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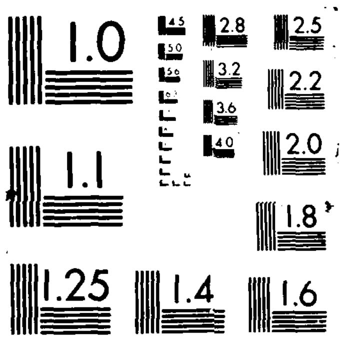
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AD-A186 303

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

COORDINATED STEERING
OF A SURFACE SHIP

by

Sang Sik, Lee

September 1987

Thesis Advisor George J. Thaler

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The conventional approach to ship steering is to regard the ship as a single input, single output system without cross-coupling or interaction between speed, yaw and roll. This approach has found successful application, particularly in conventional vessels where the amount of cross-coupling is normally slight. But, as a result of tight maneuvering, the modern warship suffers severe cross-coupling effects because of large control surfaces, high speed and low tonnage. Consequently, the adoption of a multivariable approach to ship steering would appear to be more suited for the design of a steering control system.

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19. ABSTRACT (cont.)

This thesis describes the results of a simulation study of precompensator design to suppress the undesirable cross-coupling effects between speed, yaw and roll.

Simulation studies using DSL and Function Minimization are the basis for accomplishing the design.

Simulation results presented indicate that the adoption of a multi-input, multi-output approach would result in a significant improvement in the combined steering and stabilization problem of a warship.

Coordinated Steering Of A Surface Ship

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ABSTRACT

The conventional approach to ship steering is to regard the ship as a single input, single output system without cross-coupling or interaction between speed, yaw and roll. This approach has found successful application, particularly in conventional vessels where the amount of cross-coupling is normally slight. But, as a result of tight maneuvering, the modern warship suffers severe cross-coupling effects because of large control surfaces, high speed and low tonnage. Consequently, the adoption of a multivariable approach to ship steering would appear to be more suited for the design of a steering control system.

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ACKNOWLEDGEMENT

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I. INTRODUCTION

Modern warships must be highly maneuverable to satisfy numerous operational requirements. However, the steering characteristics of a modern ship are nonlinear, so severe interaction or cross-coupling exists between the control surface inputs and the controlled outputs. Therefore, warship steering is a complex multivariable control problem.

Interaction between roll, yaw and speed are pronounced in warships because of their length to beam ratio and relatively large control surfaces. However, warships should be able to execute high speed maneuvers while maintaining their fighting capability. This is generally not possible due to severe cross-coupling.

In this thesis, the development of a pre-compensator to reduce the cross-coupling effects which are present in the steering characteristics of a modern ship is introduced. The design method adopted by Roberts [Ref. 1] uses the Direct Nyquist Array (DNA) frequency response technique as defined by Rosenbrock [Ref. 2] and Fricker [Ref. 3]. This thesis uses the basic ship model and the results which were reported by Roberts which have the potential to produce improved seakeeping and ship stability. Emphasis in this thesis is placed on optimizing the parameters of a pre-compensator using Function Minimization (F.M.) via a digital computer.

Simulation studies employed Function Minimization techniques together with the Dynamic Simulation Language (DSL) package.

II. BASIC MODEL

The model and data used in the study is that proposed by Roberts [Ref. 1]. The structure of the ship model is shown in Figure 2.1 and the elements of the transfer function matrix, G(S), which were derived using curve fitting techniques to measured step and frequency response data, are given in Table 1.

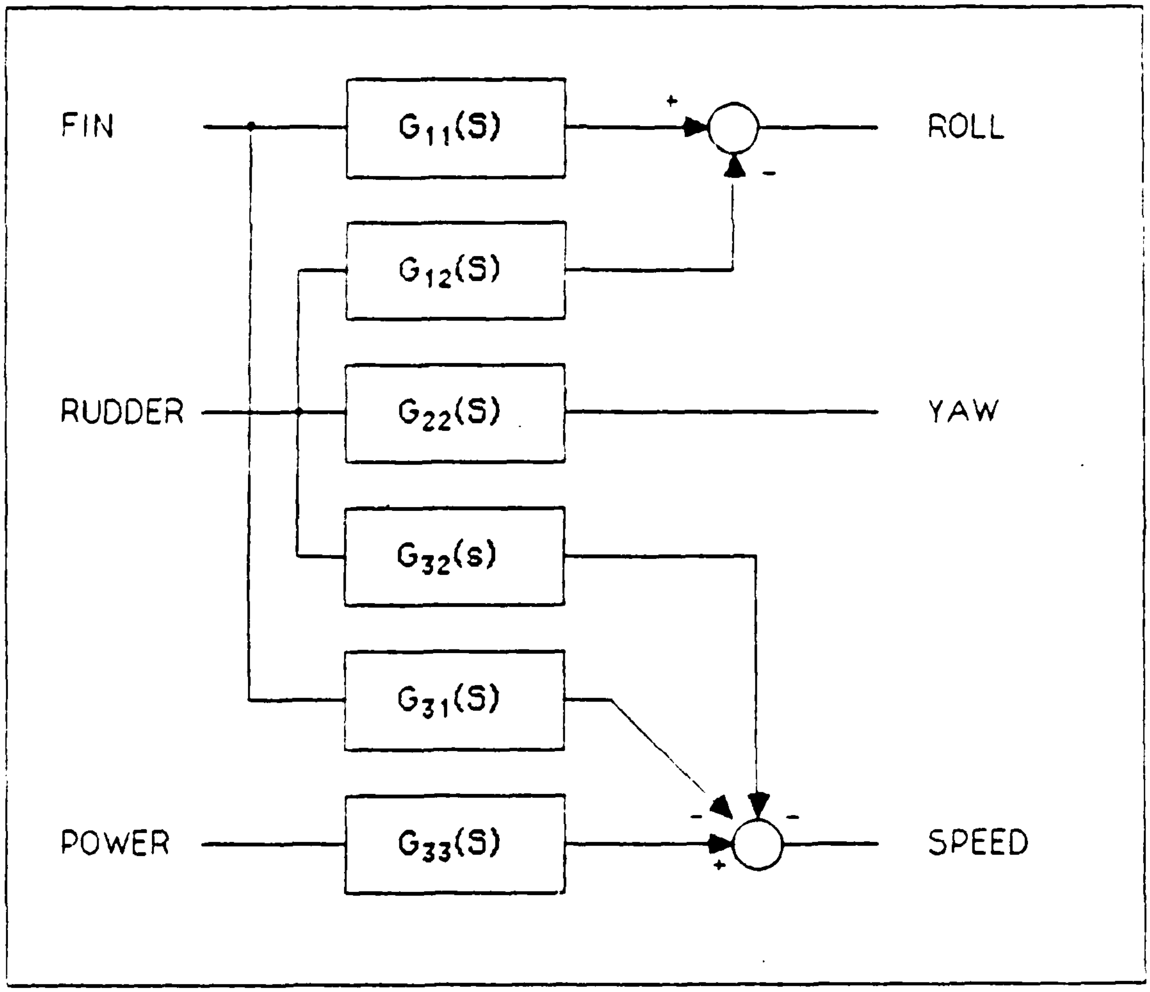

Figure 2.1 Multivariable Structure of a Warship Model.

The nonlinear nature of the ship dynamics is demonstrated by the change in steady state gain parameters as shown in Table 2.

TABLE 1
ELEMENTS OF MATRIX FOR WARSHIP MODEL [REF. 1]

$$G_{11}(S) = \frac{K_{11}}{4S^2 + 0.24S + 1}$$

$$G_{12}(S) = \frac{K_{12}(-8.57S + 1)}{53.3S^3 + 17.17S^2 + 9.52S + 1}$$

$$G_{22}(S) = \frac{K_{22}}{S(12S^3 + 32.25S^2 + 11.2S + 1)}$$

$$G_{31}(S) = \frac{K_{31}(10S + 1)}{240S^3 + 58S^2 + 26S + 1}$$

$$G_{32}(S) = \frac{K_{32}}{240S^2 + 34S + 1}$$

$$G_{33}(S) = \frac{K_{33}}{24S + 1}$$

$$G_{13}(S) = G_{21}(S) = G_{23}(s) = 0$$

TABLE 2
GAIN VARIATION [REF. 1]

Speed (Kts)	K_{11}	K_{12}	K_{22}	K_{31}	K_{32}	K_{33}
12	.114	.18	.01	.058	.096	.1
18	.18	.932	.02	.067	.146	.06
26	.168	.94	.021	.068	.165	.053

For ease of analysis the system inputs and outputs are used as defined below in Table 3.

TABLE 3
MAX VALUES OF INPUT AND OUTPUT

INPUTS	MAX VALUE
Fin Angle	±27°
Rudder Angle	±30°
Power	±10%
OUTPUTS	MAX VALUE
Roll Angle	±15°
Yaw Angle	±120°
Forward Speed	30 Kts

Figure 2.2 and Figure 2.3 show the time responses for the ship model when we use 10% demands for rudder and fin at 12 kts.

As can be seen in Figure 2.2, there are pronounced cross-coupling effects in both roll and speed outputs.

In this thesis, 10% demand for rudder at 12 kts will be always used for convenience.

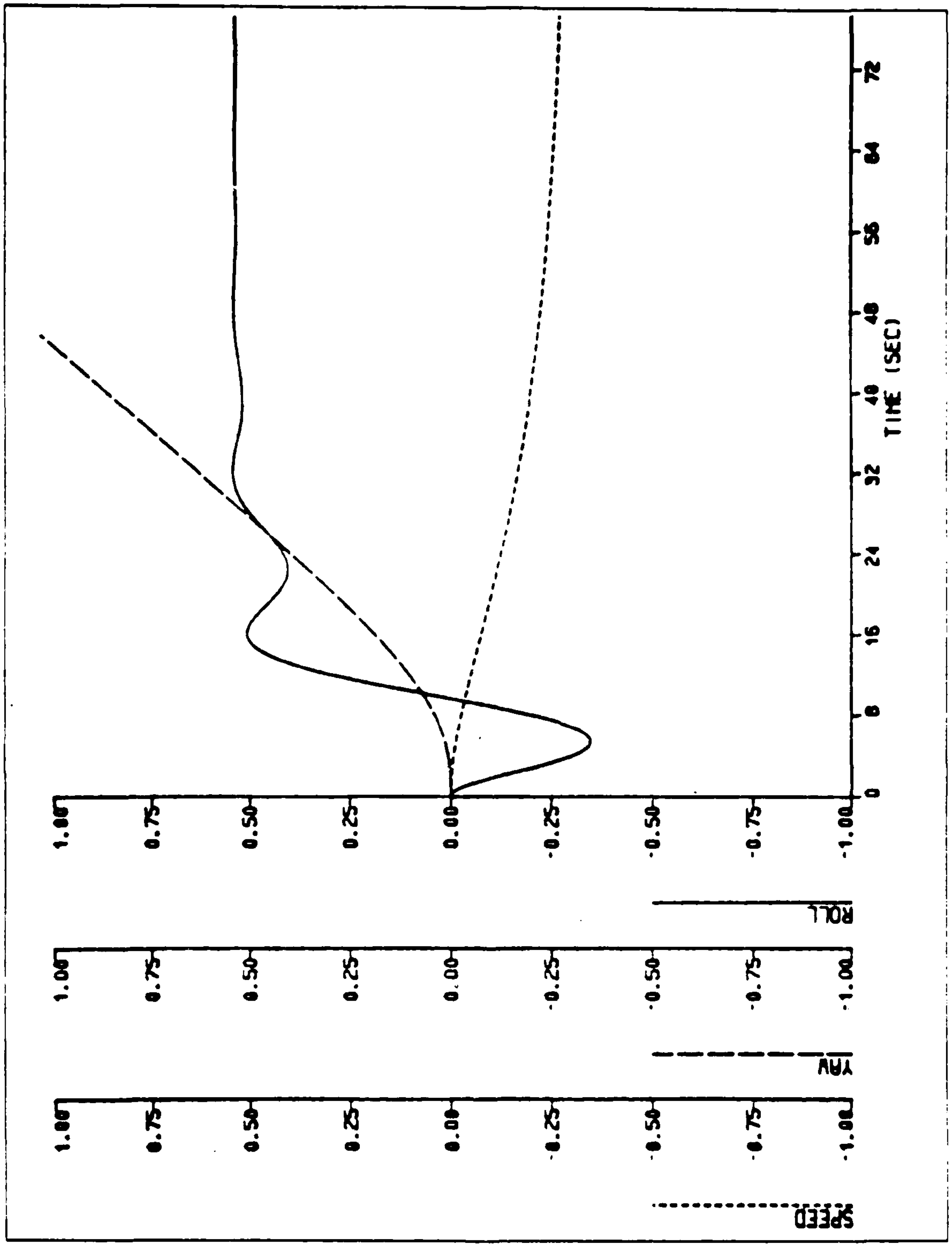

Figure 2.2 Step Response for Uncompensated Warship Model at Rudder Demand.

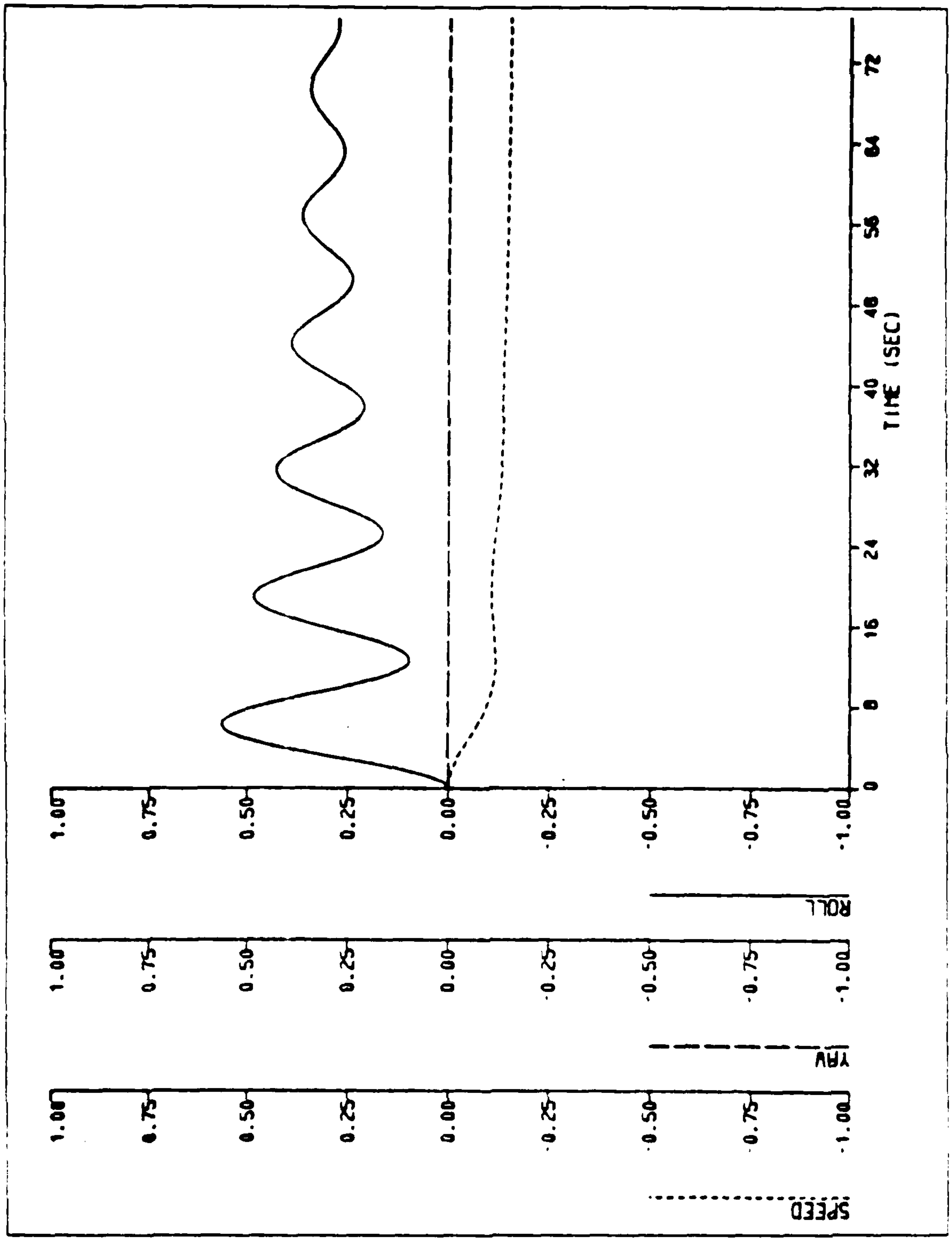

Figure 2.3 Step Response for Uncompensated Warship Model at Fin Demand.

III. PRE-COMPENSATOR DESIGN

The aim of including a pre-compensator, K(S), is to decouple the interaction present in G(S), thus enabling the reduction of interaction or cross-coupling in the system. The action of the pre-compensator is to propagate the three input demands in such a way that each input affects its associated output only.

This chapter was extracted from Roberts [Ref. 1].

The system configuration with the pre-compensator included is shown in Figure 3.1.

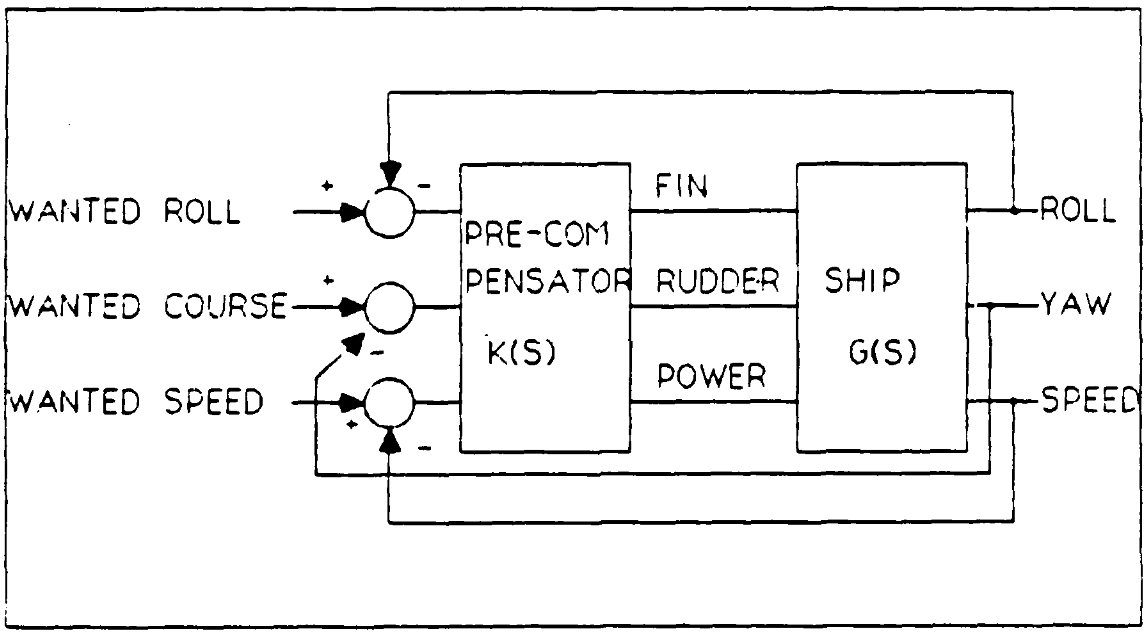

Figure 3.1 Compensated System Configuration.

The approach used in this study is to develop a pre-compensator, K(S), which totally diagonalizes the pair G(S)K(S) (= Q(S)). This is in effect non-interacting control and can result in the elements of K(S) having high order which may prove a problem when it comes to implementation, particularly if this is to be achieved using analog techniques. If necessary the complexity of the elements of K(S) can be reduced using standard reduction routines while maintaining diagonal dominance in G(S) K(S).

The diagonalizing pre-compensator was produced using the method suggested by Fricker [Ref. 3]. This technique produces an initial "ideal" pre-compensator K(S) which diagonalizes Q(S). The elements of K(S), which can be high order, are then reduced to a simpler form while ensuring that diagonal dominance in Q(S) is maintained. This involves expressing G(S) as:

$$G(S) = R(S)\,A(S) \qquad \text{(eqn 3.1)}$$

where R(S) is a diagonal matrix formed by extracting common row elements from G(S) so that A(S) contains numerator polynomial elements only.

The decoupling pre-compensator is therefore given by:

$$K(S) = A(S)^{-1} \qquad \text{(eqn 3.2)}$$

However, this method is only possible if $|A(s)| = 0$ has all stable factors, i.e., all roots of the characteristic equation are in the left half plane. If this is not the case, then K(S) is formed from:

$$K(S) = \frac{\text{Adjoint } A(S)}{\text{Realization Factor}} \qquad \text{(eqn 3.3)}$$

where the realization factor will contain the stable factors of $|A(S)|$ together with other suitable lag elements to make K(S) physically realizable.

The elements of the diagonal matrix R(S) and the elements of A(S) so formed are given in Table 4 and Table 5 respectively. As $|A(S)|$ contains all stable factors, the ideal pre-compensator can be formed directly from Equation 3.2. The results of this operation are given in Table 6.

It is necessary to scale the columns of K(S) to ensure that the steady-state gains of the diagonal elements of Q(S) remain the same as those of G(S). The elements of this final pre-compensator are given in Table 7. Table 8 gives the speed related gain variation.

Figure 3.2 and Figure 3.3 show that the addition of the pre-compensator has resulted in an improvement in outputs at 12 kts.

TABLE 4
ELEMENTS OF DIAGONAL MATRIX R(S)

$$R_{11}(S) = \frac{1}{(S^2 + .06S + .25)(S^2 + .02S + .154)(8.2S + 1)}$$

$$R_{22}(S) = \frac{1}{S(.434S + 1)(6.62S + 1)(4.18S + 1)}$$

$$R_{33}(S) = \frac{1}{(S^2 + .199S + .99)(10S + 1)(24S + 1)}$$

TABLE 5
ELEMENTS OF MATRIX A(S)

$$A_{11}(S) = .25K_{11}(S^2 + .2S + .15)(8.2S + 1)$$
$$A_{12}(S) = .15K_{12}(S^2 + .06S + .25)(-8.57S + 1)$$
$$A_{22}(S) = K_{22}$$
$$A_{31}(S) = .1K_{31}(10S + 1)(10.05S + 1)$$
$$A_{32}(S) = K_{32}(S^2 + .2S + .1)$$
$$A_{33}(S) = K_{33}(S^2 + .2S + .1)(10.05S + 1)$$
$$A_{13}(S) = A_{21}(S) = A_{23}(S) = 0$$
$$|A(S)| = .25K_{11}K_{22}K_{33}(S^2 + .2S + .15)(S^2 + .2S + .1)(8.23S + 1)(10.05S + 1)$$

This "ideal" pre-compensator can be reduced to the individual elements of K(s) using step response data.

After the reduction process is completed, the elements of the reduced pre-compensator so formed are given in Table 9. The terms K_{c1}, K_{c2}, and K_{c3} given in Table 9 are the speed related compensator gain changes necessary for the pre-

TABLE 6

ELEMENTS OF DIAGONALIZING PRE-COMPENSATOR

$$K_{11}(S) = \frac{.00649}{53.19S^3 + 17.136S^2 + 9.5S + 1}$$

$$K_{12}(S) = \frac{-.00454(-34.143S^3 + 2S^2 - 8.29S + 1)}{53.19S^3 + 17.136S^2 + 9.5S + 1}$$

$$K_{22}(S) = .00285$$

$$K_{31}(S) = \frac{.00376(10S + 1)}{534S^5 + 278S^4 + 182.6S^3 + 46.15S^2 + 11.5S + 1}$$

$$K_{32}(S) = \frac{.00013(80050S^5 + 15650S^4 + 20665S^3 + 2255S^2 + 3S + 1)}{5352S^6 + 3326S^5 + 2113S^4 + 646S^3 + 162S^2 + 21.3S + 1}$$

$$K_{33}(S) = \frac{.00285}{100S^3 + 30S^2 + 12S + 1}$$

$$K_{13}(S) = K_{21}(S) = K_{23}(S) = 0$$

compensator to cope with the non-linearity of the warship model and these are the same as in Table 8.

