AFOSR-TR- 89 0003

An Expert System Approach To Large Space Systems Control

October 1988

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Submitted To:

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Bolling AFB, Washington, DC 20332-6448

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

ADA204460

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 89-0003
6a. NAME OF PERFORMING ORGANIZATION General Research Corporation / 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR
6c. ADDRESS (City, State, and ZIP Code) 7655 Old Springhouse Road McLean, VA 22102	7b. ADDRESS (City, State, and ZIP Code) Bolling Air Force Base Washington, DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR / 8b. OFFICE SYMBOL (If applicable) NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F49620-87-C-0105
8c. ADDRESS (City, State, and ZIP Code) Bolling Air Force Base Washington, DC 20332-6448	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 61102F / PROJECT NO. 2312 / TASK NO. K1 / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
An Expert System Approach to Large Space Structures Control (U)

12. PERSONAL AUTHOR(S)
Charles F. Gartrell, William Baracat, Barbara Skiffington

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical	FROM Sep 87 TO Oct 88	1988 October	viii + 260

16. SUPPLEMENTARY NOTATION

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Vibration damping, expert systems, large space structure control

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The purpose of this project was to develop a technique which will reduce the need for high fidelity models for the control synthesis process, provide a robust control implementation, and relieve computational burdens by utilizing artificial intelligence techniques, notably expert systems, to implement control systems for large SDI space systems. Extending an earlier proof-of-concept investigation, this research proceeds beyond simple control laws, low bandwidths, and exact pattern encoding/matching approaches to include modern control laws, higher bandwidths, and partial match inferencing procedures. Three control implementations, Direct Velocity Feedback, Independent Modal Space Control and an Expert System Controller were developed and various simulations performed to verify and compare performance. The primary finding is that an ESC has performance comparable to the numeric approaches and has a superior performance when there are changes in the system being controlled. That is an ESC indeed demonstrates a robust control implementation.

Keywords: vibration damping, (KR) ←

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☒ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Charles F. Gartrell	22b. TELEPHONE (Include Area Code) (202) 767-4937 / 22c. OFFICE SYMBOL NA

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

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PREFACE

Customarily, the performance of implemented control systems is highly dependent upon exacting knowledge of system parameters. Furthermore, the control system can suffer greatly from sensor and actuator failures. Techniques have been devised, such as system identification, to improve upon the knowledge of the distributed parameter system or to aid in locating various components in an optimum fashion. However, there has been relatively little research into what would happen when there is, in fact, inexact knowledge of the system or when failures occur in a complete, integrated control system; an eventuality which must be accounted for in implementing a control system. Finally, it is known that the computational requirements for many LSS control applications can be large. The primary benefit of this research to LSS control problems is the development of a technique which reduces the need for high fidelity models used in the control synthesis process, provides a robust control implementation, and relieve computational burdens.

The approach to solve these issues involves the use of artificial intelligence techniques, specifically expert systems. The expert system controller (ESC) investigated required the development of production type rules (i.e., if...then...) which portray the multidimensional mapping of sensor and actuator signals. Data that is required for this function can be derived from numerous simulations from an analagous numerical control implementation. In turn, the ESC reaches a decision regarding actuator commands given input sensor signals by using a K-nearest neighbor partial match inferencing procedure.

Unfortunately, it cannot generally be demonstrated mathematically that an ESC has the same or even superior performance as its "parent" numeric controller or any competing technique for the same text article. Consequently, thorough *simulations and comparison* are necessary to demonstrate capabilities. This project, of course, took that route for verification. The principle finding is that the ESC performs as well as numeric control implementation and is considerably superior to these techniques when there are any changes in the characteristics of the system being controlled.

We anticipate presenting the results of this research at forthcoming AIAA/AAS controls conferences, and AAAI/IEEE artificial intelligence/expert system conferences.

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CHAPTER 1
OVERVIEW: AN EXPERT SYSTEM APPROACH TO LARGE SPACE SYSTEMS CONTROL*

1.0 INTRODUCTION

This, the first chapter of the final report for the research project titled above, will review the purpose of the research and its findings. Discussed will be a brief description of the various control laws investigated (Direct Velocity Feedback, Independent Modal Space Control, and Expert System Control) and their individual performances. Also, to be found, is a discussion of the reference hardware and the simulation system developed for this project. First, however, a review of the purpose of the research is necessary.

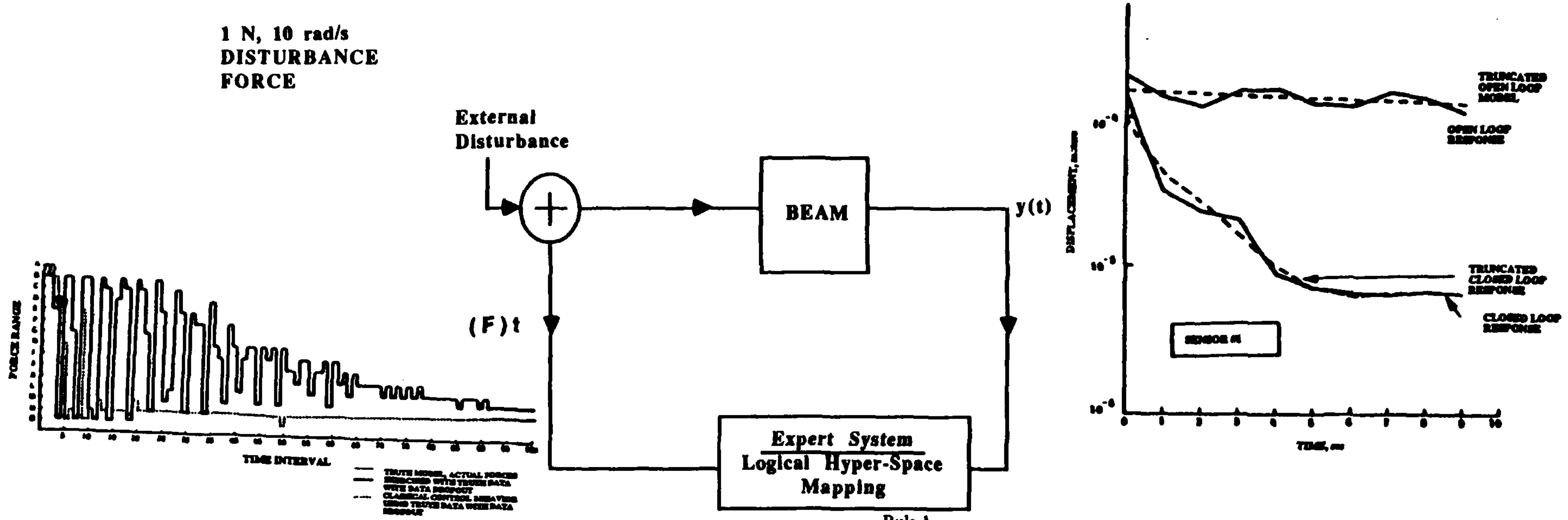
1.1 PURPOSE

This investigation seeks to develop a technique which will reduce the need for high fidelity models for the control synthesis process, provide a robust control implementation, and relieve computational burdens by utilizing artificial intelligence techniques, notably expert systems, to implement control systems for large SDI space systems. Extending an earlier proof-of-concept investigation, this research proceeds beyond simple control laws (e.g., "bang-bang"), low bandwidths, and exact pattern encoding/matching approaches to include modern control laws, higher bandwidths, and partial match inferencing procedures.

The basic approach to this research is reasonably straightforward: (a) develop numerical simulational codes for a reference structure and control systems (i.e., direct velocity feedback and independent modal space control; (b) generate an expert system control (ESC) and validate its performance; and (c) examine the performance of all controllers as a consequence of system failures. The ESC approach used here differs markedly from research largely abandoned in the 1970s in two basic aspects. The first is avoiding the need for a priori quantification of the state space of interest and subsequent pattern encoding. The second is the direct use of sensor values in establishing a pattern and the selection of actuator response using a distance-weighted k-nearest neighbor classification algorithm. In the end, the purpose of this research is to replace the mathematical complexity of system models, modal filters, modal controllers and the force synthesis process by a logical hyper-space representing the mapping of disturbances to control forces. Figure 1.1 illustrates this process.

Customarily, the performance of implemented control systems is highly dependent upon exacting knowledge of system parameters. Furthermore, the control system can suffer greatly from sensor and actuator failures. Techniques have been devised, such as system identification, to improve upon the knowledge of the distributed parameter system or to aid in locating various components in an optimum fashion. However, there has been relatively little research into what would happen when there is, in fact, inexact knowledge of the system or when failures occur in a complete, integrated control system; an eventuality which must be accounted for in implementing a control system. Finally, it is known that the computational requirements for many LSS control applications can be large. The primary benefit of this research to LSS control problems is the development of a

*This research is sponsored by the SDIO/Innovative Science and Technology Office and managed by the Air Force Office of Scientific Research.



Rule 1
If:
T =1
X1 =92
X2 =80
=13
=13
=-849
=586
=-958
=-820
=E(100)

Rule 2
If:
T =2
X1 =43
X2 =83
=-2
=-5
=-16
=-21
=24
=15
=D(100)

Rule 3
If:
T =3
X1 =28
X2 =64
=17
=8
=-14
=-17
=16
=10
=C(100)

Rule 4
If:
T =4
X1 =16
X2 =50
X3 =30
X4 =16
V1 =-9
V2 =-12
V3 =8
V4 =5
Then:
SELECTION OF F1 = C(100
(Weight = 1.000)

Figure 1.1. Expert System Control

technique which reduces the need for high fidelity models used in the control synthesis process, provides a robust control implementation, and potentially relieve computational burdens.

1.2 REFERENCE HARDWARE

In this particular situation, a uniform beam hinged at both ends was chosen as the article being controlled. Choosing for convenience unit bending stiffness, unit mass per unit of length, and an overall beam length of 10 allows for easily determined eigenvalues and eigenfunctions. This structure has many closely spaced resonant frequencies in the range of 0.02 to 1 hertz. The sensor suite chosen is composed of multiple (either 4 or 9 depending upon the control law) "displacement-sensitive vibrometers". Similar to current eddy current position sensors, these have a bandwidth of 50 hertz and damping ratio of 0.707. As a consequence, they have a unit response for input frequencies less than 10 hertz and have negligible phase angle delay. The model chosen for the actuators (4 total) is based upon a brushless dc torque motor with a torque arm and appropriate mechanical linkages. They have an effective bandwidth of 30 hertz and a maximum force output of 3 N.

1.3 FLEXIBLE STRUCTURE CONTROL SYSTEM SIMULATOR (FLEXSIM)

FLEXSIM, which operates on an IBM-PC, is a multi-purpose system with the ability to let the user choose disturbance sources, control laws, modifications to reference harware, simulate system failures, and simulate the response of the structure to these conditions. Three types of data records are available: display graphics, disk data files, and printed results. Figure 1.2 summaries the features that are available.

- **TRANSPORTABLE**
  - IBM WITH MATH CO-PROCESSOR
  - MICROSOFT FORTRAN AND ASSEMBLY
- **EXECUTION CONTROL**
  - DEFAULT CONDITIONS
  - CONTROL LAW
  - DISTURBANCE
  - MODIFY ACTUATOR DATA
  - MODIFY SENSOR DATA
  - SENSOR OR ACTUATOR FAILURES
  - MODE FREQUENCY MULTIPLER
  - MODE SHAPE MULTIPLER
  - RUNTIME
  - PRINT INTERVAL
- **GRAPHICS**
  - SCALED DISPLAY OF SENSOR AND ACTUATOR DATA EVERY 0.01 SEC
  - SUMMARY OF DISPLAY OF RESULTS
- **DATA FILE**
  - TIME, DISPLACEMENTS, VELOCITIES AND FORCES
- **HARDCOPY**
  - CONTROL LAW CHOSEN
  - GAINS
  - SENSOR DATA
  - ACTUATOR DATA
  - FAILURE FLAGS
  - TIME, DISPLACEMENT, VELOCITY AND FORCES

Figure 1.2. FLEXSIM Features

1.4 NUMERICAL CONTROL IMPLEMENTATIONS

Two numerical control systems have been implemented, known, respectively, as Direct Velocity Feedback (DVFB) and Independent Modal Space Control (IMSC). DVFB features include collocated sensors and actuators, with the number of sensors/actuator pairs corresponding to the number of flexible modes being controlled. DVFB adds damping to the structure by electronically multiplying sensor signals by appropriately selected gains, which are determined by a pole-placement technique. On the other hand, IMSC is a distributed sensor/actuator controller, where the number of sensors corresponds to the number of vibrational modes necessary to yield an accurate model of the motion. Furthermore, the physical sensor data is passed through a modal filter to extract the modal coordinates necessary to determine the modal control forces. In both controllers, the first four vibrational modes are controlled, with the next five being considered residual.

As the result of examining typical damping-frequency profiles of lightweight space materials, it was decided that a uniform 15% added damping for the four control modes would be the design goal. Consequently, the gains for each controller were chosen with this in mind. Simulations, using the FLEXSIM program, verify that both DVFB and IMSC dissipate energy, such as in Figs. 1.3 and 1.4. The spiral pattern in these figures is representative of the system energy. Analysis of the rate of change (i.e., $\delta r = a\delta\theta$) in the curves yields a negative value for the rate of change in the angle θ, indicative of a decreasing system energy.

