G_c, should be

$$G_c(s) = K_2 * S + K_1 = K_2(s + K_1/K_2). \tag{3.1}$$

In order to solve this problem, the Root-locus method was used to check the feasibility of this proposal. First, the ship's dynamics are expressed as a rolling transfer function. That is, the feedback term is neglected.

In Figure 3.1, the roll to wave transfer function, G_s, is

$$G_s(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{0.3481}{s^2 + 0.2124s + 0.3481} \tag{3.2}$$

Also, we can get the Root Locus for the roll transfer function. The result is Figure 3.2.

The rudder servo is very fast compared to the natural frequency of the ship's rolling mode, and the transfer function of the rudder servo, G_r, may be approximated as

$$G_r(s) = \frac{KRSER}{S + KRSER} = \frac{10}{S + 10} \tag{3.3}$$

The loop transfer function, G_{lo}, is

$$G_{lo}(s) = \frac{3.481(K_2 s + K_1)}{(s + 10)(s^2 + 0.2124s + 0.3481)} \tag{3.4}$$

Note that the open loop has three poles and one zero. The poles are at fixed locations, and the location of the zero can be chosen as desired. This leads to a Root-Locus as shown on Figure 3.3, where the location of the zero has been chosen arbitrarily to illustrate the behavior of the roots. The actual location of this zero is determined by the coefficients K_1 and K_2. Root locations are changed by setting the gain K_2. Proper choice of K_1 and K_2 determines the ζ and ω_n of the roots and the damping of these roots is, of course, the damping of the ship roll motion.

The closed loop transfer function, G_{cl}, is

$$G_{cl}(s) = \frac{0.3481(s+10)}{s^3 + 10.2124s^2 + (2.4721 + 3.481K_2)s + 3.481(1+K_1)} \tag{3.5}$$

From equation 3.5:

The zero at S=-10 should have little or no effect, since it is outside the bandwidth. Therefore the response depends on the roots of the denominator and on the D.C gain.

From equation 3.4:

When we feedback roll + roll rate, we change the location of the zero. So the range of the zero is from "0" to "10.0" in calculation. For a small zero the root locus will have a loop near the origin, will go to the real axis, then out to the asymptote at about -5.0. When the zero is out near -1.0, the Root-Locus from the complex poles will not go to the real axis, but will stay complex as it goes to the asymptote.

The best we can do is use the rudder to improve the damping of the roll. Then small zeros are not useful because we do not want to change ω_n.

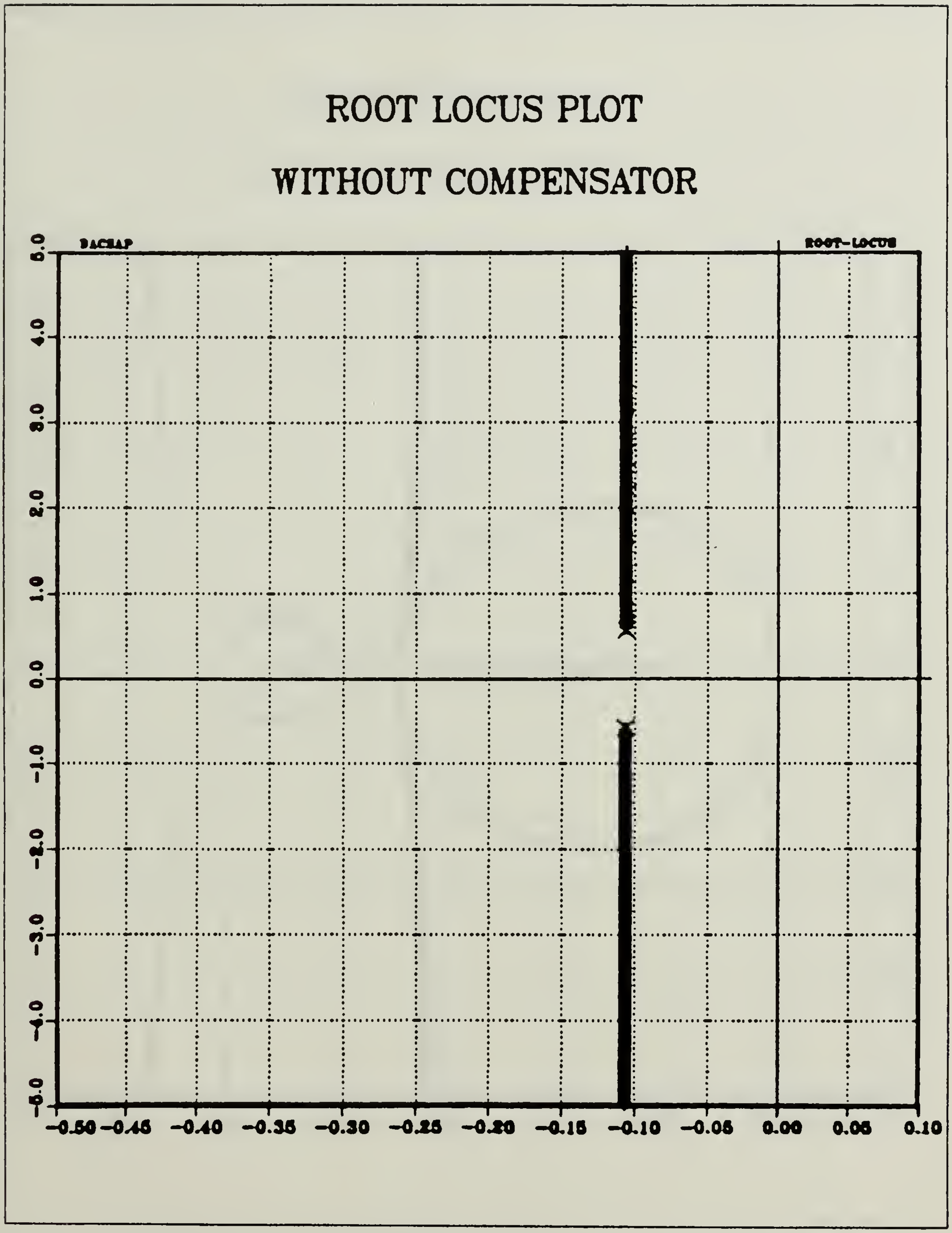

Figure 3.2 Root Locus for Wave to Roll (Without compensator).

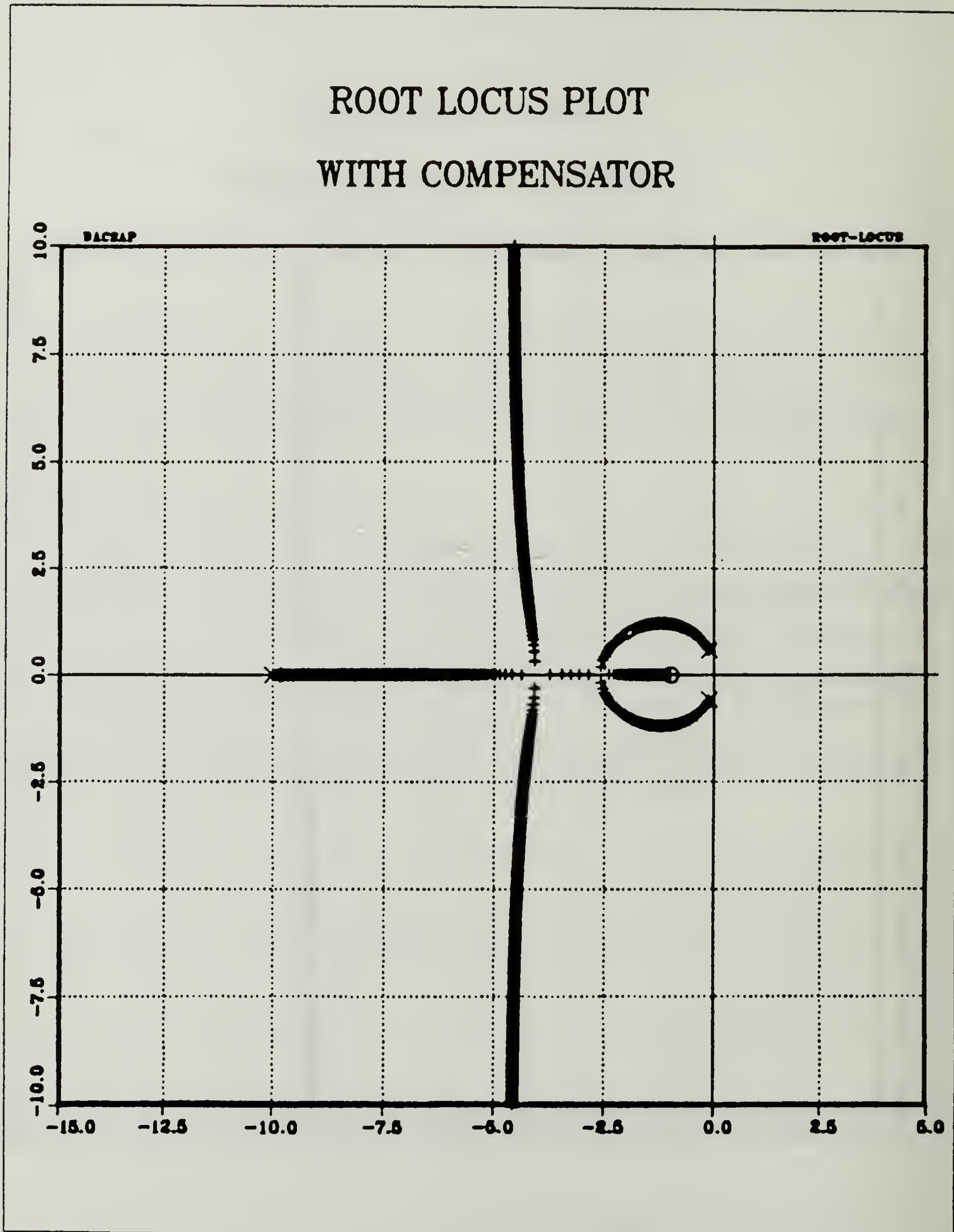

Figure 3.3a Root Locus for Wave to Roll
(With Compensator)
$z = 1.0,\ K_1 = 4.0,\ K_2 = 4.0.$

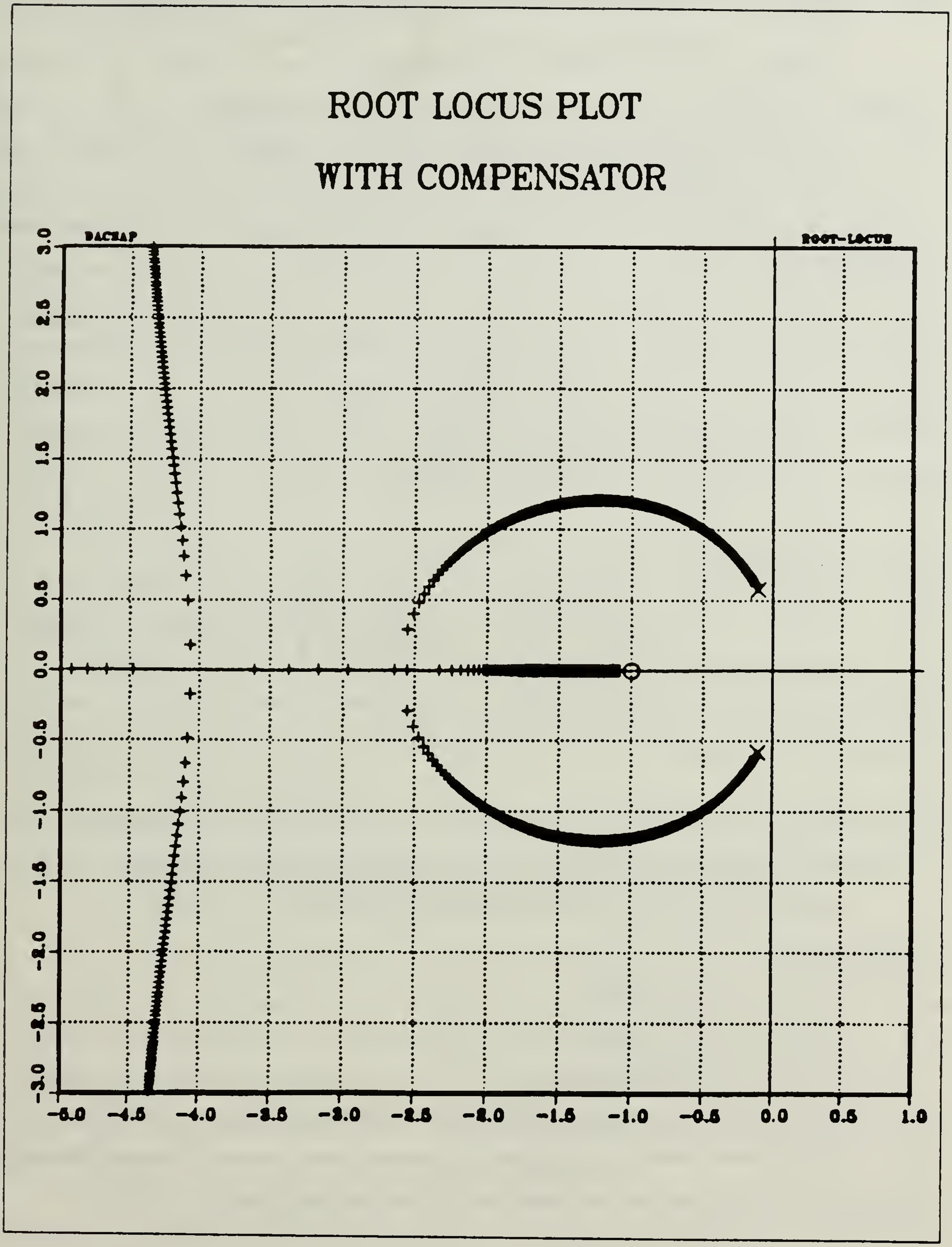

Figure 3.3b Root Locus for Stabilized Model (Main Part)
(With Compensator)
$z = 1.0$, $K_1 = 4.0$, $K_2 = 4.0$.

C. FREQUENCY-RESPONSE (BODE) APPROACH TO CONTROL SYSTEM DESIGN

In dealing with the problem of compensating control systems via frequency-domain techniques, we control the transient-response behavior in terms of such frequency-domain specifications as phase margin, gain margin, resonant peak value, and bandwidth. Design in the frequency domain is indirect because the system is designed to satisfy these frequency-domain specifications rather than time-domain specifications.

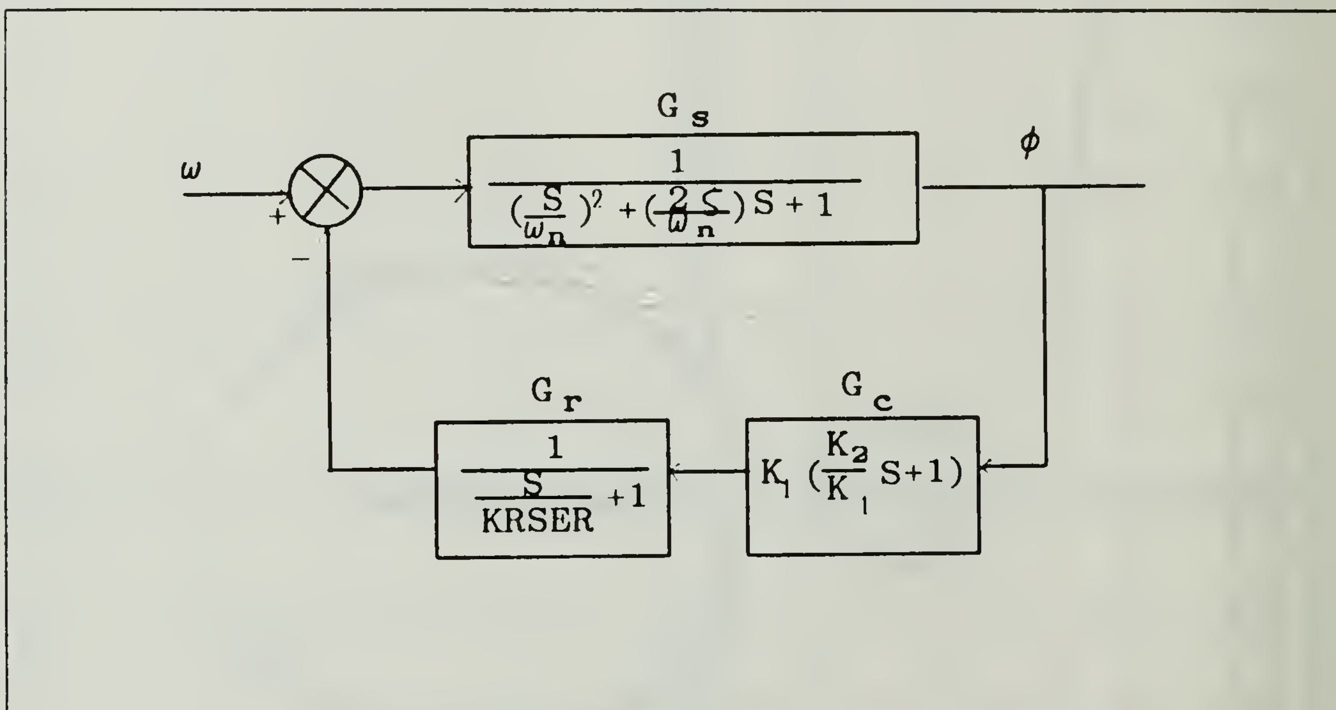

Figure 3.4 Block Diagram Manipulation for Bode Method (Wave Input to Roll Output).

In Figure 3.4

$\omega_n = 0.59$

$\zeta = 0.18$

KRSER = 10.0

From the block diagram on Figure 3.4, the closed loop contains a rudder servo, and a compensator block to stabilize the system and provide damping of system response to the wave input. The loop transfer function, G_{lo}, is

$$G_{lo}(s) = \frac{K_1\{(K_2/K_1)S + 1\}}{(0.1S + 1)(2.8727S^2 + 0.6102S + 1)} \tag{3.6}$$

If $K_1 > 1$, then Bode gain increases and the gain crossover changes accordingly. The transfer function, equation 3.6, for $G_{lo}(s)$ can be written as

$$G_{lo}(s) = [\ K_1\ \{\frac{S(K_2/K_1)+1}{(S/10)+1}\}\{\frac{1}{(S^2/0.3481)+(0.2124/0.3481)S+1}\}] \quad (3.7)$$

That is, the feedback (G_c) and rudder servo (G_r) transfer functions can be combined to have the algebraic form of a lead filter. Also, we can get the frequency responses (Bode diagram). The results are Figure 3.5 to Figure 3.7. Figure 3.5 shows the uncompensated roll to wave frequency response and Figure 3.6 and Figure 3.7 show the roll to wave frequency responses (open loop and closed loop) with compensator ($K_1 = 4.0$, $K_2 = 4.0$). From this, it was observed that the ship has a natural frequency of in roll 0.59 radians per second which corresponds to a period of 10.65 seconds.

Then the effect (seen on the Bode diagram in Figure 3.6) of any gain, K_1, is to raise or lower the |G| curve. Raising the |G| moves the gain crossover to higher frequency, regardless of the location of the zero of the filter.

The purpose of the filter zero is to increase damping of the roll frequency. To do this we want to introduce positive phase at the gain crossover. If we put the zero at a frequency lower than the gain crossover (caused by the gain K_1), we increase the bandwidth which is undesirable.

However, if we place the zero at a higher frequency, we increase the damping (phase margin) by a reasonable amount without appreciable increase in bandwidth.

These results are essentially the same as shown by Root-Locus analysis.

In Figure 3.6, the pole of the rudder servo becomes a zero of the closed loop, and the effect of compensation is to move the real root and complex roots to new locations, presumably with larger negative real parts for the complex roots. If the increase in gain has been small, on the root locus the roots have not moved very far.

Therefore the real effect of the compensator has been to move the complex roots. The effect can be seen on the closed loop Bode diagram.

The above implies that roll would be reduced at low frequency, though not very much, but would be reduced substantially in the range of frequencies near resonance.

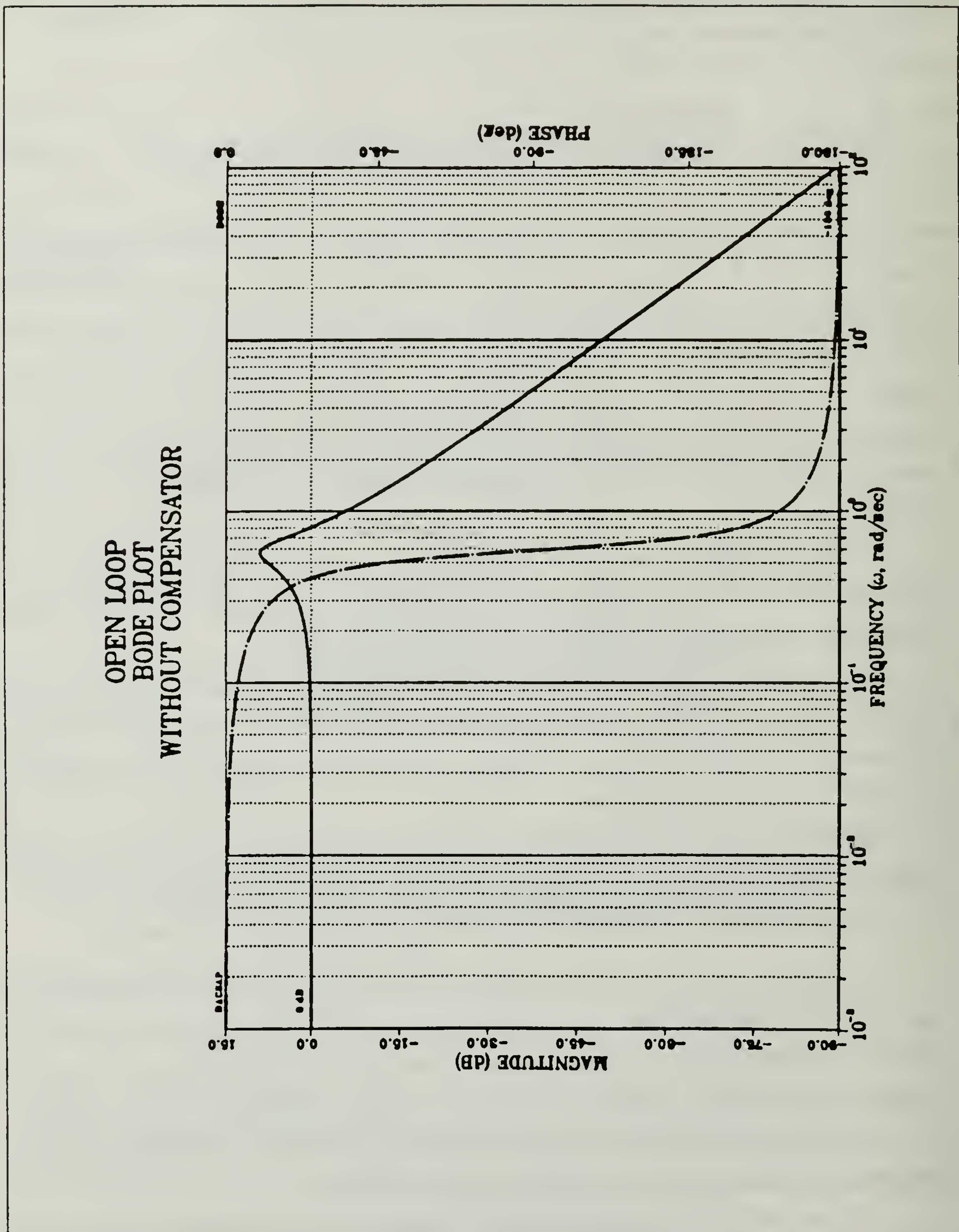

Figure 3.5 Frequency Response for Wave to Roll (without Compensator).