Figure 3.4 and Figure 3.5 show that interactions between inputs and outputs have not been eliminated in the system's time response when we use the reduced order pre-compensator also.

TABLE 7

FINAL ELEMENTS OF DIAGONALIZING PRE-COMPENSATOR

$$K_{11}(S) = \frac{1}{53.19S^3 + 17.136S^2 + 9.5S + 1}$$

$$K_{12}(S) = \frac{K_{c1}(-34.143S^3 + 2S^2 - 8.29S + 1)}{53.19S^3 + 17.136S^2 + 9.5S + 1}$$

$$K_{22}(S) = 1$$

$$K_{31}(S) = \frac{K_{c2}(10S + 1)}{534S^5 + 278S^4 + 182.6S^3 + 46.15S^2 \quad 11.5S + 1}$$

$$K_{32}(S) = \frac{K_{c3}(80050S^5 + 15650S^4 + 20665S^3 + 2255S^2 + 3S + 1)}{5352S^6 + 3326S^5 + 2113S^4 + 646S^3 + 162S^2 + 21.6S + 1}$$

$$K_{33}(S) = \frac{1}{100S^3 + 30S^2 + 12S + 1}$$

$$K_{13}(S) = K_{21}(S) = K_{23}(S) = 0$$

TABLE 8

PRE-COMPENSATOR GAIN VARIATION

Speed (Kts)	K_{c1}	K_{c2}	K_{c3}
12	-1.6	.579	.0456
18	-5.2	1.11	-3.02
26	-5.6	1.274	-4.08

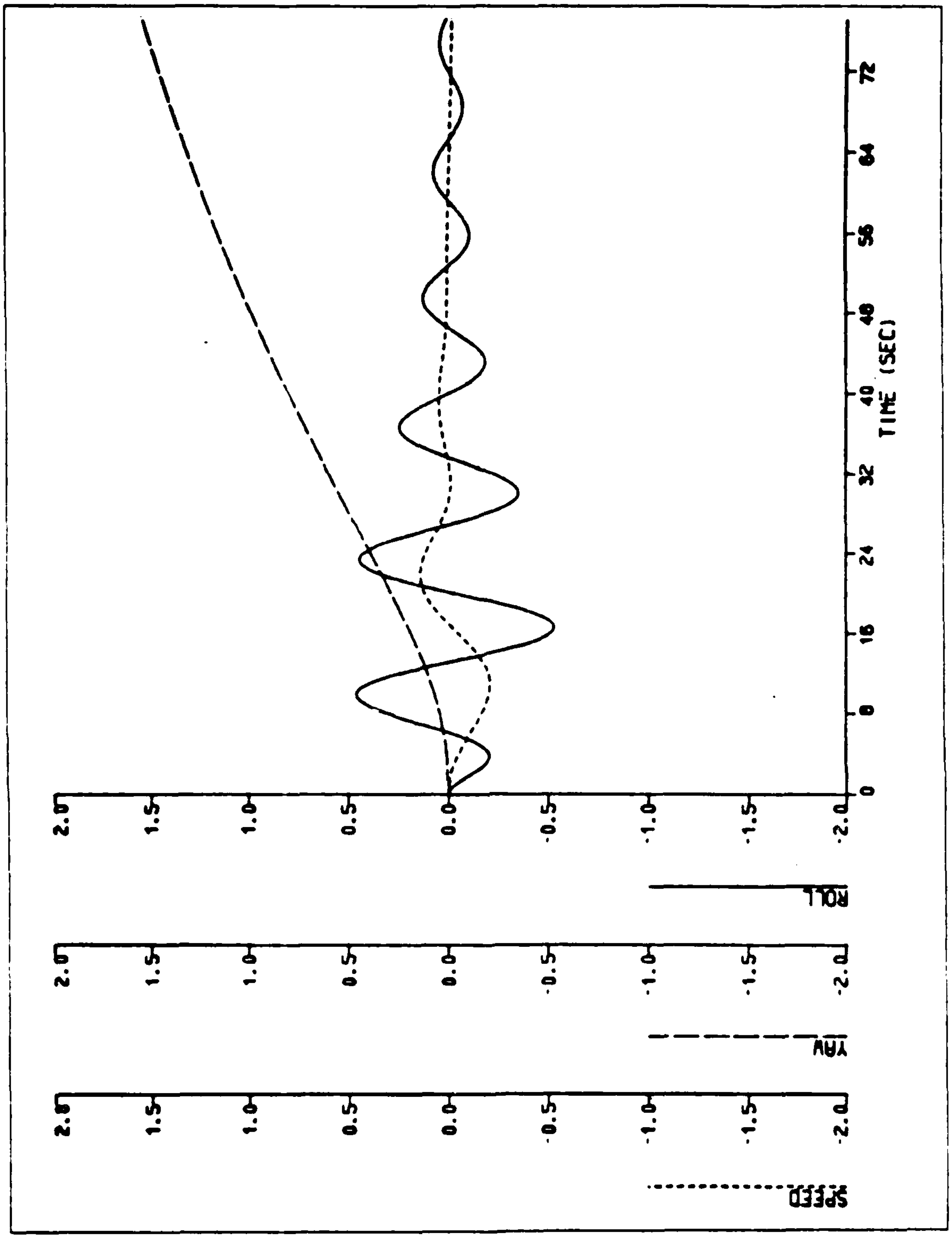

Figure 3.2 Step Response for Compensated Warship Model
at Rudder Demand.

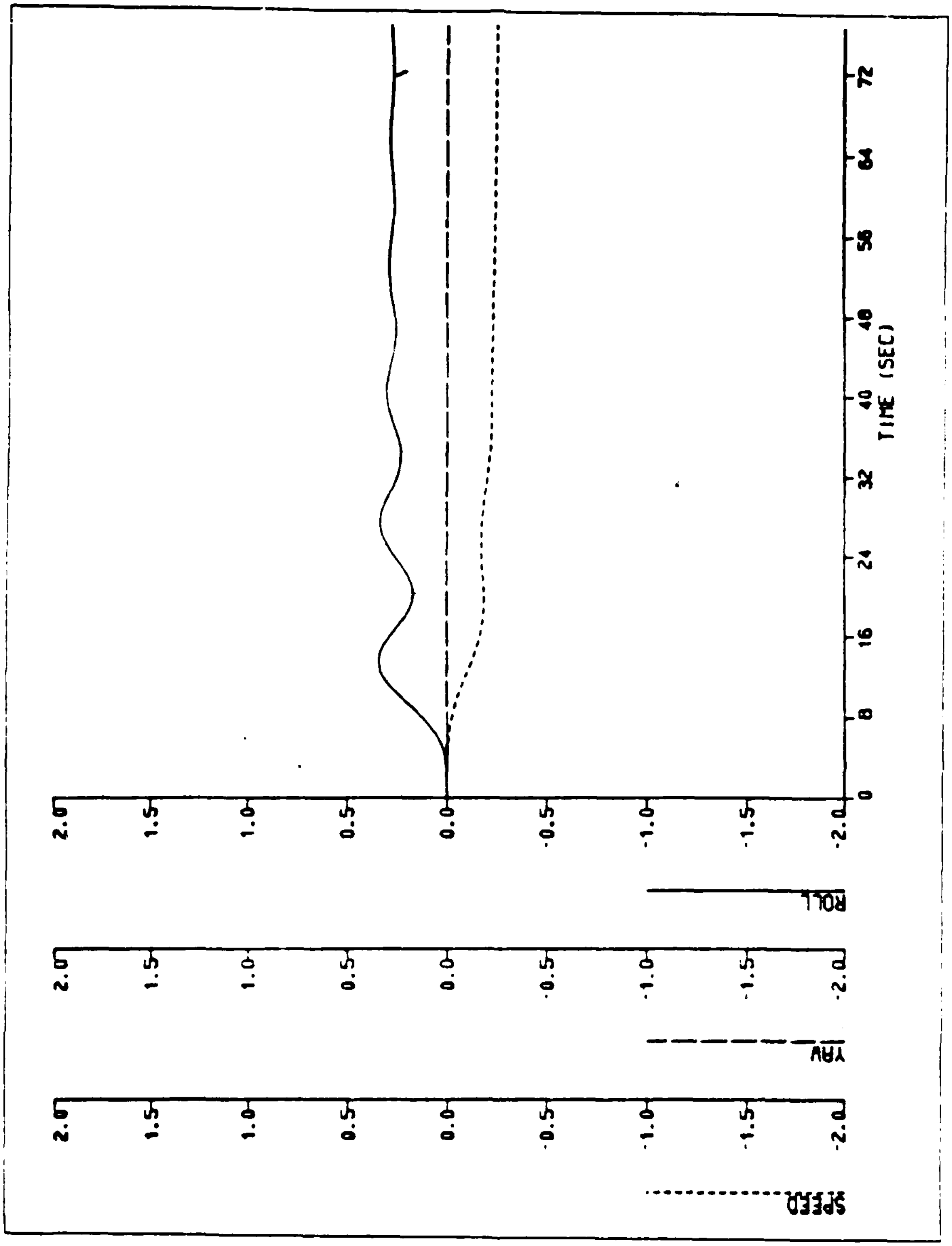

Figure 3.3 Step Response for Compensated Warship Model at Fin Demand.

TABLE 9

FINAL REDUCED PRE-COMPENSATOR ELEMENTS

$$RK_{11}(S) = \frac{1}{8.6S + 1}$$

$$RK_{12}(S) = \frac{K_{c2}(-34.14S^3 + 2S^2 - 8.3S + 1)}{53.2S^3 + 17.13S^2 + 9.5S + 1}$$

$$RK_{22}(S) = 1$$

$$RK_{31}(S) = \frac{K_{c2}}{14.8S^2 + 1.3S + 1)}$$

$$RK_{32}(S) = \frac{K_{c3}(2000S^2 - 2S + 1)}{130S^3 + 25S^2 + 12.6S + 1}$$

$$RK_{33}(S) = \frac{1}{11.4S + 1}$$

$$RK_{13}(S) = RK_{21}(S) = RK_{33}(S) = 0$$

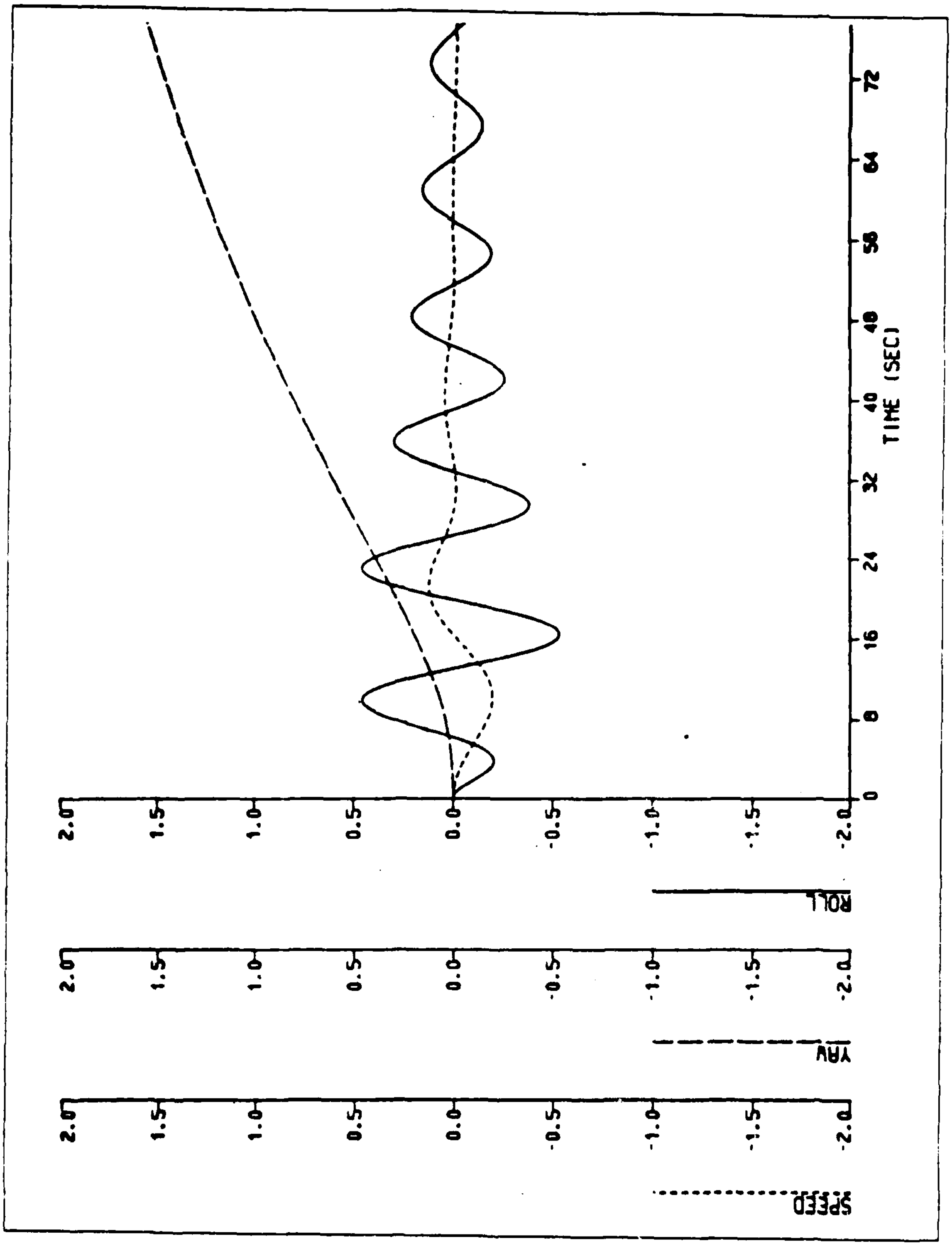

Figure 3.4 Step Response for Compensated Warship model at Rudder Demand using Reduced Order Pre-compensator.

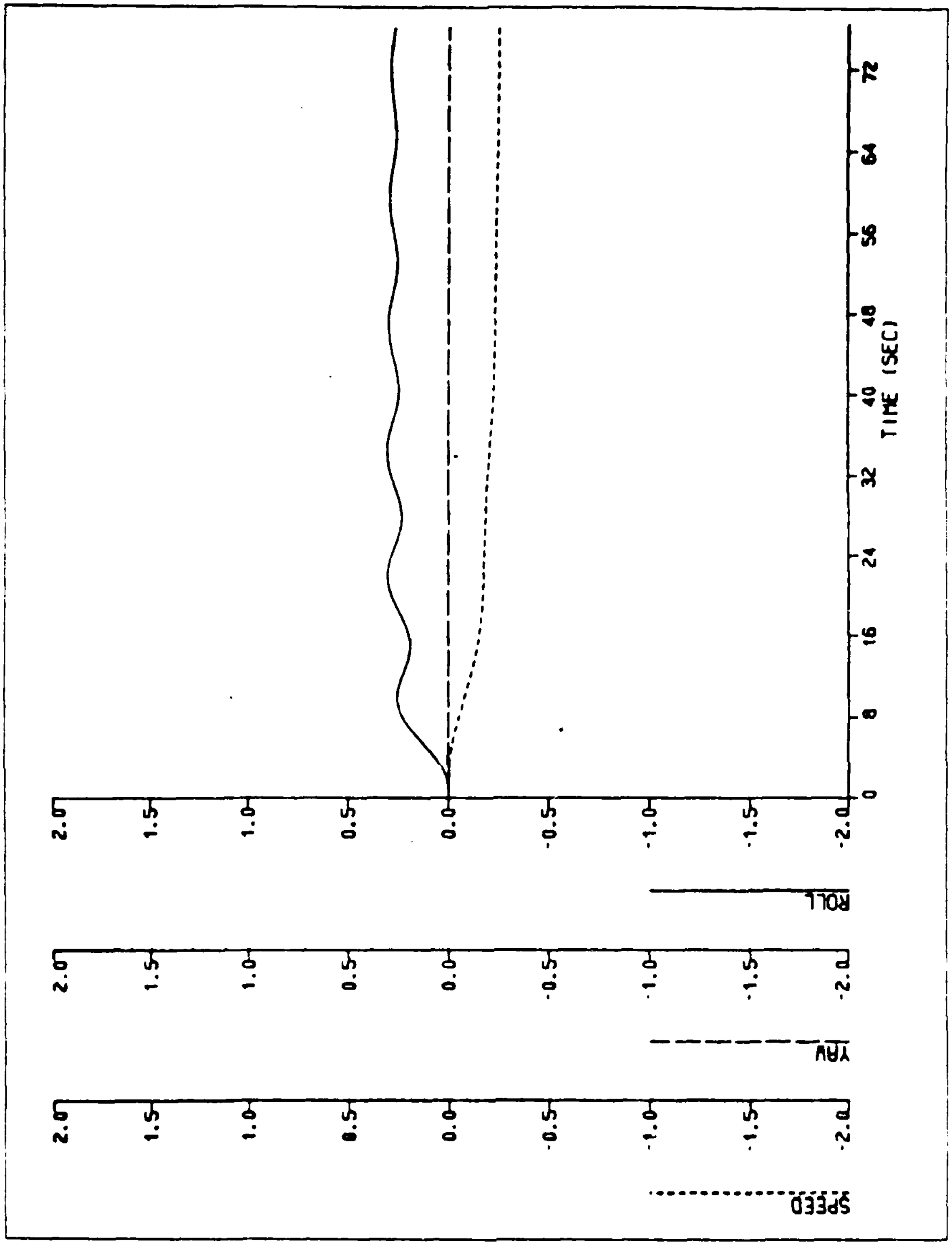

Figure 3.5 Step Response for Compensated Warship model
at Fin Demand using Reduced Order Pre-compensator.

IV. COMPUTER SIMULATION

From the results discussed so far (all of which are from Roberts but were repeated at N.P.S. as part of this thesis), it can be seen that the pre-compensator substantially reduces the interaction intensity of the compensated system and results in improved ship stability and minimal loss of speed while executing normal maneuvers. Also, it has been shown that the outputs of ship's roll angle, heading angle and speed can be controlled by a low-order pre-compensator. However, it can also be seen that large cross-coupling effects exist which cause long settling times. Therefore, a method must still be devised which controls the interactions between inputs and outputs and shortens settling time. The outputs of ship's roll angle, heading angle and speed can be changed by a few factors.

First of all, this thesis will introduce the philosophy of Function Minimization (F.M.), which is the main theme of this paper and introduce a few factors, which have important effects on outputs.

Next, using above factors, this thesis will design other pre-compensators and simulate them.

A. PHILOSOPHY OF FUNCTION MINIMIZATION

Classical control theory has historically been applied to the design problem with the assistance of graphical presentations and trial and error methods. Such methods have been quite successful in the development of good control systems, but do not answer the question "Is this the best system possible?".

If a given function has a minimum within the range of permitted parameter variation, there exist numerical methods which can be used to find the minimum. These numerical methods have been programmed and most computer libraries contain one or more subroutines which can be used for Function Minimization. This thesis uses the HOOKE [Ref. 4] subroutine of DSL.

Since one has the freedom to select the cost function to be used, certainly any of those used within optimal control theory can be chosen. We can therefore design an "optimal controller" without using the conventional theoretical approach.

We can also use any of the well known performance indices as a cost function, i.e., $\int E^2\,dt$, $\int |E|\,dt$, $\int |E|t\,dt$ are easily evaluated and minimized.

In addition, one can select the cost function to suit the particular specification of the problem.

Figure 4.1 shows the block diagram for simulation using Function Minimization.

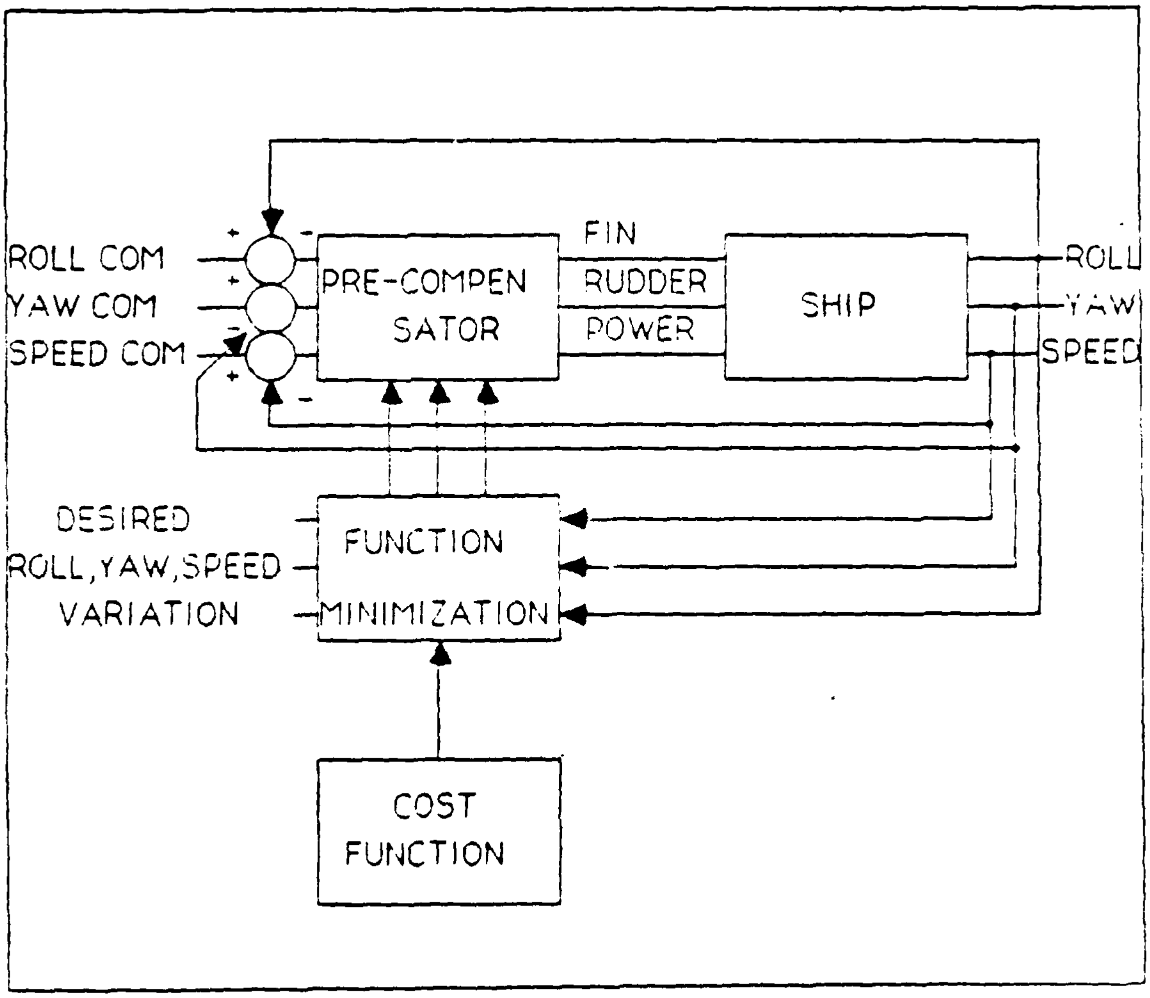

Figure 4.1 Block Diagram of Function Minimization.