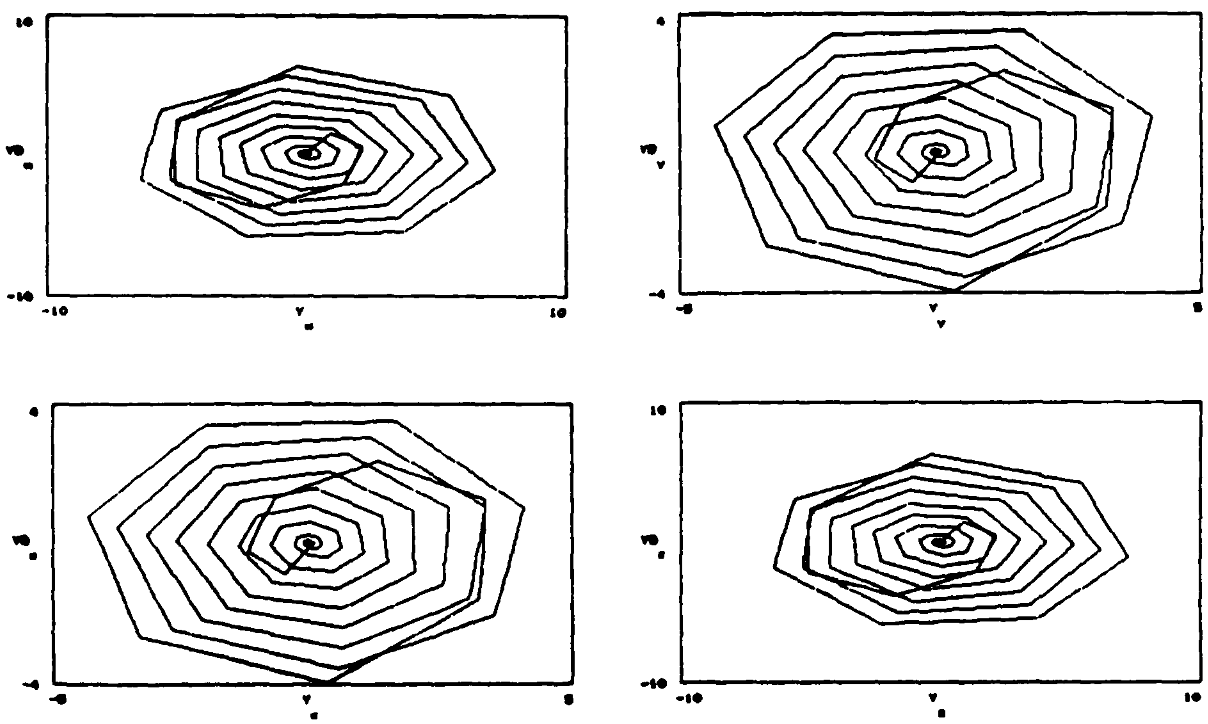


Figure 1.3. DVFB Displacement-Velocity Trajectory (Typical)

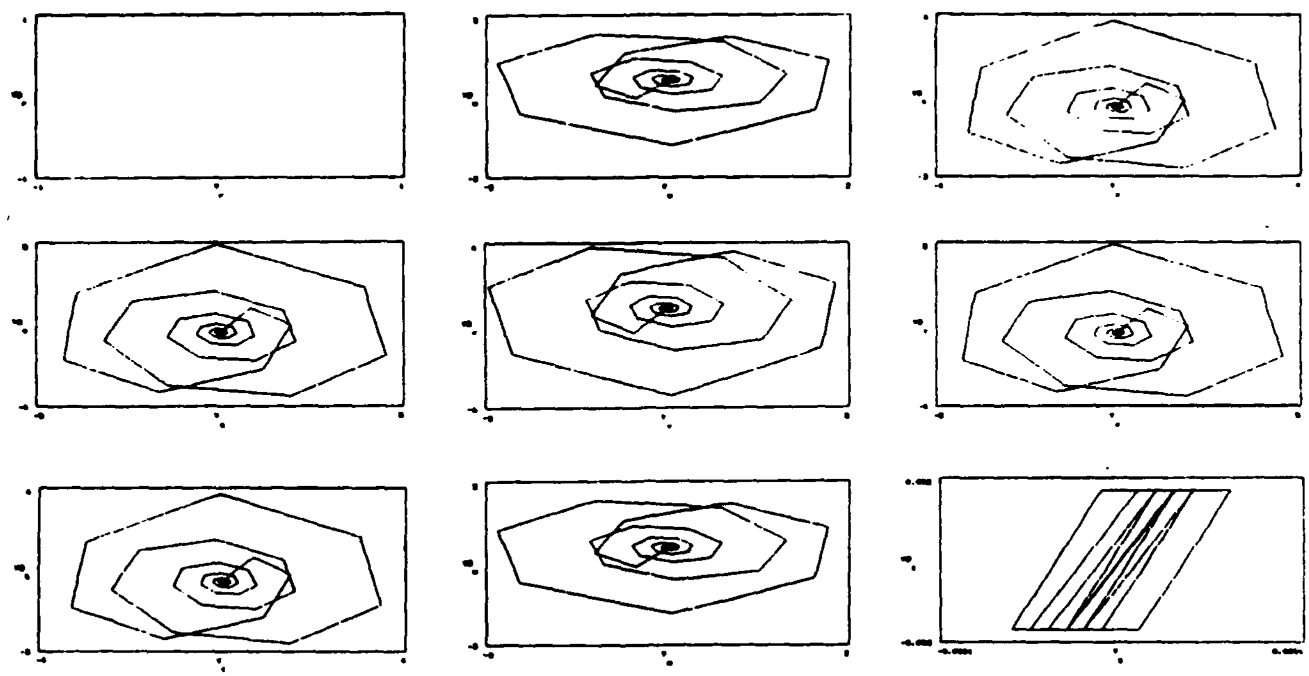
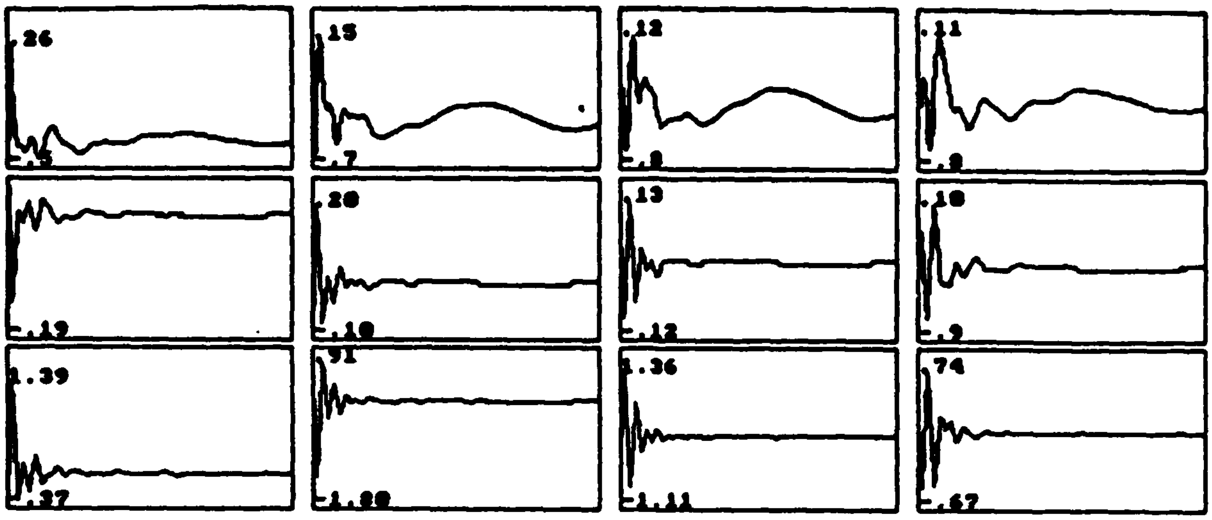


Figure 1.4. IMSC Displacement-Velocity Trajectory (Typical)

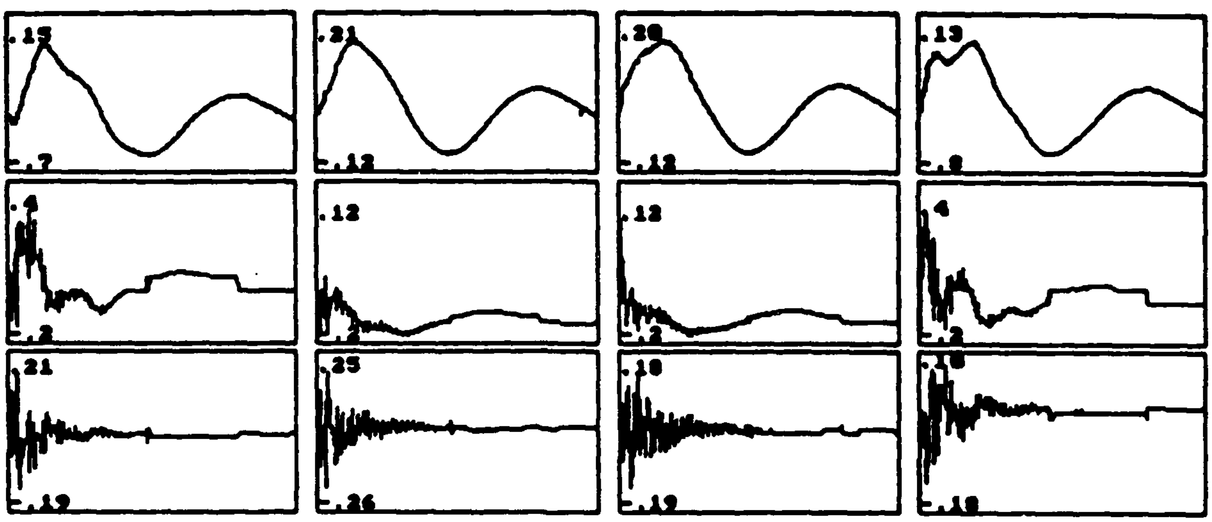
1.5 LOGIC-BASED CONTROLLER

The logic-based control system, referred to as the Expert System Controller (ESC), was developed with a PC-based expert system application generator named TIMM, The Intelligent Machine Model. The components of a logic based system include the decision structure which is the definition of the inputs and outputs, the knowledge base which contains the rules that map inputs to the outputs, and the inference engine which is the software program that interprets the knowledge base.

The definition of the decision structure for the ESC consists of the input velocities and output forces. The specific signals for each are based upon simulation of DVFB control. Note that there are four separate logic based controllers, one for each of the actuators. In turn, each of these have all four velocity signals as input values. Essentially, the ESC models the behavior of the DVFB controller. The knowledge base rules were developed from multiple DVFB simulations. These simulations include disturbances near the first and third mode frequencies, various transverse impulses along the beam, a traveling wave, and a wideband disturbance source. Several examples of these "training" data sets are displayed in Fig. 1.5. The specific rules are in the form of if-then production rules. Finally the forces to be applied are determined by an analog partial matching inference engine which can reach a conclusion without the necessity of finding an exact match to a rule in the knowledge base.

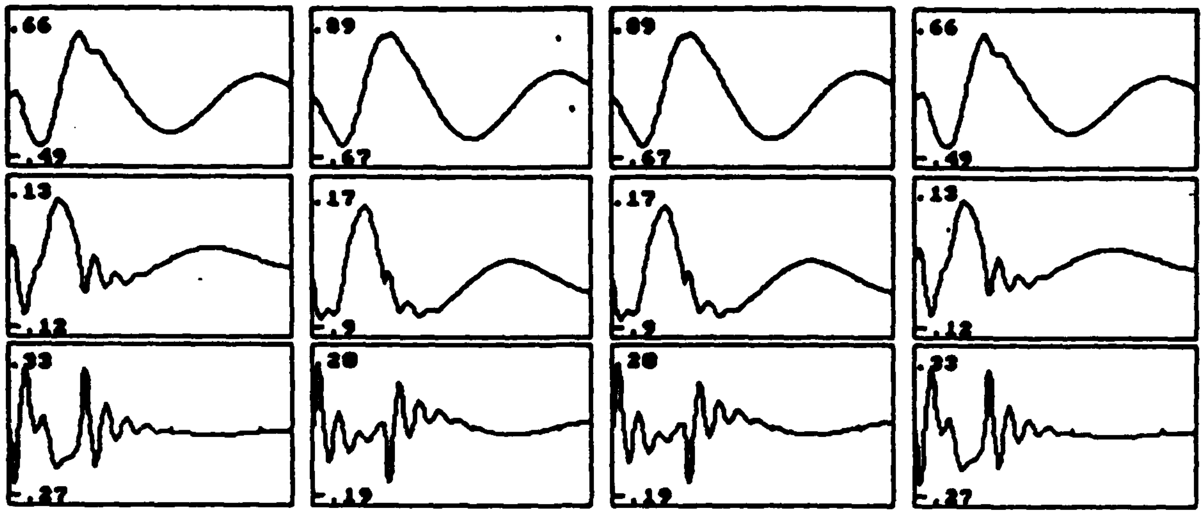


Traveling Wave: 50 cm 100 seconds at 0.5 second intervals; (LSS.TW2: 202 pts.)

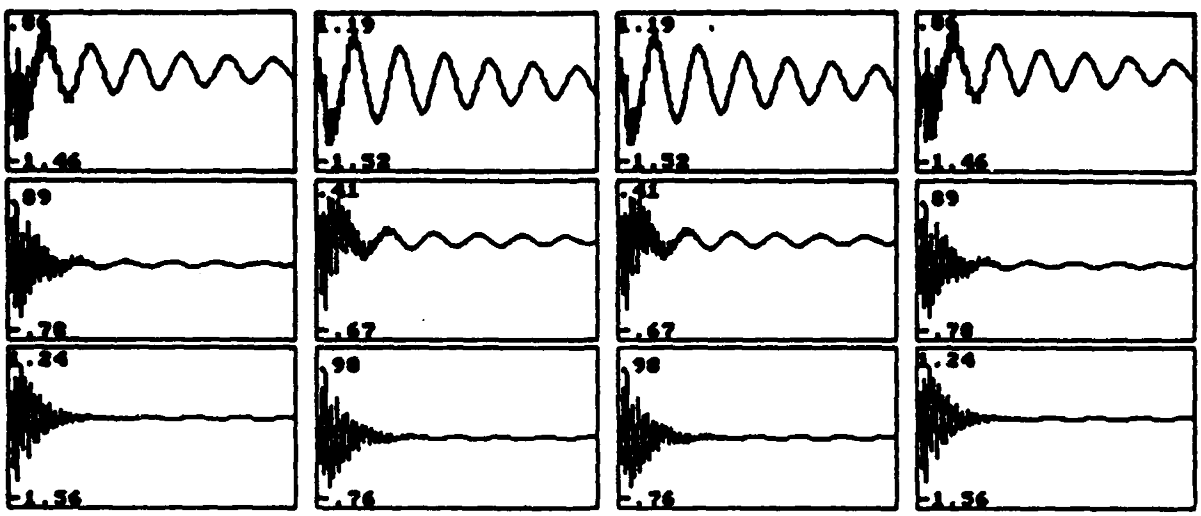


Impulse: 1N at 6.3m 100 seconds at 0.5 second intervals; (LSS.IMP: 202 pts.)

Figure 1.5. Representative Training Data



Standing Wave: 1M @ 0.04Hertz 100s @ 0.5s intervals; (LSS.SW: 202 pts.)



Wideband Disturbance: 400s at 2s intervals (LSS.WD2: 201pts)

Figure 1.5. Representative Training Data (Cont.)