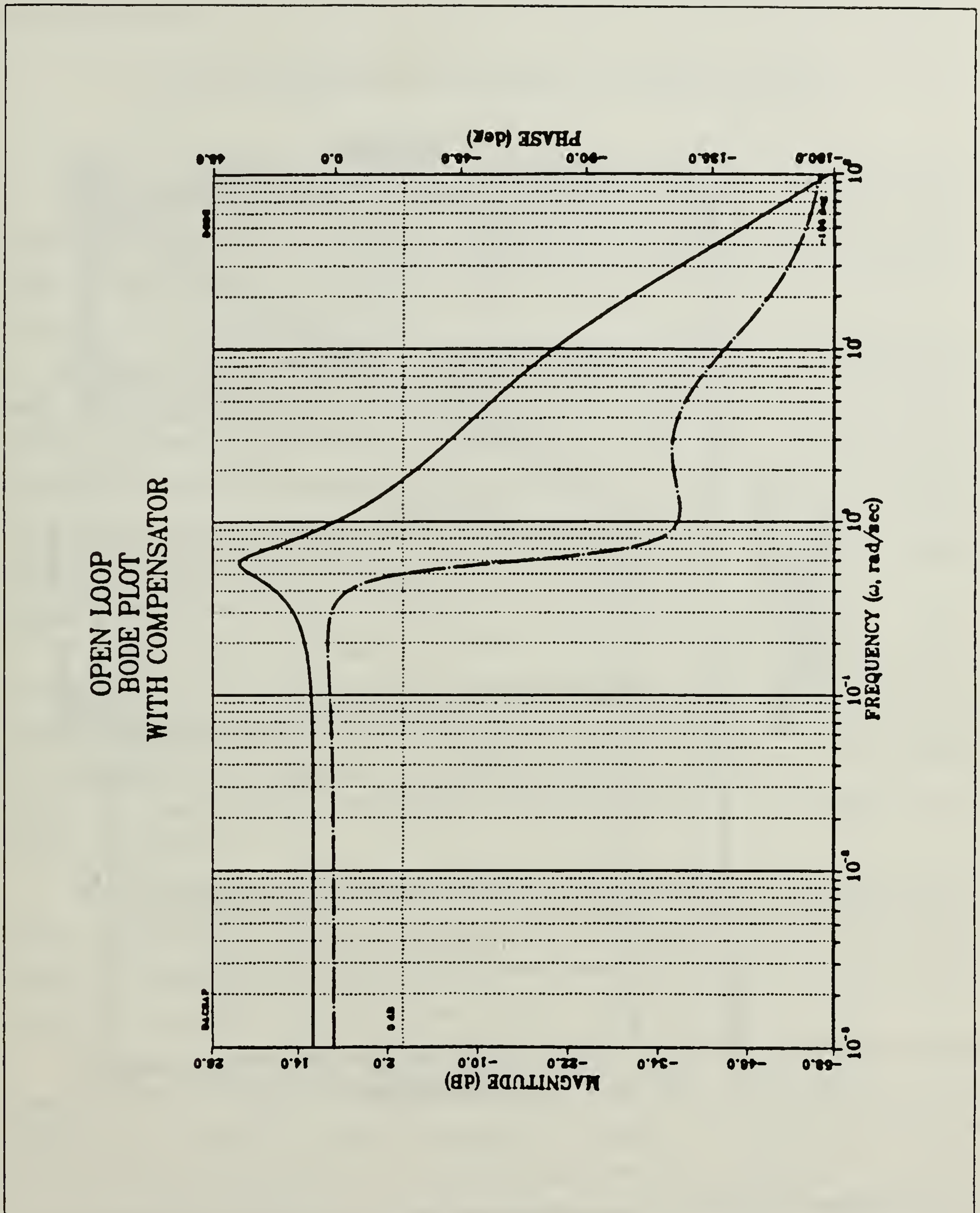

Figure 3.6 Frequency Response in Open Loop for Wave to Roll (With Compensator)

$Z = 1.0, K_1 = 4.0, K_2 = 4.0.$

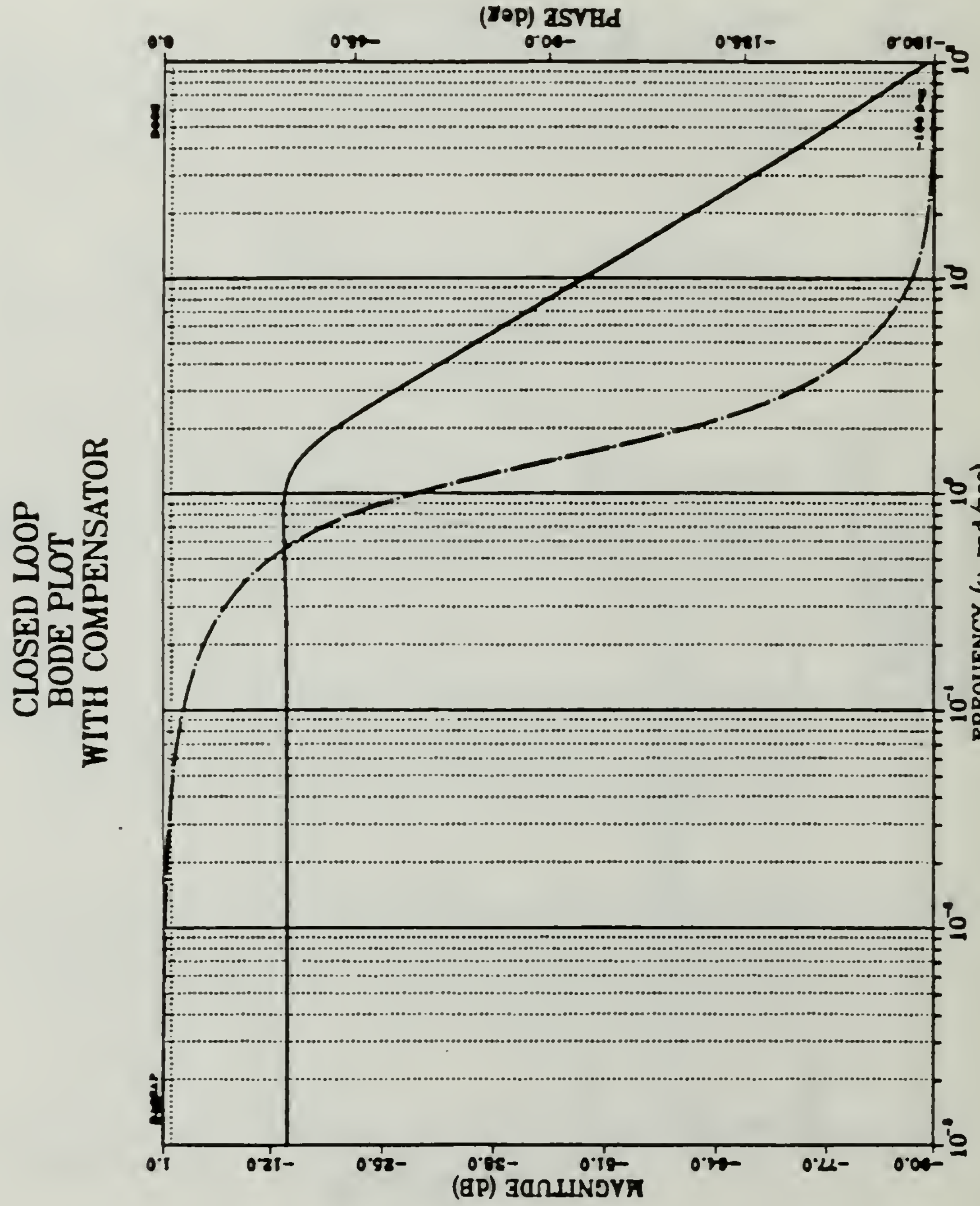

Figure 3.7 Frequency Response in Closed Loop for Wave to Roll (With Compensator)
$Z = 1.0,\ K_1 = 4.0,\ K_2 = 4.0.$

IV. THE RESULTS OF COMPUTER SIMULATION

A. SIMULATION TEST STUDIES

This chapter will give a few results of the computer simulations. During the computer simulation, the parameter values used in this thesis are taken from in Table 1 with ship speed at 17.5 knots. The autopilot gain constant and rudder servo gain constant are given in Figure 2.4.

The wave disturbance was generated as a sinusoidal input which produced a roll angle of ± 20 degrees in the open system at the resonant frequency which is 0.5 rad/sec. This was used for analysis and design. A complex wave consisting of a sum of sinusoids of different frequencies and amplitudes (see program, Appendixces E and F) was used to test the chosen designs. The test waves are shown in Figure 4.1. These input waves were used to drive the 'open system', the system with ideal rudder, and the system with real rudder.

Figure 4.2 used the single sine wave to test the system with ideal rudder. Response of the compensated system is compared with that of the uncompensated system. In the ideal system with compensator in this reduces the maximum roll angle to approximately ± 9 degrees. So the roll reduction is 55 percent. The numerical results are given in table 5 in Appendix I. System response to the complex wave is given in Figure 4.3.

It appears that a considerable reduction with ideal rudder (approximately 71 percent : $Z = 2.0$, $K_1 = 8.0$, $K_2 = 4.0$) can be obtained, while the heading deviation is increased a small amount. However, it appears that a rudder angle of ± 32.6 degree and rudder speeds of ± 16.3 deg/sec are required to achieve this.

In practice there are limitations on both the maximum rudder angle and the maximum rudder speed. The maximum rudder angle limits the maximum moment which can be applied. Figures 4.4 through 4.8 compare the behavior of the open system with that of the rudder roll stabilized ship when the rudder angle is limited to ± 20 degrees and the rudder rate limit is ± 10 deg/sec. Each Figure shows the effect of a different compensation design. The system of Figure 4.5 appears to have minimum rudder activity and minimum yawing, but (from Table 5, Appendix I) the maximum roll angle is slightly larger than for the other design.

Data for various real rudder rate limits and various rudder angle limits were obtained and are given in Table 5. From this table, we can summarize the results as shown in Table 3 :

TABLE 3

MINIMUM VALUES OF Φ_{MAX} WITH DIFFERENT ZERO LOCATIONS

$\omega = 0.5$

$\dot{\delta}_{max}$(deg/sec)	δ_{max}(deg)	Z	K_1	K_2	Ψ_{max}	Φ_{max}
5.0	5.0	1.0	4.0	4.0	0.2	17.9
	10.0	1.0	4.0	4.0	0.5	16.2
	20.0	1.0	4.0	4.0	0.6	17.4
	30.0	1.0	4.0	4.0	0.8	17.4
10.0	5.0	1.0	4.0	4.0	0.3	17.7
	10.0	1.0	4.0	4.0	0.6	14.9
	20.0	1.0	4.0	4.0	1.0	10.5
	30.0	1.0	4.0	4.0	1.2	9.0
15.0	5.0	1.0	4.0	4.0	0.3	17.7
	10.0	1.0	4.0	4.0	0.6	14.8
	20.0	1.0	4.0	4.0	1.1	10.5
	30.0	1.0	4.0	4.0	1.4	9.0
20.0	5.0	1.0	4.0	4.0	0.3	17.6
	10.0	1.0	4.0	4.0	0.6	15.0
	20.0	1.0	4.0	4.0	0.6	10.5
	30.0	1.0	4.0	4.0	0.6	9.0

It is clear that considerable reduction in roll angle can be achieved. A major requirement is high rudder rate. However for a given rudder rate good roll reduction can be obtained with several locations of the compensator zero. It may also be observed that roll reduction is accompanied by increased yawing unless the rudder rate is quite high. Thus a number of options are available.

Maximum rudder rate is determined by the design of the rudder actuator system, but rudder rate less than the maximum could be set in the autopilot. In like manner rudder angle limits can be set in the autopilot, and with proper design the feedback gains K_1 and K_2 can be made adjustable. Thus it is possible to design a rudder roll stabilization system which has considerable capability for roll reduction, but permits the user to choose the specific operating condition.

Figures 4.9 through 4.12, shows system response for different feedback gains (K_1 and K_2) with the same zero location when a complex wave causes rolling. Rudder activity and yaw motion are compared with that which would result if no stabilization was used.

Figures 4.13 through 4.16 show the effect of rudder rate on the maximum roll angle when the maximum rudder angle is limited. It is clear that for small rudder angle limits there is very little reduction in roll angle, and the rudder rate and zero locations have no noticeable effect. As the rudder angle limit is increased greater roll reduction becomes available providing the rudder rate is increased. From Figure 4.16 it is seen that maximum roll reduction is obtained when both rudder angle and rudder rate are maximum. Under these conditions the location of the compensator zero is important and from the data available it appears that the zero locations should be in the range of $1.5 < Z < 2.0$.

Figures 4.17 through 4.20 give a simulation study of the effects of roll stabilization on ship yawing. It is seen that those conditions which provide maximum roll reduction also result in increased yawing. Thus the user must choose operating values which best suit his needs in a particular sea state.

Design of the roll stabilization was accomplished by considering rolling motions at the natural frequency only. To verify the results, the system was tested at a number of frequencies within the wave spectrum. Results are illustrated in Figures 4.21 through 4.25. Rolling is maximum when the system is 'open system' ie, no stabilization. Suppression of roll is greatest with an ideal rudder. When the rudder angle and rate are limited the effectiveness of the stabilization is reduced. A high rudder rate is essential, and if this is combined with a large rudder angle, roll reduction is significant over the entire spectrum.

B. SIMULATION RESULTS

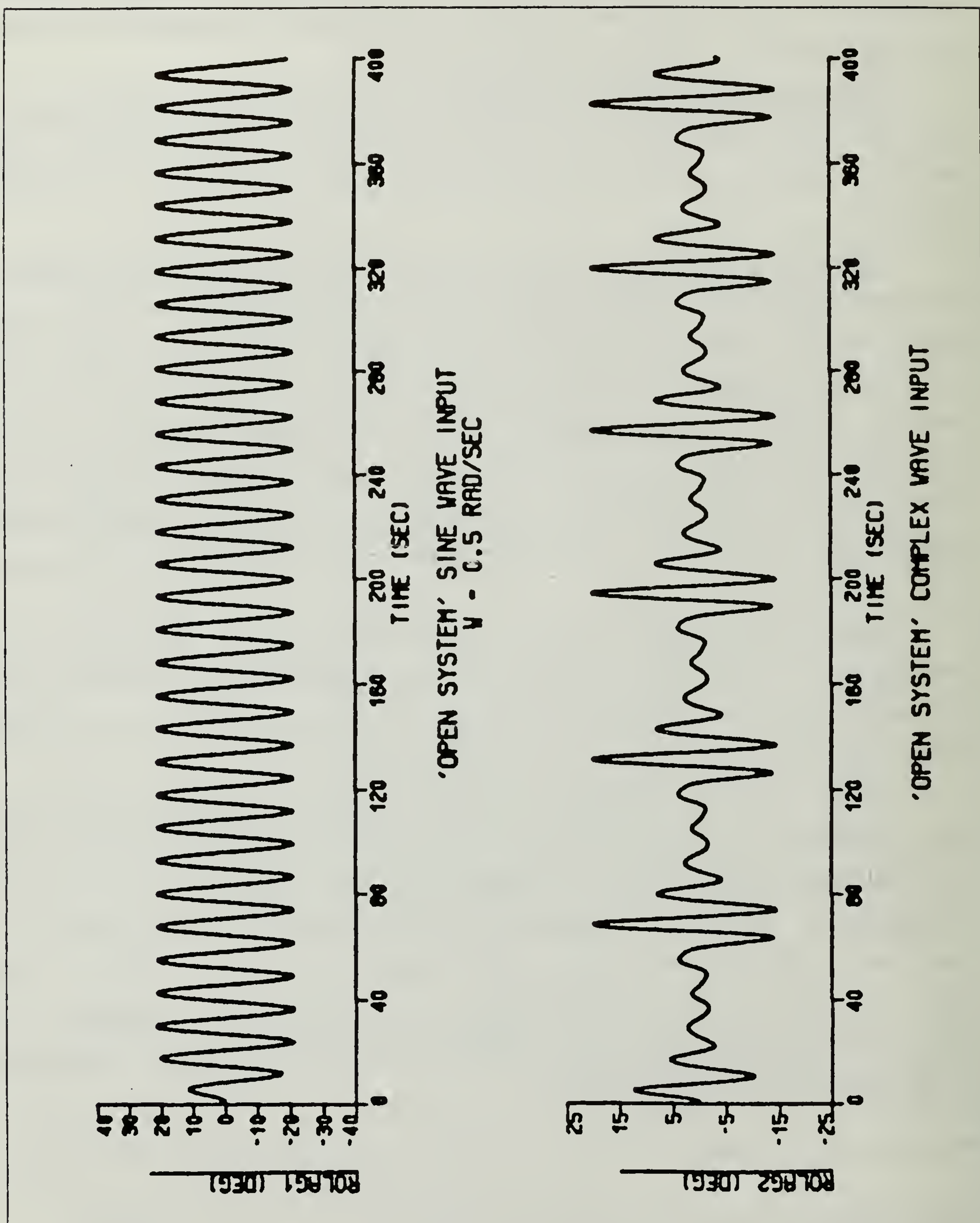

Figure 4.1 Performance of Roll Angle for Open System, Sine and Complex Wave Input.

Figure 4.2 Performance of Ideal System, Compensated, Sine Wave Input
$K_1 = 4.0$, $K_2 = 4.0$, $\omega = 0.5$ rad/sec.

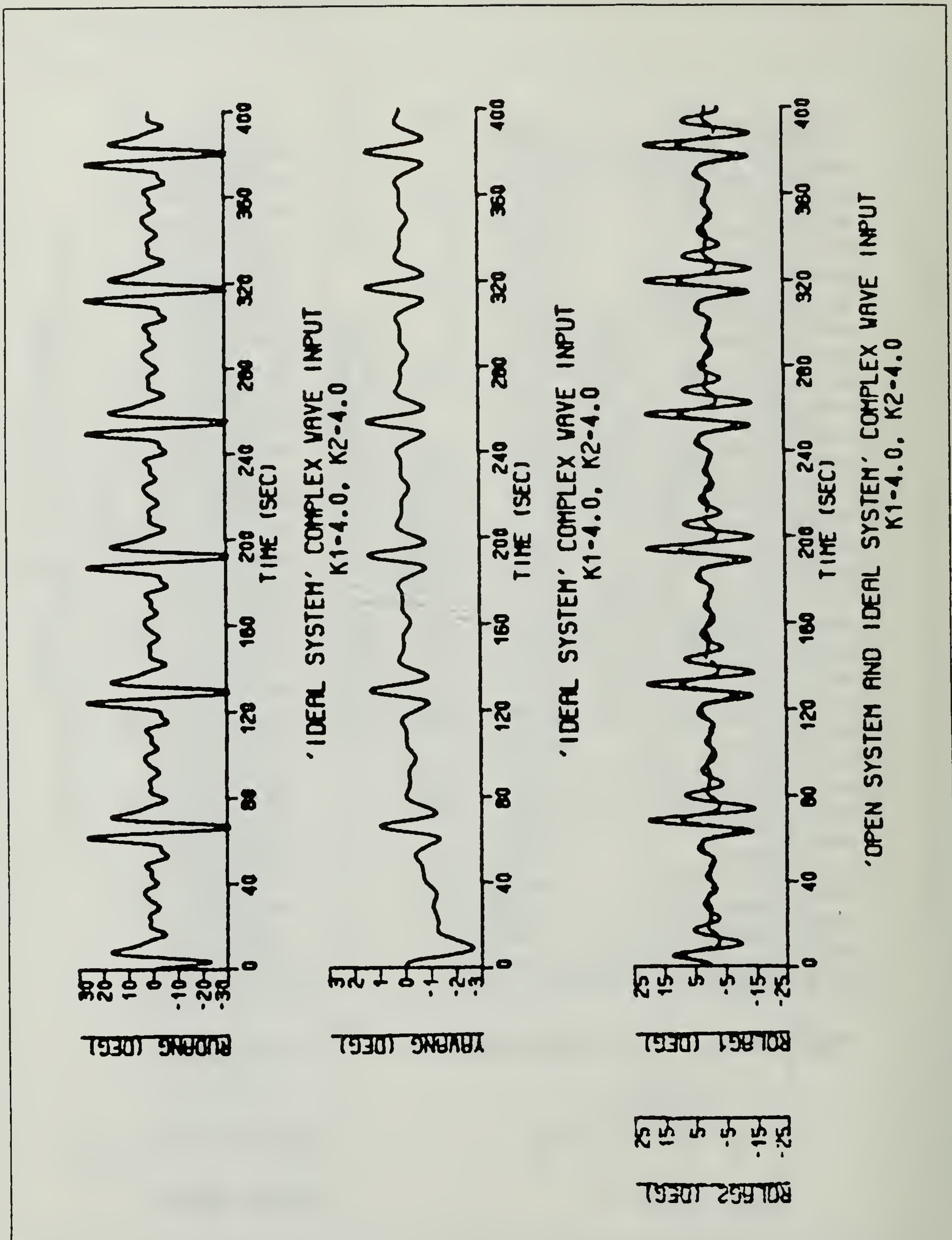

Figure 4.3 Performance of Ideal System, Compensated, Complex Wave Input
$Z = 1.8$, $K_1 = 4.0$, $K_2 = 4.0$.

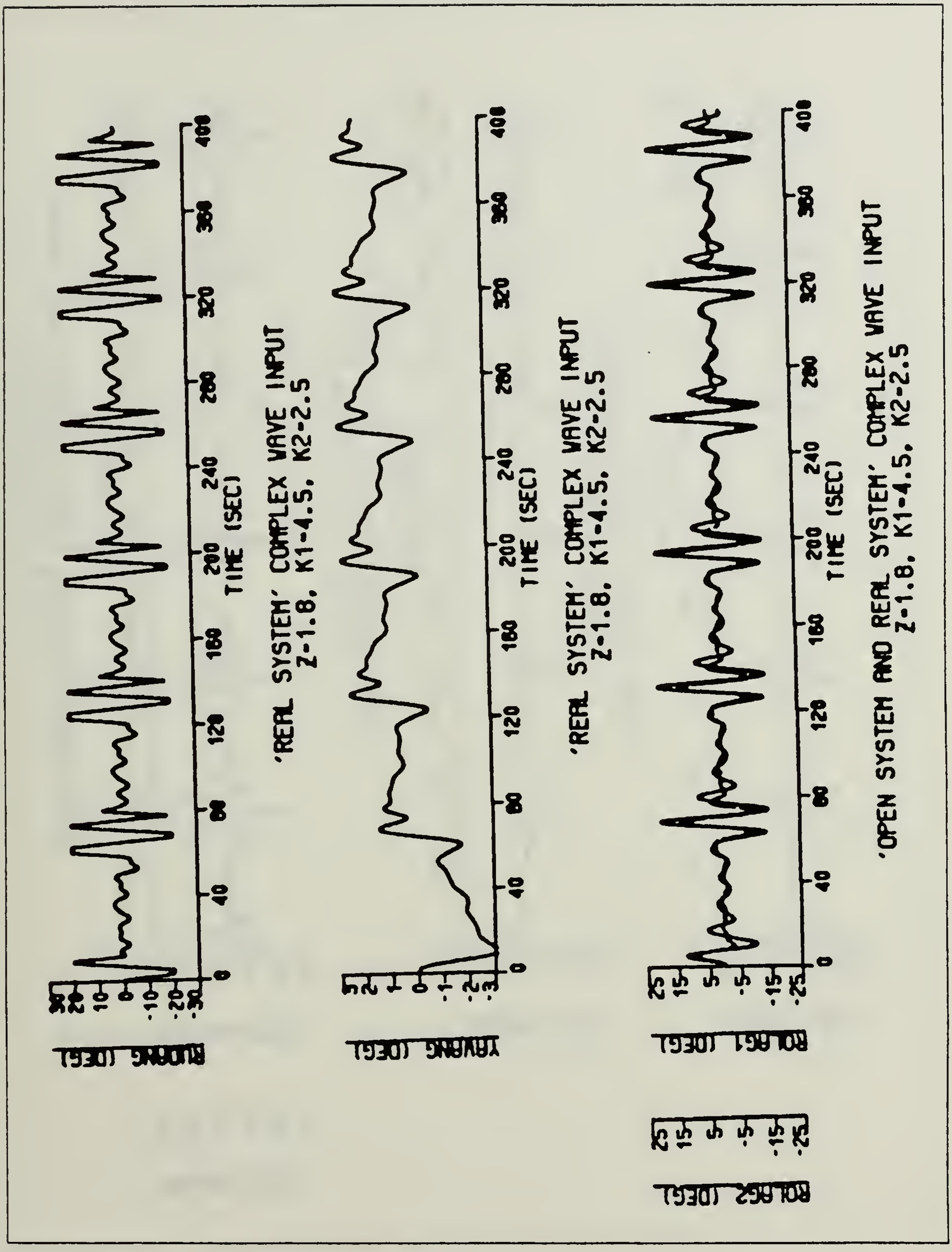

Figure 4.4 Performance of Real System, Compensated, Complex Wave Input
$Z = 1.8$, $K_1 = 4.5$, $K_2 = 2.5$
Maximum Rudder Rate: ± 10 deg/sec, Maximum Rudder Angle : ± 20 deg.