B. CHOICE OF COMPENSATORS

Use of Function Minimization in the computer is relatively expensive, so some preliminary analysis and design is desirable to avoid excessive computer time. For a simple system (one output) a BODE design or a ROOT LOCUS design might be a good starting point. The compensator thus found is then simulated and improved through use of Function Minimization. For the ship problem in this thesis, the preliminary work was done by Roberts as can be seen in Chapters II and III.

This thesis uses Roberts' compensators and outputs as a starting point. The desired output curves were obtained by modifying the known outputs. The questions to be answered are:

- Can better performance be obtained using the original compensator but requiring a better output?
- Can the compensator be reduced and the resulting output be as good or better than the original compensators?
- Can a better output be obtained by increasing the order of the compensator?

When the Function Minimization subroutine minimizes the function, it moves the poles and zeroes of the compensator to the best locations in the S-plane. If the compensator has too many poles and zeroes, the program tends to set Z = P for the unneeded poles and zeroes, thus the compensator order may be reduced.

In many cases, even though the poles and zeroes may not exactly cancel, they are placed so close to each other that they contribute very little to the result and so we may efficiently cancel them. Thus one can start the design by simply choosing each K_c to have numerous zeroes and poles as can be seen in Table 7 and Figure 3.2, which is the original pre-compensator. However, this thesis will show us that we don't need that many poles and zeroes for the choice of compensators.

In this thesis, as shown in Table 9 and Figure 3.4, the reduced order pre-compensator was used.

The optimum parameter values of this reduced order pre-compensator, which reduces the corresponding cross-coupling, can be determined by Function Minimization and Table 10 shows the optimum parameter values of the reduced order pre-compensator in Table 9 by Function Minimization.

Figure 4.2 shows the positive damping effect on the system's time response when optimum parameter values are used in the reduced pre-compensator.

Figures 4.3 through Figure 4.5 show the difference between Roberts' method and the Function Minimization method, where the continuous line is the output of Roberts and the dotted line is the output of Function Minimization.

As shown in Figure 4.4 and Figure 4.5, cross-coupling is decreased dramatically in the case of Function Minimization.

C. CHOICE OF DESIRED OUTPUTS

One can always choose the ideal output as the desired output for the Function Minimization subroutine. However, this may not be a good choice because that

TABLE 10

OPTIMUM PARAMETER VALUES OF REDUCED PRE-COMPENSATOR

$$RK_{11}(S) = \frac{1}{8.6S + 1}$$

$$RK_{12}(S) = \frac{K_{c2}(-72.14S^3 + 1.98925S^2 - 2.3S + 1)}{76.2S^3 + 28.63S^2 + 11.5S + 1}$$

$$RK_{22}(S) = 1$$

$$RK_{31}(S) = \frac{.63525}{32.05S^2 + 2.975S + 1}$$

$$RK_{32}(S) = \frac{K_{c3}(1741.25S^2 - 1.94375S + 1)}{9.25S^3 + 111.25S^2 + 47.1S + 1}$$

$$RK_{33}(S) = \frac{1}{11.4S + 1}$$

$$RK_{13}(S) = RK_{21}(S) = RK_{33}(S) = 0$$

particular output may be impossible to achieve. Although the minimization process will determine a closest fit, if the cost function is a "least squares" function the solution may not be acceptable. For example, with the ship problem of this thesis, the ideal output might be

- Turn radius of two ship lengths
- Zero speed change
- Zero roll angle

None of these characteristics are possible. The results of a Function Minimization design will not satisfy any of them and the design achieved may not be acceptable. The desired output must therefore be chosen realistically, i.e., within the physical capabilities of the system. For the ship control problem, outputs were chosen based upon the results obtained by Roberts. In order to obtain better performance the desired outputs were chosen to be similar.

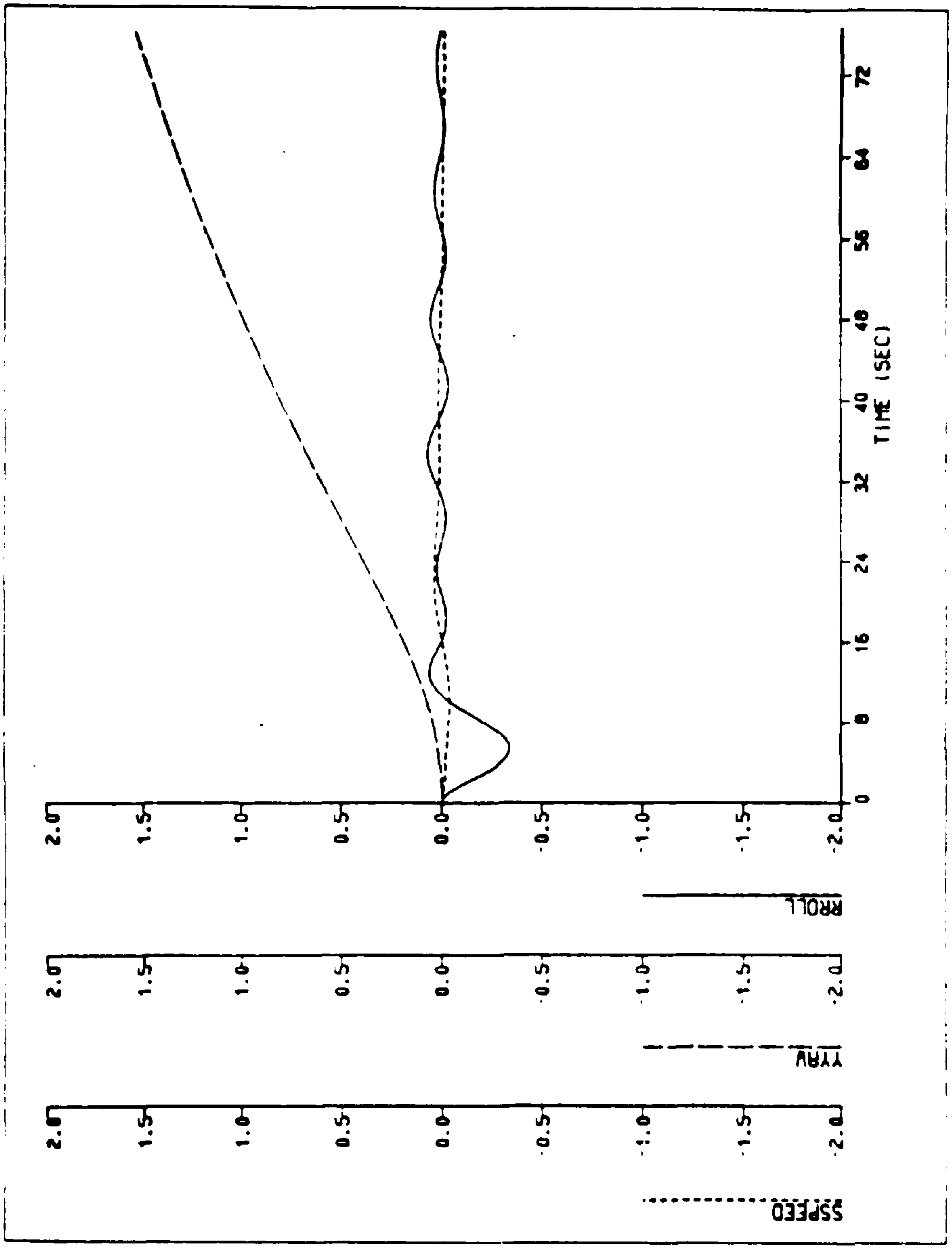

Figure 4.2 Output when we use the Optimum values of Reduced Pre-compensator at Rudder Demand.

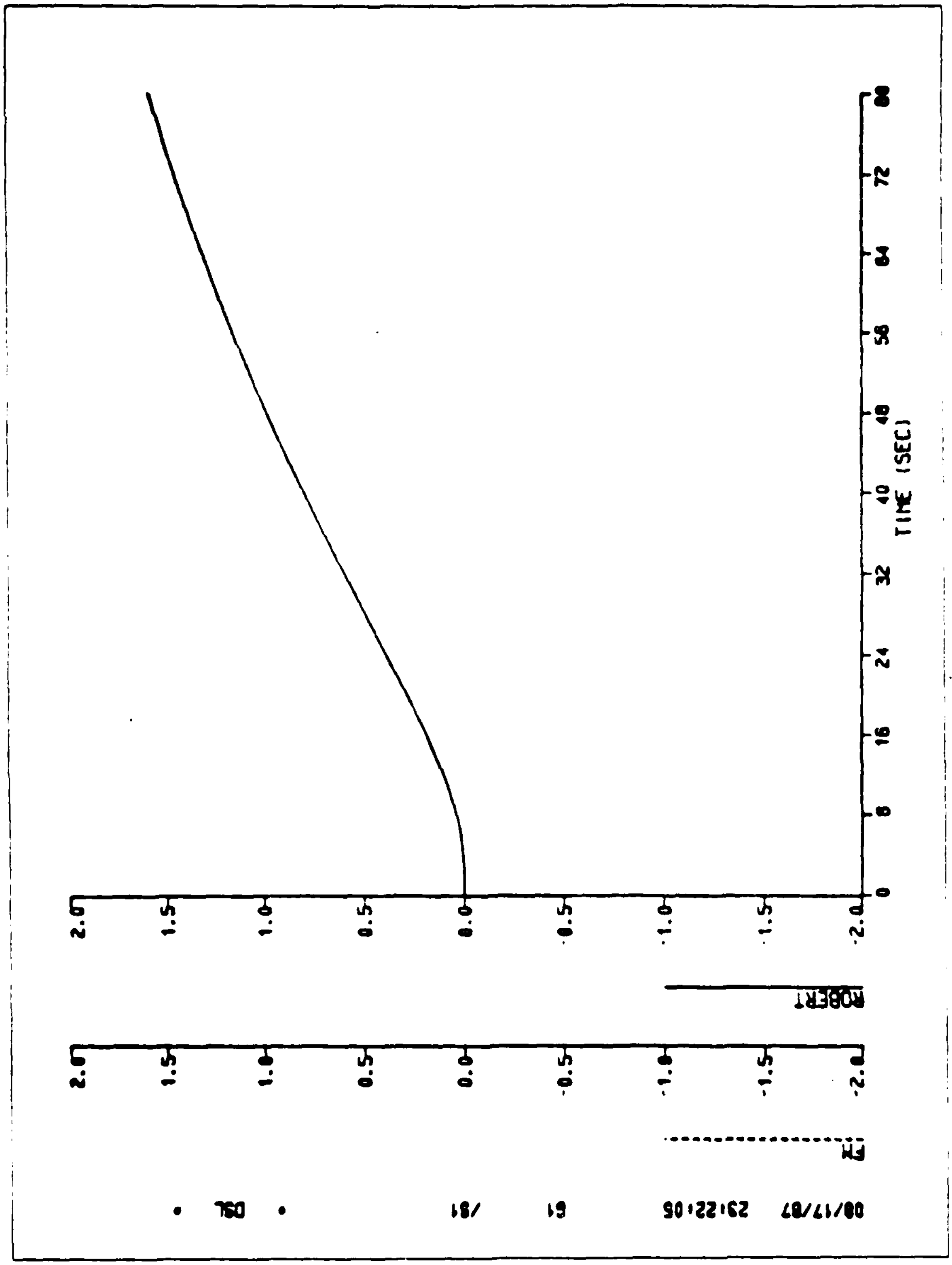

Figure 4.3 Comparison between Roberts and F.M at Yaw output.

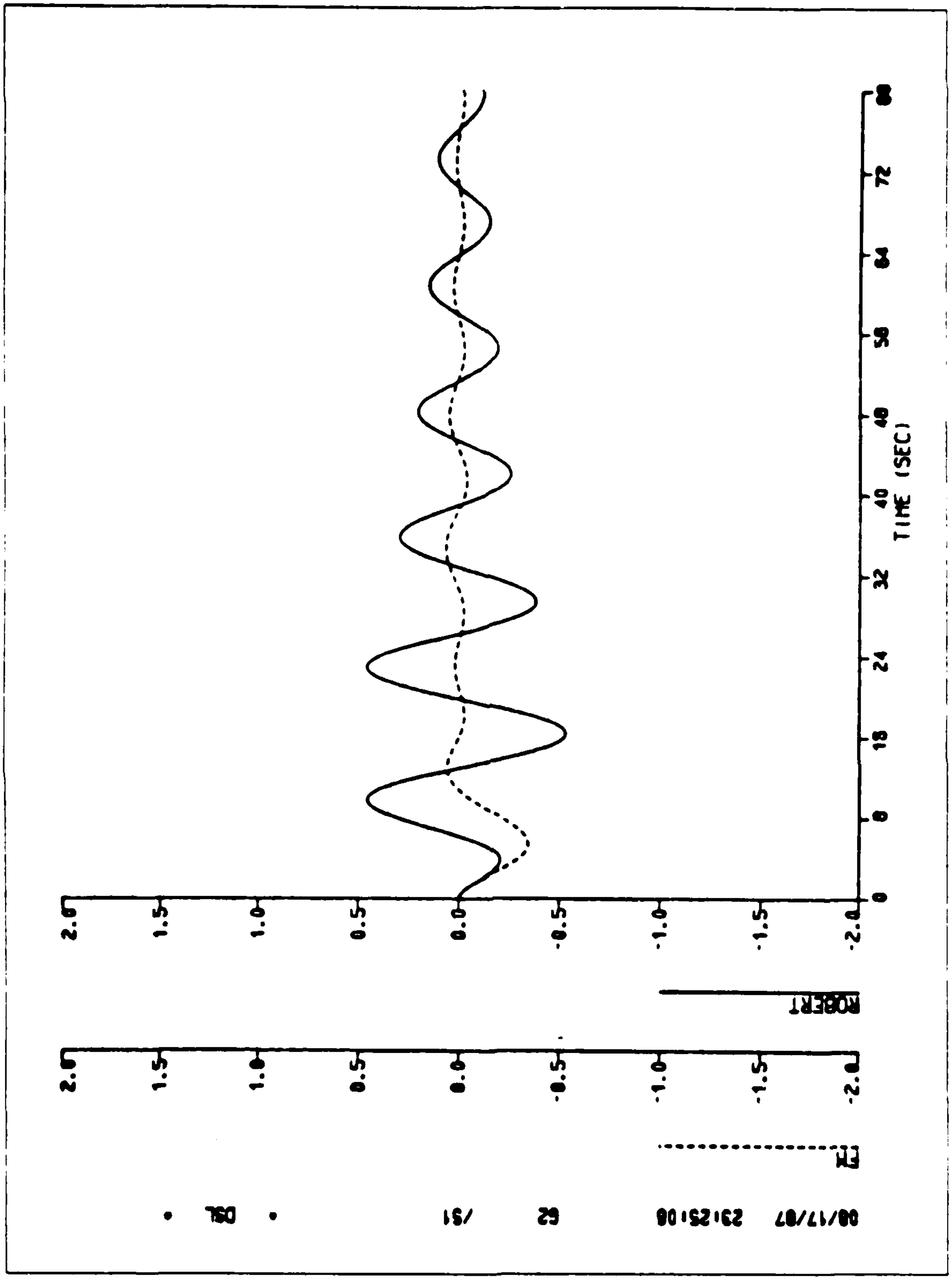

Figure 4.4 Comparison between Roberts and F.M at Roll output.

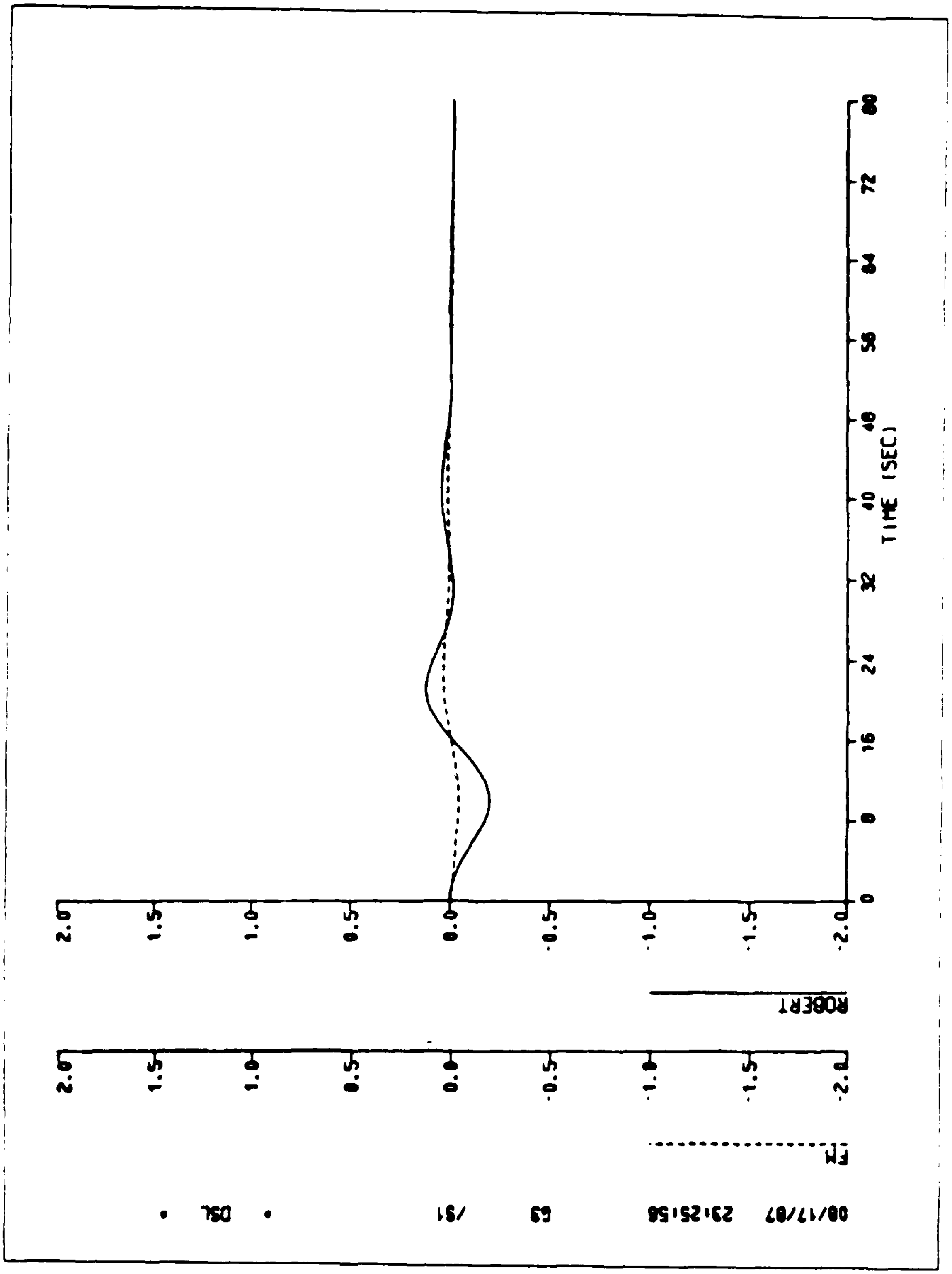

Figure 4.5 Comparison between Roberts and F.M at Speed output.

This thesis chose 3 desired system outputs , each consisting of a specification for heading, roll and speed. These desired output curves (AFGEN1, 2 and 3) were obtained by modifying the known outputs (Figure 3.3) using Arbitrary Function Generators (AFGEN) provided by DSL.

Figure 4.6, Figure 4.7 and Figure 4.8 show AFGEN1, AFGEN2 and AFGEN3 respectively.

We can know that the AFGEN3 is better than the other two cases by the trial and error method. Therefore this thesis will use the AFGEN3 for desired outputs for another simulation.

D. COST FUNCTIONS

When using Function Minimization as a design tool, a cost function must be chosen. This cost function is usually an integral.

One possible procedure is to choose the desired performance as a reference and select a cost function which is the integral of the square of the difference between desired output and actual output. When the system has several outputs, the cost function must consider all of them, usually as a weighted sum.

E. WEIGHTING FACTORS

For the three outputs system, the cost function is of the form

$$E = \lambda_1 \int E_1^2\, dt + \lambda_2 \int E_2^2\, dt + \lambda_3 \int E_3^2\, dt.$$

There are no fixed rules for choosing the values factors λ_1, λ_2 and λ_3. One approach is as follows:

- Select the output which is considered most important, say # 1. Use this as a reference and select $\lambda_1 = 1.0$.
- Base the value assigned to the second weighting factor, λ_2 in this case, on the importance of output # 2 with respect to output # 1. If output # 2 is equally important as output # 1, then $\lambda_2 = 1.0$. If it is half as important, then $\lambda_2 = .5$.
- The third weighting factor is chosen in like manner. If the third output is less important than the first, then $\lambda_3 < \lambda_1$. If it is also less important than the second output, then $\lambda_3 < \lambda_2$.

The actual numbers chosen, for example $\lambda_2 = 0.1$, are simply estimates based on experience. The designer may decide to change them after studying simulation results of a first design.

In the case of ship control, the primary output is heading. Therefore, assign λ_h a value of 1.0. Some change in speed is unavoidable and the desired response should

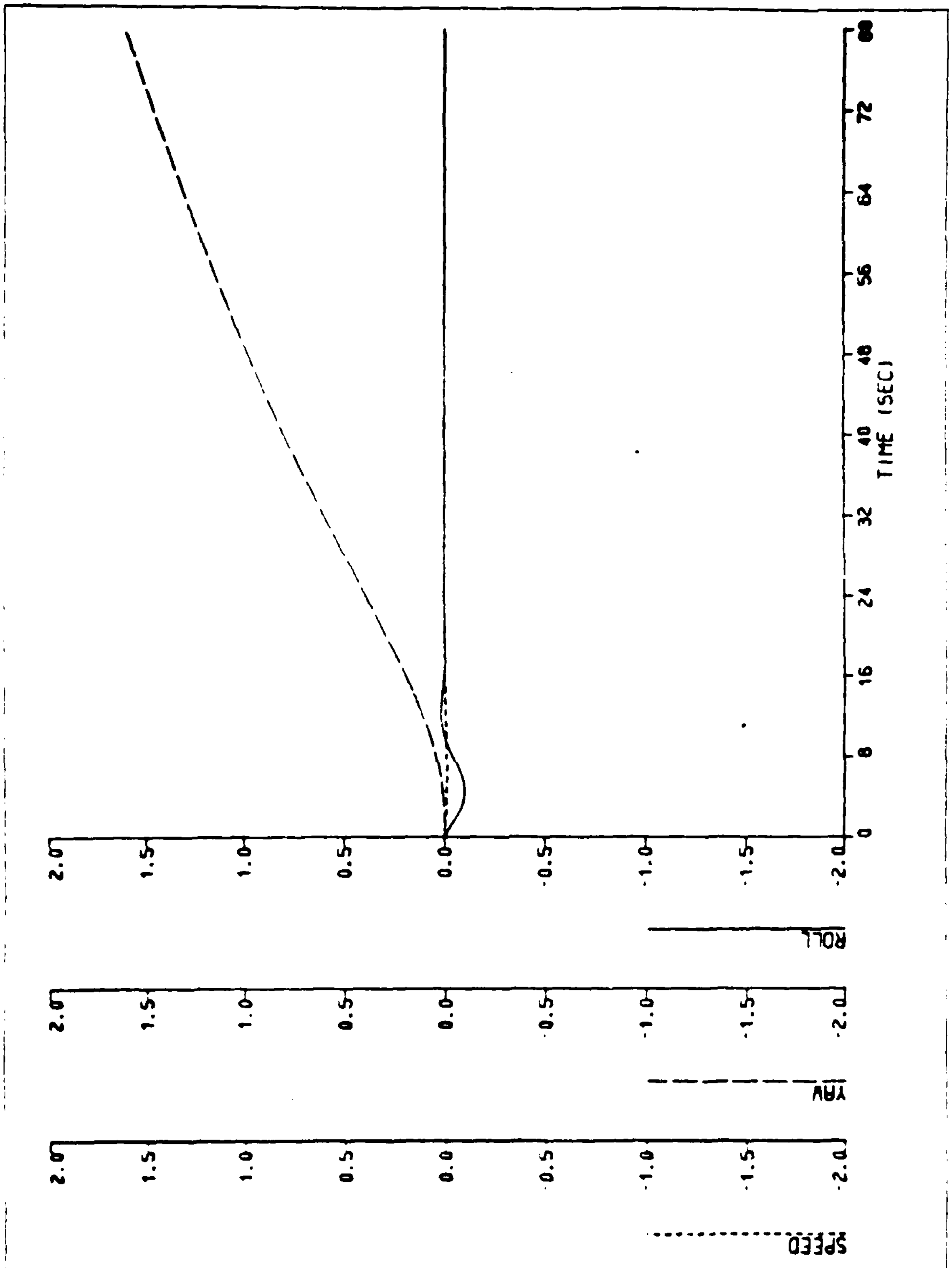

Figure 4.6 AFGEN 1.