Simulations using the ESC have verified t[illegible]o dissipates energy, which can be deduced from the spiral-like patterns shown in Fig. 1.6.

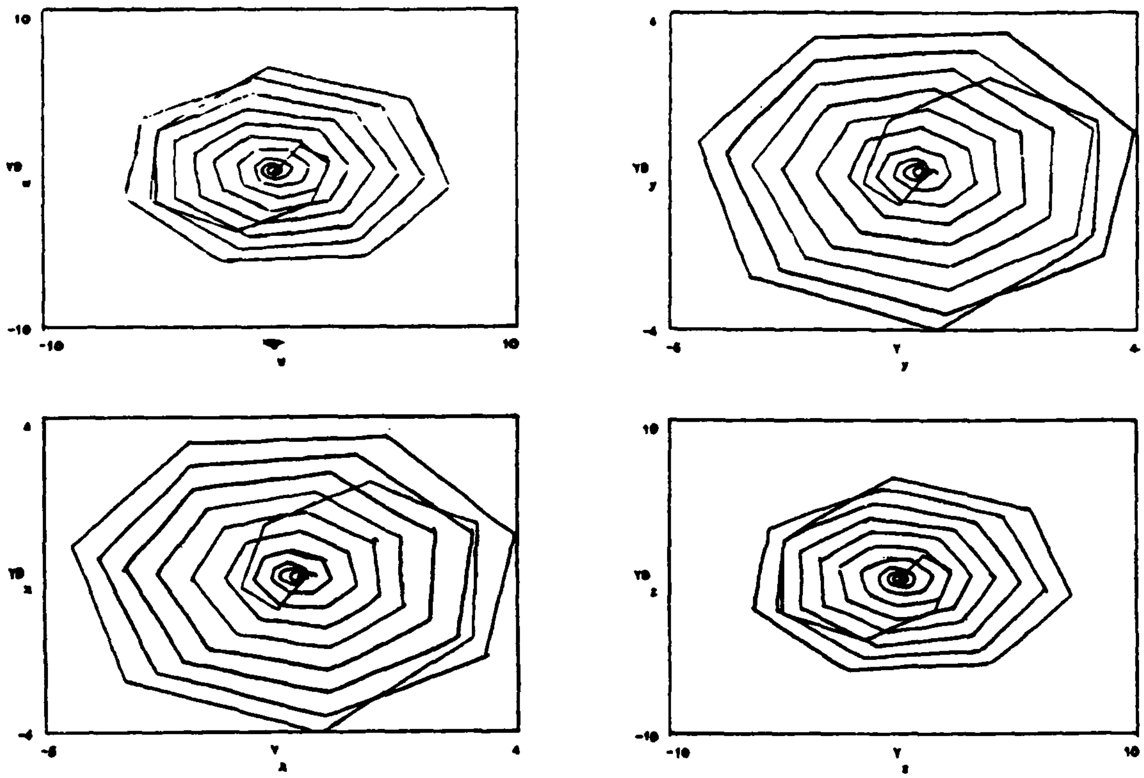


Figure 1.6. ESC Displacement-Velocity Trajectory (Typical)

1.6 COMPARISON OF NUMERICAL AND LOGIC BASED CONTROLLER PERFORMANCE

A useful measure of the controller's performance is the global control evaluation functional, which is a measure of the quadratic cost expended on an infinite dimensional distributed parameter system. The value that this parameter will take is dependent upon: (a) the number, type, and location of actuators; (b) the particular control design chosen; (c) the order of the control design model and the closed-loop eigenvalues; (d) structural parameters; and (e) the disturbance. Another useful value is the work expended by the controller per cycle; which should be the asympotically the same for each controller given an identical disturbance. These observations can be seen by examining Fig. 1.7 for a 1 N impulse at 6.3 m along the beam; showing that DVFB and ESC have about the same cost value, IMSC being significantly lower, but that all perform essentially the same work.

One of the key features observed from this research was the ability of the ESC to produce good results (i.e., damping) when changes are introduced into the system. In this particular case, a sensor failure was considered. While all controllers added damping to the structure, the ESC used far less cost and power than the other two approaches (see Table 1.1 for details). This capability is the attractiveness of a logic-based controller--namely the ability to be a robust controller regardless of the source of change in the system, be it parameter changes, disturbances outside nominal experience, or system failures.

The remaining portions of this report examine the hardware, simulator and control system performance.

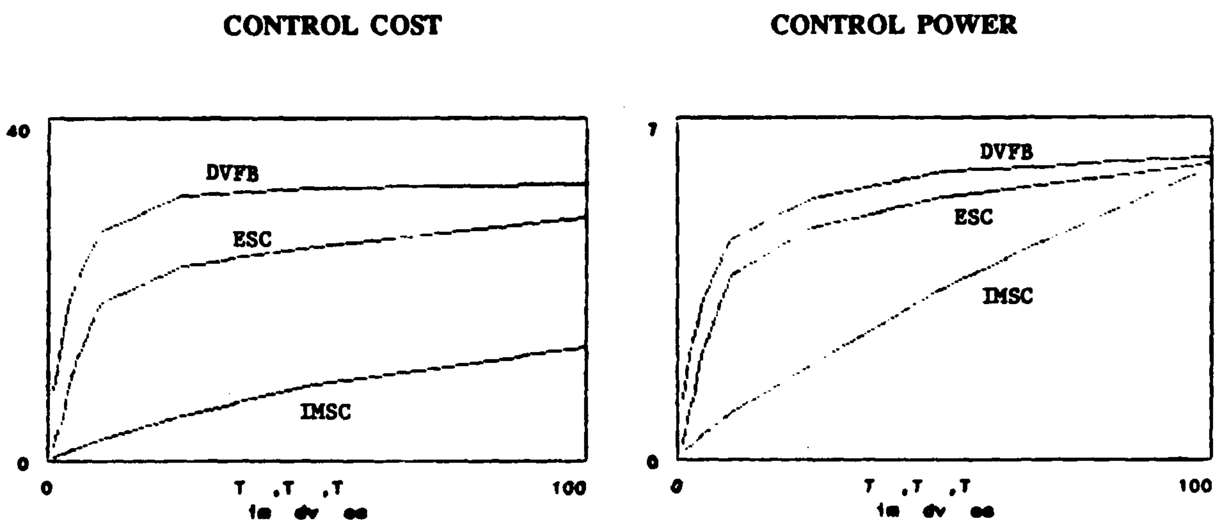


Figure 1.7. Control Cost and Power

TABLE 1.1
PERFORMANCE SUMMARY*

	DVFB	ESC	IMSC
ELAPSED TIME (SEC)	100	100	100
CONTROL COST (N^2)	332.6	76.5	317.4
CONTROL POWER (W)	90.2	43.8	140.5
RSS DISPLACEMENT (m)	0.078	0.082	0.118
RSS VELOCITY (m/s)	0.012	0.0084	0.015

*1 N Disturbance at 0.04 Hz.

CHAPTER 2
REFERENCE HARDWARE

2.0 INTRODUCTION

This section of the report presents the mathematical models which are used throughout the simulator to describe the behavior of the hardware being controlled. The reader is reminded that for all the controllers that can be simulated, that the hardware set is invariant. The reference structure, actuators and sensors have been chosen to be as realistic as practical with respect to available devices. Nonetheless, scaling relationships which would allow different configurations to be used are described.

2.1 EQUATIONS OF MOTION FOR REFERENCE STRUCTURE

The equations of motion for distributed parameter systems, such as the lightweight structure modelled in this research, can be written in the usual partial differential equation form

$$M(P)\partial^2u(P,t)/\partial t^2 + Lu(P,t) = f(P,t) \qquad (1)$$

which must be satisfied at every point P of the domain D under consideration. The function u(P,t) represents the displacement of an arbitrary point P, L is a linear self-adjoint positive definite differential operator of order 2p, expressing the system stiffness, M(P) is the distributed mass, and f(P,t) the distributed controls.

The displacement u(P,t) is subject to the boundary conditions

$$B_i\, u(P,t) = 0 \quad ; i = 1,2..,p \qquad (2)$$

to be satisfied everywhere on the boundary of the domain, where the B_i are linear differential operators of order ranging from zero to 2p-1.

The associated eigenvalue problem consists of the differential equation

$$L\, \phi_r = \lambda_r M \phi_r \quad ; r = 1,2,.... \qquad (3)$$

and the boundary conditions

$$B_i\phi_r = 0 \quad ; i = 1,2,..,p;\ r=1,2,... \qquad (4)$$

The solution to these equations consists on an infinite set of eigenvalues, λ_r , and associated eigenfunctions ϕ_r. This representation is convenient as it allows the use of the expansion theorem to form the solution to the structure's displacements in an infinite series of the product of the eigenfunctions and a time-dependent generalized coordinate

$$u(P,t) = \sum_{r=1}^{\infty} \phi_r (P)\, u_r (t) \qquad (5)$$

Introducing this result into the prior partial differential equation, yields the infinite set of ordinary differential equations

$$\ddot{u}_r(t) + \omega_r^2\, u_r (t) = f_r (t) \qquad ; r = 1,2,...$$

commonly known as modal equations.

In this particular situation, we have chosen a uniform beam hinged at both ends as the article whose bending vibrations are being controlled. Choosing for convenience unit bending stiffness, unit mass per unit of length, and an overall beam length of 10, the stiffness and mass operators from equation (1) and the boundary operators of equation (2) can be written as

$$\begin{gathered} L = d^4/dx^4 \qquad M=1 \\ B_1 (0) = B_1 (10) = 1 \qquad B_2 (0) = -B_2 (10) = d^2/dx^2 \end{gathered} \qquad (6)$$

In turn, the eigen problem has an easily determined closed-from solution, with the following eigenvalues and eigenfunctions

$$\begin{gathered} \lambda_r = \omega_r^2 = (r\pi/10)^4 \qquad \phi_r (x) = (5)^{-1/2} \sin (r\pi x/10) \\ r=1,2,... \end{gathered} \qquad (7)$$

Figures 2.1 and 2.2, respectively, are plots of these eigenvalues and eigenfunctions. As is usual in these class of problems, the eigenvalues are the square of the mode frequencies characteristic of the structure, and the eigenfunctions are termed the mode shapes.

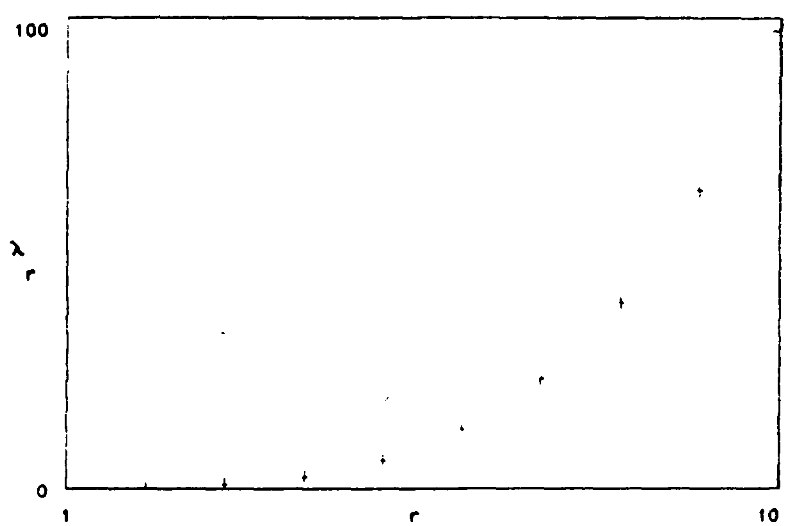


Figure 2.1. Eigen Values

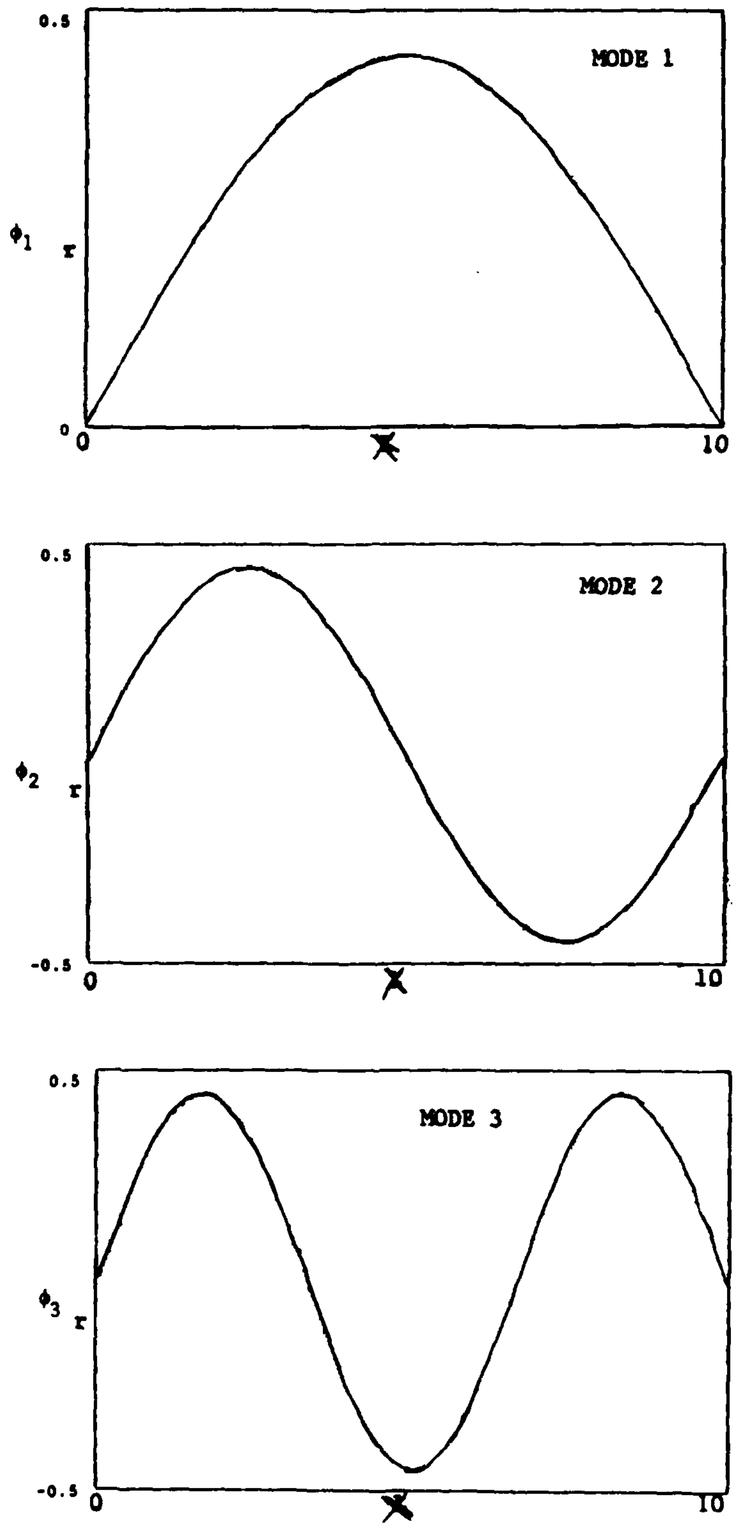


Figure 2.2. Eigen Functions (Mode Shapes)