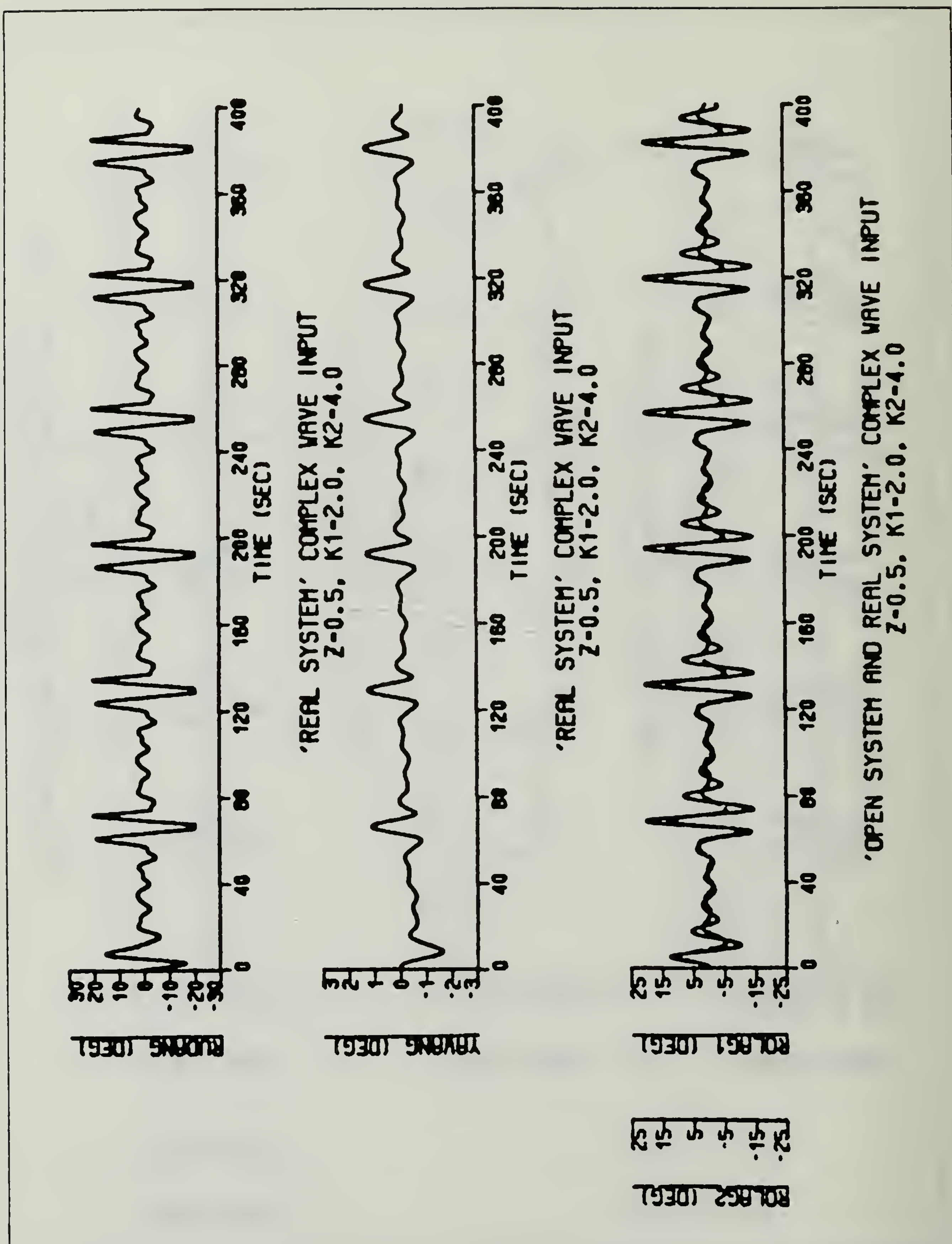

Figure 4.5 Performance of Real System, Compensated, Complex Wave Input
$Z = 0.5$, $K_1 = 2.0$, $K_2 = 4.0$
Maximum Rudder Rate : ± 10 deg/sec, Maximum Rudder Angle : ± 20 deg.

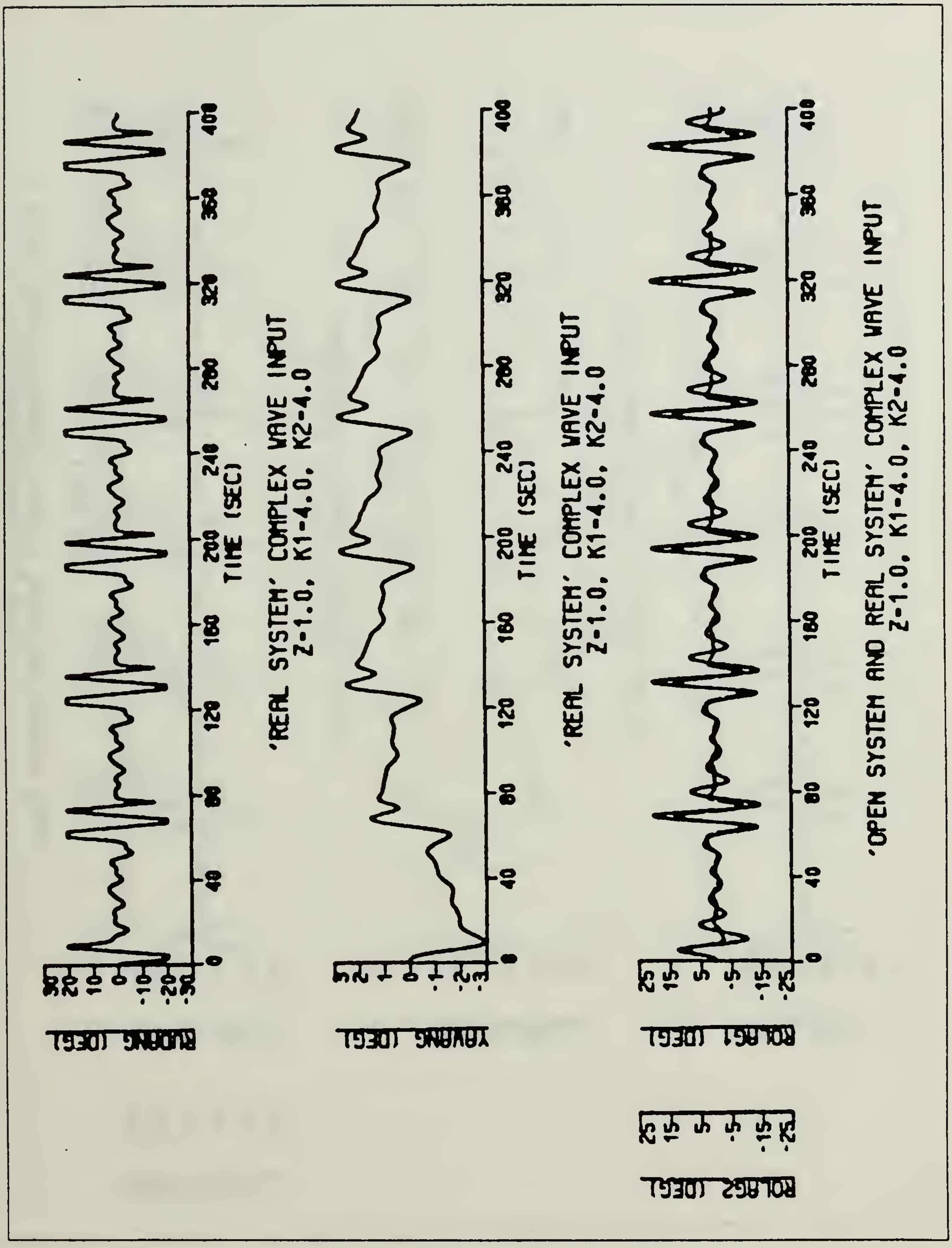

Figure 4.6 Performance of Real System, Compensated, Complex Wave Input
$Z = 1.0$, $K_1 = 4.0$, $K_2 = 4.0$
Maximum Rudder Rate : ± 10 deg/sec, Maximum Rudder Angle : ± 20 deg.

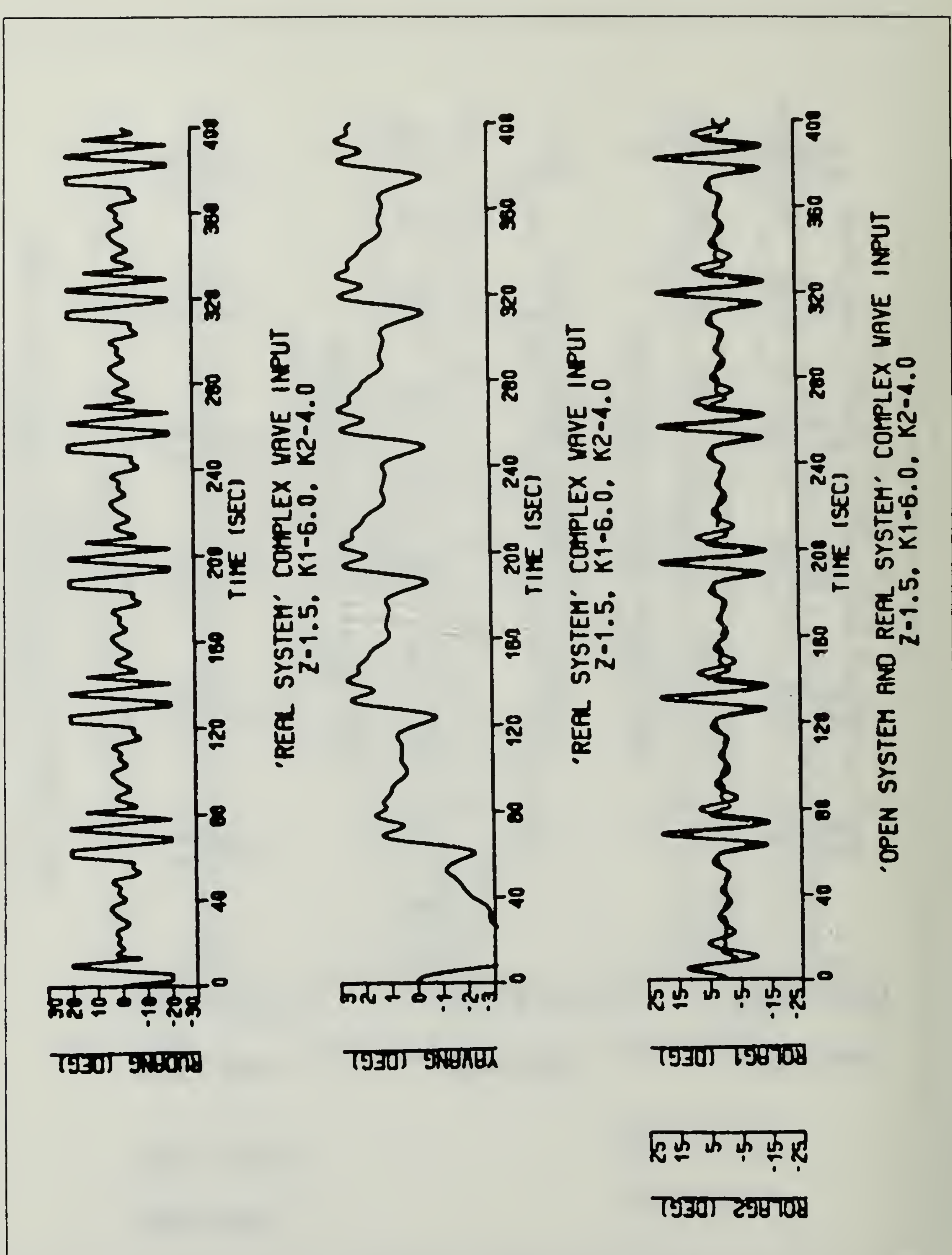

Figure 4.7 Performance of Real System, Compensated, Complex Wave Input
$Z = 1.5$, $K_1 = 6.0$, $K_2 = 4.0$
Maximum Rudder Rate : ± 10 deg/sec, Maximum Rudder Angle : ± 20 deg.

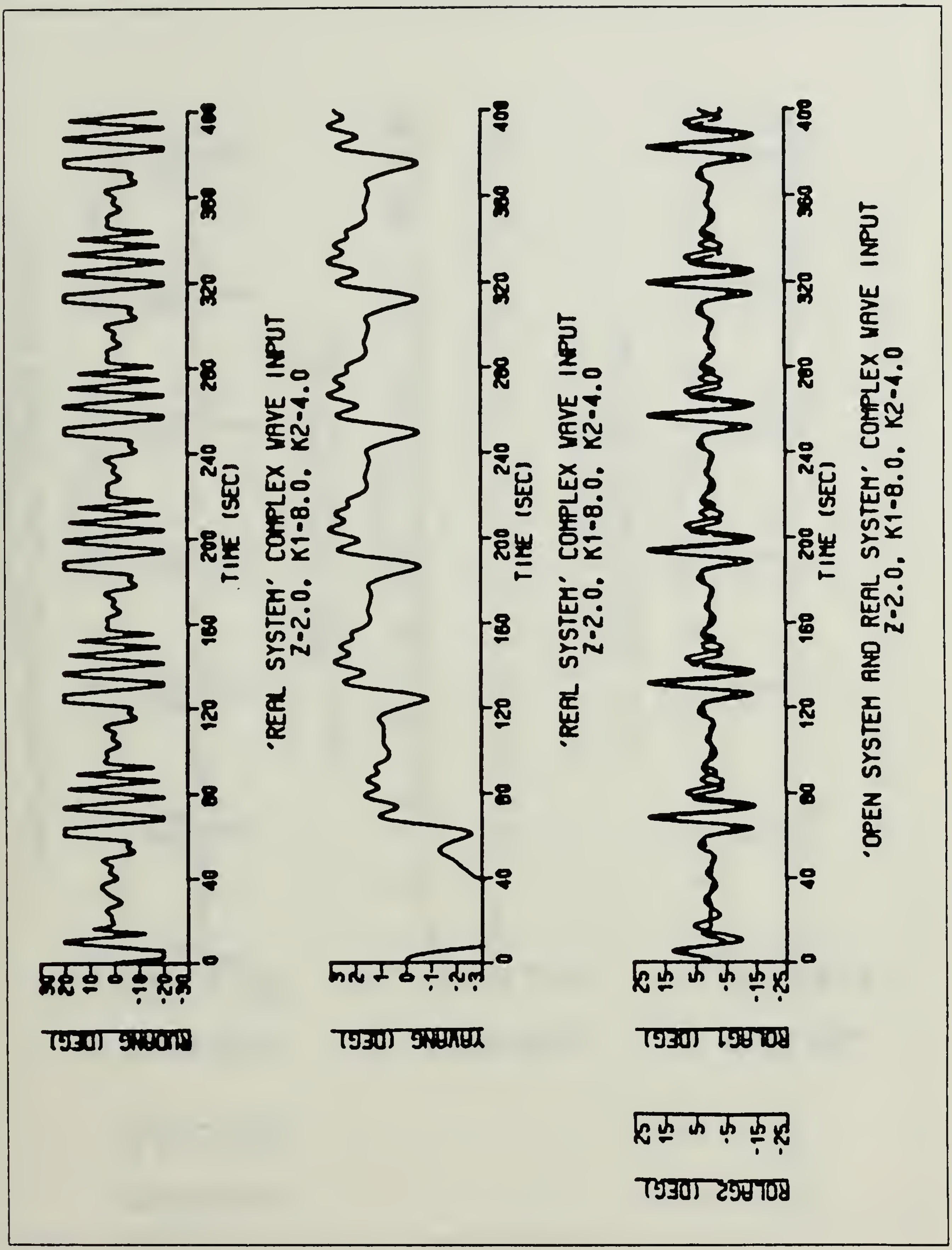

Figure 4.8 Performance of Real System, Compensated, Complex Wave Input
$Z = 2.0$, $K_1 = 8.0$, $K_2 = 4.0$
Maximum Rudder Rate : ± 10 deg/sec, Maximum Rudder Angle : ± 20 deg.

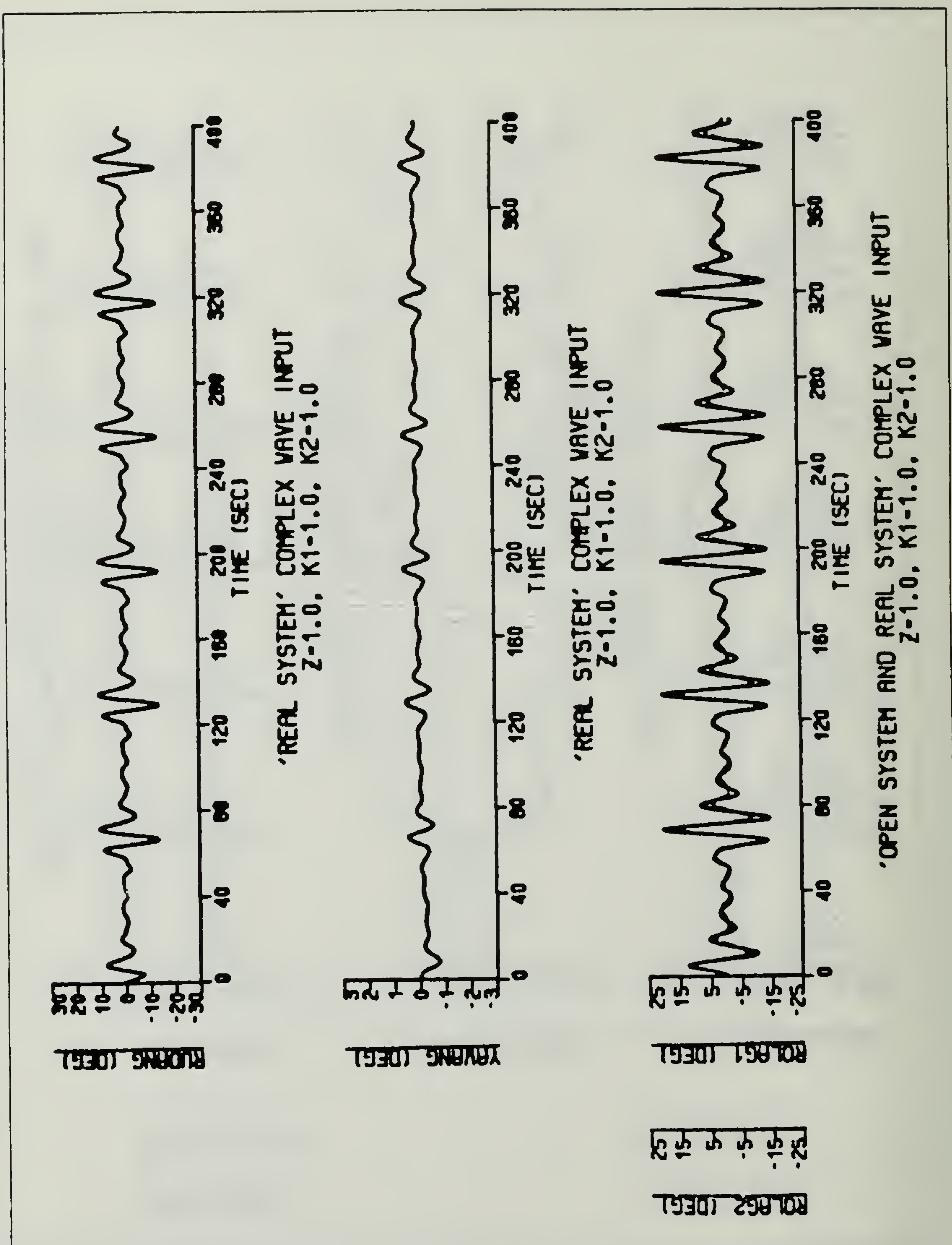

Figure 4.9 Performance of Real System, Compensated, Complex Wave Input

$Z = 1.0$, $K_1 = 1.0$, $K_2 = 1.0$

Maximum Rudder Rate : ± 10 deg/sec, Maximum Rudder Angle : ± 20 deg.