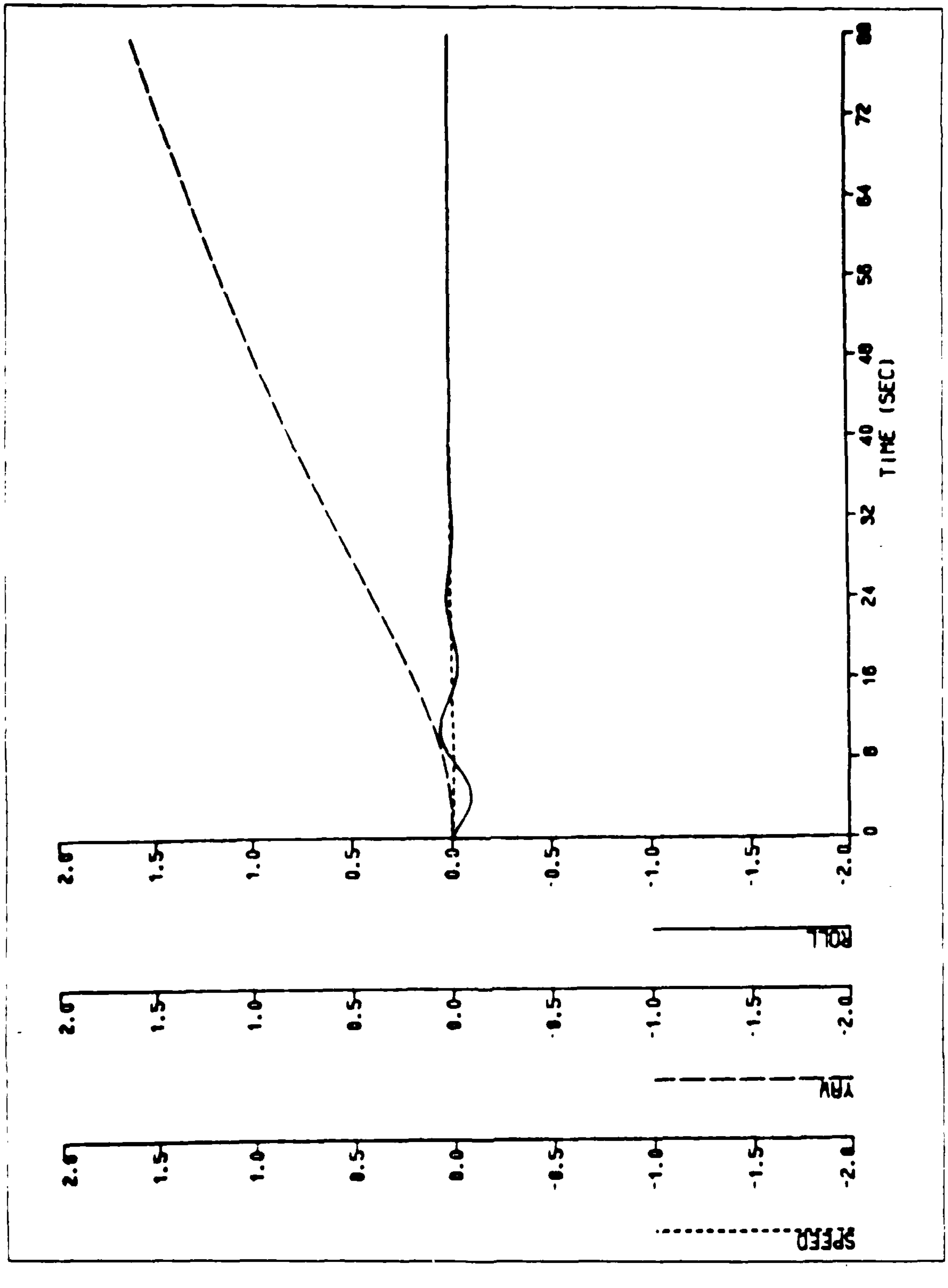

Figure 4.7 AFGEN 2.

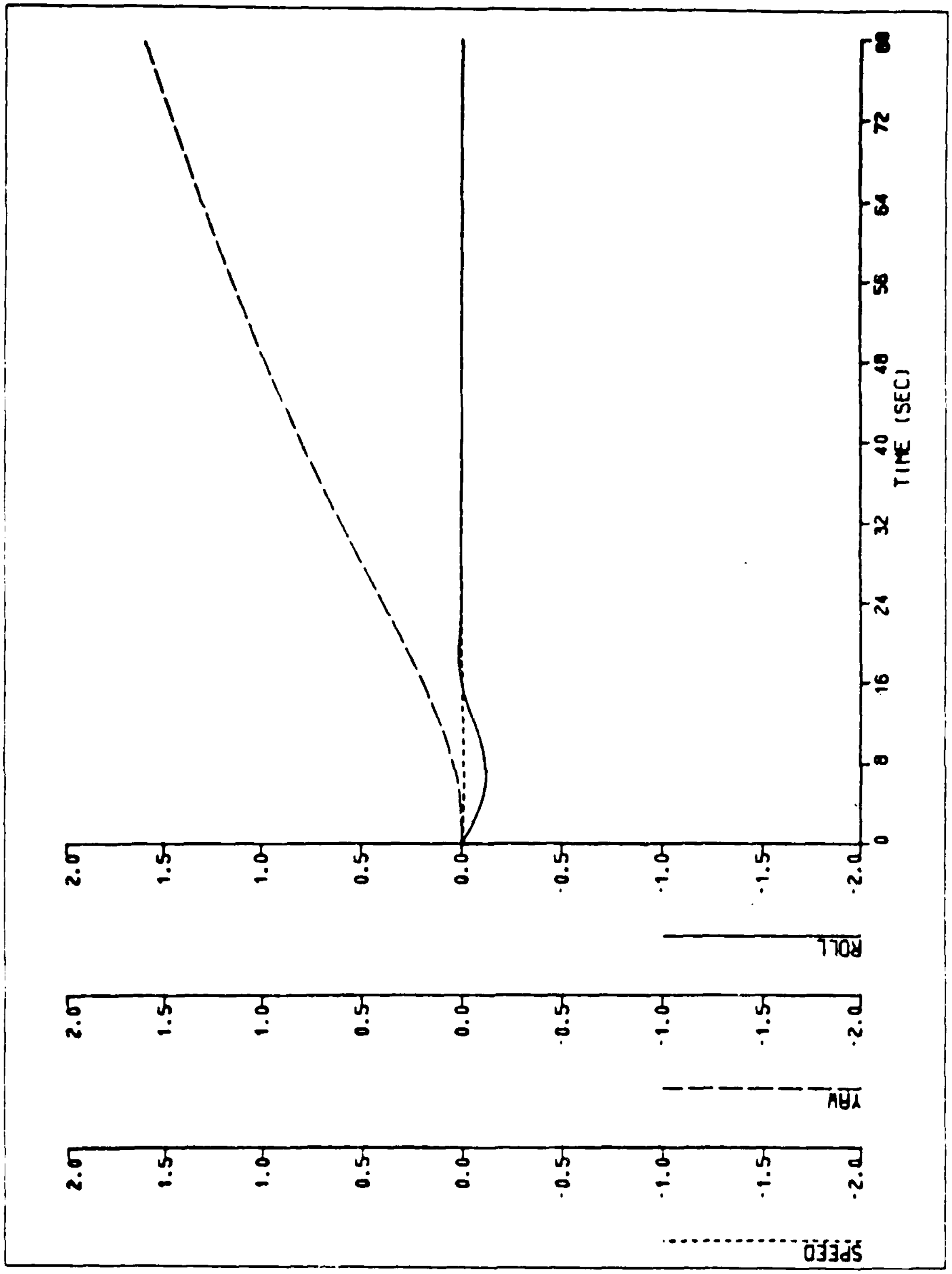

Figure 4.8 AFGEN 3.

show this. However, if the desired response cannot be achieved perhaps more fluctuation in speed would be acceptable. For example, a value of approximately 0.1 could be assigned to λ_s. If the desired roll output is twice as important as the speed output, then λ_r would be assigned a value of 0.2.

Table 11 shows each case for simulation using weighting factors.

TABLE 11

SIMULATION CASES USING WEIGHTING FACTORS(W.F.)

CASE	λ_h	λ_r	λ_s	OUTPUTS
1	1	.2	.1	Figure 4.9
2	1	.6	.1	Figure 4.10
3	1	.6	.4	Figure 4.11
4	1	1	1	Figure 4.12

CASE4 is from Table 10, which uses $\lambda_h = 1$, $\lambda_r = 1$ and $\lambda_s = 1$ and this was repeated in Table 11 for comparison when we consider the weighting factors.

Table 12 through Table 15 show the elements of the resulting compensators for each of the above when we used the F.M. approach.

When F.M. was used for all coefficients in compensators, RK_{12}, RK_{31} and RK_{32} were the parameters that the F.M. subroutine adjusted.

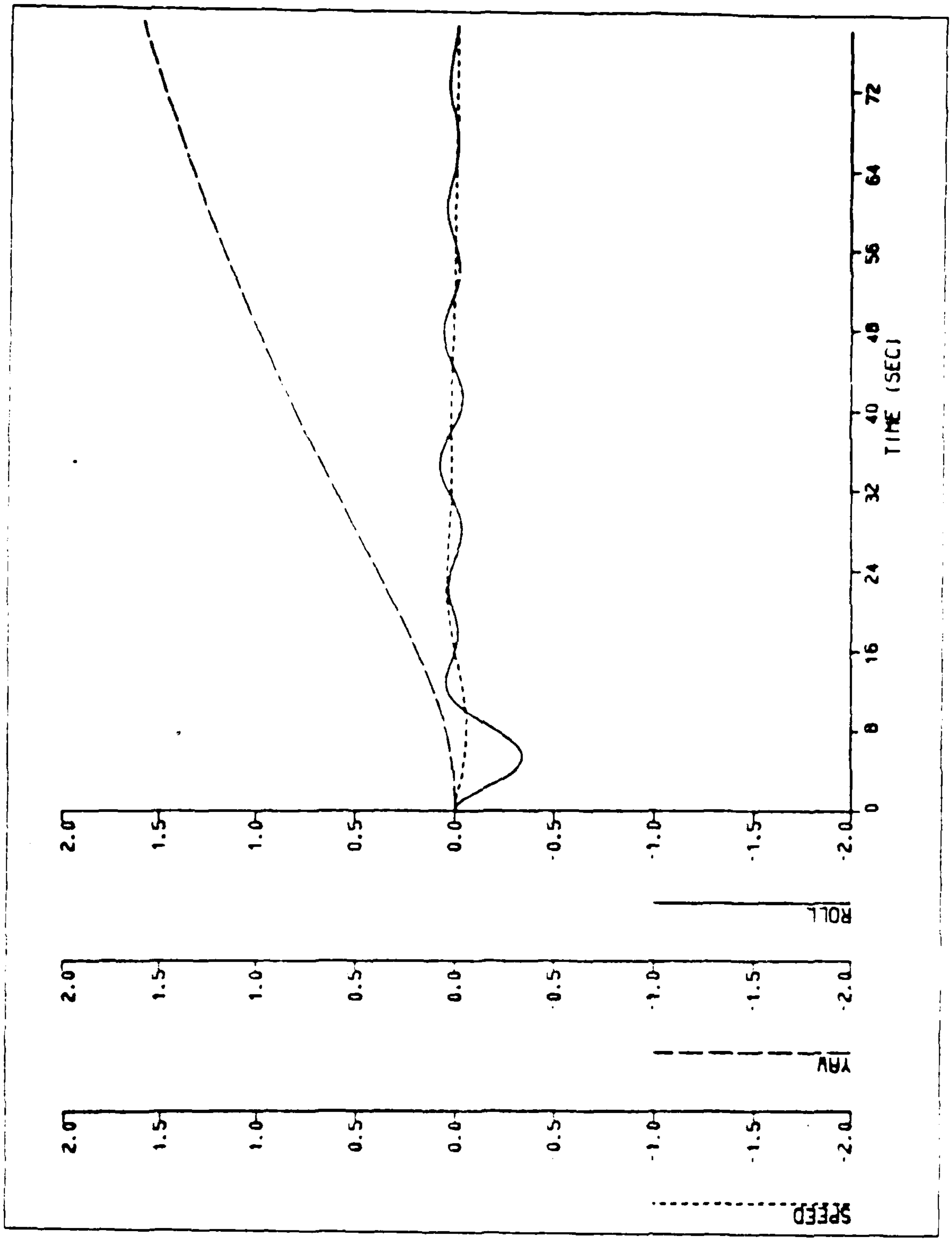

Figure 4.9 Step Response when $\lambda_h = 1$, $\lambda_r = .2$ and $\lambda_s = .1$ at Rudder Demand.

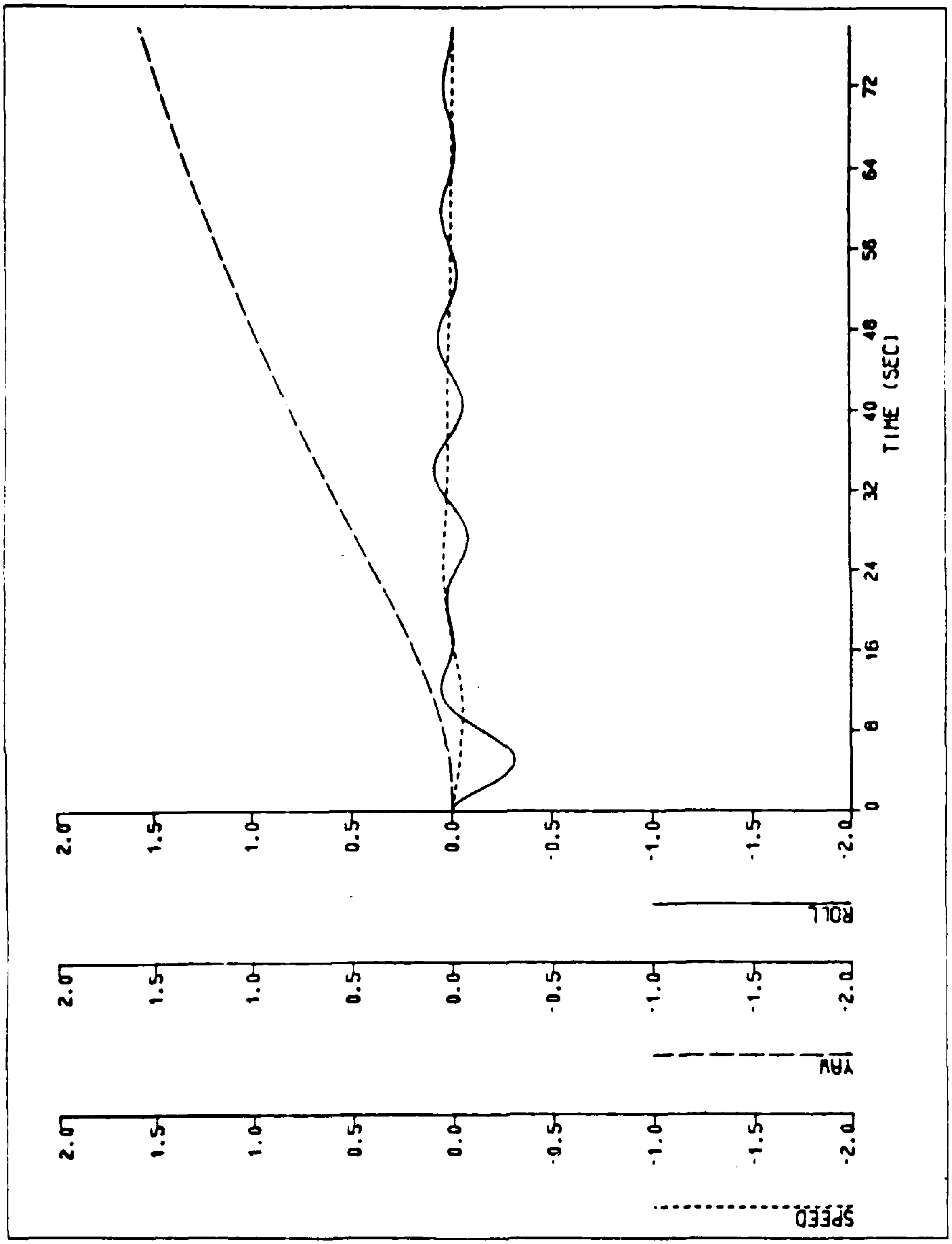

Figure 4.10 Step Response when $\lambda_h = 1$, $\lambda_r = .6$ and $\lambda_s = .1$ at Rudder Demand.

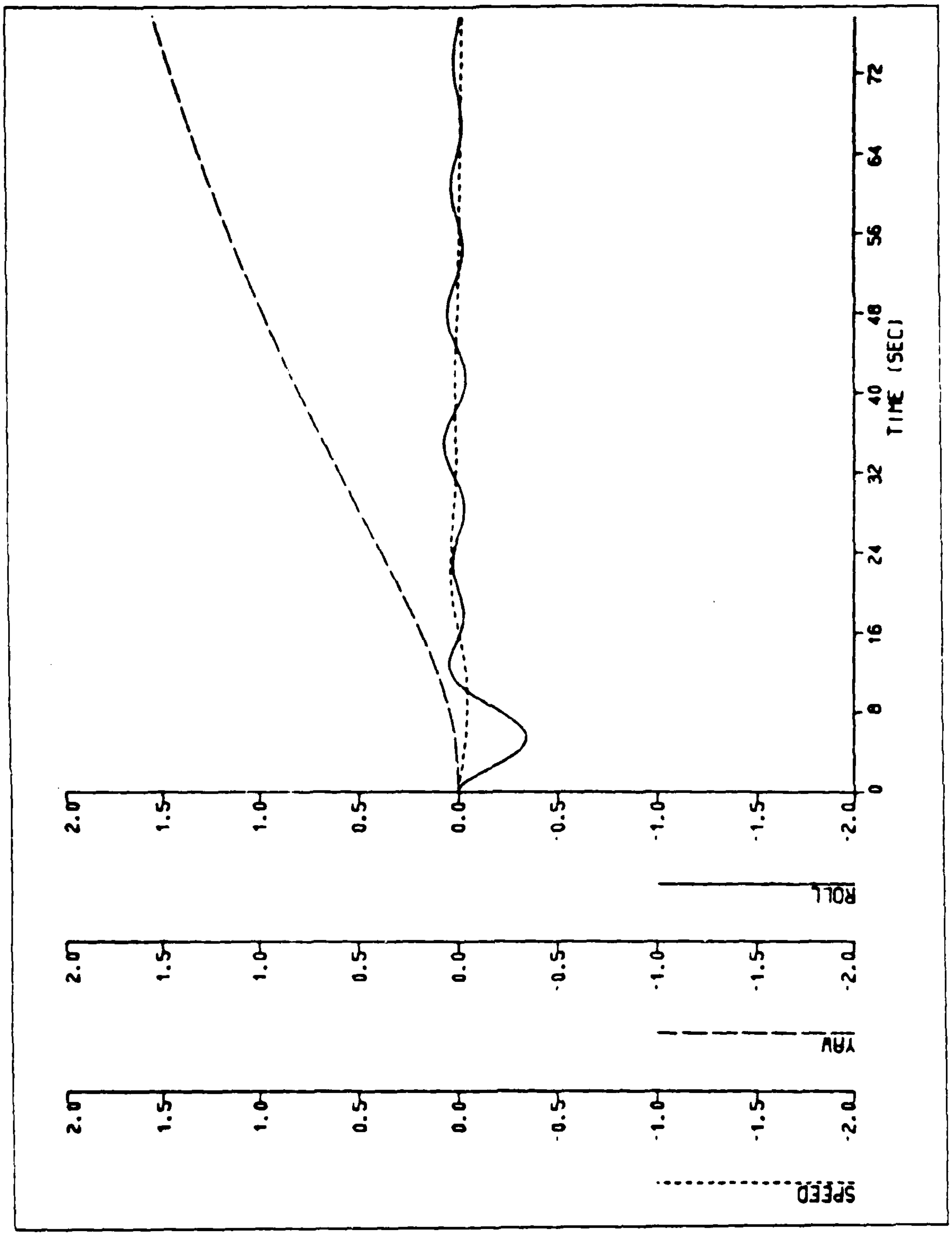

Figure 4.11 Step Response when $\lambda_h = 1$, $\lambda_r = .6$ and $\lambda_s = .4$ at Rudder Demand.

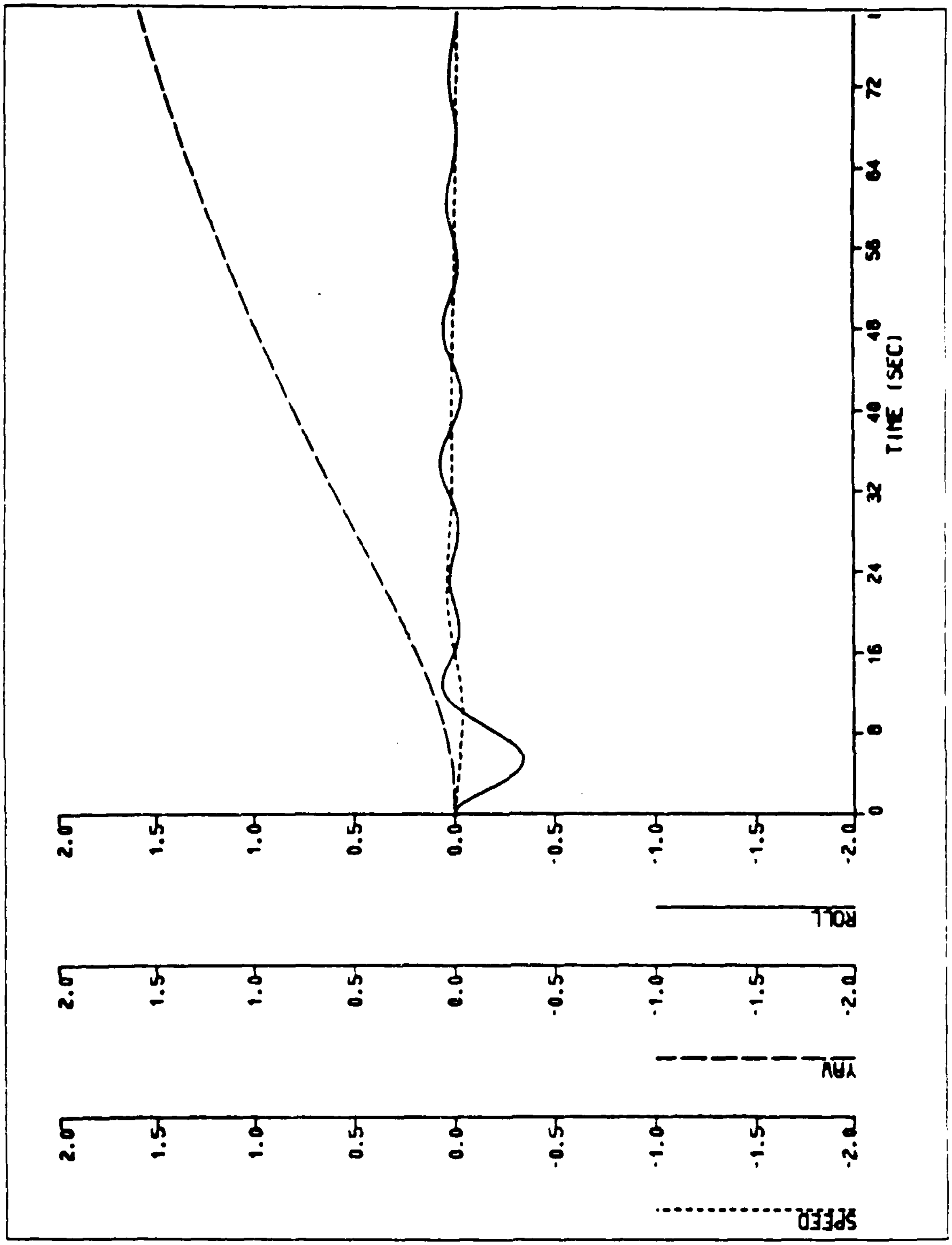

Figure 4.12 Step Response when $\lambda_h = 1$, $\lambda_r = 1$ and $\lambda_s = 1$ at Rudder Demand.