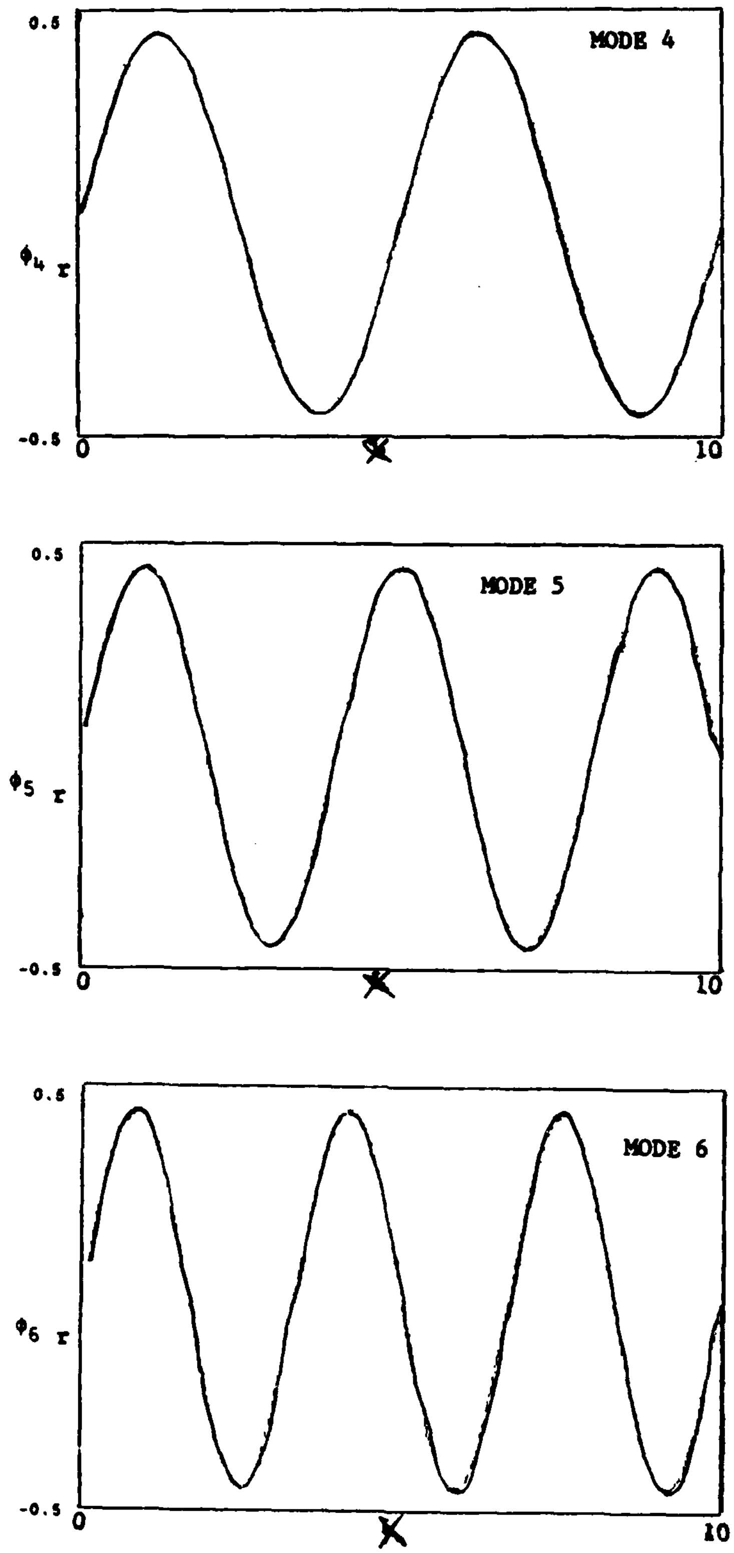


Figure 2.2. Eigen Functions (Mode Shapes) (Cont.)

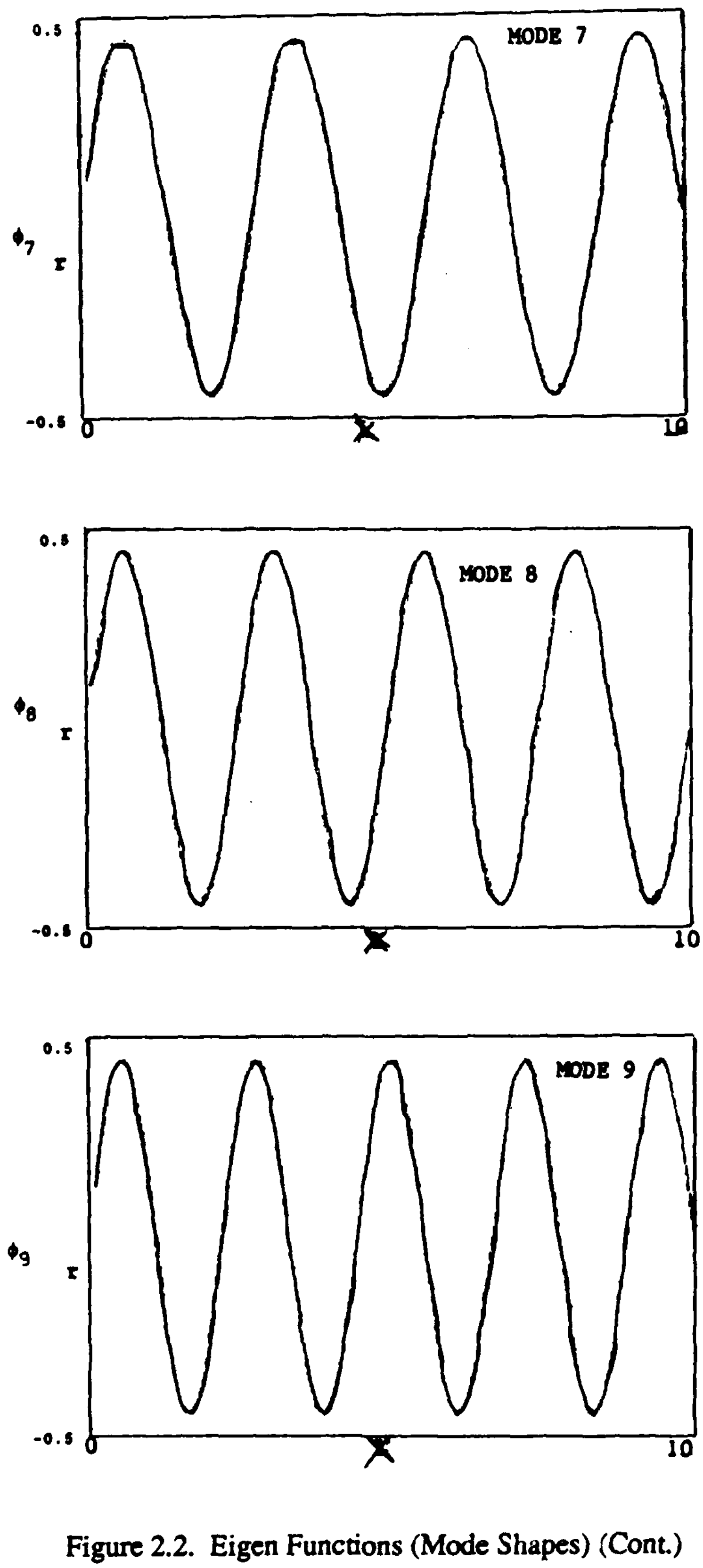


Figure 2.2. Eigen Functions (Mode Shapes) (Cont.)

Insight into the physical response of this second order system to input disturbances, regardless of the source, can be obtained by using the Laplace transform with respect to time of the differential equation, namely

$$f(s) = \sum_{r=1}^{\infty} \frac{\omega_r^2}{s^2 + \omega_r^2} \tag{8}$$

A plot of this function can be found in Figure 2.3. This plot clearly shows large mechanical gains in the vicinity of the fundamental mode frequencies. In addition, it can be surmised that disturbances with frequencies above a fractional hertz are unlikely to excite the structure in a significant fashion.

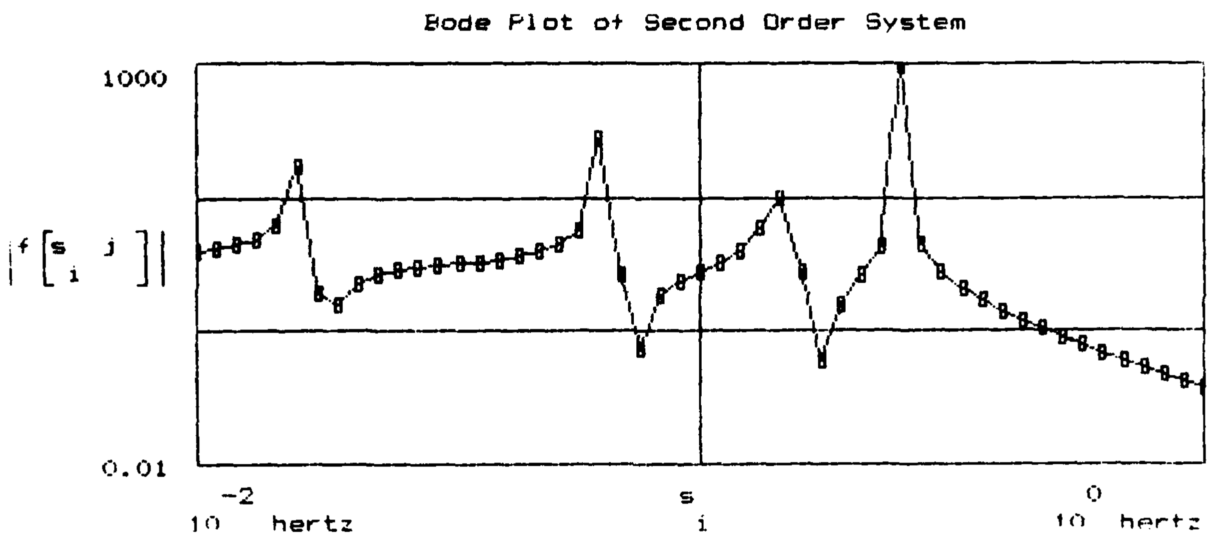


Figure 2.3. Open Loop System Response

2.2 STRUCTURAL SCALING RELATIONSHIPS

Alternate structural parameters can be accommodated within the simulation tool, FLEXSIM, via mode shape and mode frequency multipliers. The rationale behind these choices can be made by examining the fundamental mechanical engineering relations for the modes. First, lets examine the mode frequency.

The fundamental mode frequencies can be written in the basic form

$$\omega_r = (r\pi/L)^2 \, (EI/\gamma)^{1/2} \tag{9}$$

where the term EI/γ is the ratio of stiffness and linear mass density, which for the reference structure is one. Simple manipulation of this result can be used to find the multiplicative scale factor, K, as defined below

$$K = (10/L_A)^2 \, (EI/\gamma)_A{}^{1/2} \tag{10}$$

Note that this is valid for any length, L_A, and stiffness-linear mass density ratio values, $(EI/\gamma)_A$. The FLEXSIM program will query the user to input such a value.

On the other hand, the multipler for mode shapes is not quite that straightforward. If the derivative of the mode shape function is derived and then unitized with respect to the "nominal" mode shape, the following result is found

$$M = 1 - \delta L/2L - \cot(n\pi x/L)[n\pi x \delta L/L^2] \tag{11}$$

This result has a somewhat complicated dependency on the position along the beam and the change in the beam length from nominal. However, this can be eliminated by a power series expansion of the cotangent, which to first order yields

$$M \approx 1 - 3\delta L/20 \tag{12}$$

Thus the multiplier, M, to first order, is only a function of the change in the length of the beam. Note that this approximation is valid only if the change in length, δL, is much less than 20/3. Furthermore, the actual length of the beam can be either 10 meters or 10 feet, provided all other parameters are specified in consistent units. For convenience, we have chosen the length to be expressed in meters.

2.3 SENSORS

It is quite obvious that for the control problem one must be able to sense the behavior of the vibrating structure. In order to permit reasonable comparisons with typically available hardware, we have chosen a class of instruments collectively known as "displacement-sensitive vibrometers". Without going through a significant derivation, it can be shown that the response Z of a sensor to an input disturbance, in particular a sinusoid of amplitude X at a frequency ω_f, is represented by the equation

$$Z = \frac{r^2}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}} X \sin(\omega_f t - \psi)$$

where (13)

$$\tan\psi = 2\zeta r/1-r^2, \quad r = \omega_f/\omega$$

where the first portion of the equation, the parameter r and the phase angle ψ are important characteristics. This first portion of the relation is in fact the transfer function of the sensor. If it's value is approximately equal to one, then the sensor is yielding an accurate representation of the motion. It should be noted that the measurements will lag behind the true behavior due to the phase angle ψ. This angle is generally of little importance, except where complicated wideband disturbances are being measured. Figure 2.4 is a plot of the transfer functions for this type of sensor. As can be seen values of r greater than 3 accompanied with significant damping ratios are to be preferred.

A sensor with a bandwidth of 50 hertz and a damping ratio of 0.707 has been chosen for simulation. These values are similar to an eddy current position sensor that has been commonly used in laboratory investigations. The response function and phase angle for this sensor are presented in Figures 2.5 and 2.6, respectively. As can be seen from inspecting Figure 2.5, the sensor has a unit response for frequencies less than 10 hertz. Similarly, the phase angle associated timing delay for this sensor is small, being much less than 0.003 seconds in the cases of interest. The reader should be made aware of the fact that the simulator, FLEXSIM, permits the user to change these parameters to emulate any other displacement sensitive sensor.