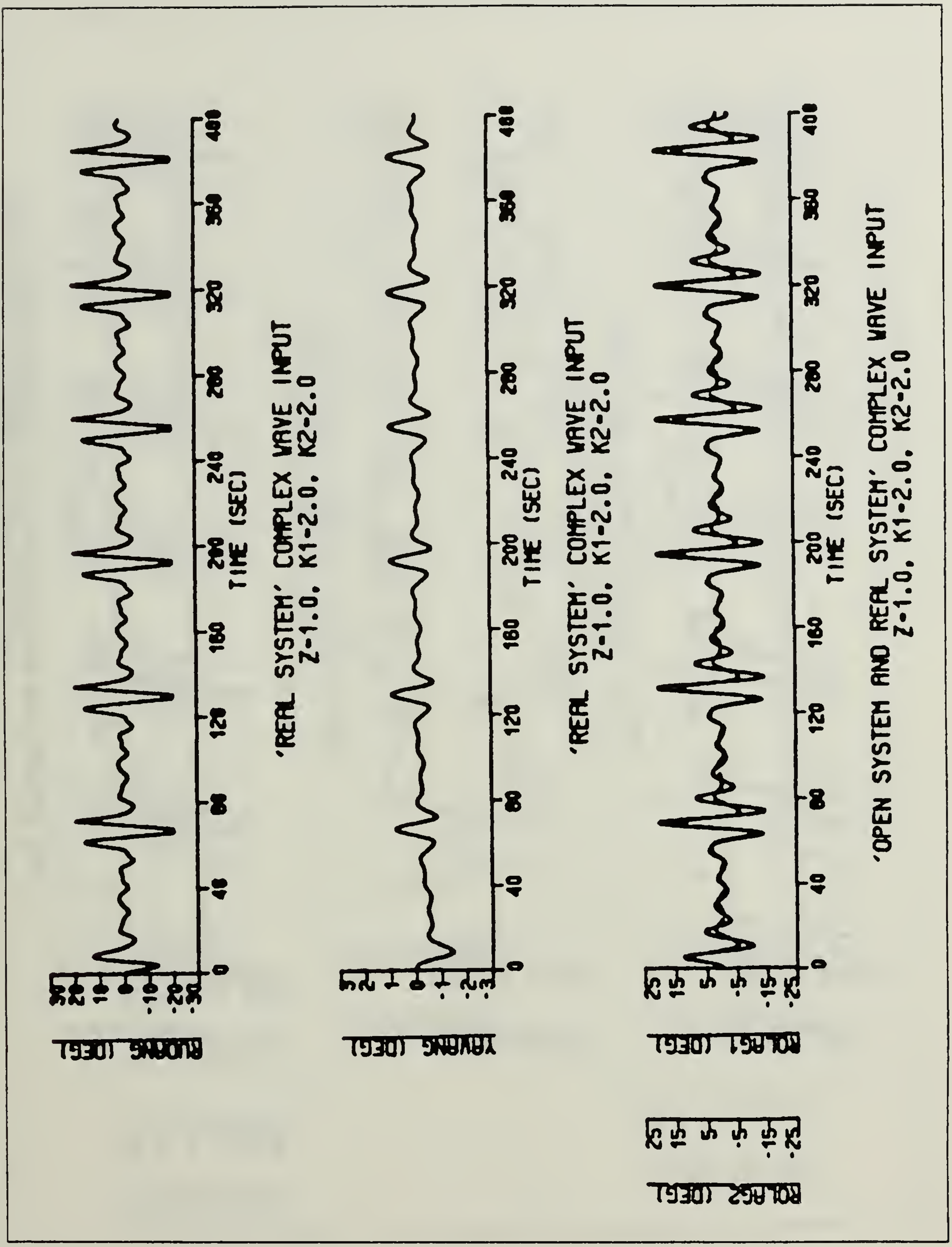

Figure 4.10 Performance of Real System, Compensated, Complex Wave Input
$Z = 1.0,\ K_1 = 2.0,\ K_2 = 2.0$
Maximum Rudder Rate : ± 10 deg/sec, Maximum Rudder Angle : ± 20 deg.

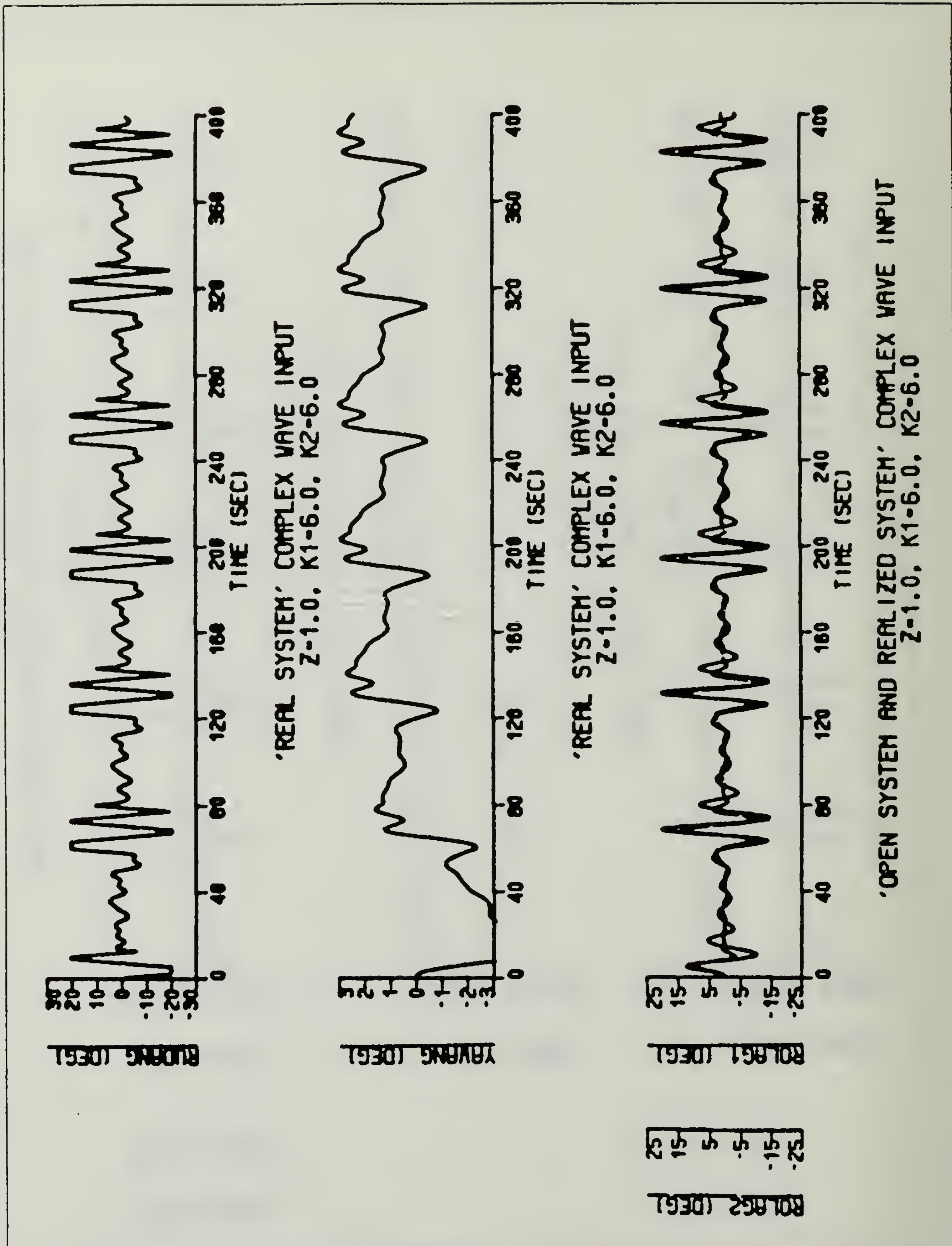

Figure 4.11 Performance of Real System, Compensated, Complex Wave Input
$Z = 1.0$, $K_1 = 6.0$, $K_2 = 6.0$
Maximum Rudder Rate : ± 10 deg/sec, Maximum Rudder Angle : ± 20 deg.

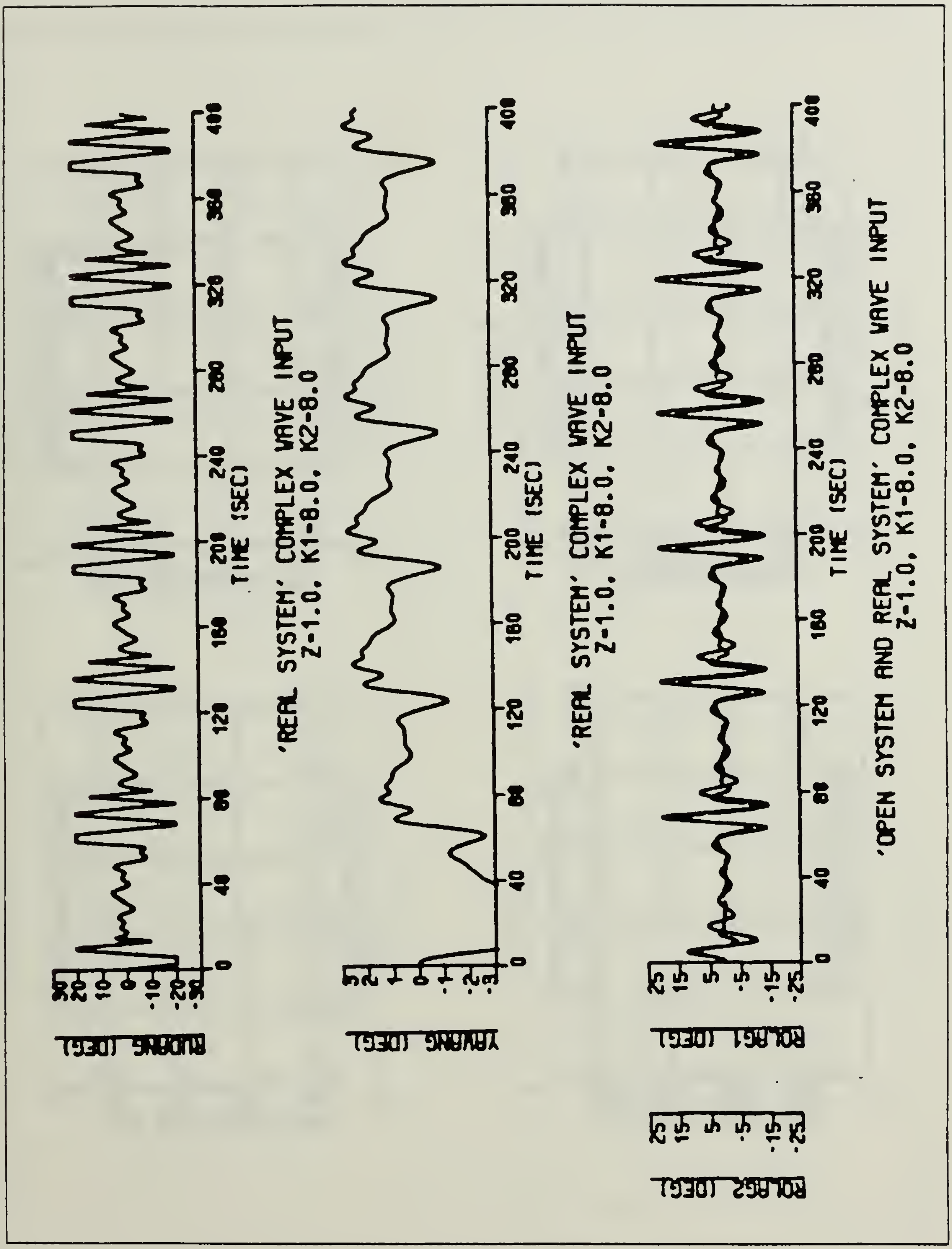

Figure 4.12 Performance of Real System, Compensated, Complex Wave Input
$Z = 1.0$, $K_1 = 8.0$, $K_2 = 8.0$
Maximum Rudder Rate : ± 10 deg/sec, Maximum Rudder Angle : ± 20 deg.

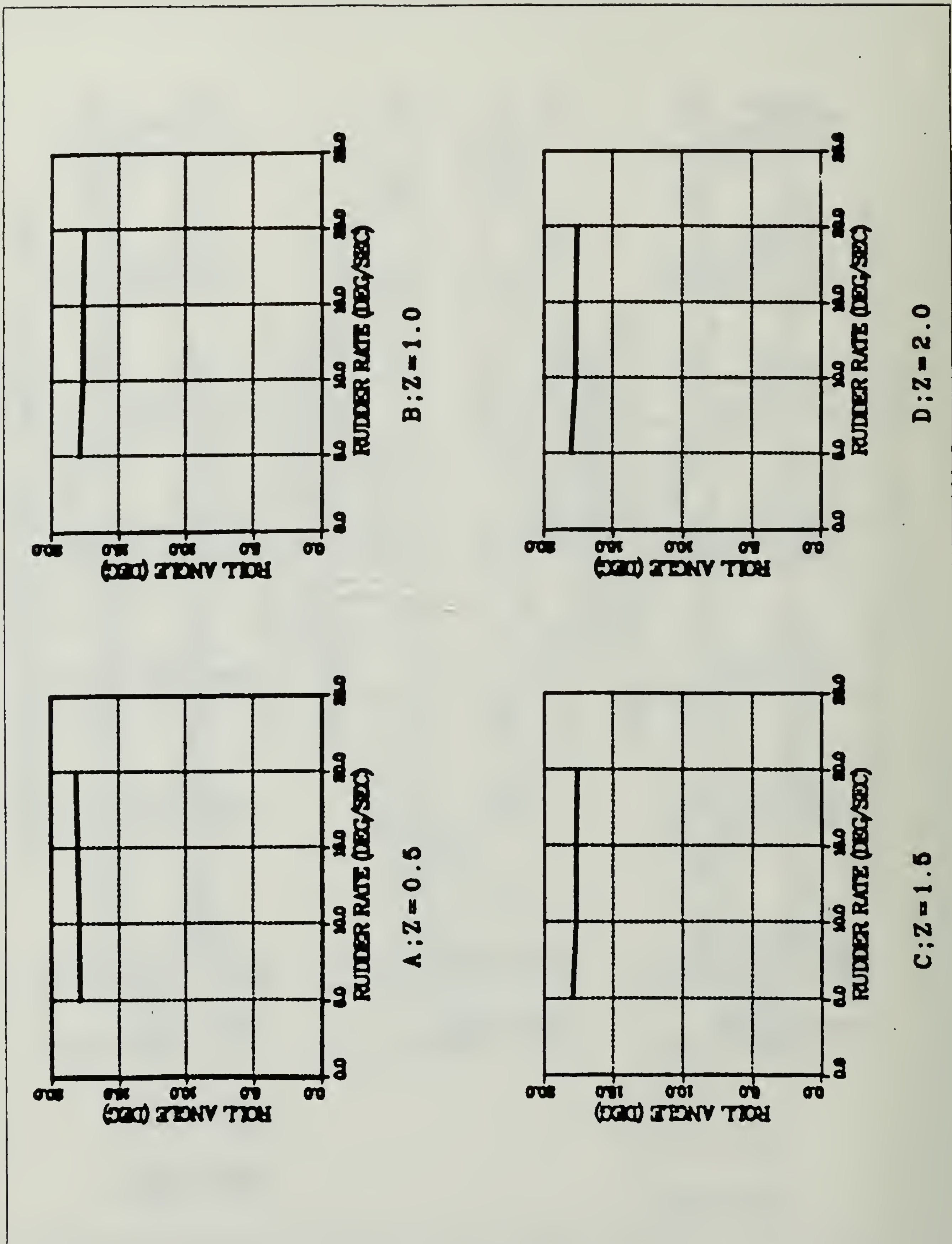

Figure 4.13 Maximum Rudder Rate vs Maximum Roll Angle
Maximum Rudder Angle : 5 deg
ω = 0.5 rad/sec.

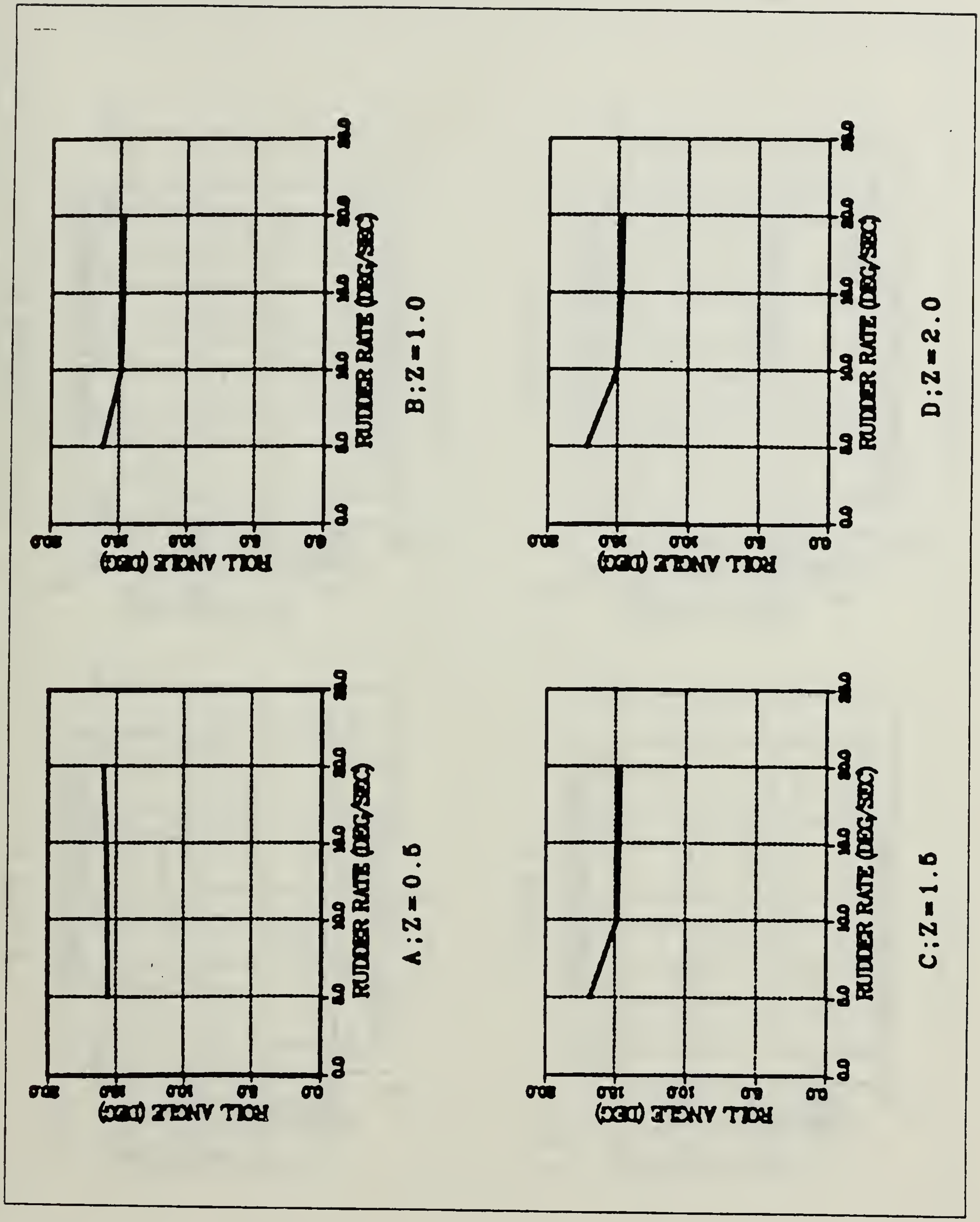

Figure 4.14 Maximum Rudder Rate vs Maximum Roll Angle, Maximum Rudder Angle = 10 deg/sec
ω = 0.5 rad/sec.

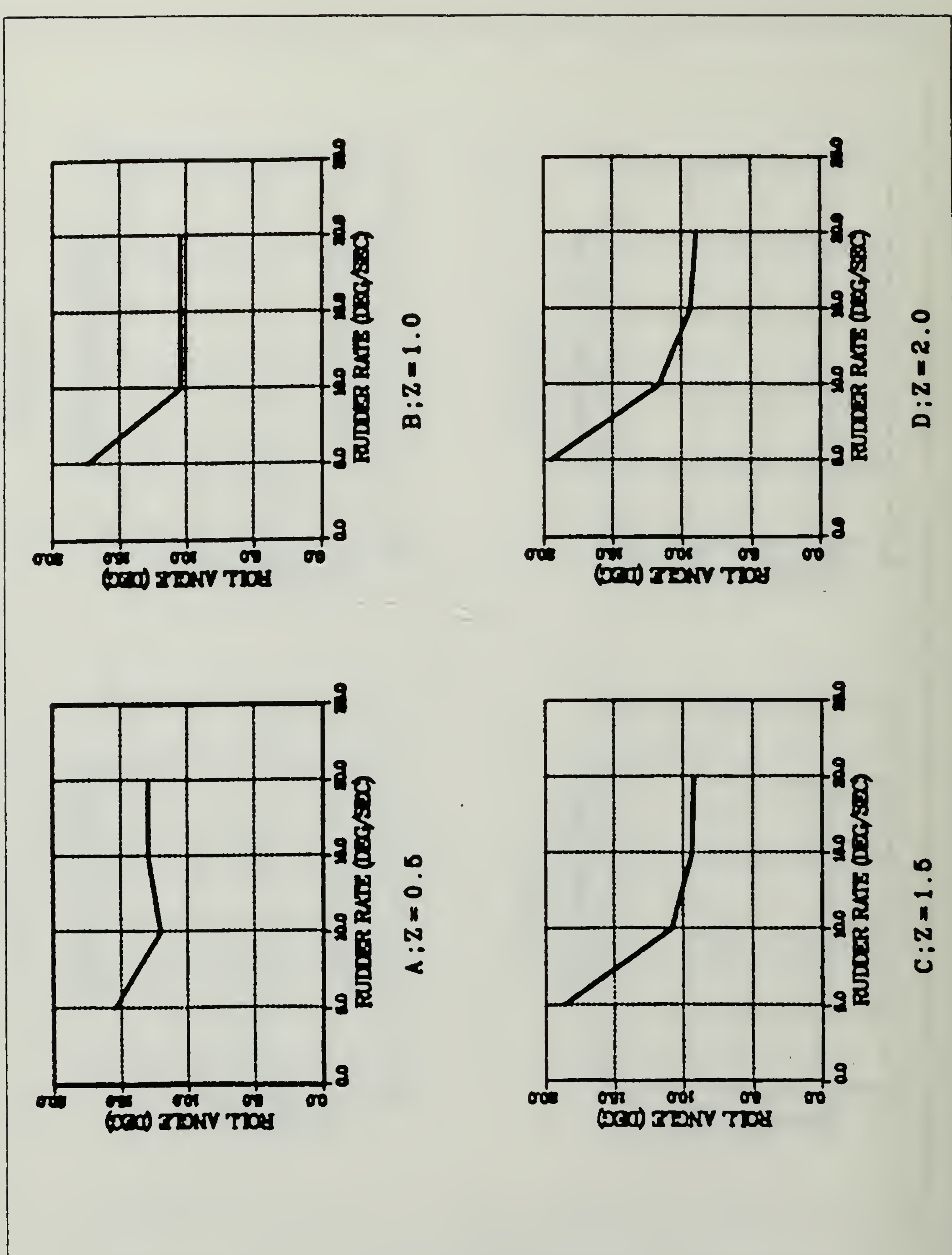

Figure 4.15 Maximum Rudder Rate vs Maximum Roll Angle,
Maximum Rudder Angle = 20 deg
ω = 0.5 rad/sec.