TABLE 12

OPTIMUM PARAMETER VALUES OF REDUCED PRE-COMPENSATOR AT CASE 1 W.F.

$$RK_{11}(S) = \frac{1}{8.6S + 1}$$

$$RK_{12}(S) = \frac{K_{c2}(-47.64S^3 + 2.000625S^2 - 2.3S + 1)}{67.7S^3 + 27.38S^2 + 11.375S + 1}$$

$$RK_{22}(S) = 1$$

$$RK_{31}(S) = \frac{.577125}{20.425S^2 + 1.8625S + 1}$$

$$RK_{32}(S) = \frac{K_{c3}(1915.625S^2 - 2.001875S + 1)}{90.625S^3 + 53.125S^2 + 23.85S + 1}$$

$$RK_{33}(S) = \frac{1}{11.4S + 1}$$

$$RK_{13}(S) = RK_{21}(S) = RK_{33}(S) = 0$$

TABLE 13

OPTIMUM PARAMETER VALUES OF REDUCED PRE-COMPENSATOR AT CASE 2 W.F.

$$RK_{11}(S) = \frac{1}{8.6S + 1}$$

$$RK_{12}(S) = \frac{K_{c2}(-66.14S^3 + 1.99525S^2 - 3.3S + 1)}{45.2S^3 + 31.13S^2 + 10.5S + 1}$$

$$RK_{22}(S) = 1$$

$$RK_{31}(S) = \frac{.603999}{25.8S^2 + 2.4S + 1}$$

$$RK_{32}(S) = \frac{K_{c3}(1835S^2 - 1.975S + 1)}{53S^3 + 80S^2 + 34.6S + 1}$$

$$RK_{33}(S) = \frac{1}{11.4S + 1}$$

$$RK_{13}(S) = RK_{21}(S) = RK_{33}(S) = 0$$

TABLE 14

OPTIMUM PARAMETER VALUES OF REDUCED PRE-COMPENSATOR AT CASE 3 W.F.

$$RK_{11}(S) = \frac{1}{8.6S + 1}$$

$$RK_{12}(S) = \frac{K_{c2}(-56.14S^3 + 1.996S^2 - 2.3S + 1)}{71.2S^3 + 27.13S^2 + 11.25S + 1}$$

$$RK_{22}(S) = 1$$

$$RK_{31}(S) = \frac{.6015}{25.3S^2 + 2.35S + 1}$$

$$RK_{32}(S) = \frac{K_{c3}(1842.5S^2 - 1.9775S + 1)}{56.5S^3 + 77.5S^2 + 33.6S + 1}$$

$$RK_{33}(S) = \frac{1}{11.4S + 1}$$

$$RK_{13}(S) = RK_{21}(S) = RK_{33}(S) = 0$$

TABLE 15

OPTIMUM PARAMETER VALUES OF REDUCED PRE-COMPENSATOR AT CASE 4 W.F.

$$RK_{11}(S) = \frac{1}{8.6S + 1}$$

$$RK_{12}(S) = \frac{K_{c2}(-72.14S^3 + 1.98925S^2 - 2.3S + 1)}{76.2S^3 + 28.63S^2 + 11.5S + 1}$$

$$RK_{22}(S) = 1$$

$$RK_{31}(S) = \frac{.63525}{32.05S^2 + 2.975S + 1}$$

$$RK_{32}(S) = \frac{K_{c3}(1741.25S^2 - 1.94375S + 1)}{9.25S^3 + 111.25S^2 + 47.1S + 1}$$

$$RK_{33}(S) = \frac{1}{11.4S + 1}$$

$$RK_{13}(S) = RK_{21}(S) = RK_{33}(S) = 0$$

From simulation, it appears that the most desirable output can be obtained at - $\lambda_h = 1$, $\lambda_r = .2$ and $\lambda_s = .1$.

Figure 4.13 through Figure 4.15 show the comparison between the Figure 3.4 for Roberts, Figure 4.2 for CASE 4 and Figure 4.9 for CASE 1. Where the output of Roberts is from Table 9, which gives the final reduced pre-compensator elements, the output of CASE 4 is from Table 10, which gives the optimum parameter values of reduced order pre-compensator by Function Minmization. The output of CASE 1 is the best case when we consider the weighting parameters for CASE 1, 2 and 3 in Table 11.

The continuous line is used for Roberts, the dotted line for CASE 4 and the dashed line for CASE 1 outputs.

Figure 4.16 through Figure 4.18 show the comparison between the above three cases for Fin, Rudder and Power respectively.

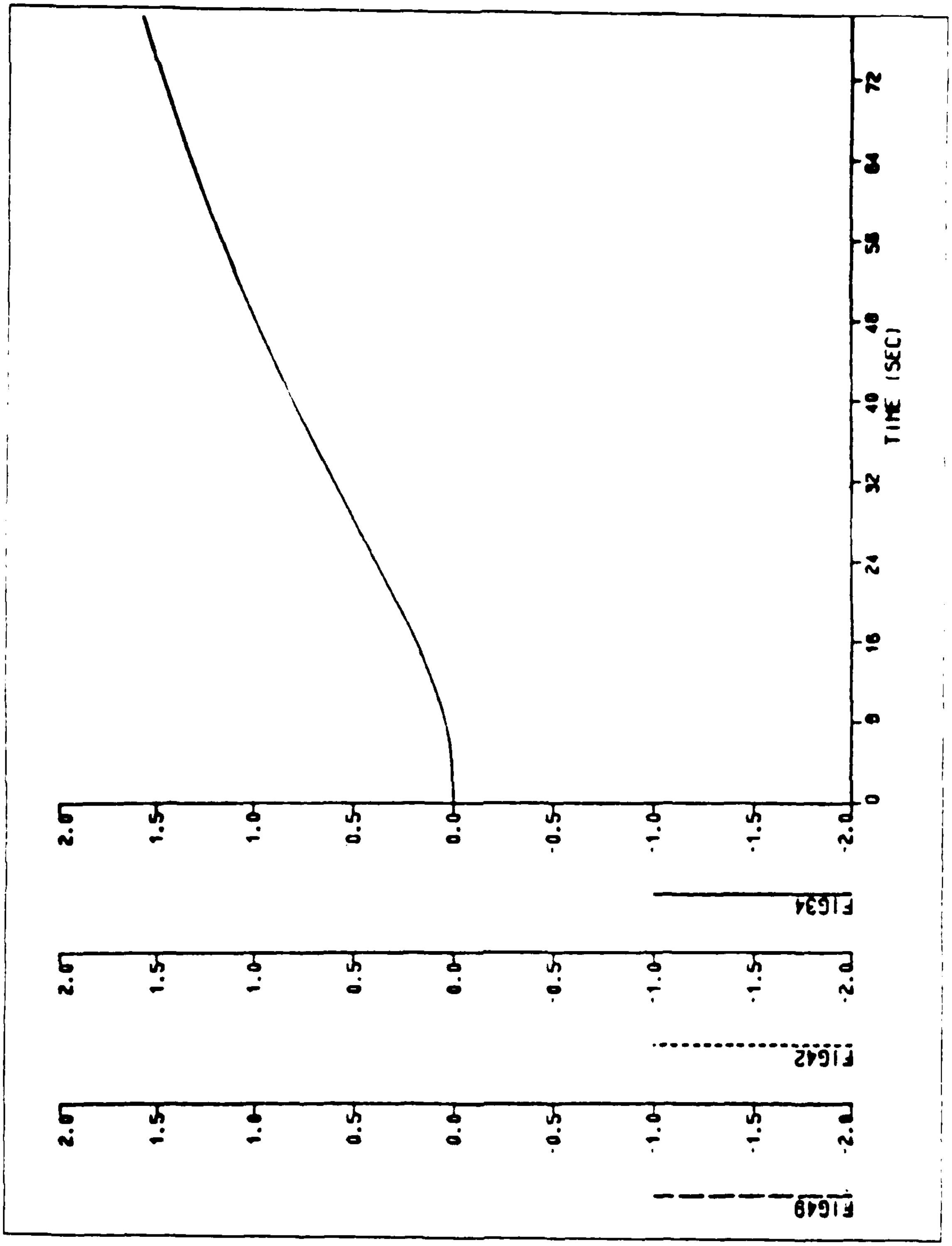

Figure 4.13 Comparison between Fig 3.4, Fig 4.2 and Fig 4.9 at Yaw Output.

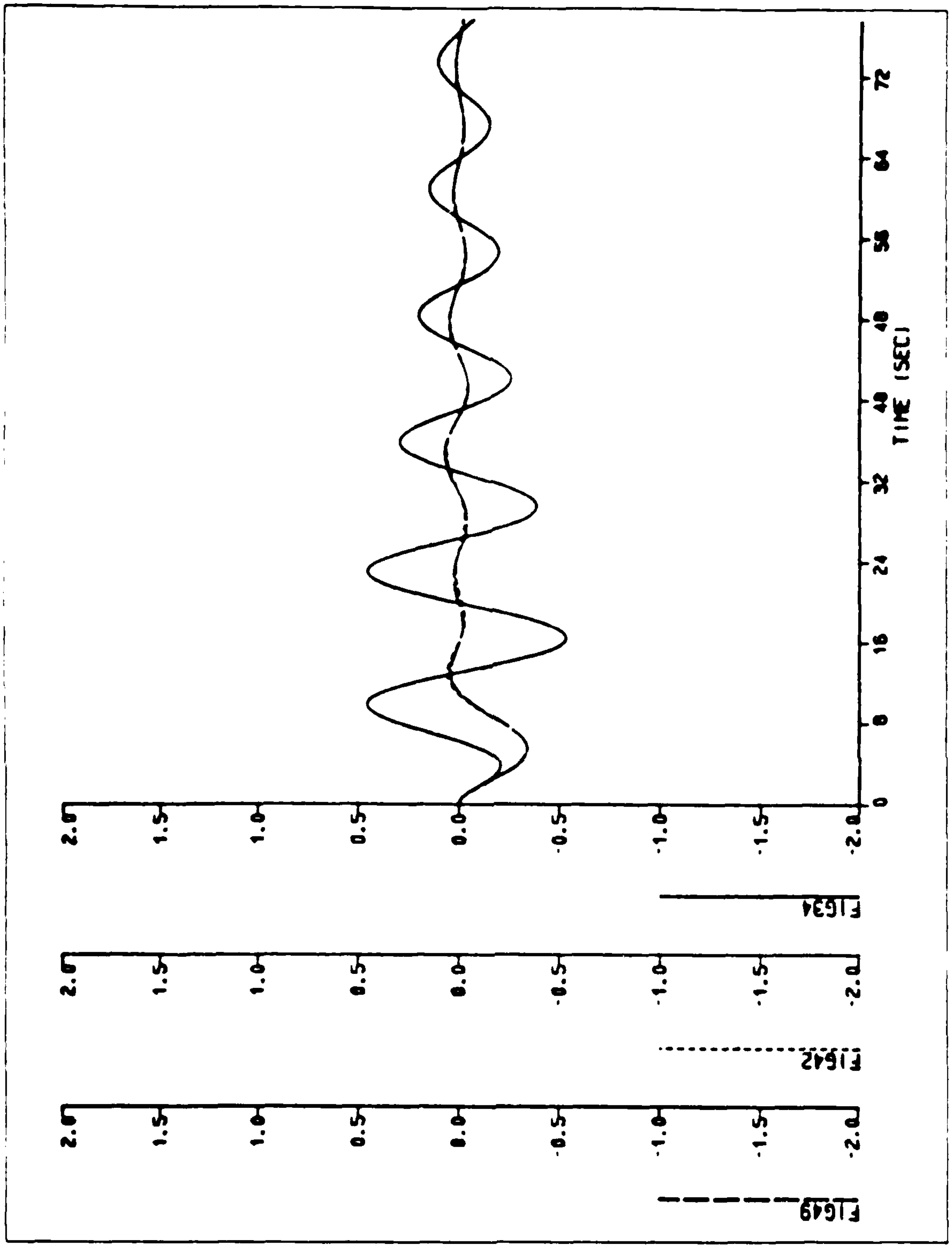

Figure 4.14 Comparison between Fig 3.4, Fig 4.2 and Fig 4.9 at Roll Output.

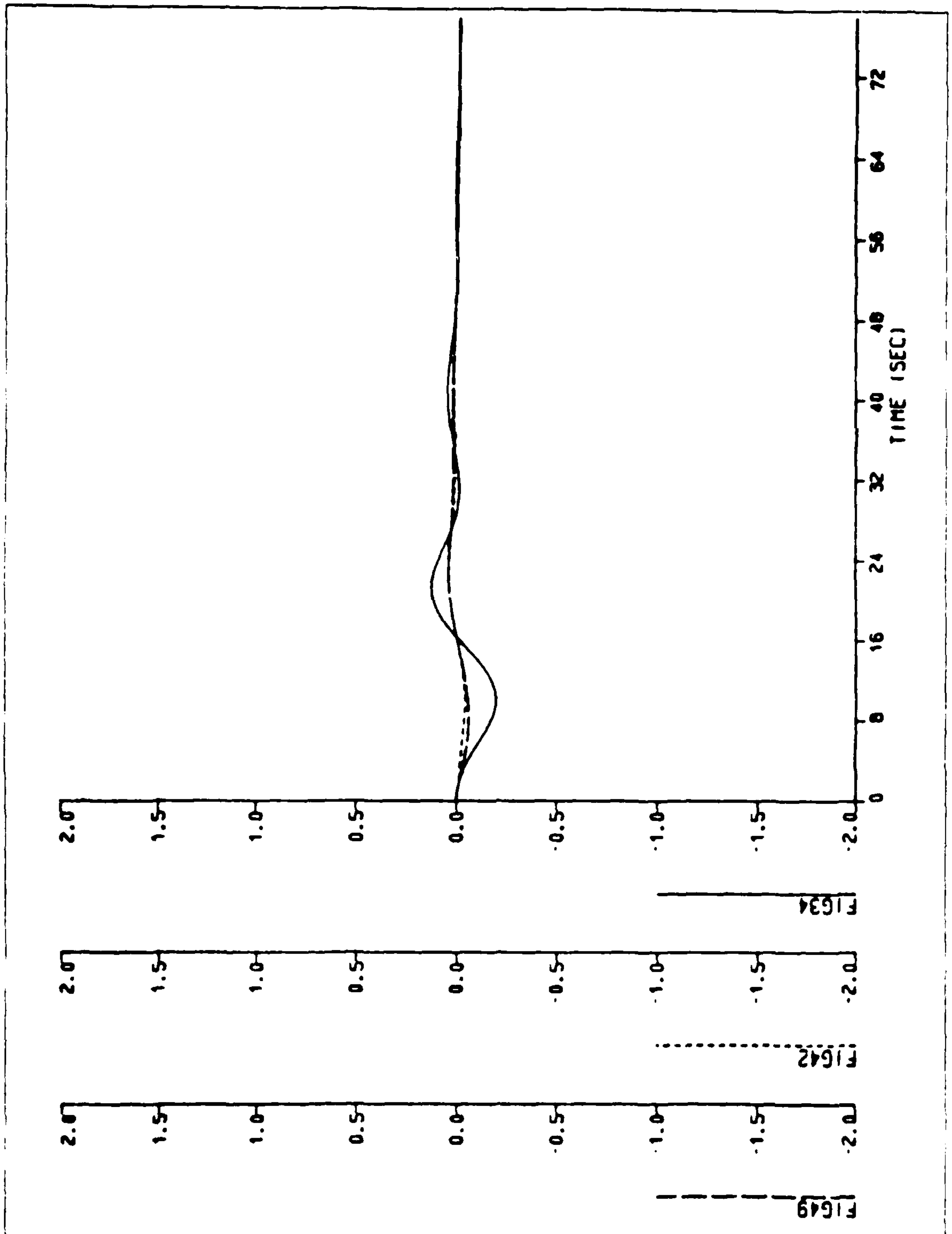

Figure 4.15 Comparison between Fig 3.4, Fig 4.2 and Fig 4.9 at Speed Output.

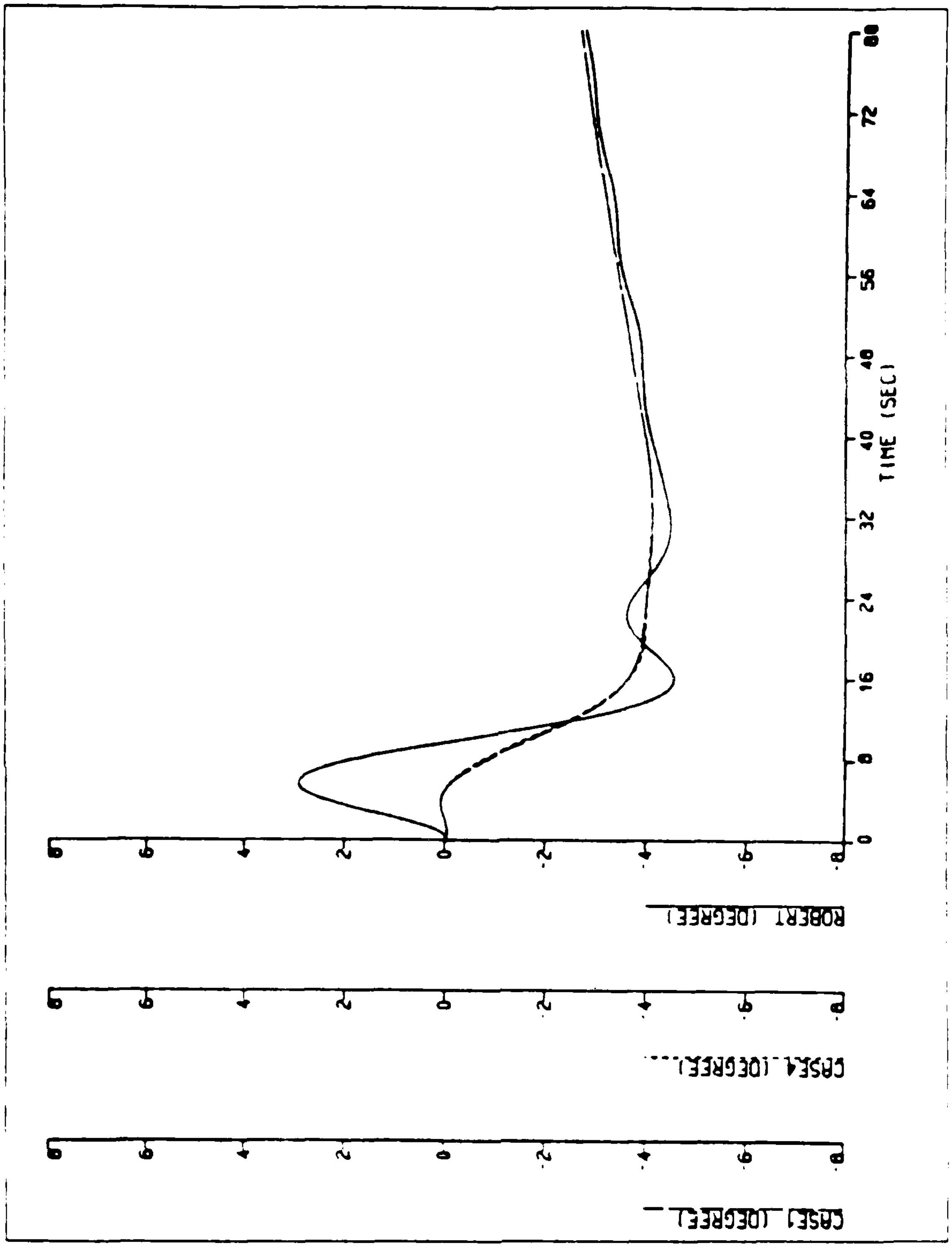

Figure 4.16 Comparison between Roberts, CASE 4 and CASE 1 for Fin Output at 3° Rudder Demand.

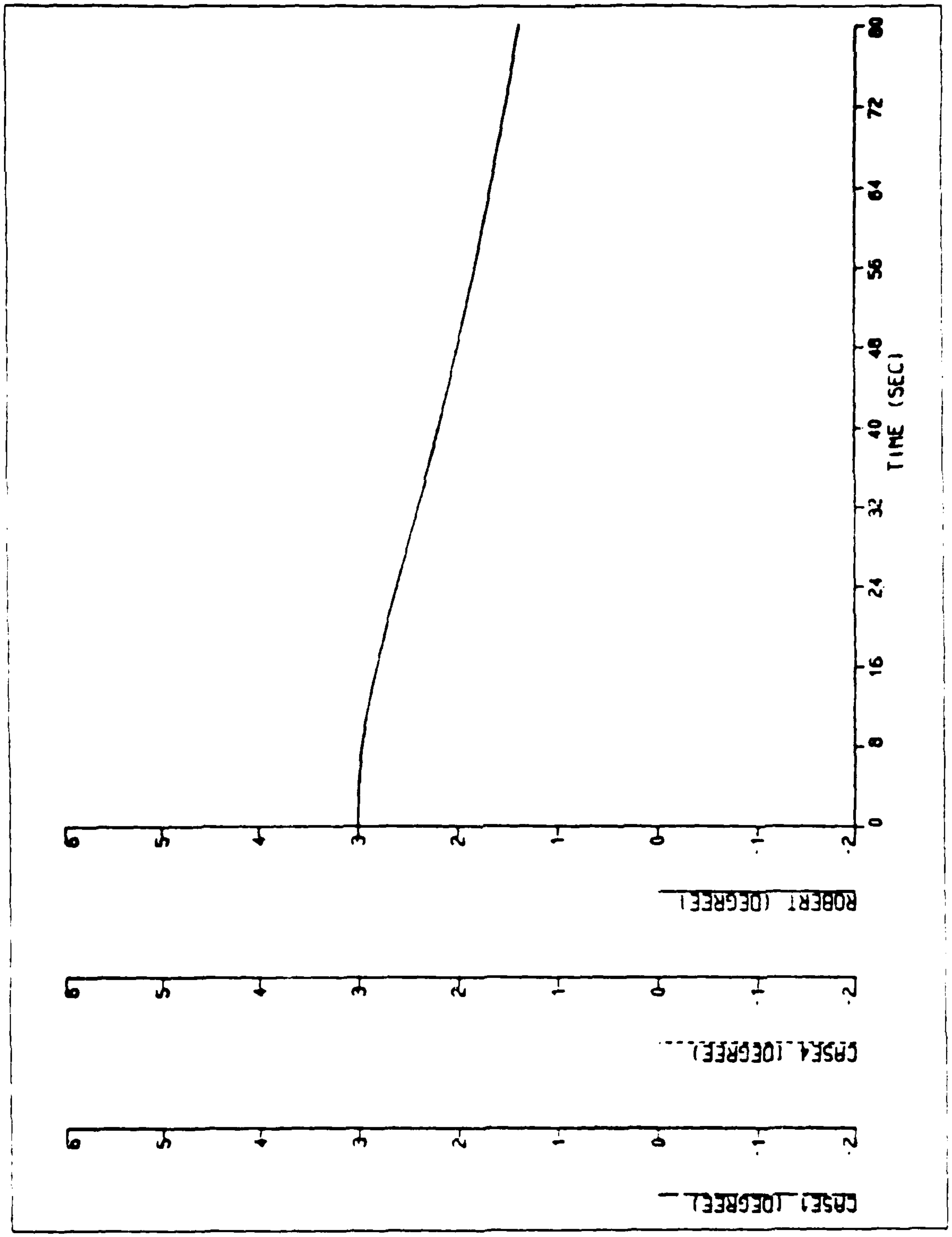

Figure 4.17 Comparison between Roberts, CASE 4 and CASE 1 for Rudder Output at 3° Rudder Demand.