2.4 ACTUATORS

The last items of hardware which need to be described are the actuators. In order to understand the actuator requirements, an estimate of sizing is needed. The function of the controller in this investigation was to add damping to the structure, hence the following relations can be written

$$F/M = -2\zeta_r\omega_r\dot{q}_r \qquad \ddot{q}_r + \omega_r^2 q_r = F/M \tag{14}$$

where F is the control force. If the magnitude of F is small, then the time dependent variable $q_r(t)$ is estimated by

$$q_r = A \sin(\omega_r t + \phi) \tag{15}$$

and its time derivative as

$$\dot{q}_r = A\,\omega_r \cos(\omega_r t + \phi) \tag{16}$$

These relations allow the root mean square (rms) value of F to be determined as follows

$$F_{rms} \sim \sqrt{2}\,\zeta_r\,\omega_r^2\,AM \tag{17}$$

Assuming a 10 cm disturbance amplitude for the 10 kg beam, the rms control force is estimated to be approximately 0.35 N for 15% added damping in the fourth mode.

The model chosen for the actuator is based upon a brushless dc torque motor with a torque arm and appropriate mechanical linkages. It has an effective bandwidth of 30 hertz and a maximum force output of 3 N. Figure 2.7 is a plot of its transfer function, which indicates that it has essentially unit response at frequencies less than 10 hertz.

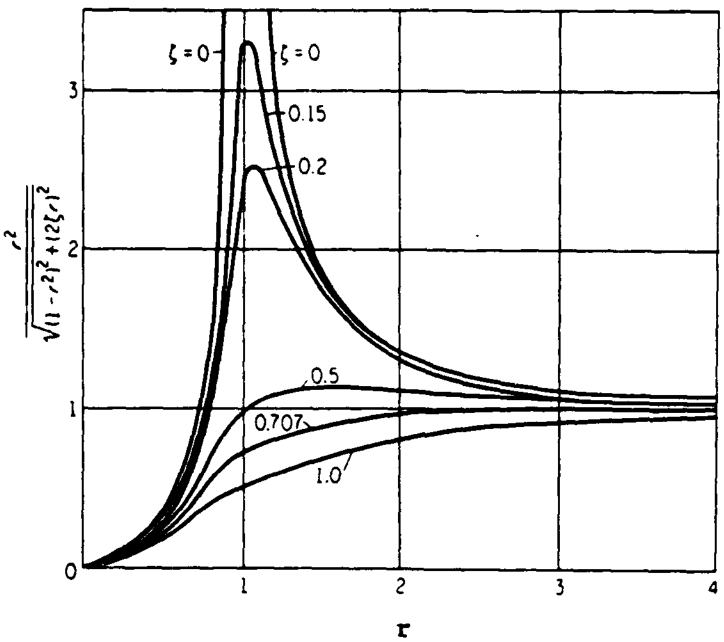


Figure 2.4. General Displacement Sensor Transfer Function

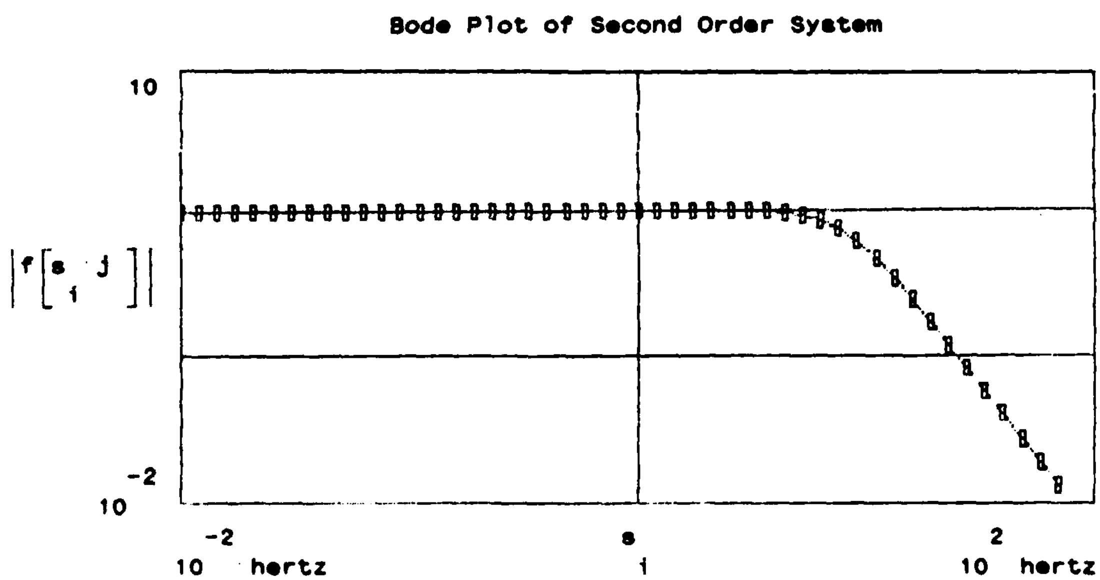


Figure 2.5. Sensor Response Function

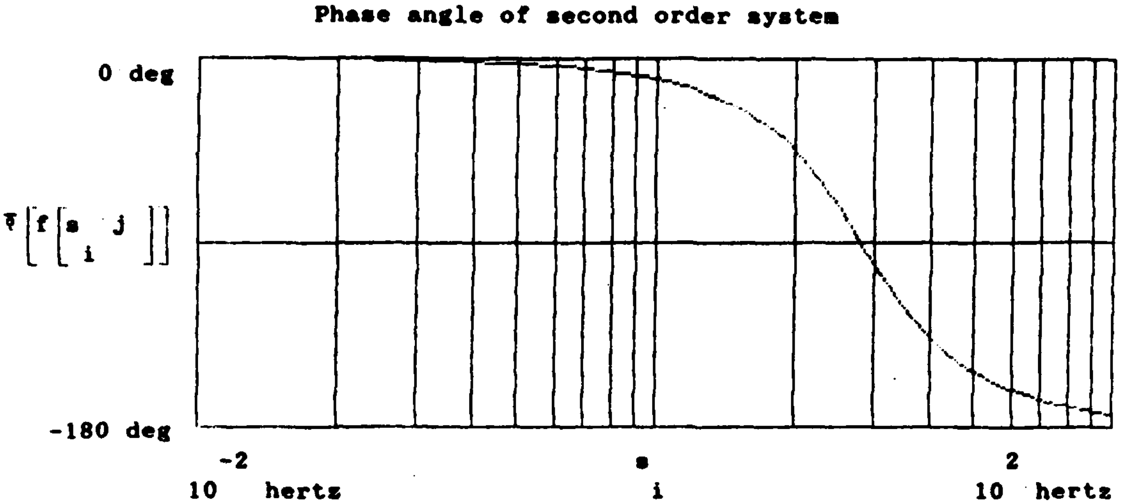


Figure 2.6. Sensor Phase Angle Function

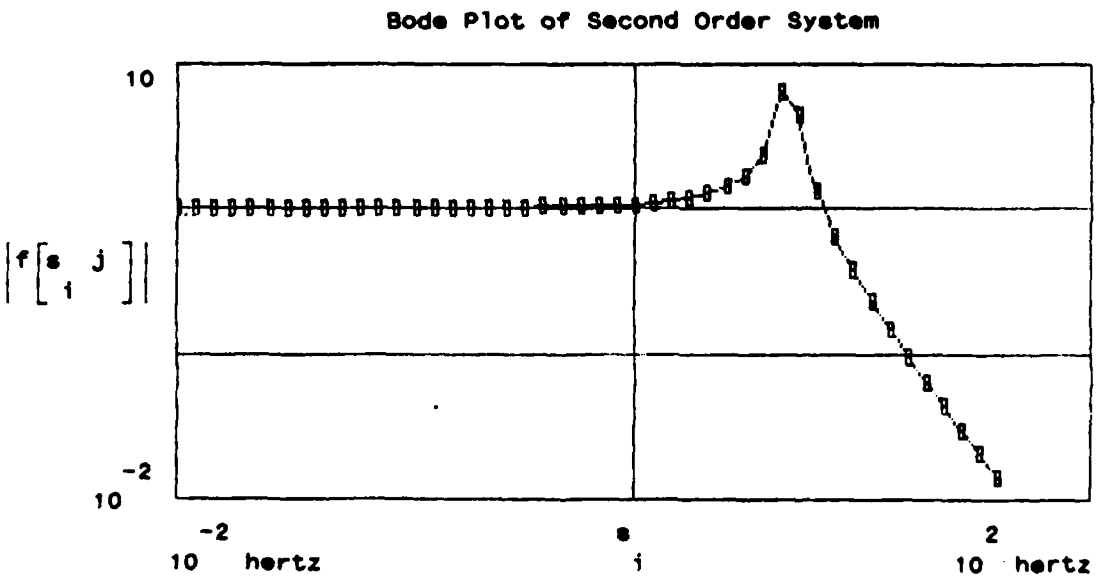


Figure 2.7. Actuator Response Function

2.5 SYSTEM TIMING

A particularly important key issue is the frequency at which the measurements of the structural vibrations occur. Some experience in laboratory environments has suggested that equivalent phase angle delays of greater than 10 degrees are likely to cause considerable difficulty in controlling the vibrations. This primarily arises from the need to estimate the time derivative of the system motion in the following fashion

$$\dot{V} = \frac{V(t + \Delta t) - V(t)}{\Delta t}$$

This implies that the control forces are in fact constant over the time interval $(k+1)\Delta t \leq t \leq k\Delta t$. Under these circumstances the system being controlled, i.e., the closed loop system, behaves in the following discrete fashion

$$V(k+1) = V(k) + \Delta t\, A_c\, V(k)$$

where A_c is the differential operator of the stable system. As has been shown by Balas, the sample interval, Δt, which ensures stability is estimated by the relation

$$\Delta t < \lambda_{min}(Q)/[\lambda_{max}(P) \left|A_c\right|^2]$$

where $\lambda_{max}(\cdot)$ *is the largest eigen* value of the indicated matrix, $\lambda_{min}(\cdot)$, similarly, the smallest, Q is the gain matrix for the particular control law, and P the solution to a characteristics Lyapunov equation for the system. In the case at hand, regardless of which control law is considered (i.e., Direct Velocity Feedback or Independent Modal Space Control), the sample time must be less than 0.012 sec; for convenience, a sample time of 0.01 sec has been chosen. Note that the equivalent phase angle delay corresponding to control through the fourth fundamental is less than 2 degrees, easily satisfying the earlier observation.

2.6 REFERENCES

L. Meirovitch, H. Baruh, and H. Oz, "A Comparison of Control Techniques for Large Flexible Systems," Journal of Guidance, Control and Dynamics, Vol. 6, No. 4, pp. 302-310, July-August 1983.

R. K. Vierck, Vibration Analysis, International Textbook Company, Scranton, Pennsylvania, pp. 149-165, 1967.

M. J. Balas, "Discrete-Time Stability of Continuous-Time Controller Designs for Large Space Structures," Journal of Guidance, Control and Dynamics, Vol. 5, No. 3, pp. 541-542, September-October 1982.

L. Meirovitch, Analytical Methods in Vibrations, Macmillan Co., New York, 1967.

CHAPTER 3
FLEXIBLE STRUCTURE CONTROL SYSTEM SIMULATOR

3.0 INTRODUCTION

In this section of the final report, a review of the capabilities and features of the software-based simulator, FLEXSIM, is discussed. The intent here is not to be exhaustive, but rather to cover the important points. Further detail on FLEXSIM and its use can be found in a separately available user's guide. As designed, FLEXSIM is a multipurpose system with the ability to let the user choose disturbance sources, control laws, modifications to reference hardware, simulate system failures, and simulate the response of the structure to these conditions. Three types of data records are available: "real-time" graphics, disk data files, and printed results. These features allow the user to observe the structural behavior as it evolves, inspect the results at his or her leisure, and manipulate the resultant data, such as with the various data plotting software packages available.

3.1 FLEXSIM DESIGN FEATURES

As designed, the flexible structure control system simulator, FLEXSIM, is driven by user prompts. This allows the user to select from the types of disturbances to be simulated, the control law, possible changes in the reference hardware, and the time duration of the simulation. Figure 3.1 portrays the basic modular nature of the system. If there was a need to change some basic feature, such as the reference structure from the simply supported beam to a cantilevered beam, the manner in which the software has been developed would permit reasonably straightforward changes to be made. From the standpoint of utilization, as shown in Fig. 3.2, FLEXSIM is transportable, has user selected options, graphics display, disk data file and a printed record of the simulation; each of these will be briefly discussed in what follows.

3.1.1 Transportability

FLEXSIM is developed to operate on an IBM-PC or similar computer. As a means to further ensure its utility, the software has been developed using a commonly available FORTRAN compiler, Microsoft, and assembly language routines previously developed by GRC for the graphics display.

3.1.2 Execution Control

The user of FLEXSIM has a number of different options from which to select in order to perform a simulation of the controlled structure. As shown in Fig. 3.3, these include the disturbance source, control laws, sensor and actuator characteristic data, timing control, and parameter variation.