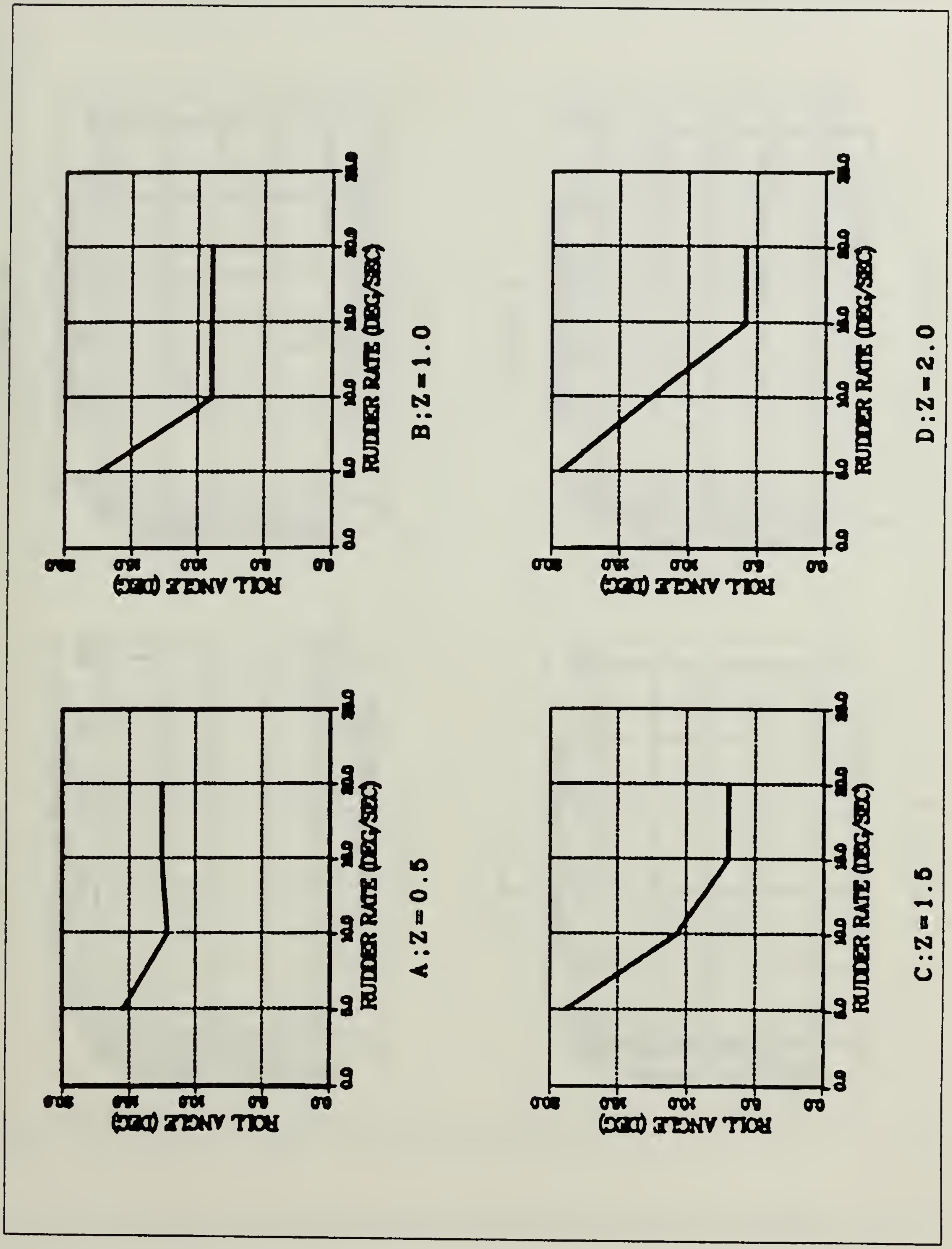

Figure 4.16 Maximum Rudder Rate vs Maximum Roll Angle,
Maximum Rudder Angle = 30 deg
ω = 0.5 rad/sec.

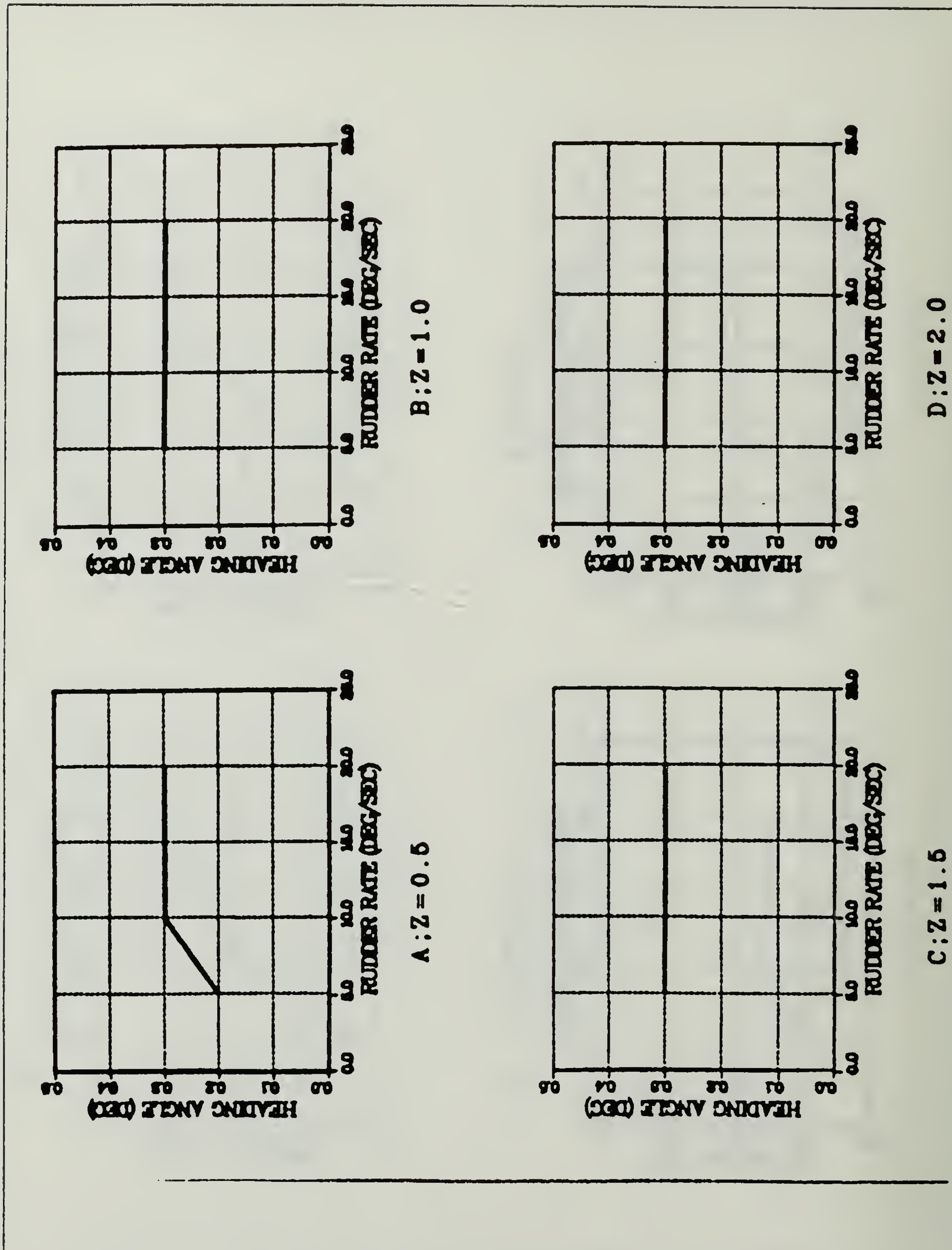

Figure 4.17 Maximum Rudder Rate vs Maximum Heading Angle,
Maximum Rudder Angle = 5 deg
ω = 0.5 rad/sec.

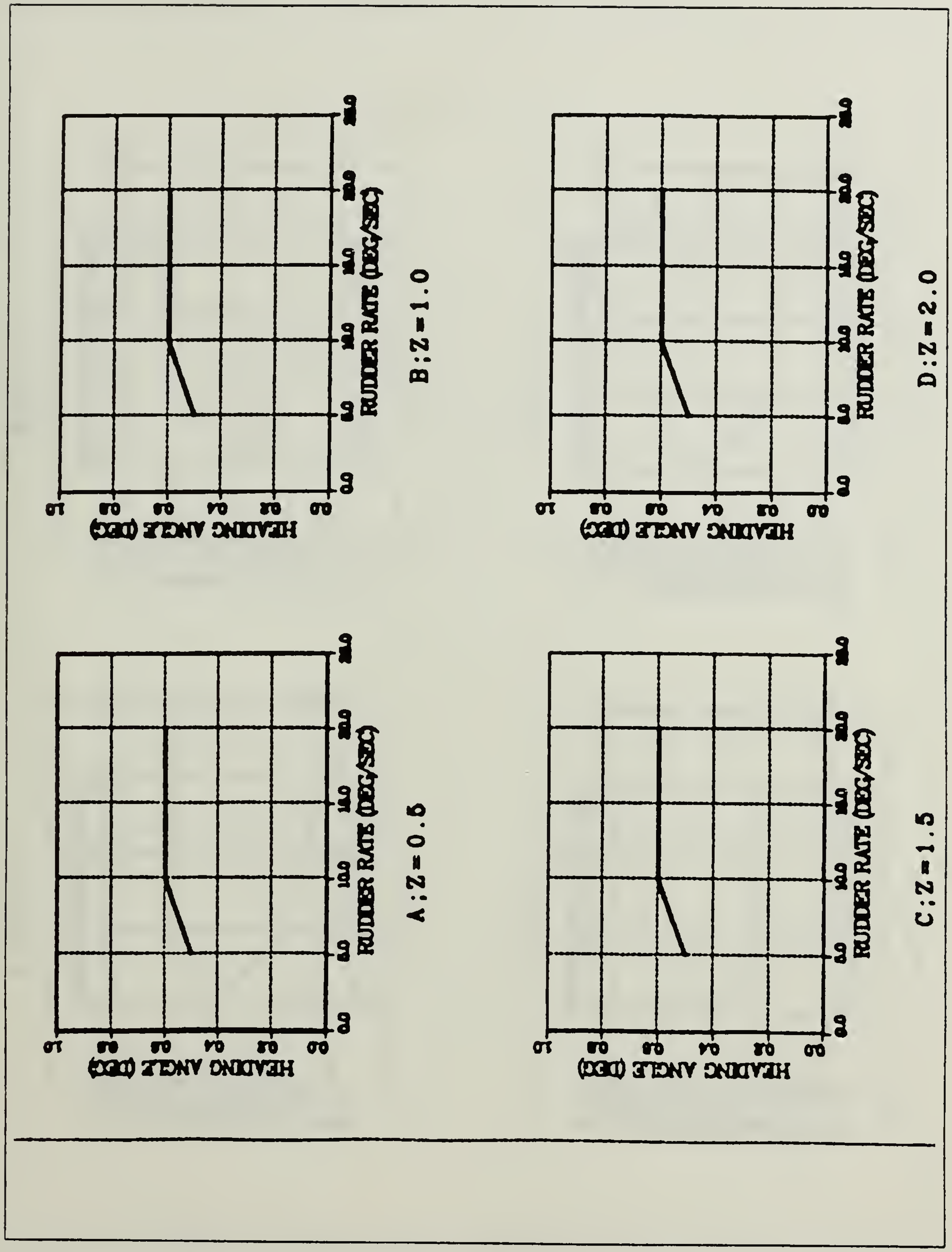

Figure 4.18 Maximum Rudder Rate vs Maximum Heading Angle,
Maximum Rudder Angle = 10 deg
ω = 0.5 rad/sec.

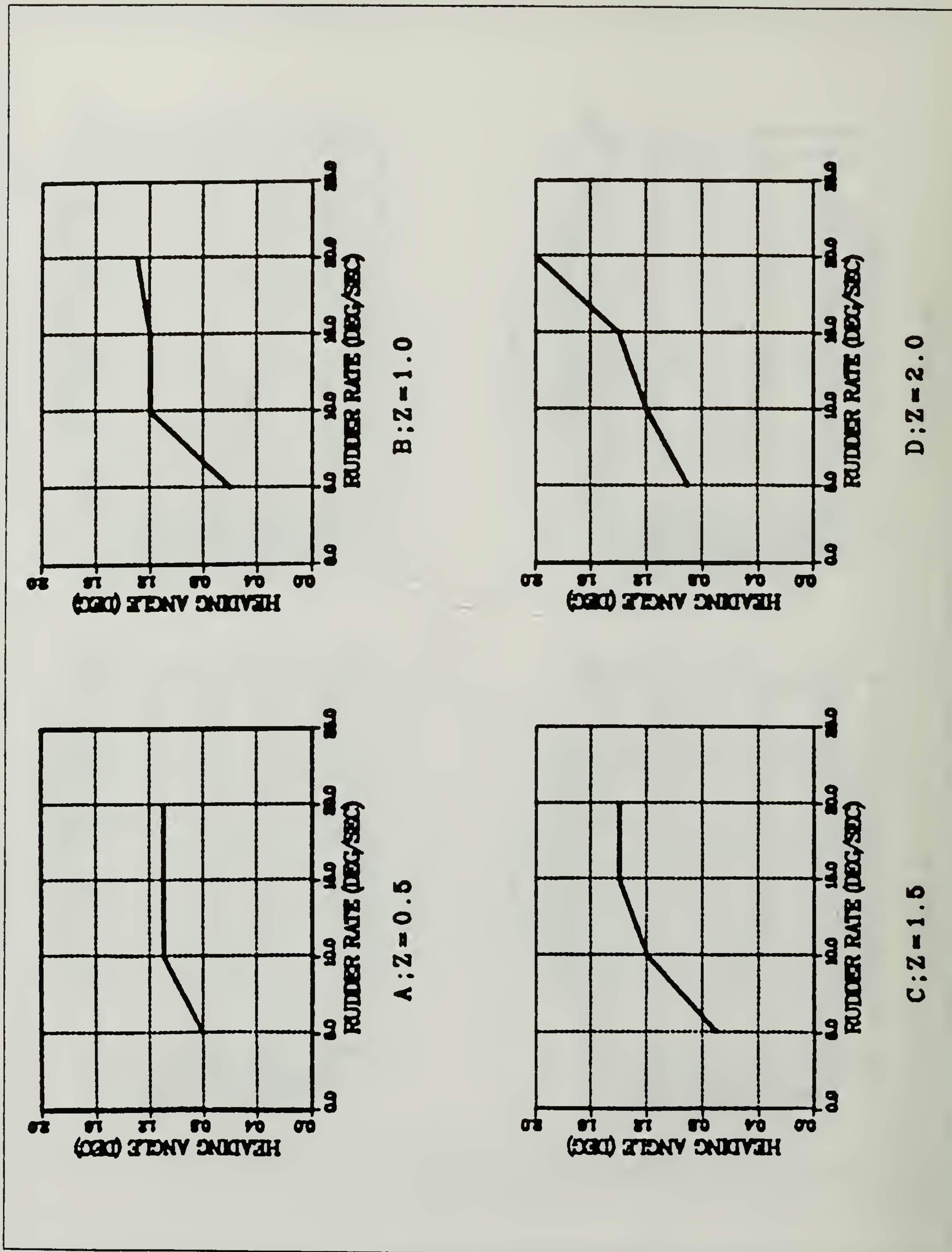

Figure 4.19 Maximum Rudder Rate vs Maximum Heading Angle,
Maximum Rudder Angle = 20 deg
ω = 0.5 rad/sec.

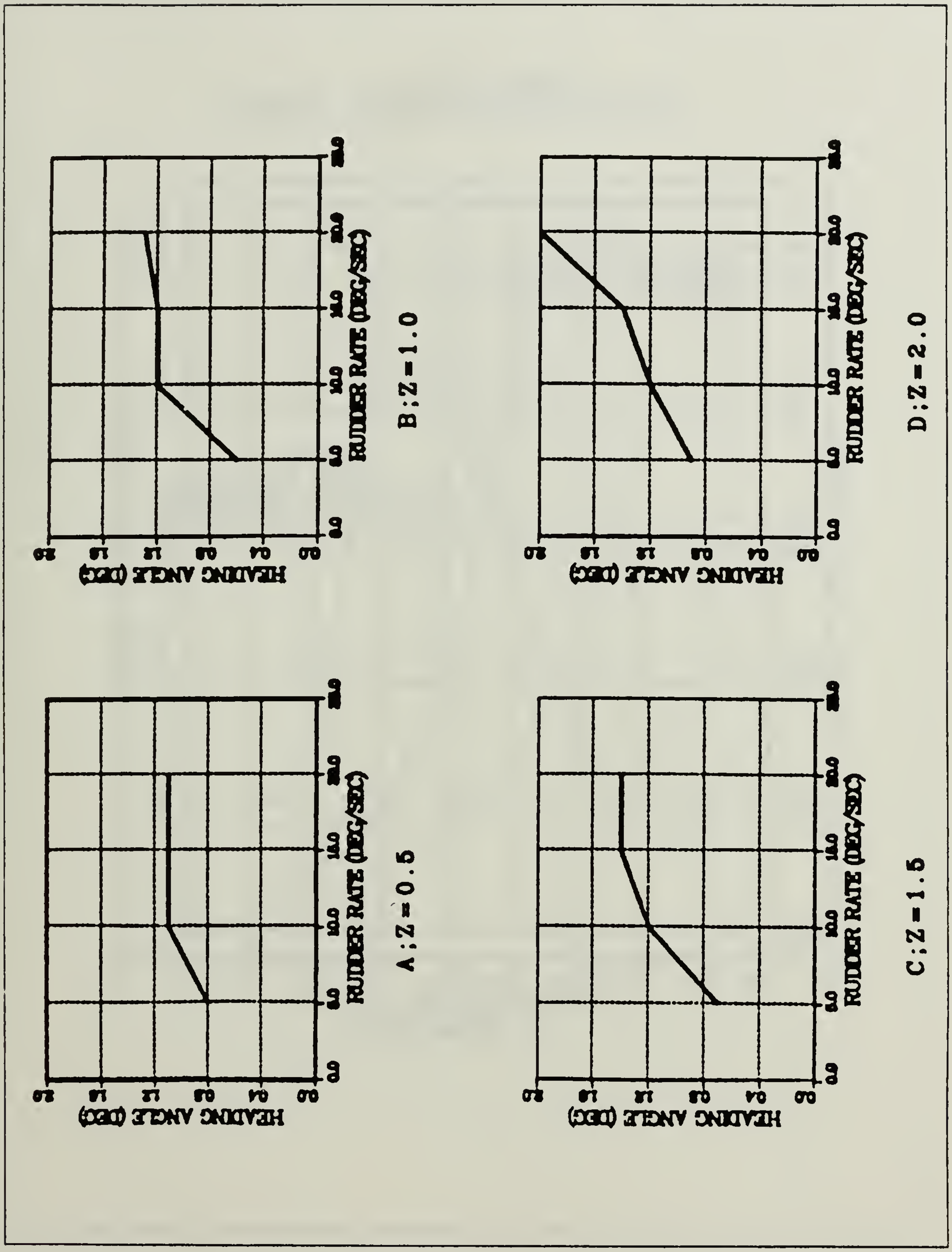

Figure 4.20 Maximum Rudder Rate vs Maximum Heading Angle,
Maximum Rudder Angle = 30 deg
ω = 0.5 rad/sec.

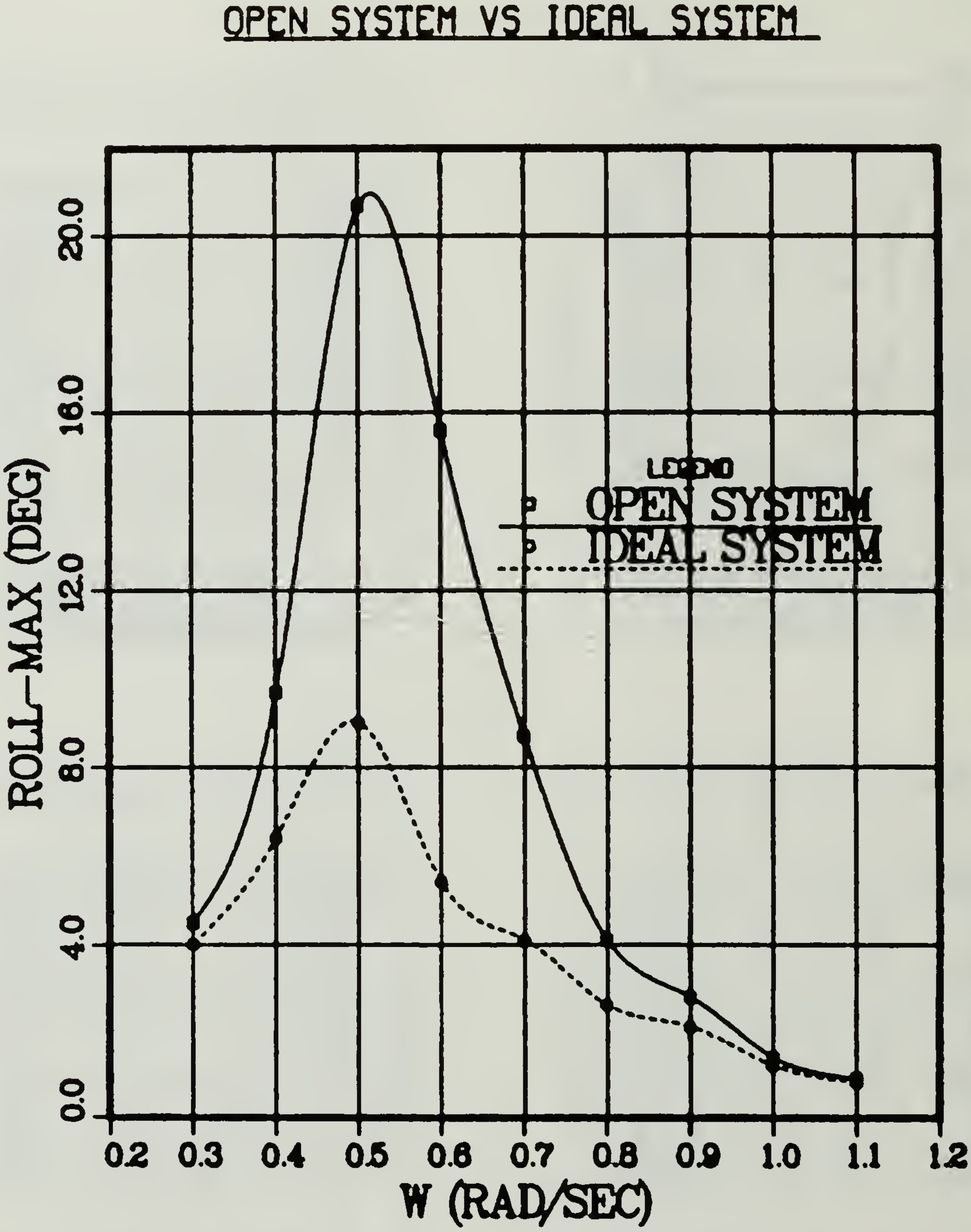

Figure 4.21 Performance of Roll Reduction : Frequency vs Maximum Roll Angle
$Z = 1.0$, $K_1 = 4.0$, $K_2 = 4.0$
Open System vs Ideal Rudder.