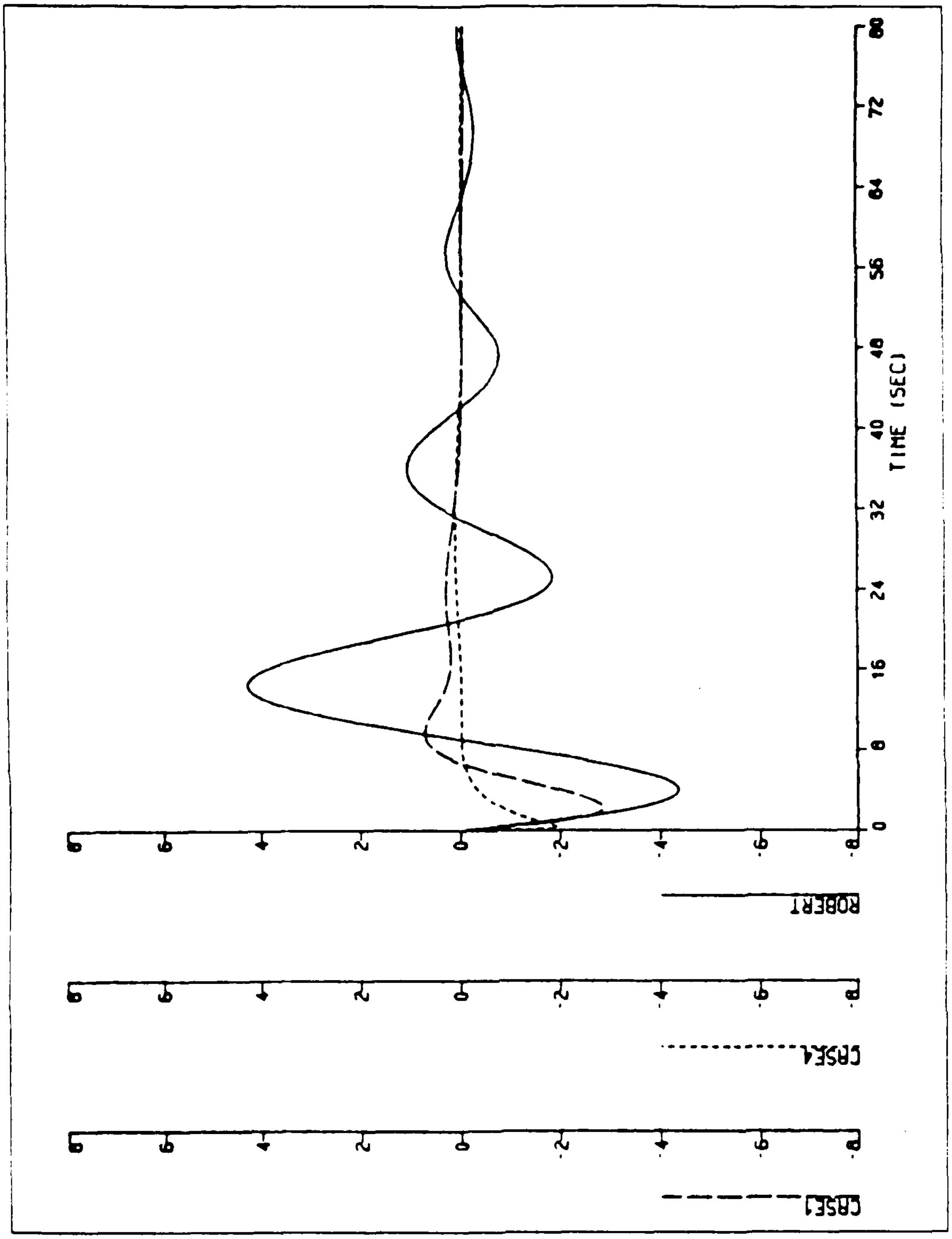

Figure 4.18 Comparison between Roberts, CASE 4 and CASE 1 for Power Output at 3° Rudder Demand.

The simulation obtained so far was performed using three degrees for rudder demand and we can know that there is no problem about maximum values of input and output shown by Table 3 for each output.

As can be seen in Figure 4.16 through Figure 4.18, CASE 1 is better than the other two cases. But we have to consider carefully the physical realization in Figure 4.18 because the power curve varies very fast. Therefore when we design the pre-compensator using weighting factors or other factors, we have to always consider physical realization limitations.

Figure 4.19 through Figure 4.21 show the comparison between the above three cases for Fin, Rudder and Power when we use twenty degrees for rudder demand.

From the above outputs, we can see that CASE 4 is better than the other two cases when we use twenty degrees for rudder demand.

F. VARIATION OF NUMBER OF POLES AND ZEROES

As shown by Table 7, the original pre-compensator by Roberts requires complex mathematical equations for a complete and detailed description. For many problems in the analysis and design of many modern dynamic systems, a simplified description, i.e., a low order model, is adequate and desirable. This thesis is concerned with the development of such low order models for the pre-compensator.

Two types of situations are commonly encountered in practice:

- A system exists and can be tested, but its equations are not well known or not clearly defined.
- A high order complex model of the system is known and can be used, but it is undesirable for the problem to be studied.

In either case the response of the system to a chosen signal can be obtained, and a low order model developed which has essentially identical outputs for identical inputs as the higher model.

By carefully planned studies it should be possible to see how much reduction in order can be achieved, how closely the behavior of the low order compares to that of the system and perhaps a best or optimum order can be found for the reduced order models.

In addition, by careful selection and classification of the pole-zero geometry of the high order system, it is hoped that a correlation may be found between such geometry and that of the best low order model. In any event, it is anticipated that some rules may be established for the choice of the number of poles and zeroes in the

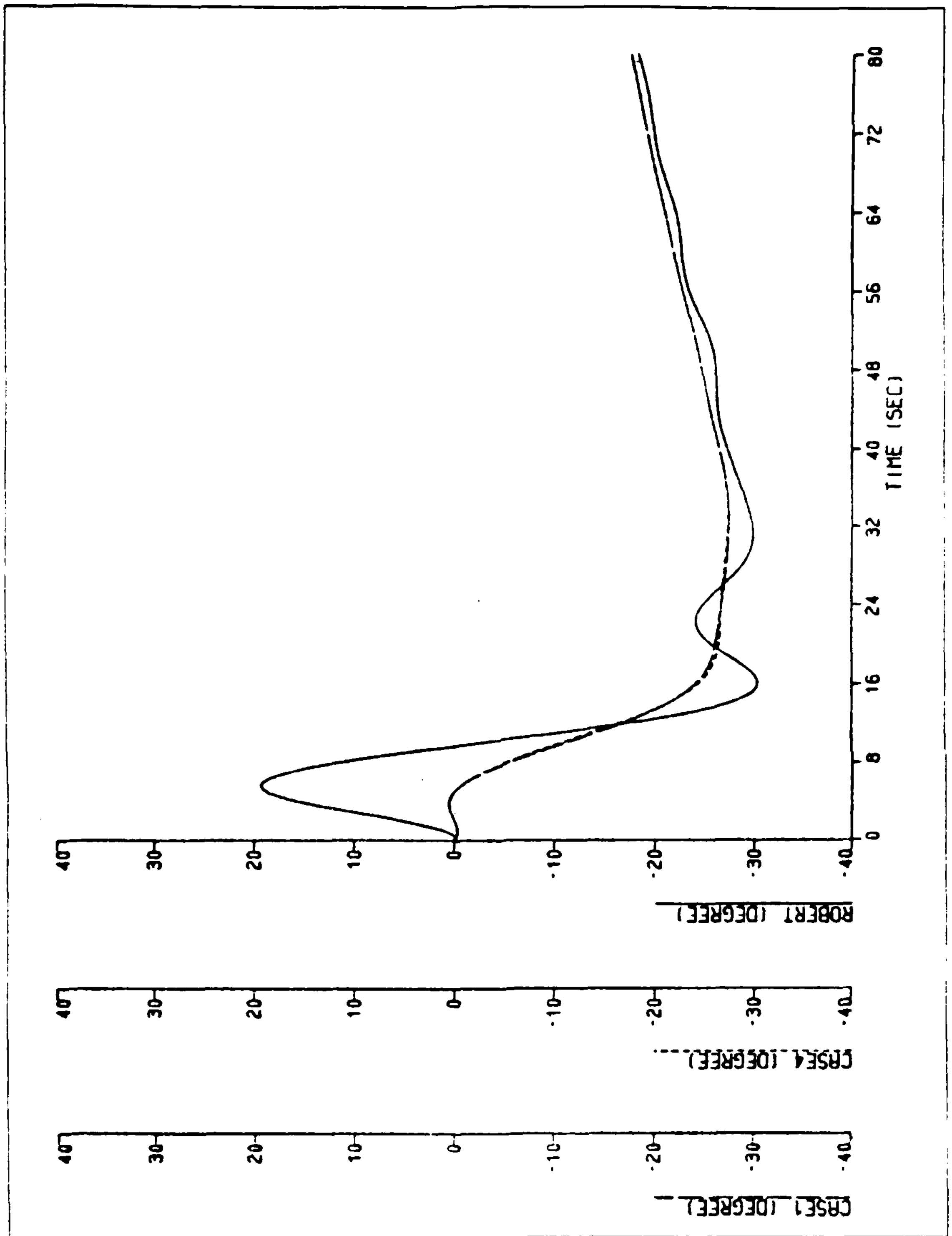

Figure 4.19 Comparison between Roberts, CASE 4 and CASE 1 for Fin Output at 20° Rudder Demand.

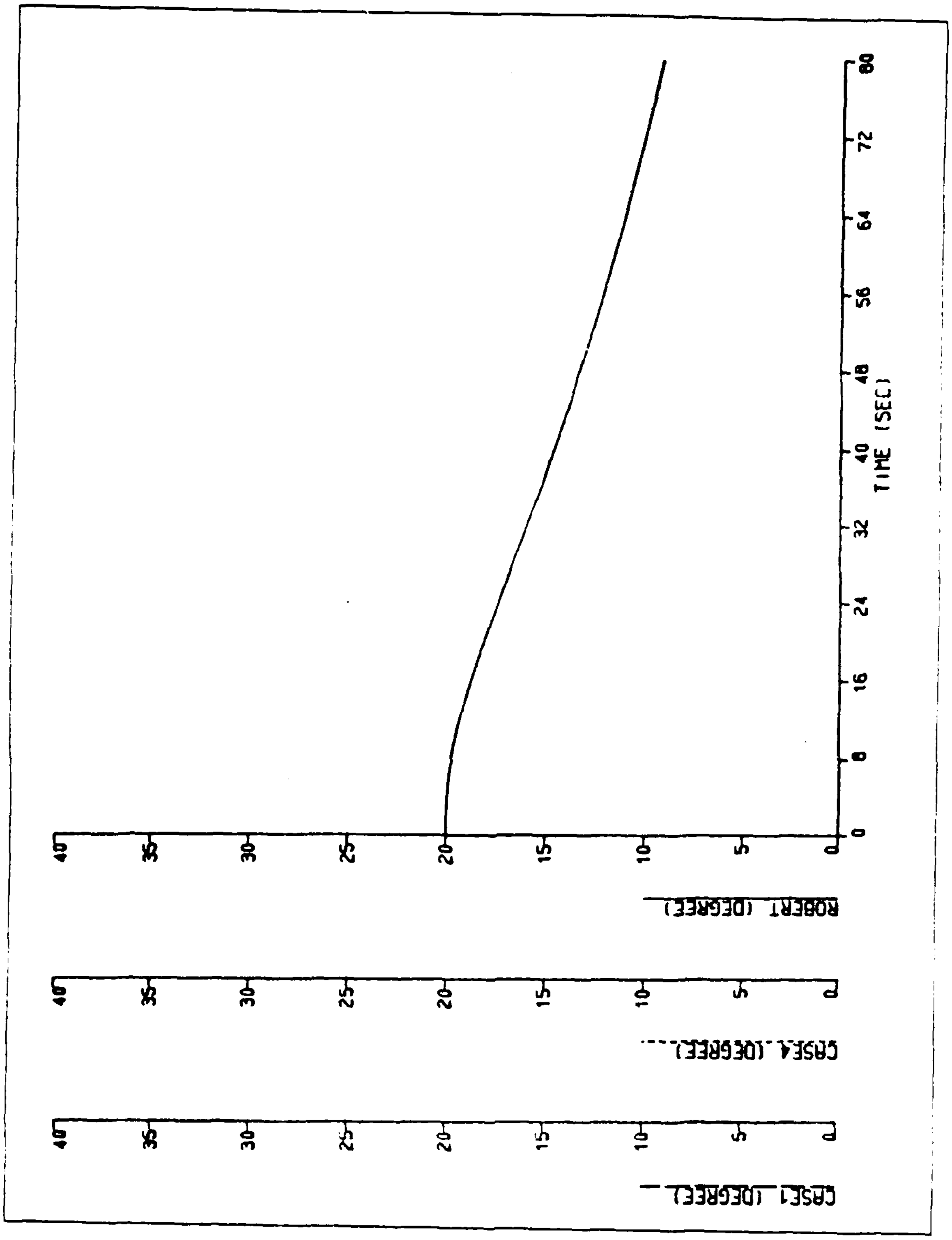

Figure 4.20 Comparison between Roberts, CASE 4 and CASE 1 for Rudder Output at 20° Rudder Demand.

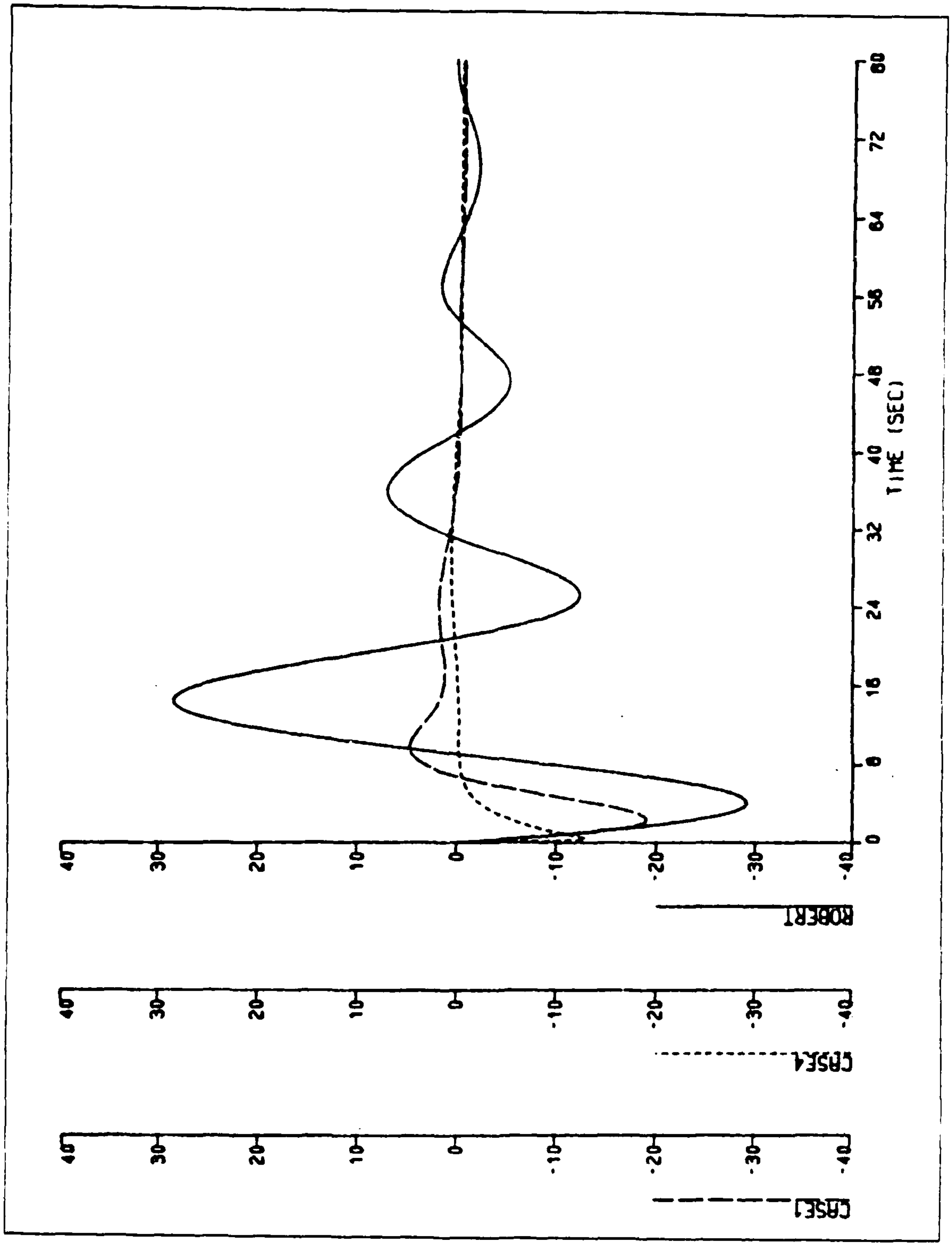

Figure 4.21 Comparison between Roberts, CASE 4 and CASE 1
for Power Output at 20° Rudder Demand.

low order model, such that evaluation of the pole, zero and gain will require only a few computer runs.

As shown in Figure A.1 of System Block Diagram for Simulation, K_{11} and K_{12} affect the Fin output of the system and K_{31}, K_{32} and K_{33} affect the Power output of the system. Therefore when we change the order of these elements, outputs, i.e., roll and speed will be changed by them also.

Unfortunately there is no known mathematical basis for choosing the "best" order for a low order model for each element of the pre-compensator. For convenience, this thesis has changed the order of K_{11} and K_{33} for two cases only.

Table 16 and Table 17 show the values of element for two cases and Figure 22 through Figure 25 show the outputs for comparison between original reduced order pre-compensator by Table 10 and the above two cases respectively. Other elements are the same as in Table 10.

TABLE 16

OPTIMUM PARAMETER VALUES OF REDUCED PRE-COMPENSATOR WHEN WE CHANGE K_{11} ONLY

$$K_{11}(S) = \frac{97.18759S + 3.94875}{7.53125S^2 + 21.075S + 12.025}$$

$$K_{12}(S) = \frac{K_{c2}(-72.14S^3 + 1.98925S^2 - 2.3S + 1)}{76.2S^3 + 28.63S^2 + 11.5S + 1}$$

$$K_{22}(S) = 1$$

$$K_{31}(S) = \frac{.63525}{32.05S^2 + 2.975S + 1}$$

$$K_{32}(S) = \frac{K_{c3}(1741.25S^2 - 1.94375S + 1)}{9.25S^3 + 111.25S^2 + 47.1S + 1}$$

$$K_{33}(S) = \frac{1}{11.4S + 1}$$

$$K_{13}(S) = K_{21}(S) = K_{33}(S) = 0$$

TABLE 17

OPTIMUM PARAMETER VALUES OF REDUCED PRE-COMPENSATOR WHEN WE CHANGE K_{33} AGAIN IN TABLE 16

$$K_{11}(S) = \frac{97.18759S + 3.94875}{7.53125S^2 + 21.075S + 12.025}$$

$$K_{12}(S) = \frac{K_{c2}(-72.14S^3 + 1.98925S^2 - 2.3S + 1)}{76.2S^3 + 28.63S^2 + 11.5S + 1}$$

$$K_{22}(S) = 1$$

$$K_{31}(S) = \frac{.63525}{32.05S^2 + 2.975S + 1}$$

$$K_{32}(S) = \frac{K_{c3}(1741.25S^2 - 1.94375S + 1)}{9.25S^3 + 111.25S^2 + 47.1S + 1}$$

$$K_{33}(S) = \frac{98.1875S + 2.05625}{6.65625S^2 + 28.05625S + 4.43625}$$

$$K_{13}(S) = K_{21}(S) = K_{33}(S) = 0$$

By the same algorithm, we can approach the appropriate order of pre-compensator and the values of each element for better design.

As can be seen in Figure 4.22 through Figure 4.25, when we put the additional zero and pole to the element of the pre-compensator, the cross-coupling of the roll output is decreased dramatically.

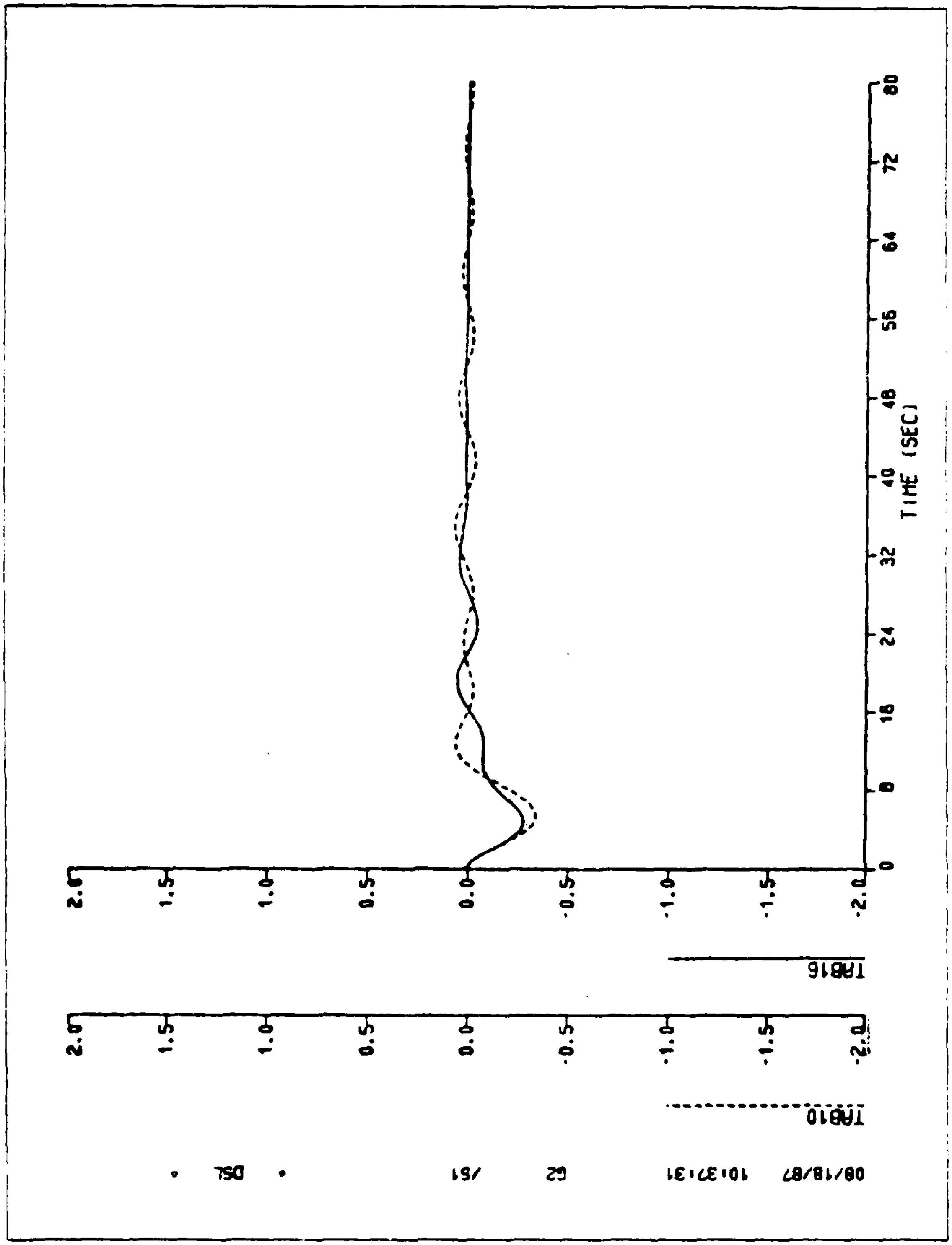

Figure 4.22 Comparison between Table 10 and Table 16 for Roll Output.