The disturbance sources that can be selected are an impulse, standing wave, wideband, and a traveling wave; all are modelled mathematically by fourier transforms into modal space. The impulse is characterized by a transverse force applied at a certain location along the beam. It is presumed that the duration of the impact is much less than sampling period. The impulse can be expressed as

$$f_e(x,t) = F_o \cdot \delta(x - x_o) \cdot \delta(t)$$

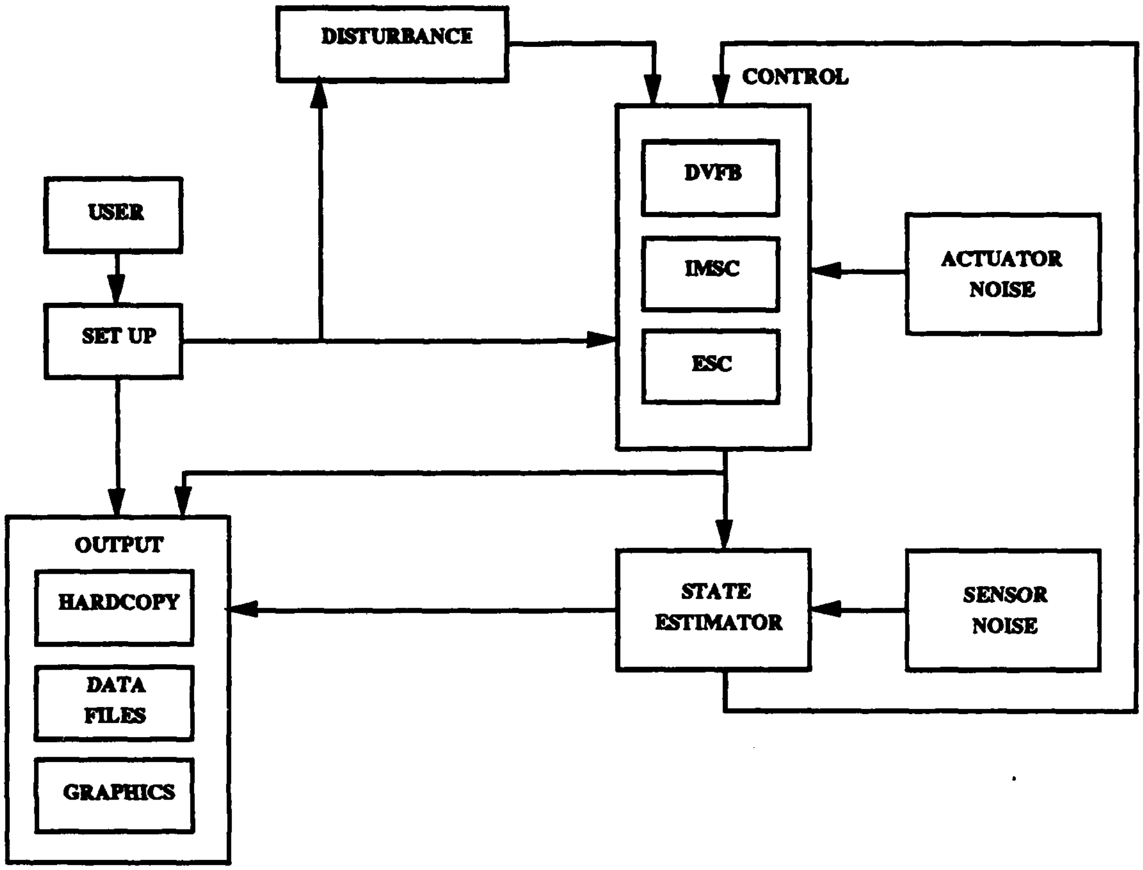


Figure 3.1. FLEXSIM Design

- **TRANSPORTABLE**
  IBM WITH MATH CO-PROCESSOR
  MICROSOFT FORTRAN AND ASSEMBLY

- **EXECUTION CONTROL**
  DEFAULT CONDITIONS
  CONTROL LAW
  DISTURBANCE
  MODIFY ACTUATOR DATA
  MODIFY SENSOR DATA
  SENSOR OR ACTUATOR FAILURES
  MODE FREQUENCY MULTIPLER
  MODE SHAPE MULTIPLER
  RUNTIME
  PRINT INTERVAL

- **GRAPHICS**
  SCALED DISPLAY OF SENSOR
  AND ACTUATOR DATA EVERY 0.01 SEC
  SUMMARY OF DISPLAY OF RESULTS

- **DATA FILE**
  TIME,DISPLACEMENTS, VELOCITIES
  AND FORCES

- **HARDCOPY**
  CONTROL LAW CHOSEN
  GAINS
  SENSOR DATA
  ACTUATOR DATA
  FAILURE FLAGS
  TIME, DISPLACEMENT, VELOCITY
  AND FORCES

Figure 3.2. FLEXSIM Features

- **DISTURBANCE SOURCE**
  - IMPULSE
  - HARMONIC
  - WIDEBAND
  - TRAVELING WAVE
- **CONTROL LAWS**
  - DVFB
  - IMSC
  - ESC
- **SENSOR/ACTUATORS**
  - LIMIT VALUES
  - ACCURACY
  - NOISE
  - DAMPING
- **TIME CONTROL**
  - TIME DURATION
  - PRINT INTERVAL
- **PARAMETER VARIATION**
  - MODE FREQUENCIES, SHAPES
  - SENSOR/ACTUATOR FAILURES
- **DEFAULT PARAMETERS**
  - IMPULSE (1 Nt AT 6.3 m)
  - DVFB CONTROL
  - NO PARAMETER VARIATION
  - 100 SEC RUN TIME
  - 0.5 SEC PRINT INTERVAL

Figure 3.3. FLEXSIM Execution Control

which results in the initial modal velocities

$$\dot{u}_r(o) = F_o \cdot \phi_r(X_o) \qquad ; r=1,2,...$$

The standing wave excitation is modelled as a simple harmonic oscillation in the form

$$F_e = F_o \cdot \cos(\omega_o \cdot t)$$

This vibration source is allowed to stay "on" for one complete cycle, after which it is presumed to have been removed. The wideband disturbance is modelled by the following integral representation

$$F_e = \int_0^{\infty} A(\omega) \cdot \cos(\omega \cdot t) \cdot d\omega$$

where in practice the frequency of the disturbance is limited to 100 hertz. The function $A(\omega)$ is represented by the power-spectral-density function found in Fig. 3.4. This disturbance is allowed to remain "on" for ten seconds. Finally, the traveling wave is given in the form

$$u(x,t) = \begin{cases} A \cos[2\pi/\lambda(x - \gamma t)] & ; 0 \leq x \leq \lambda \\ 0 & ; \lambda < x \leq L \end{cases}$$

and allowed to propagate for one wavelength along the beam.

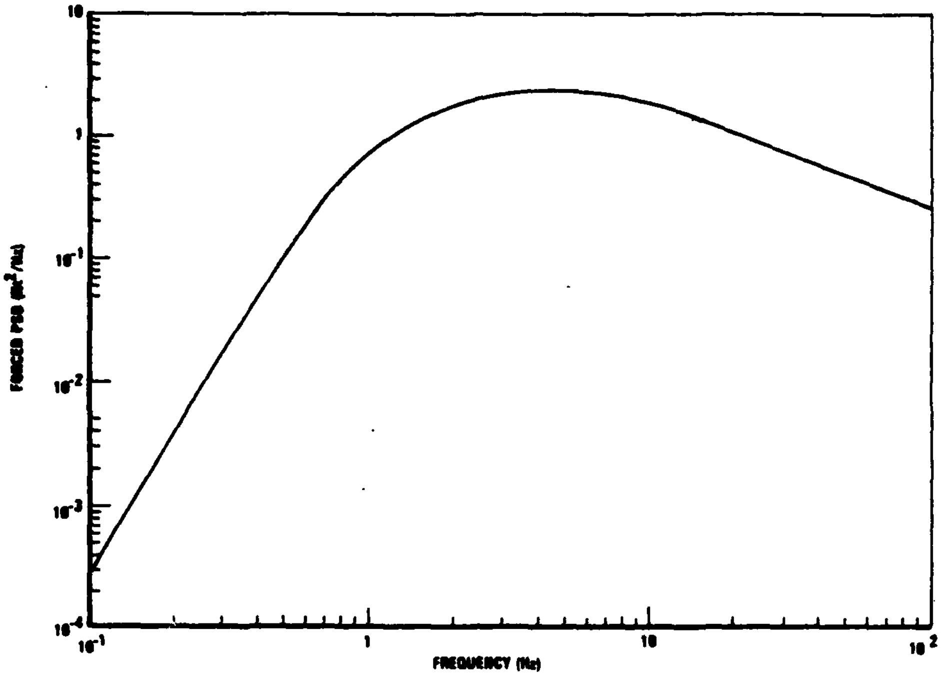


Figure 3.4. Wideband Power Spectral Density

The next series of user queries allows for modification of the sensor/actuator characteristics and permits specification of output degradation or failure. Similarly, the structural characteristics can be modified via the multiplers discussed in Chapter 2. The time duration of the simulation can also be specified; along with the interval at which the data is archived. There is also a default set of parameters, as indicated in Fig. 3.3, which allows the first time user to operate FLEXSIM immediately upon loading it into the computer memory.

3.1.3 Graphics

High quality graphics have been built into FLEXSIM. These displays serve the purpose of introducing the simulator and its goals' providing a means of querying the user for execution options, displaying the sensor and actuator data, and a final summary of the control performance. Figure 3.5 is a replica of the first two displays in the system which summarizes the overall intent of the three control system options--namely to add 15% damping to the structure.

The next display is a series of questions which the user must answer in order for the control simulation to start. An example of this can be found in Fig. 3.6. One of the features of this query approach is that it re-displays the input data and requests the user to verify its accuracy prior to proceeding. Details on the meaning of the responses can be found in the user's guide.

The next display is that of the displacements and forces resulting from the prior choices. Note that for the DVFB and ESC controllers that there are four sensor measurements displayed and 9 for the IMSC. The results are scaled to a maximum magnitude of 0.2 m for the disturbances and 0.5 Nt for the forces. The location of the individual "squares" corresponds roughly to their locations along the beam. Much like any graphics display, there is limitations due to the resolution of the system, which in this instance corresponds to 0.05 m in displacement and 0.1 Nt in force. Several typical examples are found in Fig. 3.7. The final display in the FLEXSIM graphics is a summary of the performance on the controller, such as shown in Fig. 3.8.

```
                                        ************
                                        * FLEXSIM *
                                        ************

                                   Flexible Structure
                                   Control System
                                   Simulator

                              *Direct Velocity Feedback
                              *Independent Modal Space Control
                              *Expert System Control

General Research Corporation
     1988
Pause.
Please press <return> to continue.
```

```
                                        ************
                                        * FLEXSIM *
                                        ************

          Reference structure:        Free-free beam
                                      10-meters long
                                      10 kg mass
                                      unit stiffness

          Control Systems
             DVFB - 4 collocated sensors/actuators
             IMSC - 9 sensors, 4 actuators
             ESC - 4 collocated sensors/actuators

          Control goal:      15% damping added to first 4 modes

          Pause.
          Please press <return> to continue.
```

Figure 3.5. FLEXSIM Introduction Displays

```
*************
* FLEXSIM *
*************

change default setup (yes/no)
yes
input default value changes

input control system flag:0=DVFB; 1=IMSC; 2=ESC
0

input disturbance type; 0-Impulse, 1-Standing wave, 2-Traveling wave, 3-Wideband
0
input disturbance force(Nt)/amplitude(m);frequency(Hz) or wavelength/location
(m)

1,2.5
change actuator performance (yes/no)
no
have any actuactors failed (yes/no)?
no
change sensor performance data (yes/no)?
no
have any sensors failed (yes/no)?
no
change mode shape or frequency (yes/no)?

change max time and print interval (yes/no)?
yes
input max time (sec) and print interval
5, 100
current run time values
DVFB control chosen
disturbance type
          .0000000
disturbance data
          1.0000000      2.5000000
actuator performance data
          3.0000000    3.000000E-003    3.000000E-004     30.0000000
actuator failure values
          1.0000000      1.0000000        1.0000000        1.0000000
sensor performance data
    2.540000E-005    2.540000E-006        50.0000000    7.071000E-001
sensor failure values
          1.0000000      1.0000000        1.0000000        1.0000000
percent change in mode shape and frequency
           .0000000       .0000000
run time control data
    1.000000E-002       5.0000000        100.0000000

are these ok (yes/no)?
yes
```

Figure 3.6. FLEXSIM User Prompt Display

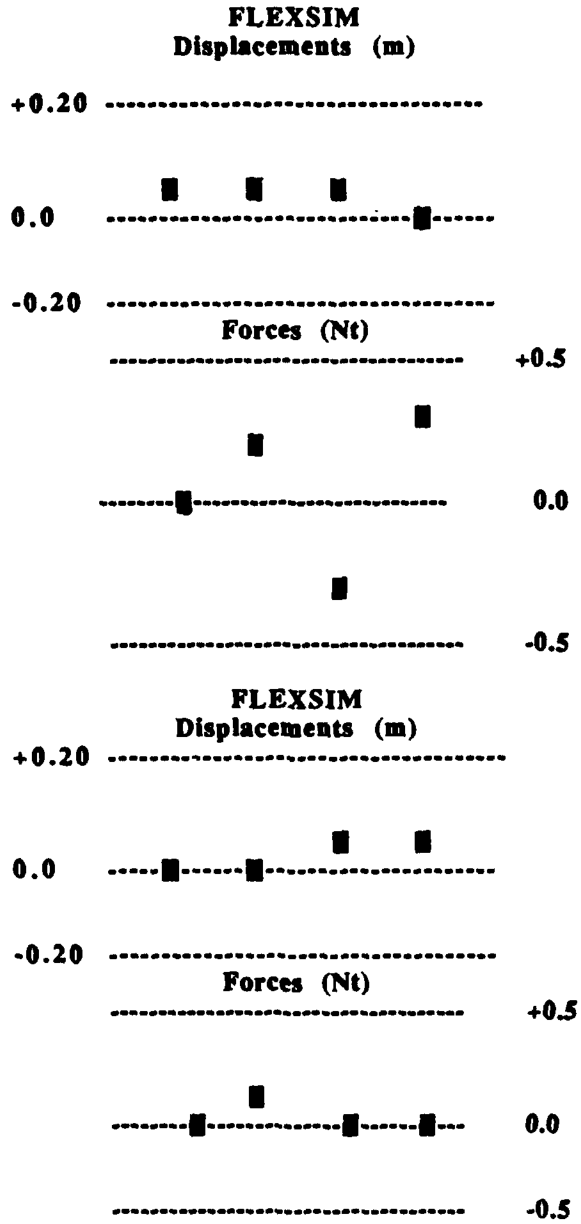


Figure 3.7. FLEXSIM Dynamic Display Examples

FLEXSIM

```
DVFB Control Option
Elapsed Time (sec.)
        1.0000000
Total Control Cost (N**2)
        3.5298710
Total Control Power (w)
  6.976908E-001
Displacement Rss Error (m)
  1.234808E-002
Velocity Rss Error (m/s)
  2.208675E-002

Pause.
Please press <return> to continue.
```

Figure 3.8. FLEXSIM Summary Display

3.1.4 Data Files

During the simulation process, the data for the motion of the structure and the control forces is being recorded to a disk file. Information contained in this file, such as shown in Fig. 3.9, includes an elapsed time tag, measured displacements and estimated velocities for each sensor, and control forces for each actuator. The file can be used in post-processing functions to produce plots and so forth using any of the plot packages that are on the open market. Note that the time interval corresponds to the output time step chosen in the "set-up" portion of the program.