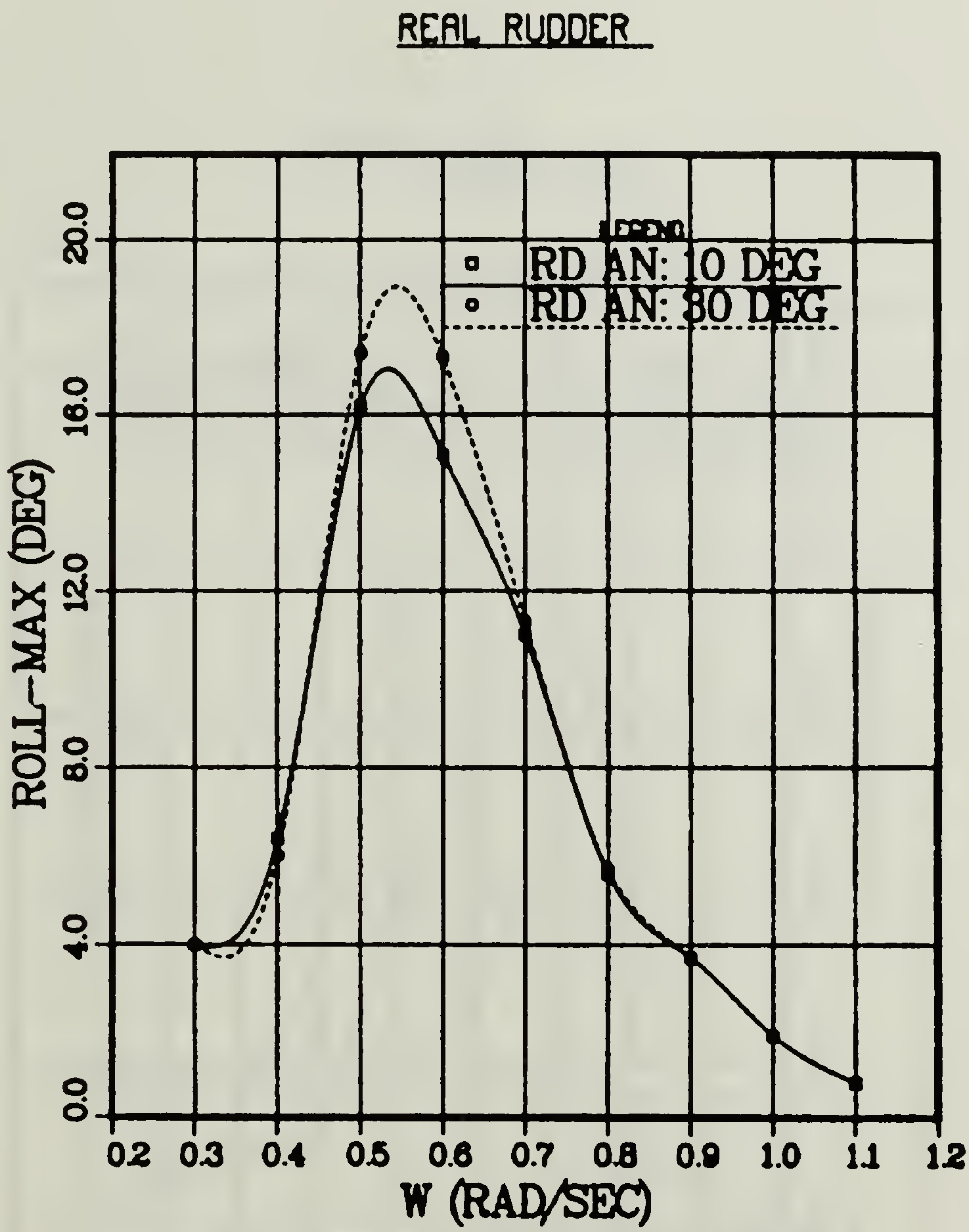

Figure 4.22 Performance of Roll Reduction : Frequency vs Maximum Roll Angle
$Z = 1.0$, $K_1 = 4.0$, $K_2 = 4.0$
Real Rudder : Maximum Rudder Rate = ± 5 deg/sec.

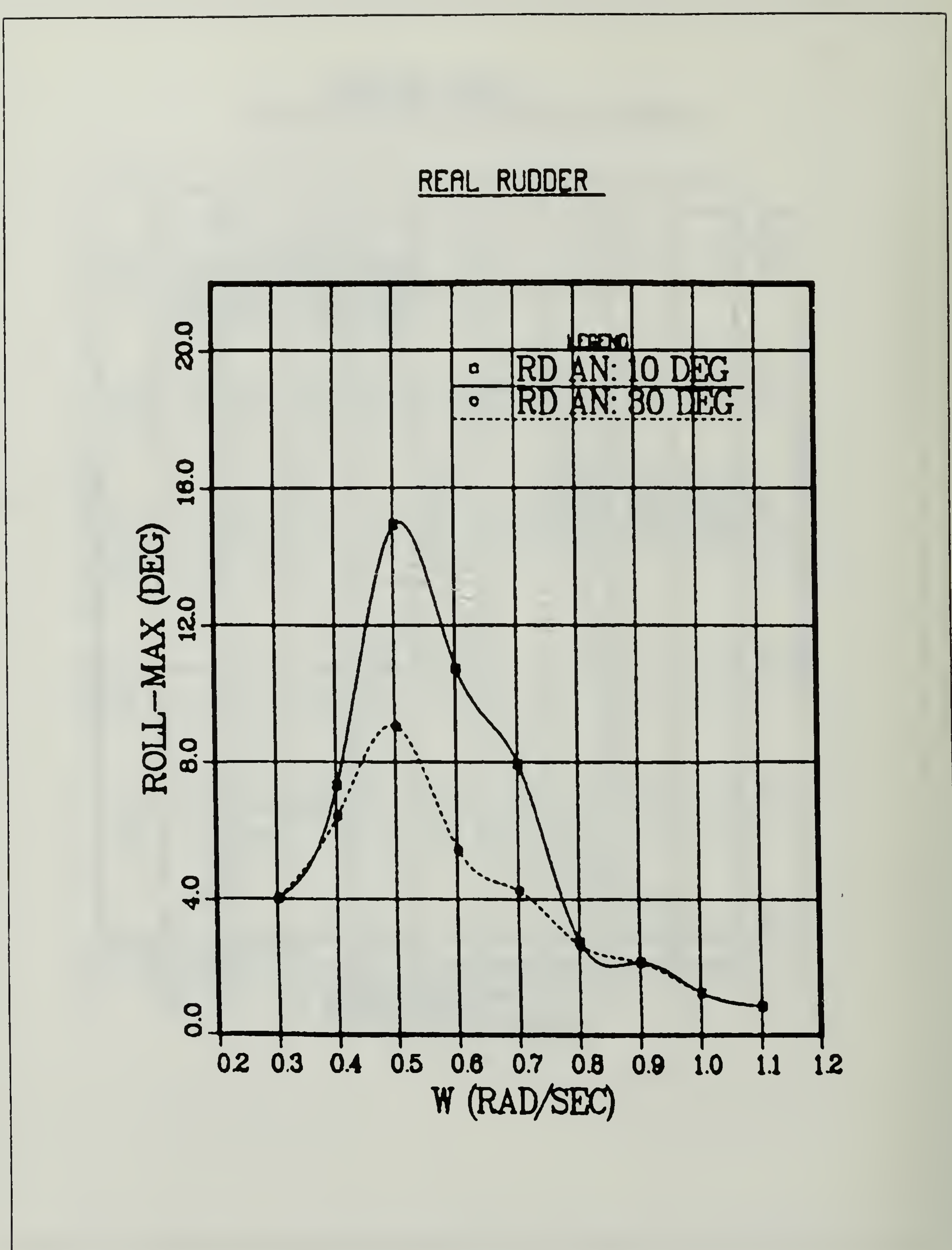

Figure 4.23 Performance of Roll Reduction : Frequency vs Maximum Roll Angle
$Z = 1.0$, $K_1 = 4.0$, $K_2 = 4.0$
Real Rudder : Maximum Rudder Rate = ± 10 deg/sec.

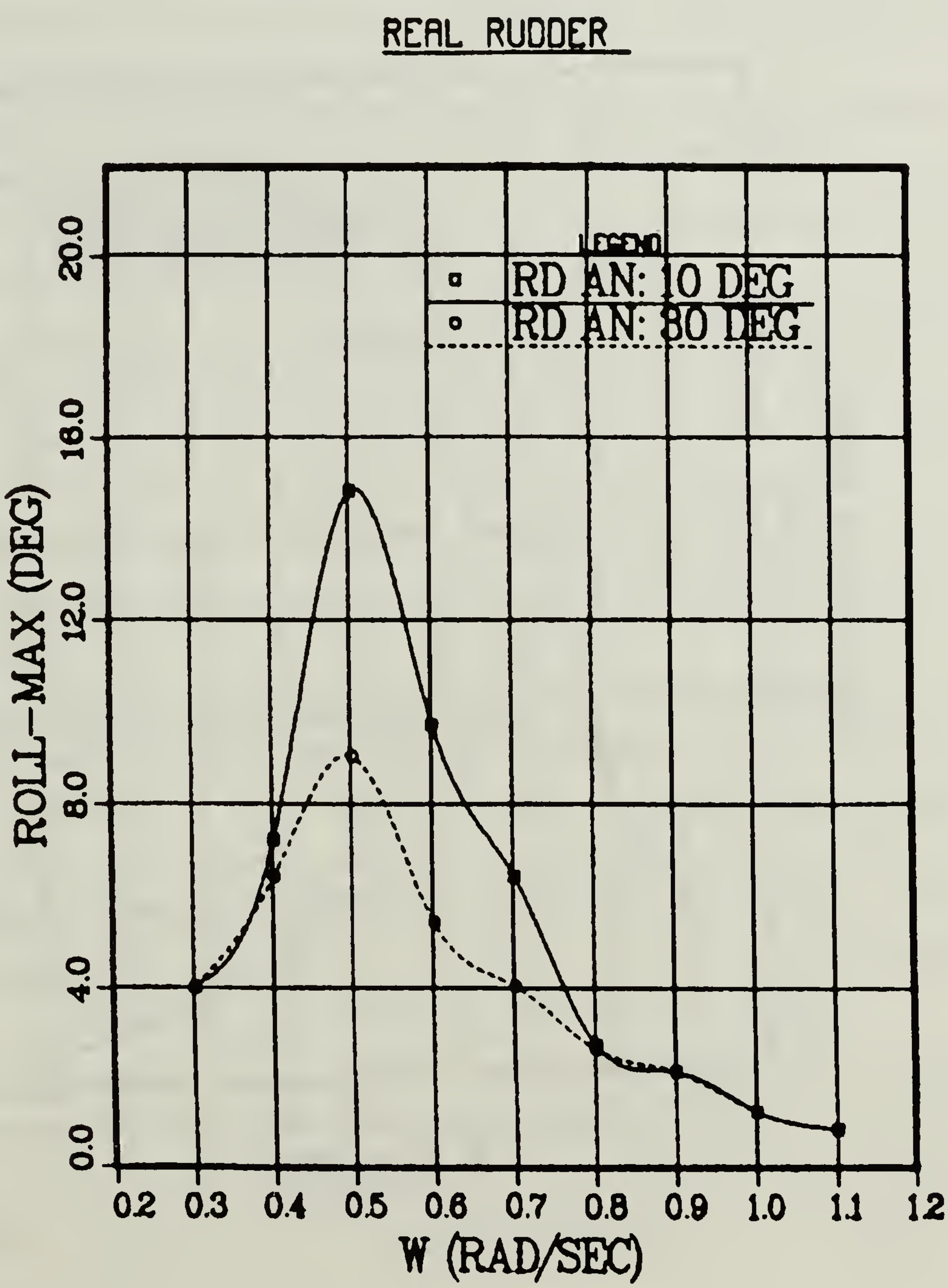

Figure 4.24 Performance of Roll Reduction : Frequency vs Maximum Roll Angle
$Z = 1.0$, $K_1 = 4.0$, $K_2 = 4.0$
Real Rudder : Maximum Rudder Rate = ± 15 deg/sec.

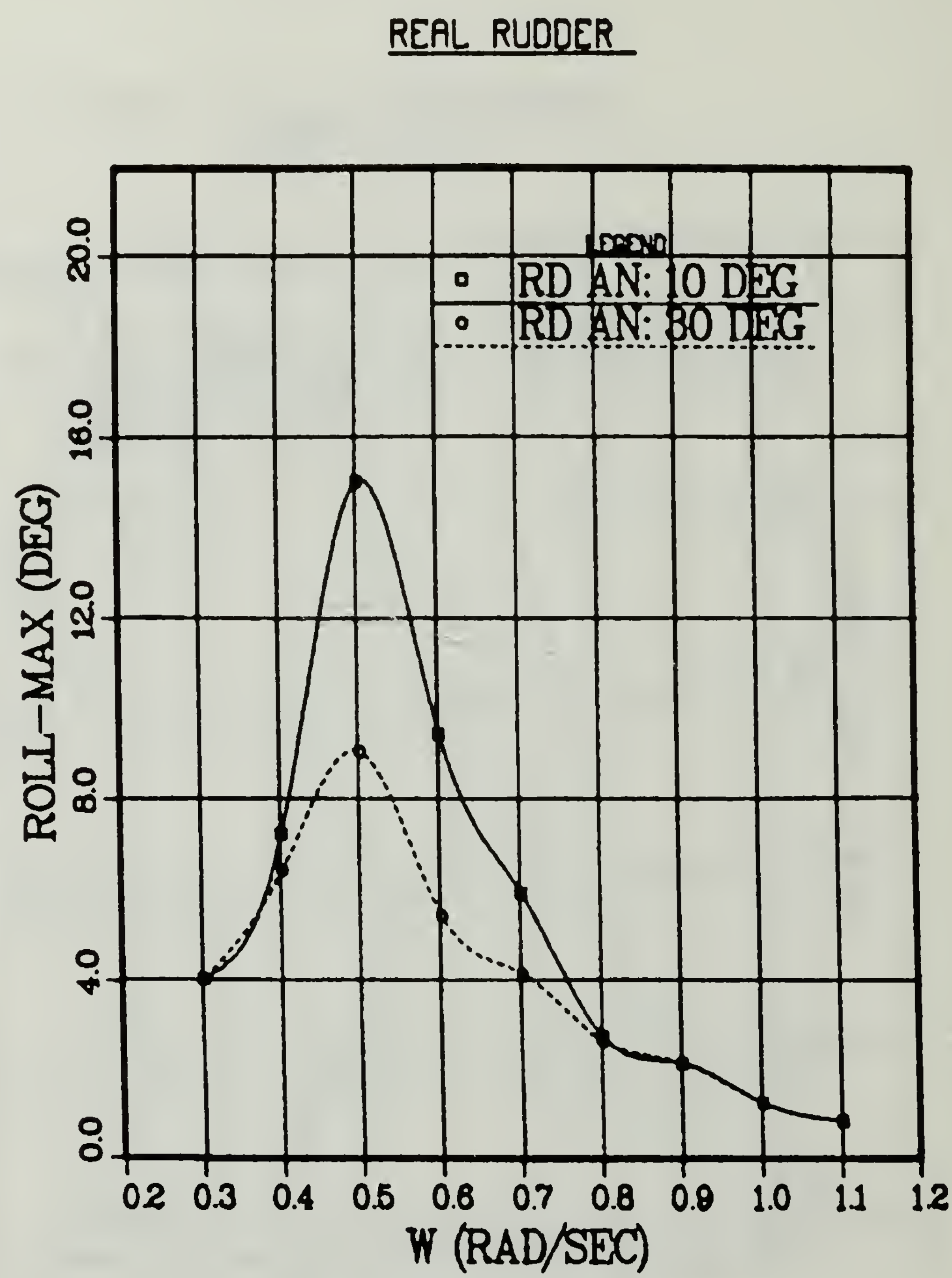

Figure 4.25 Performance of Roll Reduction : Frequency vs Maximum Roll Angle
$Z = 1.0$, $K_1 = 4.0$, $K_2 = 4.0$
Real Rudder : Maximum Rudder Rate = ± 20 deg/sec.

V. CONCLUSION AND RECOMMENDATION

A. CONCLUSION

From the results of the Rudder Roll Stabilization (RRS) computer simulations, the following conclusions have been reached :

(1) Simple models can be derived to describe how wave forcing input and rudder angle affect the roll angle.

(2) A properly designed roll controller will minimize the roll angle response and provide the desired heading angle as well.

(3) This thesis has presented some practical aspects of a Rudder Roll Stabilization system. It has been shown that the steering machine may act as a severe limitation. When the rudder speed is sufficiently increased good roll reduction can be realized on existing ships. When it is possible, by means of a modified rudder construction, to increase the effect of the rudder on the roll without changing its effect on the heading an even better performance can be obtained.

(4) It appears that both the rudder angle limit and the rudder speed limit have to be chosen carefully in order to realize a reasonable roll reduction. That is, the effectiveness of a RRS system is directly dependent upon available rudder moment. The available moment, in turn, depends on rudder rate. RRS system performance is rudder rate limited. Another parameter which is very important with respect to the roll reduction achieved by means of the rudder is the gain of roll and roll rate feedback (see Tables 3, 5 and 7).

(5) The primary objective of the RRS has been achieved. That is, maximum roll reduction up to 55 percent has been measured with an ideal rudder ($Z = 1.0$, $K_1 = 4.0$, $K_2 = 4.0$), and maximum roll has also been reduced to 47.5 percent with a reasonable real rudder ($Z = 1.0$, $K_1 = 4.0$, $K_2 = 4.0$, $\dot{\delta}_{max} = 10$ deg/sec, $\delta_{max} = 20$ deg), (see Tables 4 and 5).

B. RECOMMENDATION

The results and conclusions of the RRS computer simulation lead to the following recommendation :

(1) The results of this thesis demonstrate that roll stabilization using the rudder is feasible. Only one roll controller has been studied. It used roll angle and roll rate feedback. It is recommended that roll controllers including roll acceleration feedback should be studied.

(2) In this thesis it has been assumed that cross coupling between the parameters of roll and yaw rate ($N\Phi$) is zero. However, it is recommended that cross coupling between these parameters be considered in further studies on this topic.

(3) The study does not consider wave input effects on the yawing moment. Further research should consider these effects.

(4) Future research should investigate the use of advanced adaptive control and optimal estimation techniques to solve the problem of Rudder Roll Stabilization.

(5) Future research should investigate the effects of various sea state conditions on the Rudder Roll Stabilization.

APPENDIX A
CONCEPT BEHIND THE RUDDER-ROLL-STABILIZATION

Roll stabilization is actually a secondary function of the rudder. Its primary purpose is to steer. However, as shown in Figure A.1, the rudder produces simultaneously a roll moment and a yaw moment which is needed to change ship course.

Typical ship response periods to a roll moment are about 8 to 12 seconds, where as, typical response periods a yaw moment are about 30 to 35 seconds.

The significant difference between these response periods allows the simultaneous superposition of yaw and roll control signals on the rudder without adversely affecting the response in either mode.

The rudder moment is proportional to of the ship velocity and to the rudder angle. Using the rudder for roll stabilization involves opposing the wave induced roll moment by the rudder induced roll moment.

Stabilization is achieved by adding to the steering control signal a roll control signal.

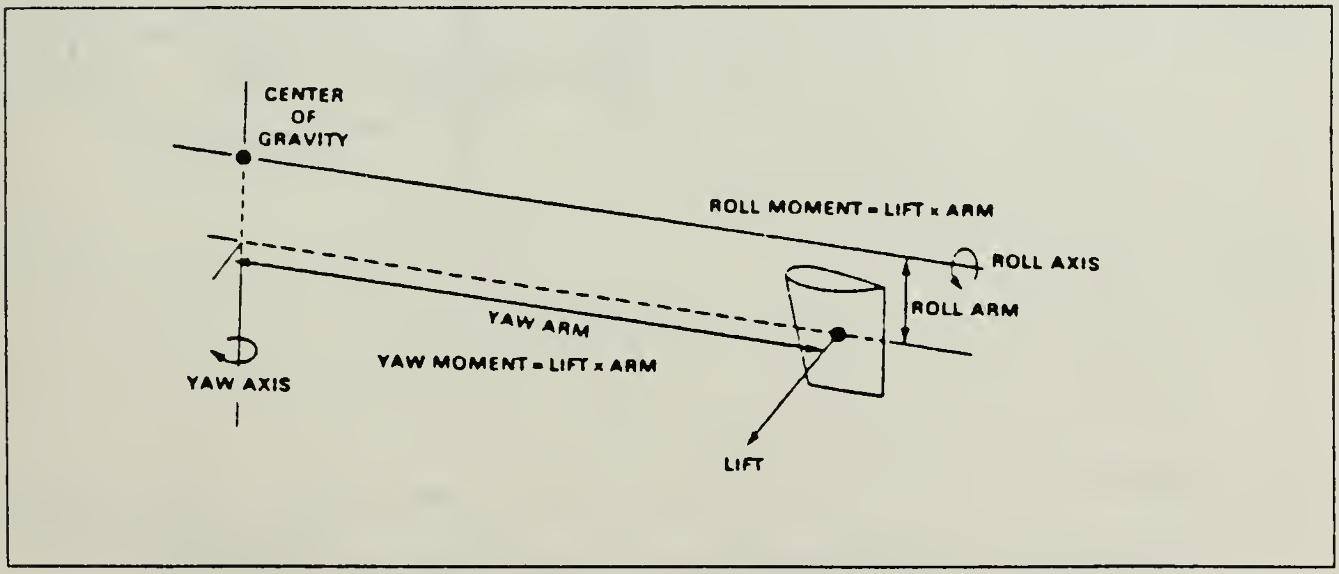

Figure A.1 Rudder Moments and Ship Response.

APPENDIX B

THE ROLL MODEL WITHOUT COMPENSATOR

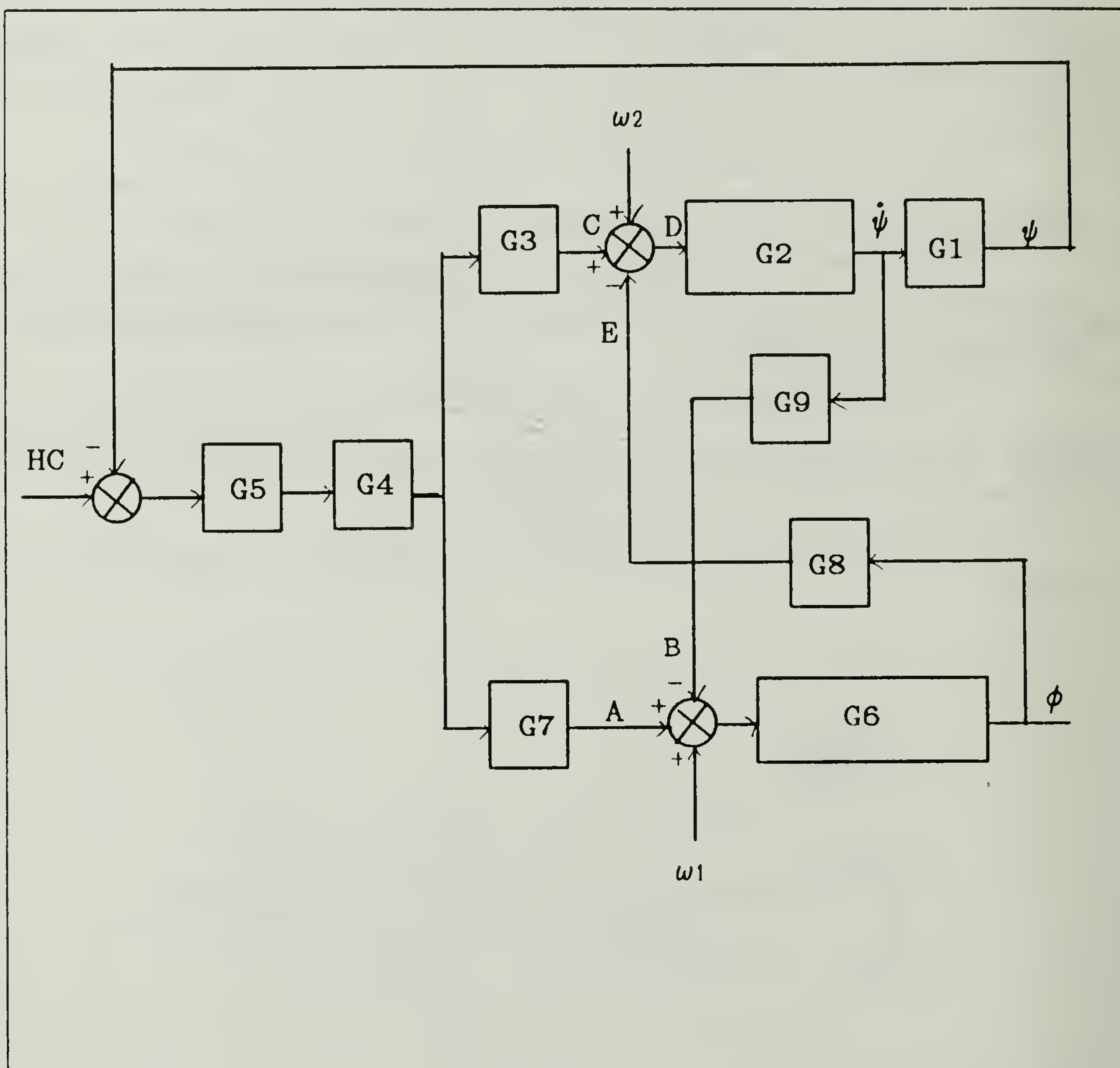

Figure B.1 Block Diagram Model of Ship's Dynamics with Autopilot (without compensator).

where

G_1 is the integration function $\{= 1/S\}$.