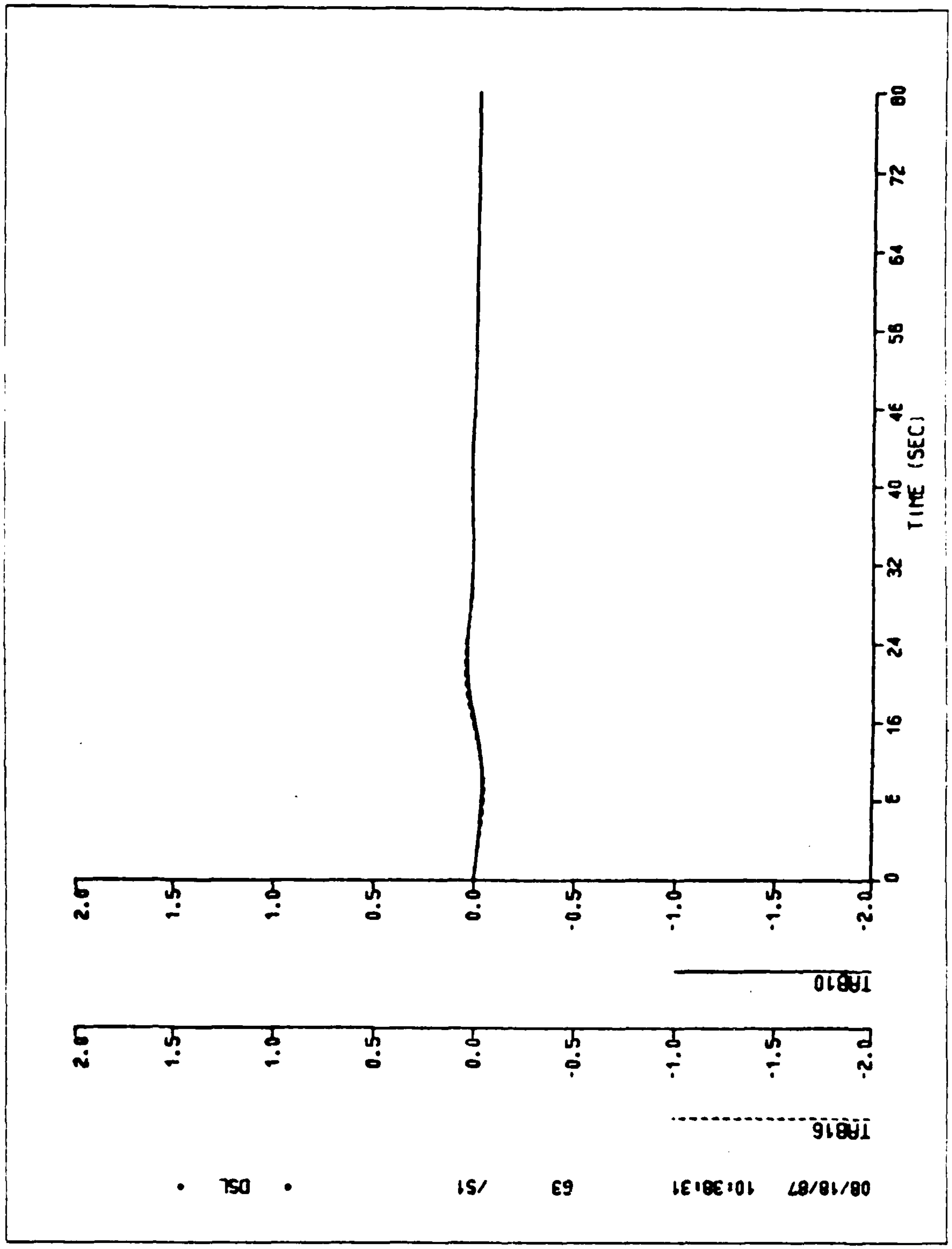

Figure 4.23 Comparison between Table 10 and Table 16
for Speed Output.

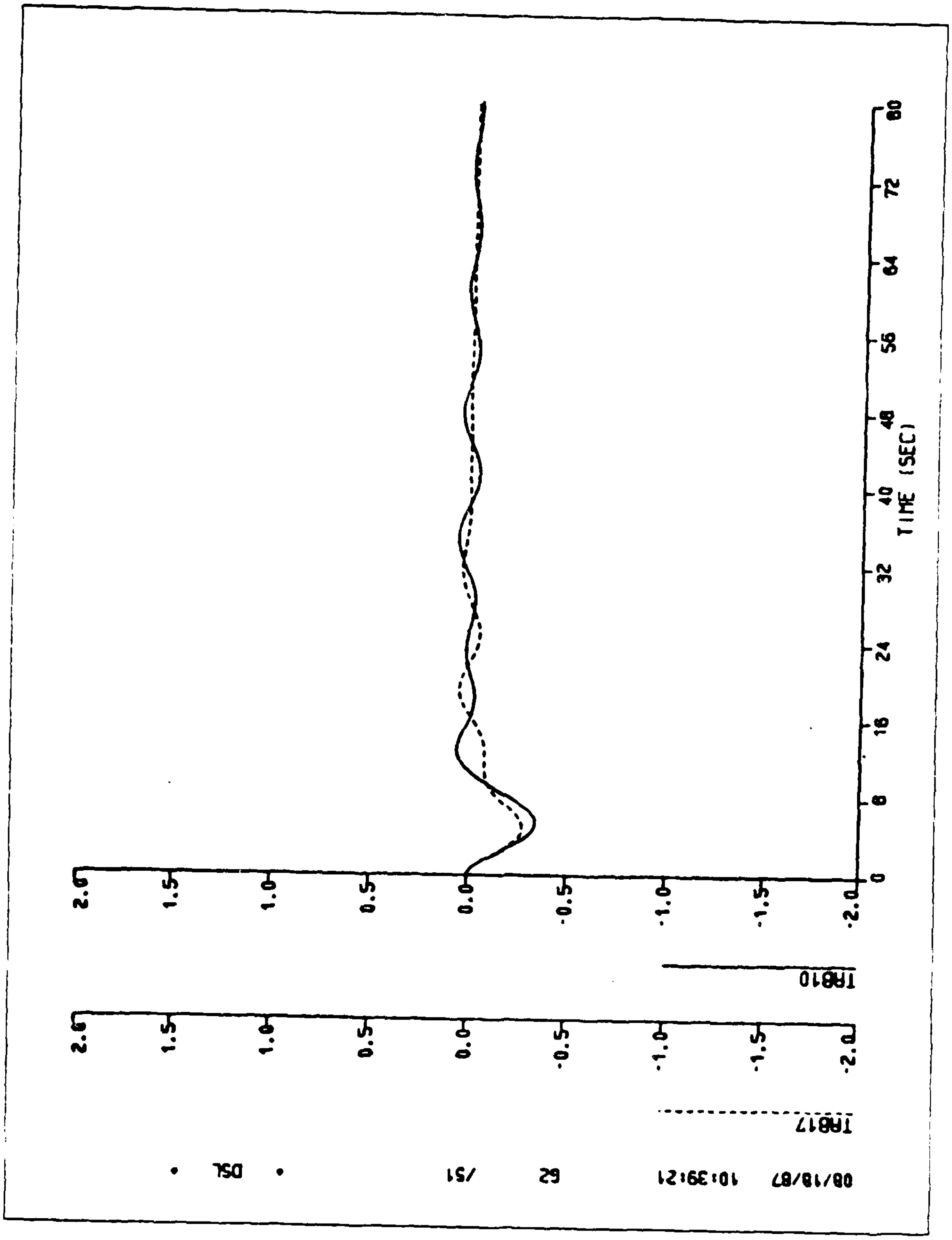

Figure 4.24 Comparison between Table 10 and Table 17 for Roll Output.

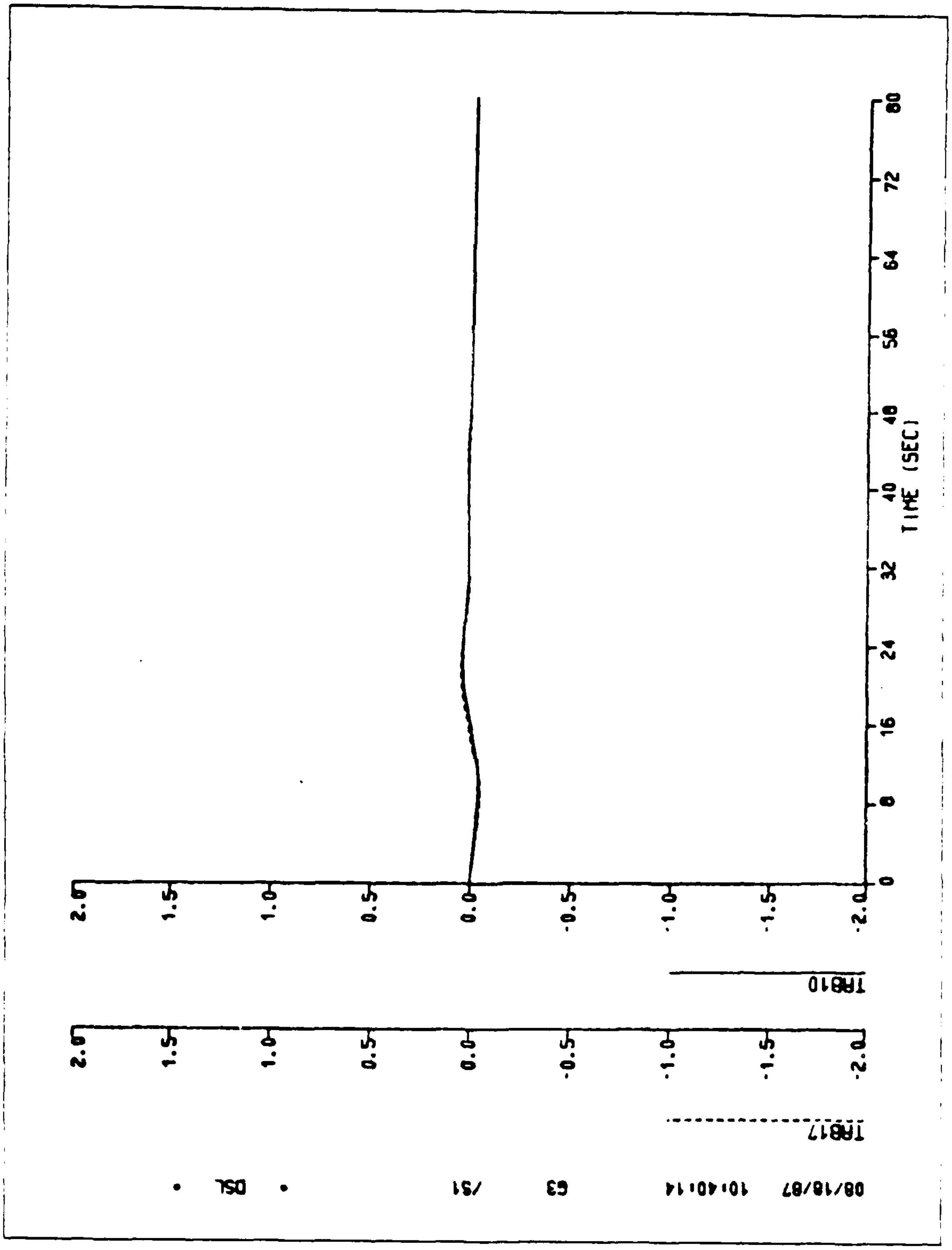

Figure 4.25 Comparison between Table 10 and Table 17 for Speed Output.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

In this thesis, the development of a pre-compensator to reduce the undesired and highly nonlinear cross-coupling effects in the maneuvering characteristics of a modern warship has been presented. Simulation results have shown that Function Minimization procedures for coordinated steering of a surface ship would significantly improve ship stability, minimize loss of speed and reduce the interaction intensity of the compensated system.

Simulation results have also shown that the reduced pre-compensator can be determined by Function Minimization directly from an ideal pre-compensator based on given specifications.

B. RECOMMENDATIONS

Computer simulation for Function Minimization leads to the following recommendations:

- This thesis uses the "HOOKE" subroutine of DSL for Function Minimization. It has certain constraint parameters, i.e., ITMAX, CFT. Simulation outputs are changed by changing initial values and the step size for Function Minimization. Therefore, for given specifications initial values and step size for Function Minimization by constraint parameters should be determined by experience.
- In this thesis, it has been shown that Function Minimization can be used for various cases as shown in Table 11. A particular case for needed specification should be determined and simulated by trial and error method for element optimum values which have undesired cross-coupling effects.
- In this thesis, it has been assumed that the stabilizer fin to yaw cross-coupling term, $G_{21}(S)$, is a null entry for the class of warship considered. However, it is recommended that cross-coupling between these parameters be considered in further studies on general surface ships.
- Further research should investigate ship characteristic constraints.
- Further research should investigate the effects of various sea state conditions, speeds and maneuvering.

APPENDIX A
SYSTEM BLOCK DIAGRAM FOR SIMULATION

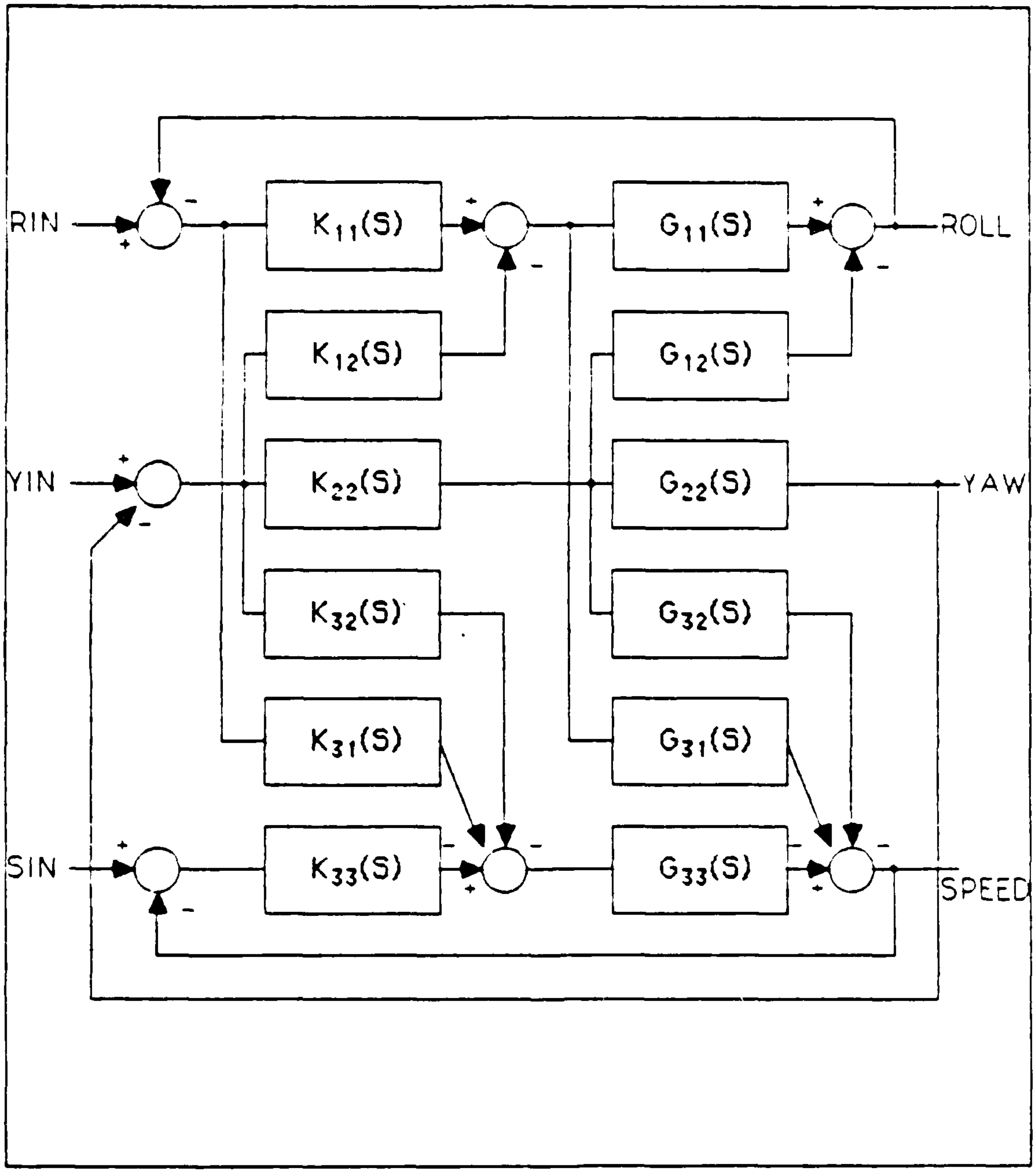

Figure A.1 System Block Diagram for Simulation.

APPENDIX B
CONSTRAINT PARAMETERS OF FUNCTION MINIMIZATION

To use HOOKE, the user must initialize the following arguments and, in the main program,

CALL HOOKE (X, STEP, N, ITMAX, CFTOL, ALPHA, BETA, CF, Q, QQ, W, IPRINT, MINMAX)

All of these arguments must be initialized in MAIN, except for X, CF, Q, QQ, and W. Recommended values for ALPHA and BETA are ALPHA = 2., BETA = 0.5. All of the arrays, i.e., X, STEP, Q, QQ and W, must be declared and dimensioned in MAIN.

TABLE 18

THE LIST OF PARAMETERS

ARGUMENT	MEANING
X	the array of N parameter values. The user must supply the initial guesses, either in the DSL program or in MAIN.
STEP	an array of dimension N containing the initial stepsizes to be used in the search.
N	the number of parameters (a positive integer, at most 15).
ITMAX	the maximum number of function calls to be performed.
CFTOL	the error in the criterion function to be reached before the program terminates (difference between the current value and the previous stage value).
ALPHA	the factor of (Y - X) which is added to Y to get XNEW; a number greater than or equal to 1.
BETA	the stepsize reduction factor; a number between 0. and 1.
CF	the value of the criterion function.
Q,QQ,W	arrays of dimension N, to be used as work space. They must be declared and dimensioned in the MAIN program.
IPRINT	an integer flag: = 0 for no intermediate printout = 1 for intermediate printout of X, CF, the number of function evaluation and notification of step-reduction.
MINMAX	an integer flag: = -1 searches for a minimum = +1 searches for a maximum

APPENDIX C

COMPUTER PROGRAM FOR UNCOMPENSATED SYSTEM

```
TITLE SIMULATION OF UNCOMPENSATED SYSTEM
ARRAY A1(1),B1(3),A2(2),B2(4),A3(1),B3(5),A4(2),B4(4),...
        A5(1),B5(3),A6(1),B6(2)
TABLE A1(1)=1,B1(1-3)=4,.24,1,A2(1-2)=-8.57,1,B2(1-4)=53.3,17.17,...
        9.52,1,A3(1)=1,B3(1-5)=12.32,25,11.2,1.0,A4(1-2)=10,1,...
        B4(1-4)=240,58,26,1,A5(1)=1,B5(1-3)=240,34,1,A6(1)=1,...
        B6(1-2)=24,1
CONST K11=0.114,K12=0.18,K22=.01,K31=0.058,K32=0.096,K33=0.1,...
        RL=0.,YW=0.,SP=0.
DERIVATIVE
        FIN=0.0*STEP(0)
        RUDDER=3.*STEP(0)
        POWER=0.*STEP(0)
        ROLL1=TRNFR(0,2,RL,A1,B1,K11*FIN)
        ROLL2=TRNFR(1,3,RL,A2,B2,K12*RUDDER)
        ROLL=ROLL1+ROLL2
        YAW=TRNFR(0,4,YW,A3,B3,K22*RUDDER)
        SPEED1=TRNFR(1,3,SP,A4,B4,K31*FIN)
        SPEED2=TRNFR(0,2,SP,A5,B5,K32*RUDDER)
        SPEED3=TRNFR(0,1,SP,A6,B6,K33*POWER)
        SPEED=-SPEED1-SPEED2+SPEED3
CONTROL FINTIM=80.
PRINT 1.,ROLL,YAW,SPEED
SAVE (S1) 0.1,ROLL,YAW,SPEED
GRAPH(G1/S1,DE=TEK618,PO=0,.5) TIME(LE=8.,UN=SEC) ROLL(LO=-1,LI=1,...
       SC=.25,NI=8),YAW(LO=-1,LI=3,SC=.25,NI=8),...
       SPEED(LO=-1,LI=4,SC=.25,NI=8)
LABEL(G1)STEP RESPONSE FOR UNCOMPENSATED WARSHIP MODEL AT 12 KTS
LABEL(G1)10 %  RUDDER DEMAND
END
STOP
```