.00000	.00003	.00254	.00000
	-.00003	-.00254	.00000
	-.00003	-.00254	.00000
	.00003	.00254	.00000
.20000	.00068	.00607	-.04375
	-.00112	-.01014	.03065
	-.00112	-.01014	.03065
	.00068	.00607	-.04375
.40000	.00244	.01112	-.08370
	-.00412	-.01929	.05891
	-.00412	-.01929	.05891
	.00244	.01112	-.08370
.60000	.00511	.01524	-.11853
	-.00888	-.02779	.08396
	-.00888	-.02779	.08396
	.00511	.01523	-.11853
.80000	.00849	.01824	-.14730
	-.01527	-.03551	.10522
	-.01527	-.03551	.10522
	.00849	.01824	-.14729
1.00000	.01234	.02000	-.16927
	-.02310	-.04237	.12221
	-.02310	-.04237	.12222
	.01234	.02000	-.16927

Figure 3.9. Representative Disk Data File

3.1.5 Printed Output

In addition to the other previously described function, FLEXSIM also produces a "hardcopy" output of the simulation. As shown in Fig. 3.10, the "header record" informs the user of the conditions of the simulation; that is, which control law was chosen, where the sensors and actuators are located, closed loop gains, the disturbance data, the description of the sensors and actuators (including any failures) and any modifications to the reference structure. Subsequent to this is a record of the behavior of the structure and controller in the form of time, displacement, velocity and force. At the end of the simulation, the total control cost and power are given.

```
                    direct velocity feedback control

     sensors/actuators at the following stations (m)
             2.000      4.000      6.000      8.000

     control loop gains
               .4177     -.2648      .0530     -.0156
             -.2648      .4706     -.2805      .0530
               .0530     -.2805      .4706     -.2648
             -.0156      .0530     -.2648      .4176

                 harmonic disturbance
  force=            1.0000 newtons at         .0400 hertz

  sensor accuracy=  .2540E-04 m     sensor noise=  .2450E-05 m

  sensor bandwidth=   50.0000 hz      damping=   .7071

  sensor failure values
     1.0000       1.0000       1.0000       1.0000
  actuator max. force= 3.0000     accuracy= .0030     noise= .30000E-03 newtons

  actuator bandwidth=    30.0000 hz

  actuator failure values
     1.0000       1.0000       1.0000       1.0000

  mode shape multiplier=   1.0000      mode frequency multipler=    1.0000

  time (s)    displacement (m)      velocity (m/s)       force (n)
   .00000          .00003               .00254            .00000
                  -.00003              -.00254            .00000
                  -.00003              -.00254            .00000
                   .00003               .00254            .00000

   .20000          .00068               .00607           -.04375
                  -.00112              -.01014            .03065
                  -.00112              -.01014            .03065
                   .00068               .00607           -.04375
```

Figure 3.10. Representative Hardcopy Output

3.2 FLEXSIM LAB INTERFACE POSSIBILITIES

During the course of this investigation, a brief examination was made regarding the possibilities of interfacing this simulation system with laboratory hardware. As was expected, key to this capability is the availability of interface cards and software. While as it currently exists FLEXSIM cannot be directly transported to the lab environment, this section does indicate that given appropriate software changes, FLEXSIM can be used to control a lab test article.

For data acquisition on a LSS control experiment the IEEE-488 communications standard is the obvious choice because it offers both high-speed communications and simultaneous control of devices. The IEEE-488 or GPIB (general-purpose interface bus), which has long been recognized as the premier instrumentation bus, provides for the transfer of digital data among as many as 14 programmable instruments by using standard signals, techniques, and a single interface to the party-line GPIB. PC-based data-acquisition systems provide signal conditioning. A/D and D/A conversion, real-time data monitoring, and multiple inputs for as many as 32 channels on a standard IBM PC-compatible computer.

Also, by using an IEEE-488 interface to control the instruments via a desktop PC, additional data-storage and analysis capabilities that naturally compliment any test and measurement task can be obtained.

Almost all IEEE-488 boards for the PC use TI's TMS9914A or the NEC uPD7210 IEEE-488 chip. Most newer designs are using the 7210 chip because of its ability to detect the receipt of a specific character automatically, which allows the system to set up a high speed direct memory access (DMA) transfer and then proceed to other tasks until it detects the terminating character.

The maximum transfer rate on most PC-based systems is 300 kbytes/s, which takes advantage of the DMA circuitry built into the computer's mother board. Nearly all IEEE-488 boards support DMA capability, and because they all use the same DMA circuitry and the same IEEE-488 chips, most boards with DMA capability operate at the same speed.

3.2.1 Output

Most software packages for the PC support serial or parallel printers and dedicated IEEE-488 controllers. Because the IEEE-488 port is the primary I/O port, IEEE-488 printer and plotter support is built into these machines. However, if the programmer wants to use a language or environment with "canned" plotter or printer support, he can use an IEEE-488 board or external IEEE-488 box that can convert the serial or parallel output to the IEEE-488 protocol. These boards convert data received from the PC's bus to the IEEE-488 protocol software, which can then access standard parallel or serial ports and IEEE-488 peripherals, with no modifications to the software. Another solution is to use external RS-232-to-IEEE-488 or parallel-to-IEEE-488 converters. These converters attach to the PC's serial or parallel ports and convert data from either of these PC ports to IEEE-488 format within the box.

A unique approach to GPIB control is to use a DOS-installable device driver that automatically loads the IEEE-488 control software each time the PC is booted. A device driver is an element of the operating system that lets the programming environment access a device without the language or environment requiring environment-specific code. It's architecture enables IEEE-bus control from any language with device I/O capability, including languages as Basic, Quick Basic, Turbo Pascal, Microsoft C, and Microsoft

FORTRAN. Only one driver is needed regardless of how many or what languages are used. The architecture also improves subroutine call for applications in Basic. Both literals (constant characters or numbers) and variables can be passed from the language to the driver.

A system based on an IEEE-488 device driver has much simpler code than a subroutine passed system. It also can be loaded automatically at power up from the AUTOXEC.BAT file and do not need to be loaded at the beginning of every program as do IEEE-488 subroutines.

Device drivers, like dedicated IEEE-488 controllers, allow error conditions to be automatically tested and reported back to the operator. This is especially important because a system can consist of as many as 14 different instruments from 14 different manufacturers, connected with as many as 14 IEEE-488 cables. Some of the available software products are sophisticated enough that they can treat the input from multiple IEEE-488 boards as separate channels and can even provide different scale factors, sampling rates, and triggering conditions for each.

3.2.2 Control Software

The greatest difference between PC-based IEEE-488 controllers and dedicated IEEE-488 controllers is in the software selection. Most dedicated IEEE-488 controllers are programmed with BASIC or a language similar to BASIC. The greatest burden in converting an ordinary PC into an IEEE-488 controller lies with the software that enables the programming environment to access the IEEE-488 hardware. This software can come in the form of IEEE-488 subroutines supplied by the interface manufacturer, and IEEE-488 device driver supplied by the interface manufacturer, or an IEEE-488 software module supplied by the software manufacturer.

Many IEEE-488 boards are available with IEEE-488 subroutines that can be called from languages such as BASIC, C, FORTRAN, and Pascal. These subroutines are called to perform specific bus activities, such as programming an instrument, reading data from a device, triggering devices on the bus, clearing the bus, and polling information.

3.2.3 Analysis Software

Integrated modules offer an alternative to specialized programming environments that support IEEE-488 programming. They are software modules that are created by the developer of the language or environment to add IEEE-488 capability. One advantage of integrated IEEE-488 systems is that they can provide features beyond those of most languages. For example, Lotus Measure can take advantage of the graphics capabilities of Lotus 1-2-3, freeing the programmer from writing graphics routines.

Other examples of integrated software that can support the IEEE-488 are ASYST and TBASIC, ASYST (Asyst Software Technologies, Rochester, NY) is a programming environment, similar to the language FORTH, that has built-in advanced data analysis and graphics functions. The IEEE-488 module is available separately and supports IEEE-488 control with many of the features of a dedicated IEEE-488 controller. TBASIC (TransEra Corporation, Provo, UT), an advanced BASIC with many built-in graphics commands, is supplied with standard support for IEEE-488, including features that closely resemble a dedicated IEEE-488 controller.

For analysis, these software modules can provide support for: Fast fourier transforms, waveform smoothing, peak detection, linear and non-linear curve-fitting, waveform integration and differentiation, statistics, anovas, and matrix operations. Their graphics capabilities can offer: x-y, contour, axonometric plots, pie and bar charts, interactive graphics, software data scroller, log/linear/polar axes, plot modification capabilities, error bars, scatter plots, and other line types.

CHAPTER 4
NUMERICAL CONTROL IMPLEMENTATION

4.0 INTRODUCTION

This portion of the report examines the mathematical formulation of the two competing numerical controls used in this research, including specific design features, their individual performance under certain circumstances, and some comparative observations. The two control systems implemented are known, respectively, as Direct Velocity Feedback (DVFB) and Independent Modal Space Control (IMSC). DVFB features include co-located sensors and actuators, with the number of sensors/actuators pairs corresponding to the number of flexible modes being controlled. As can be surmised from its name, DVFB adds additional damping to the structure by electronically multiplying sensor signals by appropriately selected gains. As will be obvious later in this discussion, the gains must be determined via as pole-placement technique. On the other hand, IMSC is considerably different as compared to DVFB. One of the basic differences is that IMSC is a distributed sensor/actuator controller, where the number of sensors corresponds to the number of vibrational modes necessary to yield an accurate model of the structure's motion. Furthermore, the physical sensor data is passed through a "modal filter" to yield the modal coordinates needed to determine the "modal forces" necessary to control the structure. The first four vibrational modes are controlled in both implementations, with the next five being considered residual.

4.1 CONTROL SYSTEM DESIGN GOAL

In order to keep comparisons of the two control techniques, as well as with the expert system controller to be described later, on a common footing a consistent definition of the net performance goal is necessary. Since DVFB can only affect damping and not modal frequencies, added damping is the issue for each. It should be noted that the IMSC approach can in principle be designed not only to add damping, but can also shift the modal frequencies; care has been taken to reduce any frequency shift to essentially negligible values. Consequently, it was decided that a uniform damping ratio for each of the four modes to be controlled would be chosen.

The choice of uniform damping may seem somewhat unusual, until one examines testing of typical lightweight materials. Testing of sample coupons for glass-fiber and carbon-fiber composite materials, has indicated considerable variations in damping ratio between samples and primary vibrational modes, such as seen in Figs. 4.1 and 4.2. However, there does appear to be a general limit curve which can be drawn. In these examples there is the indication that damping is basically uniform and small (0.003) for frequencies extending above 100 hertz. This same kind of observation can be made for complete spacecraft, such as shown in Fig. 4.3 for the Galileo spacecraft. Thus, it was felt that for the frequencies of interest (<1 hertz) that uniform damping for the modes being controlled is appropriate. Finally, a 15% damping ratio was chosen as the design goal for each of the controllers. This particular choice is a compromise between what can be accomplished with passive augmentation (estimated additonal damping using passive techniques may approach 6%) and the potential hardware available for active control.