G_2 is the ship's heading equation $\{= 1/(S\tau_r + 1)\}$.

G_3 is a constant relating rudder angle to heading rate $\{= N_\delta\}$.

G_4 is the rudder servo equation $\{= KRSER/(S + KRSER)\}$.
G_5 is the autopilot equation $\{= KHP + KHD*S\}$.
G_6 is the ship's roll equation $\{= \omega_n^2/(s^2 + 2\zeta\omega_n s + \omega_n^2)\}$.
G_7 is a constant relating rudder angle to roll moment $\{= K_\delta\}$.
G_8 is a constant relating rudder angle to heading rate $\{= N_\Phi\}$.
G_9 is a constant relating heading rate to roll moment $\{= K_r\}$.
ζ is a damping ratio of the roll dynamics.
ω_n is the natural frequency of the roll dynamics.
KRSER is a constant relating rudder servo gain.
KHP is a constant relating heading gain (Autopilot).
KHD is a constant relating heading rate gain (Autopilot).

letting $\omega_2 = 0.0$,

For convenience, products of the types $G_1G_2G_3...$ are written as $G_{1,2,3}...$,

$$\Phi = G_6(\omega_1 + A - B) \quad (B.1)$$

$$A = - G_{1,2,4,5,7}D \quad (B.2)$$

$$B = G_{2,9}D \quad (B.3)$$

$$C = - G_{1,2,3,4,5}D \quad (B.4)$$

$$D = C - E \quad (B.5)$$

$$E = G_8 \Phi \tag{B.6}$$

Thus

$$D = -G_{1,2,3,4,5} D - G_8 \Phi$$

$$= \frac{-G_8 \Phi}{1 + G_{1,2,3,4,5}} \tag{B.7}$$

$$\Phi = G_6(\omega_1 - G_{1,2,4,5,7} D - G_{2,9} D)$$

$$= G_6[\omega_1 + \frac{(G_{1,2,4,5,7,8} + G_{2,8,9})}{1 + G_{1,2,3,4,5}} \Phi] \tag{B.8}$$

$$\frac{\Phi}{\omega_1} = \frac{G_6(1 + G_{1,2,3,4,5})}{1 + G_{1,2,3,4,5} - G_{1,2,4,5,6,7,8} - G_{2,6,8,9}} \tag{B.9}$$

where G_8 is zero

$$\frac{\Phi}{\omega_1} = G_6 \tag{B.10}$$

The physical interpretation of this is that in a beam sea, the waves do not cause yawing, and there is no cross coupling from roll to yaw, so the ship stays on course and the autopilot does not need to give rudder commands. Thus ship rolling is not affected by the rudder, because the rudder remains in the neutral position.

APPENDIX C
THE ROLL MODEL WITH COMPENSATOR

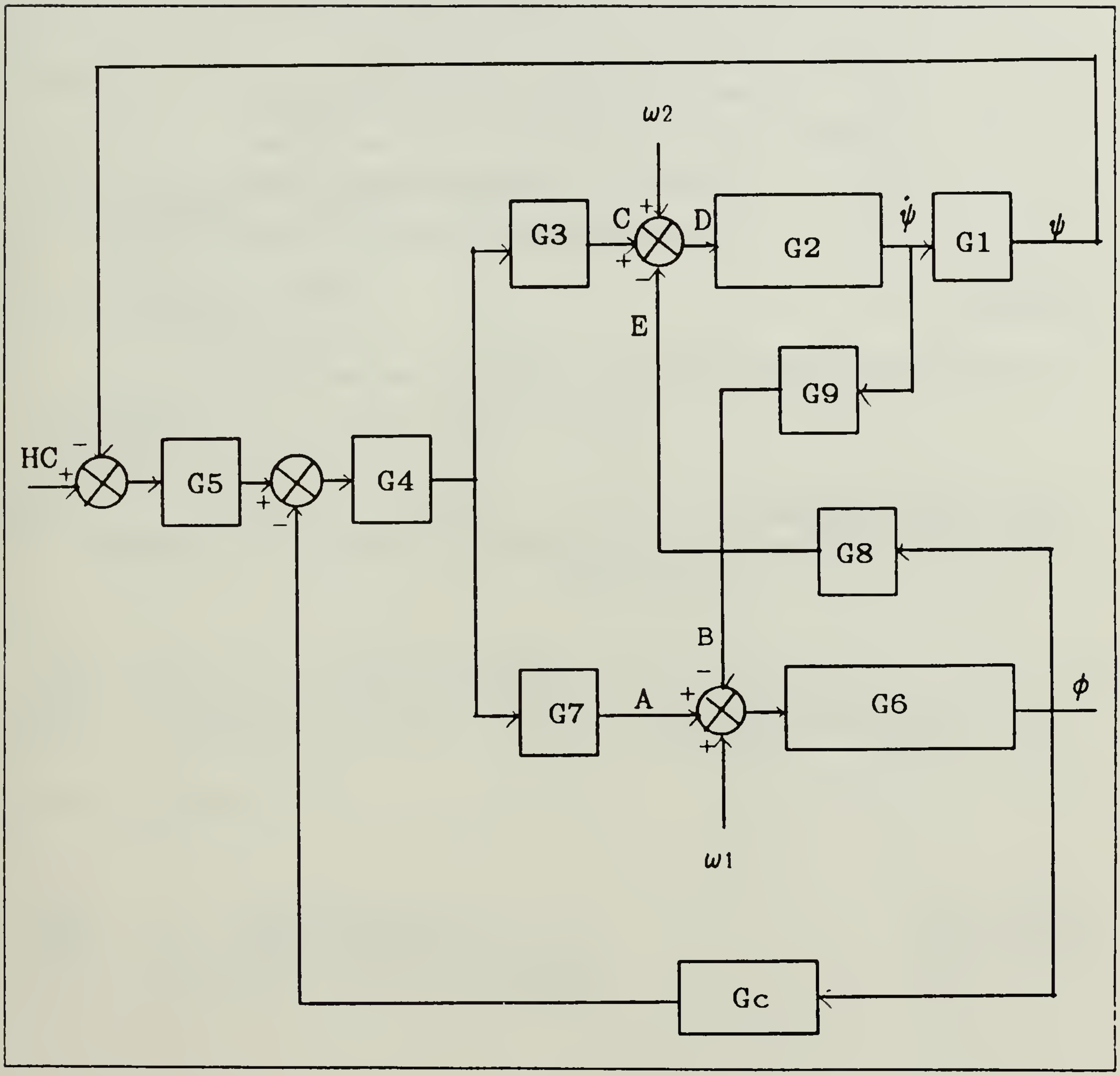

Figure C.1 Block Diagram Model of Ship's Dynamics with Autopilot (With Compensator).

where

G_1 is the integration function $\{= 1/S\}$.

G_2 is the ship's heading equation $\{= 1/(S\tau_r + 1)\}$.

G_3 is a constant relating rudder angle to heading rate $\{= N_\delta\}$.

G_4 is the rudder servo equation {= KRSER/(S + KRSER)}.

G_5 is the autopilot equation {= KHP + KHD*S}.

G_6 is the ship's roll equation $\{= \omega_n^2/(s^2 + 2\zeta\omega_n s + \omega_n^2)\}$.

G_7 is a constant relating rudder angle to roll moment $\{= K_\delta\}$.

G_8 is a constant relating rudder angle to heading rate $\{= N_\Phi\}$.

G_9 is a constant relating heading rate to roll moment $\{= K_r\}$.

G_c is a roll compensated equation $\{K_2{*}S + K_1\}$.

ζ is a damping ratio of the roll dynamics.

ω_n is the natural frequency of the roll dynamics.

KRSER is a constant relating rudder servo gain.

KHP is a constant relating heading gain (Autopilot).

KHD is a constant relating heading rate gain (Autopilot).

letting $\omega_2 = 0.0$,

For convenience, products of the types $G_1G_2G_3$... are written as $G_{1,2,3\ldots}$,

$$\Phi = G_6(\omega_1 + A - B) \tag{C.1}$$

$$A = -G_{1,2,4,5,7}D - G_{4,7,}G_c\Phi \tag{C.2}$$

$$B = G_{2,9}D \tag{C.3}$$

$$C = -G_{1,2,3,4,5}D - G_{3,4,}G_c\Phi \tag{C.4}$$

$$D = C - E \tag{C.5}$$

$$E = G_8 \Phi \tag{C.6}$$

Thus

$$D = -G_{1,2,3,4,5} D - G_{3,4,} G_c \Phi - G_8 \Phi$$

$$= \frac{-(G_{3,4,} G_c + G_8)\Phi}{1 + G_{1,2,3,4,5}} \tag{C.7}$$

$$\Phi = G_6(\omega_1 - G_{1,2,4,5,7} D - G_{4,7,} G_c \Phi - G_{2,9} D)$$

$$= G_6[\omega_1 + \{ \frac{(G_{1,2,3,4,4,5,7} G_c + G_{1,2,4,5,7,8} + G_{2,3,4,9} G_c + G_{2,8,9})}{1 + G_{1,2,3,4,5}} - G_{4,7,} G_c \} \Phi] \tag{C.8}$$

$$\frac{\Phi}{\omega_1} = \frac{G_6(1 + G_{1,2,3,4,5})}{1 + G_{1,2,3,4,5} - G_{1,2,4,5,6,7,8} - G_{2,6,8,9} + G_c(G_{4,6,7} - G_{2,3,4,6,9})} \tag{C.9}$$

where G_8 is zero

$$\frac{\Phi}{\omega_1} = \frac{G_6(1 + G_{1,2,3,4,5})}{1 + G_{1,2,3,4,5} + G_c(G_{4,6,7} - G_{2,3,4,6,9})} \tag{C.10}$$

APPENDIX D

COMPUTER PROGRAM FOR ROLL, UNCOMPENSATED

```
TITLE Model Without Compensator
*
****************************************************************
***                                                          ***
***     The Roll Response of the Open System                 ***
***                                                          ***
****************************************************************
*
CONST ZETA=0.18, OMEGAN=0.59,...
      KWH=0.0, KWR=1.0
*
PARAM W=0.3
PARAM A0=0.06
*
*
INITIAL
      Y0=0.0
      YD0=0.0
*
* The Wave Equation
*
      TH=W*TIME
      WAVE=A0*SIN(TH)
*
* The Roll Equation
*
      ERROR=(OMEGAN**2*WAVE*KWR)-SUM
      SUM=(2*ZETA*OMEGAN*RORATE)+(OMEGAN**2*ROLL)
      ROACC=ERROR
      RORATE=INTGRL(Y0,ROACC)
      rorang=rorate*180./3.14
      ROLL=INTGRL(Y0,RORATE)
      ROLANG=ROLL*180./3.14
*
CONTRL FINTIM=500.0, DELT=0.1
PRINT 1.0,rorang,ROLANG
SAVE  0.1,rorang,ROLANG
*
END
PARAM W=0.4
PARAM A0=0.10
*
END
PARAM W=0.5
PARAM A0=0.15
*
END
PARAM W=0.6
PARAM A0=0.10
*
END
PARAM W=0.7
PARAM A0=0.09
*
END
PARAM W=0.8
PARAM A0=0.07
*
END
PARAM W=0.9
PARAM A0=0.07
```

```
*
END
PARAM W=1.0
PARAM A0=0.05
*
END
PARAM W=1.1
PARAM A0=0.04
*
*
GRAPH (G,DE=TEK618,PO=0, NI=8) TIME(UN=SEC) ROLANG(UN=DEG)
LABEL (G) ROLL ANGLE
END
STOP
```

APPENDIX E

COMPUTER PROGRAM FOR ROLL COMPENSATED, IDEAL RUDDER

```
TITLE Model Ideal Rudder With Compensator : Sine Wave and Complex Wave
*
*****************************************************************
***                                                           ***
***     The Roll Response of the Open System  and             ***
***                                                           ***
***         Ideal Rudder  with Roll and                       ***
***                                                           ***
***         Roll Rate Feedback                                ***
***                                                           ***
*****************************************************************
*
TITLE THE ROLL RESPONSE WITH COMPENSATOR : IDEAL RUDDER
*
CONST COMMAX=1000.0, COMMIN=-1000.0, RATMAX=1000.0, RATMIN=-1000.0,...
      KPSDR=0.077, KPHDR=0.20, KPHSDT=4.9, KPHPH=0.0,...
      KWH=0.0, KWR=1.0,...
      KRSER=10.0, TPS=6.7,...
      OMEGAN=0.59, ZETA=0.18,...
      Z=0.025, P=1000,...
      KHP=40000.0, KHD=0.0,...
      KRP=6.0, KRD=6.0, KRDD=0.0
      W1=0.3, W2=0.4, W3=0.5, W4=0.6,...
      W5=0.7, W6=0.8, W7=0.9, W8=1.0,...
      A1=0.06, A2=0.1, A3=0.15, A4=0.1,...
      A5=0.09, A6=0.07, A7=0.07, A8=0.05,...
      K=0.3
*
INITIAL
      Y0=0.0
      YD0=0.0
*
DERIVATIVE
*
      HEDCOM=0.0
      ERROR1=HEDCOM-YAW
*
* The Auto-Pilot Equation
*
      COMK=ERROR1*KHP
      COM=ZEROPL(Y0,Z,P,COMK)
      ERROR2=COM-GC
      COMLIM=LIMIT(COMMIN,COMMAX,ERROR2)
      ERROR3=COMLIM-DELTA
*
* The Rudder Servo Equation
*
      DELLIM=LIMIT(RATMIN,RATMAX,KRSER*ERROR3)
      DELTA=INTGRL(Y0,DELLIM)
      RUDRAT=DELLIM
      RDRANG=RUDRAT*180./3.14
      RUDDER=DELTA
      RUDANG=RUDDER*180./3.14
*
* The Wave Equation
*
* PURE SINE WAVE
*
*     TH=W3*TIME
*     WAVEK=A3*SIN(TH)
*
```

```
* COMPLEX WAVE
*
      WAVE=A1*SIN(W1*TIME)+A2*SIN(W2*TIME)+A3*SIN(W3*TIME)+...
           A4*SIN(W4*TIME)+A5*SIN(W5*TIME)+A6*SIN(W6*TIME)+...
          A7*SIN(W7*TIME)+A8*SIN(W8*TIME)
      WAVEK=WAVE*K
*
* The Ship's Yaw Equation
*
      SUM1=DELTA*KPSDR-ROLL2*KPHPH+WAVEK*KWH
      YAWR=REALPL(Y0,TPS,SUM1)
      YAW=INTGRL(Y0,YAWR)
      YWRANG=YAWR*180./3.14
      YAWANG=YAW*180./3.14
*
*  THE SHIP'S ROLL EQUATION (OPEN SYSTEM)
*
      SUMO=(2*ZETA*OMEGAN*RORAT1)+(OMEGAN**2*ROLL1)
      ERRORO=(OMEGAN**2*WAVEK*KWR)-SUMO
      ROACC1=ERRORO
      RORAT1=INTGRL(Y0,ROACC1)
      ROLL1=INTGRL(Y0,RORAT1)
      ROLAG1=ROLL1*180./3.14
*
* THE SHIP'S ROLL EQUATION (COMPENSATED SYSTEM)
*
      SUM2=DELTA*KPHDR-YAWR*KPHSDT+WAVEK*KWR
      SUM3=(2*ZETA*OMEGAN*RORAT2)+(OMEGAN**2*ROLL2)
      ERROR4=(OMEGAN**2*SUM2)-SUM3
      ROACC2=ERROR4
      RORAT2=INTGRL(Y0,ROACC2)
      ROLL2=INTGRL(Y0,RORAT2)
      RORAG2=RORAT2*180./3.14
      ROLAG2=ROLL2*180./3.14
*
* The Roll Feedback Equation
*
      GC=KRP*ROLL2+KRD*RORAT2
*
TERMINAL
METHOD STIFF
CONTROL FINTIM=400, DELT=0.1
PRINT 1.0, RDRANG, RUDANG,YAWANG,ROLAG1,ROLAG2
SAVE 0.1, RDRANG, RUDANG,YAWANG,ROLAG1,ROLAG2
*
GRAPH (TOP/G,DE=TEK618,PO=0.0,6.5, NI=6) TIME(UN=SEC) RUDANG(LE=1.5,...
UN=DEG,LO=-30,SC=10,NI=6.0)
LABEL (TOP) 'IDEAL SYSTEM' SINE WAVE INPUT
LABEL (TOP)   K1=4.0, K2=4.0, W=0.5 RAD/SEC
*
GRAPH (MIDDLE/G,OV,DE=TEK618,PO=0.0,4.0, NI=6) TIME(UN=SEC) YAWANG...
(LE=1.5,UN=DEG,LO=-3.0,SC=1.0,NI=6.0)
LABEL (MIDDLE) 'IDEAL SYSTEM' SINE WAVE INPUT
LABEL (MIDDLE)   K1=4.0, K2=4.0, W=0.5 RAD/SEC
*
GRAPH (BOTTOM/G,OV,DE=TEK618,PO=0.0,1.0, NI=5) TIME(UN=SEC) ROLAG1...
(LO=-25,SC=10.0,NI=5,LE=1.5,UN=DEG) ROLAG2(LO=-25,SC=10.0,NI=5,LE=1.5,...
UN=DEG)
LABEL (BOTTOM) 'OPEN SYSTEM AND IDEAL SYSTEM' SINE WAVE INPUT
LABEL (BOTTOM)         K1=4.0, K2=4.0, W=0.5 RAD/SEC
*
END
STOP
```

APPENDIX F

COMPUTER PROGRAM FOR ROLL COMPENSATED, REAL RUDDER

```
TITLE Model Real Rudder With Compensator : Sine Wave and Complex Wave
*
*****************************************************************
***                                                           ***
***     The Roll Response of the Open System and              ***
***                                                           ***
***         Real Rudder with Roll  and Roll Rate              ***
***                                                           ***
***         Feedback, and Nonlinearity in the                 ***
***                                                           ***
***         Rudder Servo.                                     ***
***                                                           ***
*****************************************************************
TITLE THE ROLL RESPONSE WITHOUT/WITH COMPENSATOR : "K1=4.0, K2=4.0"
*     OPEN SYSTEM AND COMPENSATED SYSTEM
*     IDEAL RUDDER
*
*ONST COMMAX=0.0873, COMMIN=-0.0873, RATMAX=0.1745, RATMIN=-0.1745,...
*ONST COMMAX=0.1745, COMMIN=-0.1745, RATMAX=0.1745, RATMIN=-0.1745,...
*ONST COMMAX=0.3491, COMMIN=-0.3491, RATMAX=0.1745, RATMIN=-0.1745,...
*ONST COMMAX=0.5236, COMMIN=-0.5236, RATMAX=0.1745, RATMIN=-0.1745,...
*ONST COMMAX=0.0873, COMMIN=-0.0873, RATMAX=0.2618, RATMIN=-0.2618,...
*ONST COMMAX=0.1745, COMMIN=-0.1745, RATMAX=0.2618, RATMIN=-0.2618,...
*ONST COMMAX=0.3491, COMMIN=-0.3491, RATMAX=0.2618, RATMIN=-0.2618,...
*ONST COMMAX=0.5236, COMMIN=-0.5236, RATMAX=0.2618, RATMIN=-0.2618,...
*ONST COMMAX=0.0873, COMMIN=-0.0873, RATMAX=0.3491, RATMIN=-0.3491,...
*ONST COMMAX=0.1745, COMMIN=-0.1745, RATMAX=0.3491, RATMIN=-0.3491,...
*ONST COMMAX=0.3491, COMMIN=-0.3491, RATMAX=0.3491, RATMIN=-0.3491,...
*ONST COMMAX=0.5236, COMMIN=-0.5236, RATMAX=0.3491, RATMIN=-0.3491,...
*ONST COMMAX=0.0873, COMMIN=-0.0873, RATMAX=0.0873, RATMIN=-0.0873,...
*ONST COMMAX=0.1745, COMMIN=-0.1745, RATMAX=0.0873, RATMIN=-0.0873,...
*ONST COMMAX=0.3491, COMMIN=-0.3491, RATMAX=0.0873, RATMIN=-0.0873,...
cONST COMMAX=0.5236, COMMIN=-0.5236, RATMAX=0.0873, RATMIN=-0.0873,...
      KPSDR=0.077, KPHDR=0.20, KPHSDT=4.9, KPHPH=0.0,...
      KWH=0.0, KWR=1.0,...
      KRSER=10.0, TPS=6.7,...
      OMEGAN=0.59, ZETA=0.18,...
      Z=0.025, P=1000,...
      KHP=40000.0, KHD=0.0,...
      W1=0.3, W2=0.4, W3=0.5, W4=0.6,...
      W5=0.7, W6=0.8, W7=0.9, W8=1.0,...
      A1=0.06, A2=0.1, A3=0.15, A4=0.1,...
      A5=0.09, A6=0.07, A7=0.07, A8=0.05,...
      K=0.3,...
      KRP=4.0, KRD=4.0, KRDD=0.0
*
INITIAL
      Y0=0.0
      YD0=0.0
*
DERIVATIVE
*
      HEDCOM=0.0
      ERROR1=HEDCOM-YAW
*
* The Auto-Pilot Equation
*
      COMK=ERROR1*KHP
      COM=ZEROPL(Y0,Z,P,COMK)
      ERROR2=COM-GC
      COMLIM=LIMIT(COMMIN,COMMAX,ERROR2)
```

```
     ERROR3=COMLIM-DELTA
*
* The Rudder Servo Equation
*
     DELLIM=LIMIT(RATMIN,RATMAX,KRSER*ERROR3)
     DELTA=INTGRL(Y0,DELLIM)
     RUDRAT=DELLIM
     RDRANG=RUDRAT*180./3.14
     RUDDER=DELTA
     RUDANG=RUDDER*180./3.14
*
* The Wave Equation
*
* PURE SINE WAVE
*
*    TH=W3*TIME
*    WAVEK=A3*SIN(TH)
*
* COMPLEX WAVE
*
     WAVE=A1*SIN(W1*TIME)+A2*SIN(W2*TIME)+A3*SIN(W3*TIME)+...
          A4*SIN(W4*TIME)+A5*SIN(W5*TIME)+A6*SIN(W6*TIME)+...
         A7*SIN(W7*TIME)+A8*SIN(W8*TIME)
     WAVEK=WAVE*K
*
* The Ship's Yaw Equation
*
     SUM1=DELTA*KPSDR-ROLL2*KPHPH+WAVEK*KWH
     YAWR=REALPL(Y0,TPS,SUM1)
     YAW=INTGRL(Y0,YAWR)
     YWRANG=YAWR*180./3.14
     YAWANG=YAW*180./3.14
*
*  THE SHIP'S ROLL EQUATION (OPEN SYSTEM)
*
     SUMO=(2*ZETA*OMEGAN*RORAT1)+(OMEGAN**2*ROLL1)
     ERRORO=(OMEGAN**2*WAVEK*KWR)-SUMO
     ROACC1=ERRORO
     RORAT1=INTGRL(Y0,ROACC1)
     ROLL1=INTGRL(Y0,RORAT1)
     ROLAG1=ROLL1*180./3.14
*
* THE SHIP'S ROLL EQUATION (COMPENSATED SYSTEM)
*
     SUM2=DELTA*KPHDR-YAWR*KPHSDT+WAVEK*KWR
     SUM3=(2*ZETA*OMEGAN*RORAT2)+(OMEGAN**2*ROLL2)
     ERROR4=(OMEGAN**2*SUM2)-SUM3
     ROACC2=ERROR4
     RORAT2=INTGRL(Y0,ROACC2)
     ROLL2=INTGRL(Y0,RORAT2)
     RORAG2=RORAT2*180./3.14
     ROLAG2=ROLL2*180./3.14
*
* The Roll Feedback Equation
*
     GC=KRP*ROLL2+KRD*RORAT2
*
TERMINAL
METHOD STIFF
CONTRL FINTIM=400.0, DELT=0.1
PRINT 1.0,RDRANG,RUDANG,YAWANG,ROLAG1,ROLAG2
SAVE 0.1,RDRANG,RUDANG,YAWANG,ROLAG1,ROLAG2
*
GRAPH (TOP/G,DE=TEK618,PO=0.0,6.5, NI=6) TIME(UN=SEC) RUDANG(LE=1.5,...
UN=DEG,LO=-30,SC=10,NI=6.0)
LABEL (TOP) 'REAL SYSTEM' SINE WAVE INPUT
LABEL (TOP)   K1=4.0, K2=4.0
*
GRAPH (MIDDLE/G,OV,DE=TEK618,PO=0.0,4.0, NI=6) TIME(UN=SEC) YAWANG...
```

```
(LE=1.5,UN=DEG,LO=-3.0,SC=1.0,NI=6.0)
LABEL (MIDDLE) 'REAL SYSTEM' SINE WAVE INPUT
LABEL (MIDDLE)   K1=4.0, K2=4.0
*
GRAPH (BOTTOM/G,OV,DE=TEK618,PO=0.0,1.0, NI=5) TIME(UN=SEC) ROLAG1...
(LO=-25,SC=10.0,NI=5,LE=1.5,UN=DEG) ROLAG2(LO=-25,SC=10.0,NI=5,LE=1.5,...
UN=DEG)
LABEL (BOTTOM) 'OPEN SYSTEM AND REAL SYSTEM' SINE WAVE INPUT
LABEL (BOTTOM)         K1=4.0, K2=4.0
*
END
STOP
```