APPENDIX D

COMPUTER PROGRAM FOR ORIGINAL PRE-COMPENSATOR

```
TITLE SIMULATION OF ORIGINAL PRE-COMPENSATOR
ARRAY A1(1),B1(3),A2(2),B2(4),A3(1),B3(5),A4(2),B4(4),...
          A5(1),B5(3),A6(1),B6(2)
ARRAY C1(1),D1(4),C2(4),D2(4),C3(2),D3(6),C4(6),D4(7),C5(1),D5(4)
TABLE A1(1)=1,B1(1-3)=4,.24,1,A2(1-2)=-8.57,1,B2(1-4)=53.3,17.17,...
          9.52,1,A3(1)=1,B3(1-5)=12,32.25,11.2,1,0,A4(1-2)=10,1,...
          B4(1-4)=240,58,26,1,A5(1)=1,B5(1-3)=240,34,1,A6(1)=1,...
          B6(1-2)=24,1
TABLE C1(1)=1,D1(1-4)=53.19,17.136,9.5,1,...
          C2(1-4)=-34.143,2,-8.29,1,...
          D2(1-4)=53.19,17.13,9.5,1,C3(1-2)=10,1,...
          D3(1-6)=534,278,182.6,46.15,11.5,1,...
          C4(1-6)=80050,15650,20665,2255,3,1,...
          D4(1-7)=5352,3326,2113,646,162,21.6,1,...
          C5(1)=1,D5(1-4)=100,30,12,1
CONST K11=0.114,K12=0.18,K22=.01,K31=0.058,K32=0.096,K33=0.1,...
          RL=0.,YW=0.,SP=0.
CONST GC10=0,GC20=0,GC30=0,GC40=0,GC50=0
DERIVATIVE
          RIN=0.0*STEP(0)
          YIN=3.*STEP(0)
          SIN=0.*STEP(0)
          E1=RIN-ROLL
          E2=YIN-YAW
          E3=SIN-SPEED
          FIN1=TRNFR(0,3,GC10,C1,D1,E1)
          FIN2=TRNFR(3,3,GC20,C2,D2,-1.6*E2)
          FIN=FIN1+FIN2
          ROLL1=TRNFR(0,2,RL,A1,B1,K11*FIN)
          RUDDER=YIN-YAW
          ROLL2=TRNFR(1,3,RL,A2,B2,K12*RUDDER)
          ROLL=ROLL1+ROLL2
          YAW=TRNFR(0,4,YW,A3,B3,K22*RUDDER)
          SP1=TRNFR(1,5,GC30,C3,D3,0.579*E1)
          SP2=TRNFR(5,6,GC40,C4,D4,0.0456*E2)
          SP3=TRNFR(0,3,GC50,C5,D5,E3)
          SPEED1=TRNFR(1,3,SP,A4,B4,K31*FIN)
          SPEED2=TRNFR(0,2,SP,A5,B5,K32*RUDDER)
          POWER=SP3-SP2-SP1
          SPEED3=TRNFR(0,1,SP,A6,B6,K33*POWER)
          SPEED=SPEED3-SPEED2-SPEED1
```

```
CONTROL FINTIM=80.
*RINT 1.,ROLL,YAW,SPEED
SAVE  (S1)  0.1,ROLL,YAW,SPEED
GRAPH(G1/S1,DE=TEK618,PO=0,.5) TIME(LE=8.,UN=SEC) ROLL(LO=-2,LI=1,...
      SC=.5,NI=8),YAW(LO=-2,LI=3,SC=.5,NI=8),...
      SPEED(LO=-2,LI=4,SC=.5,NI=8)
LABEL(G1)STEP RESPONSE FOR COMPENSATED WARSHIP MODEL AT 12 KTS
LABEL(G1)10 %  RUDDER DEMAND
END
STOP
```

APPENDIX E
COMPUTER PROGRAM FOR ORIGINAL REDUCED PRE-COMPENSATOR

```
TITLE SIMULATION FOR ORIGINAL REDUCED ORDER PRE-COMPENSATOR
ARRAY A1(1),B1(3),A2(2),B2(4),A3(1),B3(5),A4(2),B4(4),...
          A5(1),B5(3),A6(1),B6(2)
ARRAY C1(1),D1(2),C2(4),D2(4),C3(1),D3(3),C4(3),D4(4),C5(1),D5(2)
TABLE A1(1)=1,B1(1-3)=4.,24,1,A2(1-2)=-3.57,1,B2(1-4)=53.3,17.17,...
          9.52,1,A3(1)=1,B3(1-5)=12,32,25,11.2,1,0,A4(1-2)=10,1,...
          B4(1-4)=240,58,26,1,A5(1)=1,B5(1-3)=240,34,1,A6(1)=1,...
          B6(1-2)=24,1
TABLE C1(1)=1,D1(1-2)=8.6,1,C2(1-4)=-34.14,2,-8.3,1,...
          D2(1-4)=53.2,17.13,9.5,1,C3(1)=1,D3(1-3)=14.8,1.3,1,...
          C4(1-3)=2000,-2,1,D4(1-4)=130,25,12.6,1,...
          C5(1)=1,D5(1-2)=11.4,1
CONST K11=0.114,K12=0.18,K22=.01,K31=0.058,K32=0.096,K33=0.1,...
          RL=0.,YW=0.,SP=0.
CONST KC1=-1.6,KC2=0.579,KC3=0.0456,...
          GC10=0,GC20=0,GC30=0,GC40=0,GC50=0
DERIVATIVE
          RIN=0.0*STEP(0)
          YIN=3.*STEP(0)
          SIN=0.*STEP(0)
          E1=RIN-ROLL
          E2=YIN-YAW
          E3=SIN-SPEED
          FIN1=TRNFR(0,1,GC10,C1,D1,E1)
          FIN2=TRNFR(3,3,GC20,C2,D2,KC1*E2)
          FIN=FIN1+FIN2
          ROLL1=TRNFR(0,2,RL,A1,B1,K11*FIN)
          RUDDER=YIN-YAW
          ROLL2=TRNFR(1,3,RL,A2,B2,K12*RUDDER)
          ROLL=ROLL1+ROLL2
          YAW=TRNFR(0,4,YW,A3,B3,K22*RUDDER)
          SP1=TRNFR(0,2,GC30,C3,D3,KC2*E1)
          SP2=TRNFR(2,3,GC40,C4,D4,KC3*E2)
          SP3=TRNFR(0,1,GC50,C5,D5,E3)
          SPEED1=TRNFR(1,3,SP,A4,B4,K31*FIN)
          SPEED2=TRNFR(0,2,SP,A5,B5,K32*RUDDER)
          POWER=SP3-SP2-SP1
          SPEED3=TRNFR(0,1,SP,A6,B6,K33*POWER)
          SPEED=SPEED3-SPEED2-SPEED1
CONTROL FINTIM=80.
```

```
*RINT 1.,ROLL,YAW,SPEED
*RINT 1.,FIN,RUDDER,POWER
SAVE (S1) 0.1,ROLL,YAW,SPEED
GRAPH(G1/S1,DE=TEK618,PO=0,.5) TIME(LE=8.,UN=SEC) ROLL(LO=-2,LI=1,...
      SC=.5,NI=8),YAW(LO=-2,LI=3,SC=.5,NI=8),...
      SPEED(LO=-2,LI=4,SC=.5,NI=8)
LABEL(G1)STEP RESPONSE FOR COMPENSATED WARSHIP MODEL AT 12 KTS
LABEL(G1)FIGURE 3.4
END
STOP
```

APPENDIX F

COMPUTER PROGRAM FOR AFGEN SUBROUTINE

```
TITLE SIMULATION FOR desired outputs using afgen subroutine
AFGEN RL=0,0,1,-.03,4,-.1,10,0,16,0,23,0,29,0,36,0,...
            42,0,48,0,54,0,61,0,67,0,80,0
AFGEN YW=0,0,1,.00006,4,.006,8,.04,10,.07,20,.29,30,.55,40,.8,80,1.61
AFGEN SD=0,0,1,-.004.10,-.01,21,0,31,0,41,0,51,0,70,0,80,0
DERIVATIVE
        X=TIME
        ROLL=NLFGEN(RL,X)
        YAW=NLFGEN(YW,X)
        SPEED=NLFGEN(SD,X)
CONTROL FINTIM=80
*RINT 1.,ROLL,YAW,SPEED
SAVE (S1) 0.1,ROLL,YAW,SPEED
GRAPH(G1 S1,DE=TEK618,PO=0,.5) TIME(LE=8.,UN=SEC),ROLL(LO=-2,LI=1,...
      SC=.5,NI=8),YAW(LO=-2,LI=3,SC=.5,NI=8),...
      SPEED(LO=-2,LI=4,SC=.5,NI=8)
LABEL(G1) AFGN 1 FOR FIGURE 4.6
END
STOP
```

APPENDIX G

COMPUTER PROGRAM FOR FUNCTION MINIMIZATION

```
D     COMMON/HANDJ/FLAG,ER,K1,K2,K3,K4,K5,K6,K7,K8,K9,K10,K11,K12
D     COMMON/HANDJ/K13,K14
TITLE SIMULATION FOR FUNCTION MINIMIZATION SUBROUTINE
ARRAY A1(1),B1(3),A2(2),B2(4),A3(1),B3(5),A4(2),B4(4),A5(1),B5(3),...
         A6(1),B6(2)
STORAG C1(1),D1(2),C2(4),D2(4),C3(1),D3(3),C4(3),D4(4),C5(1),D5(2)
TABLE A1(1)=1,B1(1-3)=4,.24,1,A2(1-2)=-8.57,1,B2(1-4)=53.3,17.17,...
         9.52,1,A3(1)=1,B3(1-5)=12,32.25,11.2,1.0,A4(1-2)=10,1,...
         B4(1-4)=240,58,26,1,A5(1)=1,B5(1-3)=240,34,1,...
         A6(1)=1,B6(1-2)=24,1
CONST K01=-34.14,K20=2,K30=-8.3,K40=53.2,K50=17.13,K60=9.5,K70=.579,...
         K80=14.8,K90=1.3,K100=2000,K110=-2,K120=130,K130=25,...
         K140=12.6
CONST C11=.114,C12=.18,C22=.01,C31=.058,C32=.096,C33=.1,IC=0,...
         KC1=-1.6,KC3=0.0456
PARAM K1MIN=-50,K1MAX=200,K2MIN=.01,K2MAX=200,K3MIN=-10,K3MAX=200,...
         K4MIN=.01,K4MAX=200,K5MIN=.01,K5MAX=200,K6MIN=.01,K6MAX=200,...
         K7MIN=.01,K7MAX=200,K8MIN=.01,K8MAX=200,K9MIN=.01,K9MAX=200,...
         K10MIN=.01,K10MAX=3000,K11MIN=-10,K11MAX=200,K12MIN=.01,...
         K12MAX=200,K13MIN=.01,K13MAX=200,K14MIN=.01,K14MAX=200
AFGEN RL=0.0,1,-.03,4,-.1,10,0,16,0,23,0,29,0,36,0,...
            42,0,48,0,54,0,61,0,67,0,80,0
AFGEN YW=0,0,1,.00006,4,.006,8,.04,10,.07,20,.29,30,.55,40,.8,80,1.61
AFGEN SD=0,0,1,-.004,10,-.01,21,0,31,0,41,0,51,0,70,0,80,0
INITIAL SEGMENT
         IF(FLAG.LT.0.) K1=K01
         IF(FLAG.LT.0.) K2=K20
         IF(FLAG.LT.0.) K3=K30
         IF(FLAG.LT.0.) K4=K40
         IF(FLAG.LT.0.) K5=K50
         IF(FLAG.LT.0.) K6=K60
         IF(FLAG.LT.0.) K7=K70
         IF(FLAG.LT.0.) K8=K80
         IF(FLAG.LT.0.) K9=K90
         IF(FLAG.LT.0.) K10=K100
         IF(FLAG.LT.0.) K11=K110
         IF(FLAG.LT.0.) K12=K120
         IF(FLAG.LT.0.) K13=K130
         IF(FLAG.LT.0.) K14=K140
         FLAG=FLAG+1
         IF((K1.LE.K1MIN).OR.(K1.GE.K1MAX)) THEN
```

```
   K1 = K01
ENDIF
IF((K2.LE.K2MIN).OR.(K2.GE.K2MAX)) THEN
   K2 = K20
ENDIF
IF((K3.LE.K3MIN).OR.(K3.GE.K3MAX)) THEN
   K3 = K30
ENDIF
IF((K4.LE.K4MIN).OR.(K4.GE.K4MAX)) THEN
   K4 = K40
ENDIF
IF((K5.LE.K5MIN).OR.(K5.GE.K5MAX)) THEN
   K5 = K50
ENDIF
IF((K6.LE.K6MIN).OR.(K6.GE.K6MAX)) THEN
   K6 = K60
ENDIF
IF((K7.LE.K7MIN).OR.(K7.GE.K7MAX)) THEN
   K7 = K70
ENDIF
IF((K8.LE.K8MIN).OR.(K8.GE.K8MAX)) THEN
   K8 = K80
ENDIF
IF((K9.LE.K9MIN).OR.(K9.GE.K9MAX)) THEN
   K9 = K90
ENDIF
IF((K10.LE.K10MIN).OR.(K10.GE.K10MAX)) THEN
   K10 = K100
ENDIF
IF((K11.LE.K11MIN).OR.(K11.GE.K11MAX)) THEN
   K11 = K110
ENDIF
IF((K12.LE.K12MIN).OR.(K12.GE.K12MAX)) THEN
   K12 = K120
ENDIF
IF((K13.LE.K13MIN).OR.(K13.GE.K13MAX)) THEN
   K13 = K130
ENDIF
IF((K14.LE.K14MIN).OR.(K14.GE.K14MAX)) THEN
   K14 = K140
ENDIF
C1(1) = 1
D1(1) = 8.6
D1(2) = 1
C2(1) = K1
C2(2) = K2
C2(3) = K3
```

```
        C2(4) = 1
        D2(1) = K4
        D2(2) = K5
        D2(3) = K6
        D2(4) = 1
        C3(1) = K7
        D3(1) = K8
        D3(2) = K9
        D3(3) = 1
        C4(1) = K10
        C4(2) = K11
        C4(3) = 1
        D4(1) = K12
        D4(2) = K13
        D4(3) = K14
        D4(4) = 1
        C5(1) = 1
        D5(1) = 11.4
        D5(2) = 1
DERIVATIVE
        RIN = 0.0*STEP(0)
        YIN = 3.*STEP(0)
        SIN = 0.*STEP(0)
        E1 = RIN-ROLL
        E2 = YIN-YAW
        E3 = SIN-SPEED
        FIN1 = TRNFR(0,1,IC,C1,D1,E1)
        FIN2 = TRNFR(3,3,IC,C2,D2,KC1*E2)
        FIN = FIN1 + FIN2
        ROLL1 = TRNFR(0,2,IC,A1,B1,C11*FIN)
        RUDDER = YIN-YAW
        ROLL2 = TRNFR(1,3,IC,A2,B2,C12*RUDDER)
        ROLL = ROLL1 + ROLL2
        YAW = TRNFR(0,4,IC,A3,B3,C22*RUDDER)
        SP1 = TRNFR(0,2,IC,C3,D3,E1)
        SP2 = TRNFR(2,3,IC,C4,D4,KC3*E2)
        SP3 = TRNFR(0,1,IC,C5,D5,E3)
        SPEED1 = TRNFR(1,3,IC,A4,B4,C31*FIN)
        SPEED2 = TRNFR(0,2,IC,A5,B5,C32*RUDDER)
        POWER = SP3-SP2-SP1
        SPEED3 = TRNFR(0,1,IC,A6,B6,C33*POWER)
        SPEED = SPEED3-SPEED2-SPEED1
        X = TIME
        YNL1 = NLFGEN(RL,X)
        YNL2 = NLFGEN(YW,X)
        YNL3 = NLFGEN(SD,X)
        EE1 = ((ROLL-YNL1)**2)
```

```
        E11 = INTGRL(IC,EE1)
        EE2 = ((YAW-YNL2)**2)
        E22 = INTGRL(IC,EE2)
        EE3 = ((SPEED-YNL3)**2)
        E33 = INTGRL(IC,EE3)
        E = E11 + E22 + E33
CONTROL FINTIM = 50,DELT = .01
TERMINAL
        ER = E
END
STOP
FORTRAN
        IMPLICIT REAL*8(A-H,O-Z)
        DIMENSION X(14),STEP(14),Q(14),QQ(14),W(14)
        STEP(1) = 4.
        STEP(2) = .001
        STEP(3) = 2.
        STEP(4) = 4.
        STEP(5) = 2.
        STEP(6) = 1.
        STEP(7) = 0.005
        STEP(8) = 1.
        STEP(9) = 0.1
        STEP(10) = 15.
        STEP(11) = .005
        STEP(12) = 7.
        STEP(13) = 5.
        STEP(14) = 2.
        N = 14
        ITMAX = 200
        CFTOL = .0000001
        ALPHA = 2
        BETA = .5
        IPRINT = 0
        MINMAX = -1
        CALL HOOKE(X,STEP,N,ITMAX,CFTOL,ALPHA,BETA,
       *CF,Q,QQ,W,IPRINT,MINMAX)
        STOP
        END
```

APPENDIX H

COMPUTER PROGRAM FOR COMPARISON BETWEEN ROBERTS AND F.M.

```
TITLE SIMULATION FOR COMPARISON BETWEEN ROBERTS AND F.M.
***** ROBERTS OUTPUT *****
ARRAY A1(1),B1(3),A2(2),B2(4),A3(1),B3(5),A4(2),B4(4),...
          A5(1),B5(3),A6(1),B6(2)
ARRAY C1(1),D1(2),C2(4),D2(4),C3(1),D3(3),C4(3),D4(4),C5(1),D5(2)
TABLE A1(1)=1,B1(1-3)=4,.24,1,A2(1-2)=-8.57,1,B2(1-4)=53.3,17.17,...
          9.52,1,A3(1)=1,B3(1-5)=12,32.25,11.2,1,0,A4(1-2)=10,1,...
          B4(1-4)=240,58,26,1,A5(1)=1,B5(1-3)=240,34,1,A6(1)=1,...
          B6(1-2)=24,1
TABLE C1(1)=1,D1(1-2)=8.6,1,C2(1-4)=-34.14,2,-8.3,1,...
          D2(1-4)=53.2,17.13,9.5,1,C3(1)=1,D3(1-3)=14.8,1.3,1,...
          C4(1-3)=2000,-2,1,D4(1-4)=130,25,12.6,1,...
          C5(1)=1,D5(1-2)=11.4,1
CONST K11=0.114,K12=0.18,K22=.01,K31=0.058,K32=0.096,K33=0.1,...
          RL=0.,YW=0.,SP=0.
CONST KC1=-1.6,KC2=0.579,KC3=0.0456,...
          GC10=0,GC20=0,GC30=0,GC40=0,GC50=0
DERIVATIVE
          RIN=0.0*STEP(0)
          YIN=3.*STEP(0)
          SIN=0.*STEP(0)
          E1=RIN-ROLL
          E2=YIN-YAW
          E3=SIN-SPEED
          FIN1=TRNFR(0,1,GC10,C1,D1,E1)
          FIN2=TRNFR(3,3,GC20,C2,D2,KC1*E2)
          FIN=FIN1-FIN2
          ROLL1=TRNFR(0,2,RL,A1,B1,K11*FIN)
          RUDDER=YIN-YAW
          ROLL2=TRNFR(1,3,RL,A2,B2,K12*RUDDER)
          ROLL=ROLL1+ROLL2
          YAW=TRNFR(0,4,YW,A3,B3,K22*RUDDER)
          SP1=TRNFR(0,2,GC30,C3,D3,KC2*E1)
          SP2=TRNFR(2,3,GC40,C4,D4,KC3*E2)
          SP3=TRNFR(0,1,GC50,C5,D5,E3)
          SPEED1=TRNFR(1,3,SP,A4,B4,K31*FIN)
          SPEED2=TRNFR(0,2,SP,A5,B5,K32*RUDDER)
          POWER=SP3-SP2-SP1
          SPEED3=TRNFR(0,1,SP,A6,B6,K33*POWER)
          SPEED=SPEED3-SPEED2-SPEED1
```

```
***** FUNCTION MINIMIZATION OUTPUT *****
ARRAY AA1(1),BB1(3),AA2(2),BB2(4),AA3(1),BB3(5),AA4(2),BB4(4),...
      AA5(1),BB5(3),AA6(1),BB6(2)
ARRAY CC1(1),DD1(2),CC2(4),DD2(4),CC3(1),DD3(3)
ARRAY CC4(3),DD4(4),CC5(1),DD5(2)
TABLE AA1(1) = 1,BB1(1-3) = 4,.24,1,AA2(1-2) = -8.57,1,...
      BB2(1-4) = 53.3,17.17,9.52,1,...
      AA3(1) = 1,BB3(1-5) = 12,32.25,11.2,1,0,AA4(1-2) = 10,1,...
      BB4(1-4) = 240,58,26,1,AA5(1) = 1,BB5(1-3) = 240,34,1,AA6(1) = 1,...
      BB6(1-2) = 24,1
TABLE CC1(1) = 1,DD1(1-2) = 8.6,1,CC2(1-4) = -72.14,1.98925,-2.3,1 ..
      DD2(1-4) = 76.2,28.63,11.5,1,DD3(1-3) = 32.05,2.975,1,...
      CC4(1-3) = 1741.25,-1.94375,1,DD4(1-4) = 9.25,111.25,47.1,1,...
      CC5(1) = 1.,DD5(1-2) = 11.4,1,CC3(1) = .63525
CONST KK11 = 0.114,KK12 = 0.18,KK22 = .01,KK31 = 0.058,KK32 = 0.096,KK33 = 0.1,...
      RRL = 0.,YYW = 0.,SSP = 0.,KKC1 = -1.6,KKC3 = 0.0456
CONST GGC10 = 0,GGC20 = 0,GGC30 = 0,GGC40 = 0,GGC50 = 0
DERIVATIVE
      RRIN = 0.0*STEP(0)
      YYIN = 3.*STEP(0)
      SSIN = 0.*STEP(0)
      EE1 = RRIN-RROLL
      EE2 = YYIN-YYAW
      EE3 = SSIN-SSPEED
      FFIN1 = TRNFR(0,1,GGC10,CC1,DD1,EE1)
      FFIN2 = TRNFR(3,3,GGC20,CC2,DD2,KKC1*EE2)
      FFIN = FFIN1 - FFIN2
      RROLL1 = TRNFR(0,2,RRL,AA1,BB1,KK11*FFIN)
      RRUDDE = YYIN-YYAW
      RROLL2 = TRNFR(1,3,RRL,AA2,BB2,KK12*RRUDDE)
      RROLL = RROLL1 - RROLL2
      YYAW = TRNFR(0,4,YYW,AA3,BB3,KK22*RRUDDE)
      SSP1 = TRNFR(0,2,GGC30,CC3,DD3,EE1)
      SSP2 = TRNFR(2,3,GGC40,CC4,DD4,KKC3*EE2)
      SSP3 = TRNFR(0,1,GGC50,CC5,DD5,EE3)
      SSPEE1 = TRNFR(1,3,SSP,AA4,BB4,KK31*FFIN)
      SSPEE2 = TRNFR(0,2,SSP,AA5,BB5,KK32*RRUDDE)
      PPOWER = SSP3-SSP2-SSP1
      SSPEE3 = TRNFR(0,1,SSP,AA6,BB6,KK33*PPOWER)
      SSPEED = SSPEE3-SSPEE2-SSPEE1
CONTROL FINTIM = 80.
*RINT 1.,FFIN,RRUDDER,RROLL,YYAW,SSPEED
SAVE (S1) 0.1,ROLL,RROLL,YAW,YYAW,SPEED,SSPEED
GRAPH(G1,S1,DE = TEK618,PO = 0,.5) TIME(LE = 8.,UN = SEC) YAW(LO = -2,LI = 1,...
     SC = .5,NI = 8),YYAW(LO = -2,LI = 4,SC = .5,NI = 8)
LABEL(G1)COMPARISON BETWEEN ROBERT AND F.M
LABEL(G1)FOR YAW OUTPUT
```

```
GRAPH(G2/S1,DE=TEK618,PO=0,.5) TIME(LE=8.,UN=SEC) ROLL(LO=-2,LI=1,...
        SC=.5,NI=8),RROLL(LO=-2,LI=4,SC=.5,NI=8)
LABEL(G2)COMPARISON BETWEEN ROBERT AND F.M
LABEL(G2)FOR ROLL OUTPUT
GRAPH(G3/S1,DE=TEK618,PO=0,.5) TIME(LE=8.,UN=SEC) SPEED(LO=-2,LI=1,...
        SC=.5,NI=8),SSPEED(LO=-2,LI=4,SC=.5,NI=8)
LABEL(G3)COMPARISON BETWEEN ROBERT AND F.M
LABEL(G3)FOR SPEED OUTPUT
END
STOP
```

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