APPENDIX G

COMPUTER PROGRAM FOR PLOTTING IN DISSPLA : A

```
**************************************************
***                                            ***
***     This is a program for plotting         ***
***                                            ***
***     in DISSPLA in maximum rudder rate      ***
***                                            ***
***     vs maximum roll angle and maximum      ***
***                                            ***
***     rudder rate vs maximum heading angle   ***
***                                            ***
**************************************************
c
C PLOTTING THE GIVEN FUNCTION
      PROGRAM GRF2D
        CALL COMPRS
        CALL XYPLOT
        CALL DONEPL
        STOP
        END
C
      SUBROUTINE XYPLOT
      DIMENSION X(50),Y(50)
      REAL X,Y
      INTEGER I,J,N,M
      CALL PAGE(21.,18.)
C
C GRF 1ST
c
      CALL PHYSOR(2.,12.)
      CALL AREA2D(7.,5.)
      CALL YAXANG(90.)
      CALL HEIGHT(0.25)
      CALL COMPLX
      CALL XNAME('RUDDER RATE (DEG/SEC)',21)
      CALL YNAME('HEADING ANGLE (DEG)',19)
      CALL FRAME
      CALL DASH
      CALL GRAF(0.,5.,25.,0.,0.1,0.5)
      CALL GRID(1,1)
      CALL RESET('DASH')
      CALL THKCRV(0.05)
         DO 20 J =1,4
           READ(5,15)X(J),Y(J)
 15        FORMAT(F4.1, F6.1)
 20      CONTINUE
      CALL CURVE(X,Y,4,0)
      CALL RESET('THKCRV')
      CALL ENDGR(0)
C
C GRF 2ND
c
      CALL PHYSOR(12.,12.)
      CALL AREA2D(7.,5.)
      CALL XNAME('RUDDER RATE (DEG/SEC)',21)
      CALL YNAME('HEADING ANGLE (DEG)',19)
      CALL DASH
      CALL GRAF(0.,5.,25.,0.,0.1,0.5)
      CALL GRID(1,1)
      CALL RESET('DASH')
      CALL THKCRV(0.05)
         DO 30 J =1,4
```

```
          READ(5,25)X(J),Y(J)
25        FORMAT(F4.1, F6.1)
30      CONTINUE
        CALL CURVE(X,Y,4,0)
      CALL RESET('THKCRV')
      CALL ENDGR(0)
C
C GRF 3RD
C
      CALL PHYSOR(2.,3.)
      CALL AREA2D(7.,5.)
      CALL XNAME('RUDDER RATE (DEG/SEC)',21)
      CALL YNAME('HEADING ANGLE (DEG)',19)
      CALL DASH
      CALL GRAF(0.,5.,25.,0.,0.1,0.5)
      CALL GRID(1,1)
      CALL RESET('DASH')
      CALL THKCRV(0.05)
        DO 40 J =1,4
          READ(5,35)X(J),Y(J)
 35       FORMAT(F4.1, F6.1)
 40      CONTINUE
      CALL CURVE(X,Y,4,0)
      CALL RESET('THKCRV')
      CALL ENDGR(0)
C
C GRF 4TH
C
      CALL PHYSOR(12.,3.)
      CALL AREA2D(7.,5.)
C     CALL HEIGHT(0.2)
      CALL XNAME('RUDDER RATE (DEG/SEC)',21)
      CALL YNAME('HEADING ANGLE (DEG)',19)
C     CALL RESET('HEIGHT')
      CALL DASH
      CALL GRAF(0.,5.,25.,0.,0.1,0.5)
      CALL GRID(1,1)
C     CALL HEIGHT(0.05)
      CALL RESET('DASH')
      CALL THKCRV(0.05)
        DO 50 J =1,4
          READ(5,45)X(J),Y(J)
45        FORMAT(F4.1, F6.1)
50      CONTINUE
      CALL CURVE(X,Y,4,0)
      CALL RESET('ALL')
      CALL ENDGR(0)
C
C MESSAGE
C
      CALL PHYSOR(0.,0.)
      CALL AREA2D(7.,5.)
      CALL HEIGHT(0.275)
      CALL COMPLX
      CALL MESSAG('A ; Z = 0 . 5 ',13,4.,10.25)
      CALL MESSAG('B ; Z = 1 . 0 ',13,14.,10.25)
      CALL MESSAG('C ; Z = 1 . 5 ',13,4.,1.)
      CALL MESSAG('D ; Z = 2 . 0 ',13,14.,1.)
C     CALL MESSAG('A; MAXIMUM RUDDER ANGLE : 5 (DEG)  ',35,2.,10.25)
C     CALL MESSAG('B; MAXIMUM RUDDER ANGLE : 10 (DEG) ',35,12.,10.25)
C     CALL MESSAG('C; MAXIMUM RUDDER ANGLE : 20 (DEG) ',35,2.,1.)
C     CALL MESSAG('D; MAXIMUM RUDDER ANGLE : 30 (DEG) ',35,12.,1.)
      CALL RESET('ALL')
      CALL ENDPL(0)
      RETURN
      END
```

APPENDIX H

COMPUTER PROGRAM FOR PLOTTING IN DISSPLA : B

```
*************************************************
***                                           ***
***     This is a program for plotting        ***
***                                           ***
***     in DISSPLA in FREQUENCY VS            ***
***                                           ***
***     maximum roll angle OF OPEN SYSTEM,    ***
***                                           ***
***     IDEAL RUDDER AND REAL RUDDER.         ***
***                                           ***
*************************************************
C
C     GRAPH OF XY DATA GIVEN
      PROGRAM GRF2D
      CALL TEK618
      CALL XYPLOT
      CALL DONEPL
      STOP
      END
C PLOTTING THE GIVEN FUNCTION
      SUBROUTINE XYPLOT
      DIMENSION X(100),Y1(100),Y2(100),IPKRAY(100)
      REAL X,Y1,Y2
      INTEGER I,J,N,M
C SET PAGE AND SUBPLOT SIZES
      CALL PAGE(15.,11.)
      CALL AREA2D(7.,8.)
      CALL HEIGHT(.25)
C  LABEL AND DRAW AXIS
      CALL XNAME('W (RAD/SEC)',11)
      CALL YNAME('ROLL-MAX (DEG)',14)
      CALL COMPLX
      CALL FRAME
      CALL GRAF(0.2,0.1,1.2,0.0,4.0,22.0)
      CALL GRID(1,1)
      CALL SPLINE
         DO 20 I =1,9
           READ(5,55)X(I),Y1(I),Y2(I)
55    FORMAT(F3.1,F7.1,F6.1)
20    CONTINUE
C  SET UP FOR LEGEND
      MAXLIN = LINEST(IPKRAY,100,15)
      CALL LINES ('OPEN SYSTEM$',IPKRAY,1)
      CALL LINES ('IDEAL SYSTEM$',IPKRAY,2)
      CALL LEGLIN
C PLOT CURVES
      CALL CURVE(X,Y1,9,1)
      CALL DASH
      CALL CURVE(X,Y2,9,1)
      CALL RESET('ALL')
C  WRITE LEGEND AND TITLE
      CALL LEGEND(IPKRAY,2,3.3,4.5)
      CALL HEADIN('OPEN SYSTEM VS IDEAL SYSTEM $',100,-4,2)
      CALL ENDPL(0)
      RETURN
      END
```

APPENDIX I
SIMULATION RESULTS

TABLE 4
IDEAL RUDDER WITH DIFFERENT ZERO LOCATIONS

$\omega = 0.5$

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	13.7	27.4	1.2	8.5
0.5	2.0	4.0	12.2	24.5	1.1	12.6
1.0	4.0	4.0	13.9	27.7	1.2	9.0
1.5	6.0	4.0	15.3	30.6	1.3	7.0
2.0	8.0	4.0	16.3	32.6	1.4	5.8

TABLE 5
REAL RUDDER WITH DIFFERENT ZERO LOCATIONS

$\omega = 0.5$

Maximum Rudder Angle Limit = ± 5 degree
Maximum Rudder Rate Limit = ± 5 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	5.0	5.0	0.3	17.9
0.5	2.0	4.0	5.0	5.0	0.2	17.9
1.0	4.0	4.0	5.0	5.0	0.3	17.9
1.5	6.0	4.0	5.0	5.0	0.3	17.9
2.0	8.0	4.0	5.0	5.0	0.3	18.0

TABLE 5

REAL RUDDER WITH DIFFERENT ZERO LOCATIONS (CONT'D.)

Maximum Rudder Angle Limit = ± 10 degree

Maximum Rudder Rate Limit = ± 5 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	5.0	10.0	0.5	16.8
0.5	2.0	4.0	5.0	10.0	0.5	15.6
1.0	4.0	4.0	5.0	10.0	0.5	16.2
1.5	6.0	4.0	5.0	10.0	0.5	16.8
2.0	8.0	4.0	5.0	10.0	0.5	17.2

Maximum Rudder Angle Limit = ± 20 degree

Maximum Rudder Rate Limit = ± 5 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	5.0	15.4	0.6	18.8
0.5	2.0	4.0	5.0	15.2	0.6	15.5
1.0	4.0	4.0	5.0	15.5	0.6	17.4
1.5	6.0	4.0	5.0	15.6	0.7	18.6
2.0	8.0	4.0	5.0	15.8	0.9	19.5

Maximum Rudder Angle Limit = ± 30 degree

Maximum Rudder Rate Limit = ± 5 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	5.0	15.5	0.5	18.8
0.5	2.0	4.0	5.0	15.2	0.8	15.5
1.0	4.0	4.0	5.0	15.5	0.6	17.4
1.5	6.0	4.0	5.0	16.1	0.7	18.7
2.0	8.0	4.0	5.0	17.1	0.9	19.3

TABLE 5

REAL RUDDER WITH DIFFERENT ZERO LOCATIONS (CONT'D.)

Maximum Rudder Angle Limit = ± 5 degree

Maximum Rudder Rate Limit = ± 10 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	10.0	5.0	0.3	17.7
0.5	2.0	4.0	10.0	5.0	0.3	18.0
1.0	4.0	4.0	10.0	5.0	0.3	17.7
1.5	6.0	4.0	10.0	5.0	0.3	17.7
2.0	8.0	4.0	10.0	5.0	0.3	17.7

Maximum Rudder Angle Limit = ± 10 degree

Maximum Rudder Rate Limit = ± 10 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	10.0	10.0	0.6	14.9
0.5	2.0	4.0	10.0	10.0	0.6	15.7
1.0	4.0	4.0	10.0	10.0	0.6	14.9
1.5	6.0	4.0	10.0	10.0	0.6	14.9
2.0	8.0	4.0	10.0	10.0	0.6	15.1

Maximum Rudder Angle Limit = ± 20 degree

Maximum Rudder Rate Limit = ± 10 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	10.0	20.0	1.0	10.9
0.5	2.0	4.0	10.0	20.0	0.9	12.1
1.0	4.0	4.0	10.0	20.0	1.0	10.5
1.5	6.0	4.0	10.0	20.0	1.0	10.9
2.0	8.0	4.0	10.0	20.0	1.0	11.7

TABLE 5

REAL RUDDER WITH DIFFERENT ZERO LOCATIONS (CONT'D.)

Maximum Rudder Angle Limit = ± 30 degree

Maximum Rudder Rate Limit = ± 10 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	10.0	30.0	1.2	9.2
0.5	2.0	4.0	10.0	25.9	1.1	12.2
1.0	4.0	4.0	10.0	29.9	1.2	9.0
1.5	6.0	4.0	10.0	30.0	1.2	10.8
2.0	8.0	4.0	10.0	30.0	1.2	12.8

Maximum Rudder Angle Limit = ± 5 degree

Maximum Rudder Rate Limit = ± 15 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	15.0	5.0	0.3	17.7
0.5	2.0	4.0	15.0	5.0	0.3	18.1
1.0	4.0	4.0	15.0	5.0	0.3	17.7
1.5	6.0	4.0	15.0	5.0	0.3	17.7
2.0	8.0	4.0	15.0	5.0	0.3	17.7

Maximum Rudder Angle Limit = ± 10 degree

Maximum Rudder Rate Limit = ± 15 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	15.0	10.0	0.6	14.7
0.5	2.0	4.0	15.0	10.0	0.6	15.8
1.0	4.0	4.0	15.0	10.0	0.6	14.8
1.5	6.0	4.0	15.0	10.0	0.6	14.8
2.0	8.0	4.0	15.0	10.0	0.6	14.8

TABLE 5

REAL RUDDER WITH DIFFERENT ZERO LOCATIONS (CONT'D.)

Maximum Rudder Angle Limit = ± 20 degree

Maximum Rudder Rate Limit = ± 15 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	15.0	20.0	1.1	9.9
0.5	2.0	4.0	13.5	20.0	1.0	13.0
1.0	4.0	4.0	15.0	20.0	1.0	10.5
1.5	6.0	4.0	15.0	20.0	1.1	9.4
2.0	8.0	4.0	15.0	20.0	1.1	9.4

Maximum Rudder Angle Limit = ± 30 degree

Maximum Rudder Rate Limit = ± 15 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	13.7	27.4	1.2	8.5
0.5	2.0	4.0	12.2	24.4	1.1	12.6
1.0	4.0	4.0	13.6	27.7	1.2	9.0
1.5	6.0	4.0	15.0	30.0	1.4	7.0
2.0	8.0	4.0	15.0	30.0	1.4	5.9

Maximum Rudder Angle Limit = ± 5 degree

Maximum Rudder Rate Limit = ± 20 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	20.0	5.0	0.3	17.6
0.5	2.0	4.0	20.0	5.0	0.3	18.2
1.0	4.0	4.0	20.0	5.0	0.3	17.6
1.5	6.0	4.0	20.0	5.0	0.3	17.6
2.0	8.0	4.0	20.0	5.0	0.3	17.6

TABLE 5

REAL RUDDER WITH DIFFERENT ZERO LOCATIONS (CONT'D.)

Maximum Rudder Angle Limit = ± 10 degree

Maximum Rudder Rate Limit = ± 20 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	20.0	10.0	0.6	14.7
0.5	2.0	4.0	20.0	10.0	0.6	16.0
1.0	4.0	4.0	20.0	10.0	0.6	15.0
1.5	6.0	4.0	20.0	10.0	0.6	14.7
2.0	8.0	4.0	20.0	10.0	0.6	14.7

Maximum Rudder Angle Limit = ± 20 degree

Maximum Rudder Rate Limit = ± 20 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	20.0	20.0	1.1	9.9
0.5	2.0	4.0	20.0	20.0	1.0	13.0
1.0	4.0	4.0	20.0	20.0	1.1	10.5
1.5	6.0	4.0	20.0	20.0	1.1	9.3
2.0	8.0	4.0	20.0	20.0	1.1	9.0

Maximum Rudder Angle Limit = ± 30 degree

Maximum Rudder Rate Limit = ± 20 degree/sec

Z	K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.8	4.5	2.5	13.7	27.2	1.2	8.5
0.5	2.0	4.0	12.1	24.4	1.1	12.6
1.0	4.0	4.0	13.8	27.8	1.3	9.0
1.5	6.0	4.0	15.3	30.0	1.4	7.0
2.0	8.0	4.0	17.1	30.0	2.0	5.9

TABLE 6

IDEAL RUDDER WITH DIFFERENT GAIN

$Z = 1.0$
$\omega = 0.5$

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	6.2	12.3	0.6	16.0
2.0	2.0	9.9	19.8	0.9	12.9
6.0	6.0	15.9	31.9	1.4	6.9
8.0	8.0	17.1	35.6	1.6	5.5

TABLE 7

REAL RUDDER WITH DIFFERENT GAIN

$Z = 1.0$
$\omega = 0.5$

Maximum Rudder Angle Limit = ± 5 degree

Maximum Rudder Rate Limit = ± 5 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	5.0	5.0	0.3	17.9
2.0	2.0	5.0	5.0	0.3	17.9
6.0	6.0	5.0	5.0	0.3	17.9
8.0	8.0	5.0	5.0	0.3	17.9

TABLE 7

REAL RUDDER WITH DIFFERENT GAIN (CONT'D.)

Maximum Rudder Angle Limit = ± 10 degree

Maximum Rudder Rate Limit = ± 5 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	5.0	10.0	0.5	15.9
2.0	2.0	5.0	10.0	0.5	16.0
6.0	6.0	5.0	10.0	0.5	16.4
8.0	8.0	5.0	10.0	0.5	16.5

Maximum Rudder Angle Limit = ± 20 degree

Maximum Rudder Rate Limit = ± 5 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	5.0	13.5	0.5	15.7
2.0	2.0	5.0	13.8	0.6	16.1
6.0	6.0	5.0	15.1	0.7	18.0
8.0	8.0	5.0	16.4	0.9	18.3

Maximum Rudder Angle Limit = ± 30 degree

Maximum Rudder Rate Limit = ± 5 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	5.0	13.5	0.5	15.7
2.0	2.0	5.0	15.5	0.6	16.1
6.0	6.0	5.0	16.0	0.8	18.1
8.0	8.0	5.0	18.6	0.9	18.7

TABLE 7

REAL RUDDER WITH DIFFERENT GAIN (CONT'D.)

Maximum Rudder Angle Limit = ± 5 degree

Maximum Rudder Rate Limit = ± 10 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	9.7	5.0	0.3	18.0
2.0	2.0	10.0	5.0	0.3	17.8
6.0	6.0	10.0	5.0	0.3	17.7
8.0	8.0	10.0	5.0	0.3	17.7

Maximum Rudder Angle Limit = ± 10 degree

Maximum Rudder Rate Limit = ± 10 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	6.7	10.0	0.5	16.4
2.0	2.0	10.0	10.0	0.5	15.1
6.0	6.0	10.0	10.0	0.6	14.9
8.0	8.0	10.0	10.0	0.6	14.9

Maximum Rudder Angle Limit = ± 20 degree

Maximum Rudder Rate Limit = ± 10 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	6.2	12.3	0.5	16.1
2.0	2.0	9.9	19.8	0.8	12.9
6.0	6.0	10.0	20.0	0.9	10.8
8.0	8.0	10.0	20.0	1.0	10.8

TABLE 7

REAL RUDDER WITH DIFFERENT GAIN (CONT'D.)

Maximum Rudder Angle Limit = ± 30 degree

Maximum Rudder Rate Limit = ± 10 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	6.2	12.3	0.5	16.0
2.0	2.0	9.9	19.8	0.9	12.9
6.0	6.0	10.0	30.0	1.2	10.8
8.0	8.0	10.0	30.0	1.2	10.8

Maximum Rudder Angle Limit = ± 5 degree

Maximum Rudder Rate Limit = ± 15 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	9.7	5.0	0.3	18.0
2.0	2.0	15.0	5.0	0.3	17.8
6.0	6.0	15.0	5.0	0.3	17.7
8.0	8.0	15.0	5.0	0.3	17.7

Maximum Rudder Angle Limit = ± 10 degree

Maximum Rudder Rate Limit = ± 15 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	6.9	10.0	0.5	16.3
2.0	2.0	15.0	10.0	0.5	15.3
6.0	6.0	15.0	10.0	0.8	14.8
8.0	8.0	15.0	10.0	0.8	14.8

TABLE 7

REAL RUDDER WITH DIFFERENT GAIN (CONT'D.)

Maximum Rudder Angle Limit = ± 20 degree

Maximum Rudder Rate Limit = ± 15 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	6.2	12.3	0.5	16.0
2.0	2.0	9.9	19.8	0.9	12.9
6.0	6.0	15.0	20.0	1.1	9.5
8.0	8.0	15.0	20.0	1.1	9.5

Maximum Rudder Angle Limit = ± 30 degree

Maximum Rudder Rate Limit = ± 15 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	6.2	12.3	0.5	16.0
2.0	2.0	9.9	19.8	0.9	12.9
6.0	6.0	15.0	30.0	1.4	7.0
8.0	8.0	15.0	30.0	1.4	5.9

Maximum Rudder Angle Limit = ± 5 degree

Maximum Rudder Rate Limit = ± 20 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	9.7	5.0	0.3	18.0
2.0	2.0	19.3	5.0	0.3	17.8
6.0	6.0	20.0	5.0	0.3	17.7
8.0	8.0	20.0	5.0	0.3	17.7

TABLE 7

REAL RUDDER WITH DIFFERENT GAIN (CONT'D.)

Maximum Rudder Angle Limit = ± 10 degree
Maximum Rudder Rate Limit = ± 20 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	6.6	10.0	0.5	16.3
2.0	2.0	16.7	10.0	0.6	15.4
6.0	6.0	20.0	10.0	0.6	14.7
8.0	8.0	20.0	10.0	0.6	14.7

Maximum Rudder Angle Limit = ± 20 degree
Maximum Rudder Rate Limit = ± 20 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	6.1	12.3	0.6	16.1
2.0	2.0	9.9	19.8	0.9	12.9
6.0	6.0	20.0	20.0	1.1	9.5
8.0	8.0	20.0	20.0	1.1	9.2

Maximum Rudder Angle Limit = ± 30 degree
Maximum Rudder Rate Limit = ± 20 degree/sec

K_1	K_2	$\dot{\delta}_{max}$	δ_{max}	Ψ_{max}	Φ_{max}
1.0	1.0	6.2	12.3	0.6	16.0
2.0	2.0	9.9	19.8	0.9	12.9
6.0	6.0	16.0	30.0	1.4	7.0
8.0	8.0	20.0	30.0	1.4	5.8

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