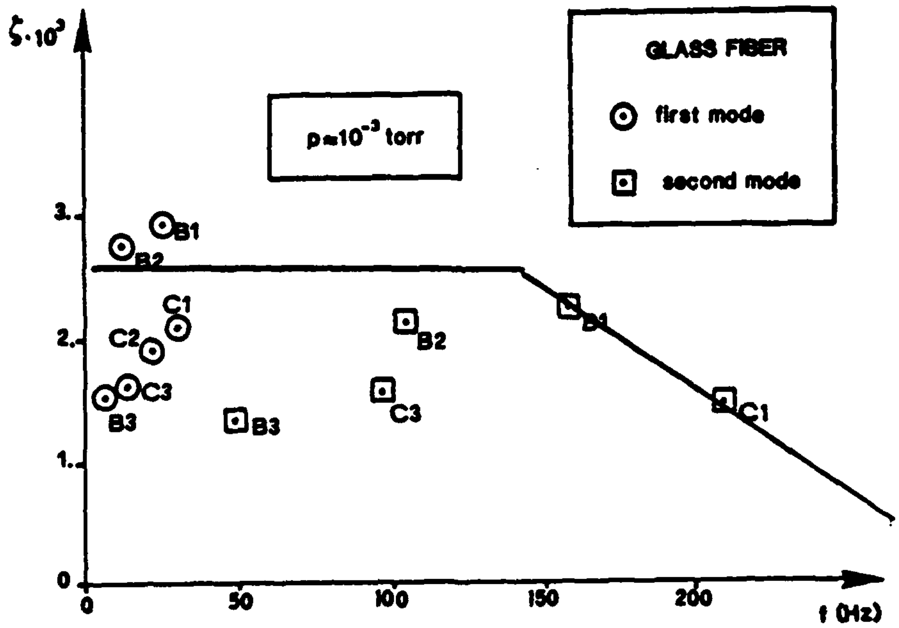


Figure 4.1. Glass Fiber Damping Factors Versus Frequency

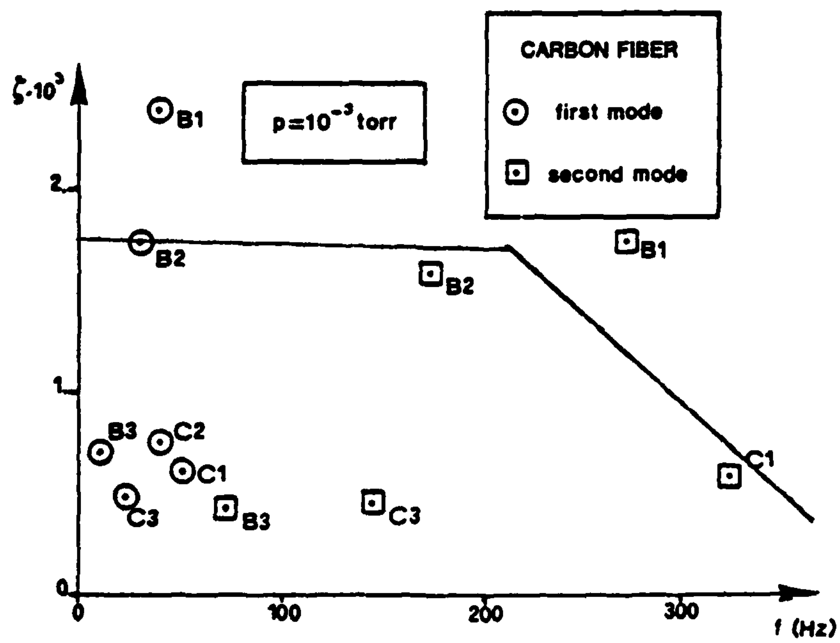


Figure 4.2. Carbon Fiber Damping Factors Versus Frequency

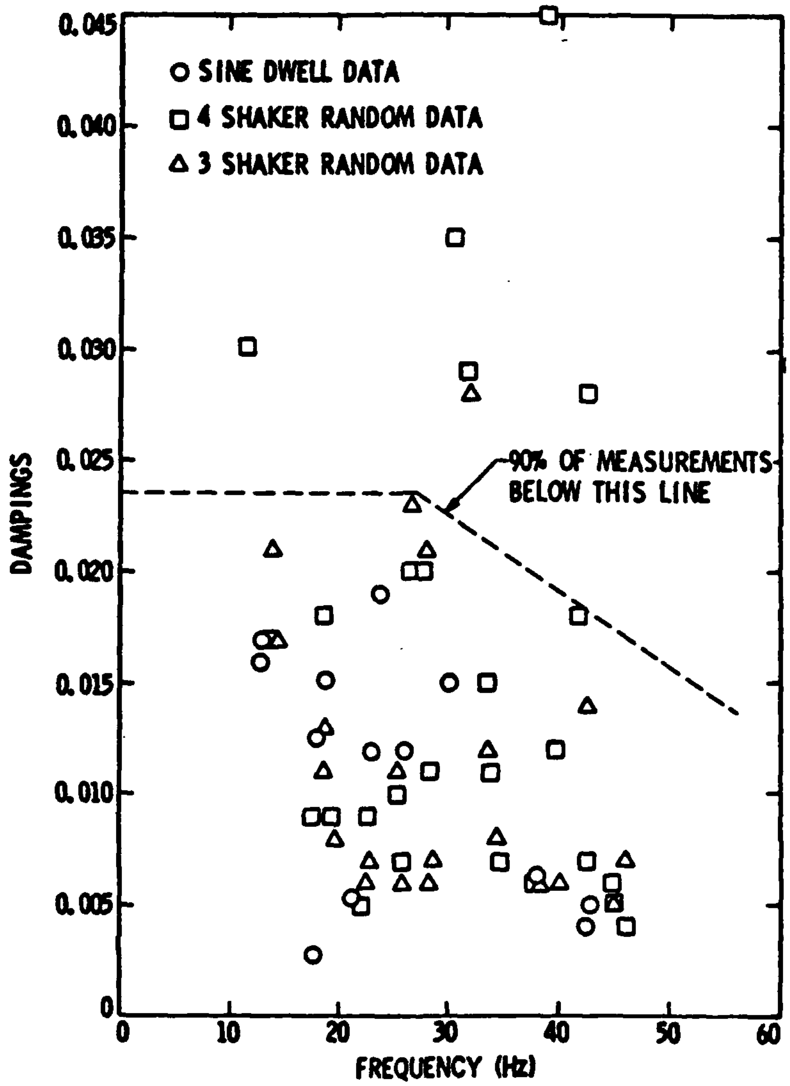


Figure 4.3. Measured Damping Ratios for the Galileo Spacecraft

4.2 DIRECT VELOCITY FEEDBACK

4.2.1 Theory

Control forces are to be provided by M point-force actuators

$$F(x,t) = \sum_{i=1}^{M} b_i(x)\, f_i(t)$$

where the actuator influence functions approximate Dirac delta functions $\delta(x-x_i)$. Referring back to Chapter 2, the modal coordinates $u(t) = [u_1(t), \ldots, u_L(t)]^T$ satisfy the following general wave equation

$$\ddot{u}(t) + \Lambda\, u(t) = Bf(t)$$

where $\Lambda^{1/2}$ = diagonal $(\omega_1,...,\omega_L)$, $\Lambda \equiv (\Lambda^{1/2})^2$, $f(t) = [f_1(t),...,f_M(t)]^T$, and B is a L x M matrix whose entries are the mode shapes $\phi_K(x_l)$. The displacements and velocities are measured by P point-sensors

$$y(t) = D_1Cu(t) + D_2C\dot{u}(t)$$

where D_1 = diagnonal $(c_1,...,cp)$, D_2 = diagonal $(d_1,...,dp)$ and C is a N x P matrix with element values $\phi_K(Z_l)$.

The following assumptions are made: (1) the number of sensors is equal to the number of actuators; (2) only velocity measurements are available; and (3) the sensors and actuators are in fact collocated. Consequently, the sensor equation becomes

$$y(t) = B^T\dot{u}(t)$$

The DVFB method is obtained with a control law of the form

$$f(t) = -Qy(t)$$

where Q is a P x P symmetric, non-negative definite gain matrix. The choice of the specific gain matrix Q is somewhat open, but can be determined by a relation from a stability criterion.

In order for the closed loop system to be stable, the energy in the system must be dissipative. This in turn requires that the derivative with respect to time of the energy be negative or zero, that is

$$\dot{E}(t) = -\dot{u}^T[BQB^T]\dot{u} \leq 0$$

where it is noted that $BQB^T > 0$. This term is in fact considered to be equivalent to an added damping term for the equations of motion. Therefore, if Z is the value of the added damping, the relation

$$BQB^T = 2Z\Lambda^{1/2}$$

can be manipulated to yield the elements of the gain matrix Q. This has in fact been done and yields the gains shown in Table 4.1. The pole locations of the closed loop system are determined from a large symmetric eigenvalue calculation

$$\det\,(s^2 + Ws + \Lambda) = 0$$

where $W = BQB^T$ and there are L conjugate pairs of poles. A plot of these poles, including the open-loop poles, appears in Fig. 4.4, clearly indicating that the poles are in the left-hand side of the plane and as such verifying that the system is stable.

TABLE 4.1
DVFB CONTROL GAIN MATRIX

.4177	-.2648	.0530	-.0156
-.2648	.4706	-.2805	.0530
.0530	-.2805	.4706	-.2648
-.0156	.0530	-.2648	.4176

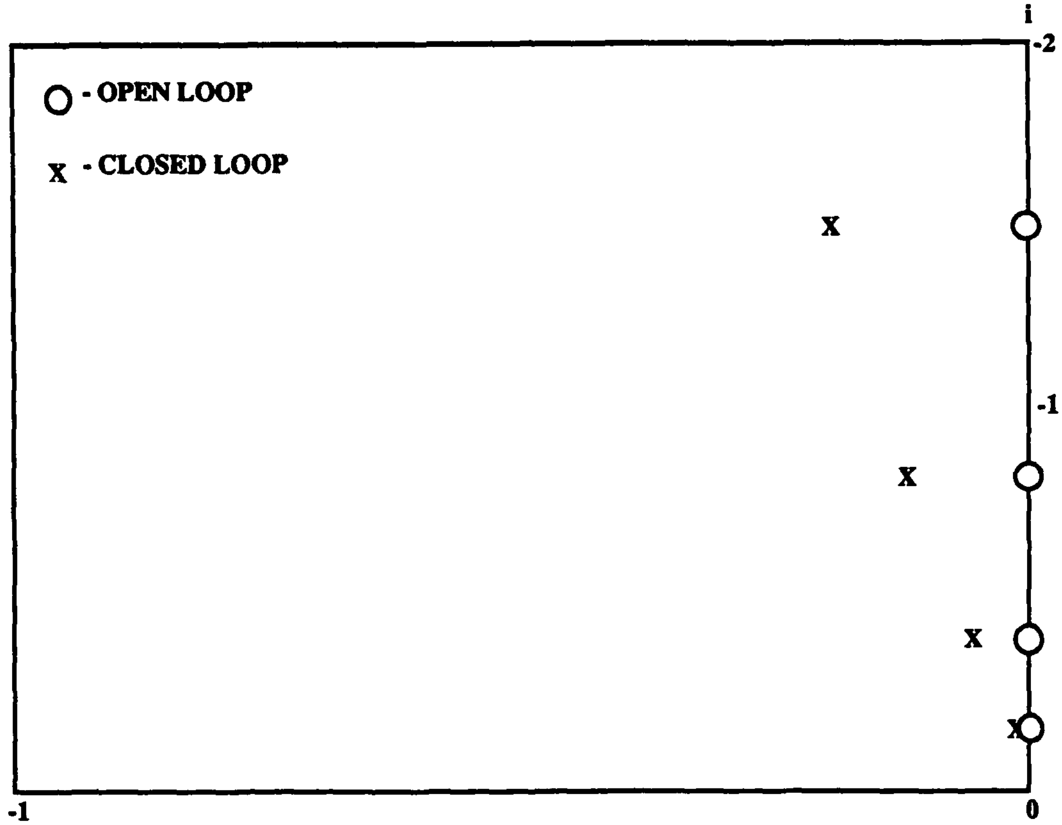


Figure 4.4. DVFB Closed Loop Poles

4.2.2 Performance

If the Laplace transform is taken of this second-order system, the closed-loop system response function can be determined, as seen in Fig. 4.5. If a comparison is made with the open-loop response found in Chapter 2, the reader will note an order-of-magnitude or greater reduction in the net behavior of the structure, except for frequencies near the third fundamental. In the event of disturbances near this value (approximately 0.13 Hz), there will be an enhanced response as compared to other frequencies. This behavior was observed in simulations, such as viewed in Fig. 4.6.

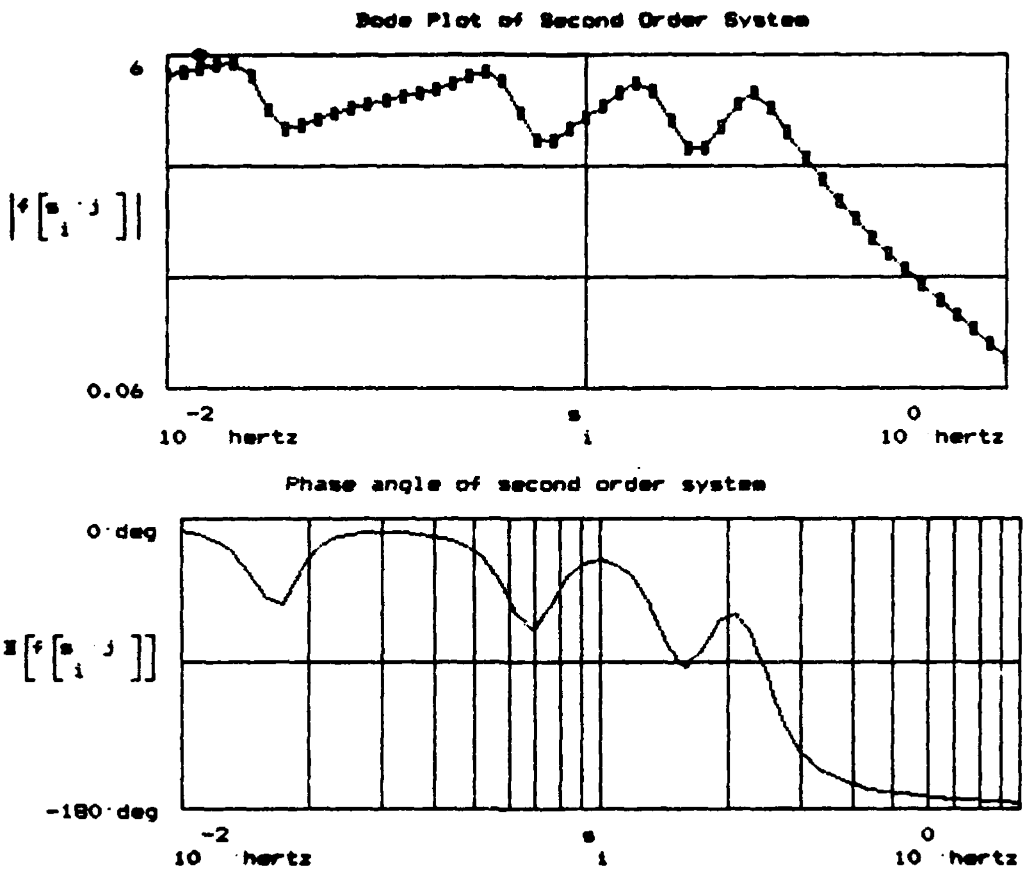
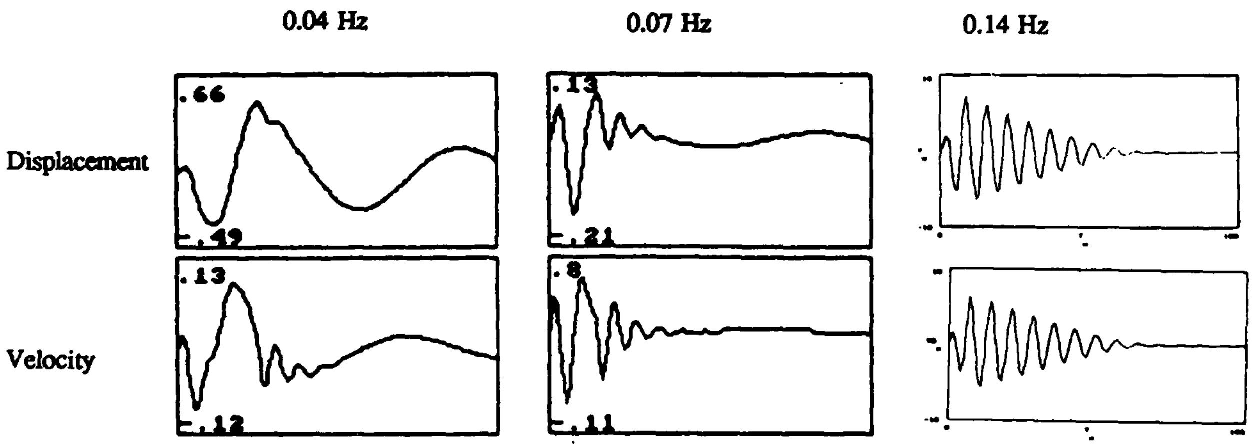


Figure 4.5. Closed Loop System Response



(Measurements Taken at First Sensor)

Figure 4.6. Closed-Loop Response to 1 N Disturbance at Different Frequencies

The performance of the DVFB controller can be best illustrated by the response of the system to the following four disturbances:

(a) A 1 Newton harmonic wave with a frequency of 0.14 hertz.

(b) A 1 Newton impulse occurring at x = 2.5 meters.

(c) A traveling wave of amplitude = 25 cm, and wavelength of $\sqrt{2}$ meters.

(d) The wideband power spectral density function.

The plots of these simulations appear at the end of this section.

A series of particularly interesting graphs is the correlation of force and velocity, and the displacement-velocity trajectory of the controlled behavior. As is evident in Fig. 4.7, the control forces have a negative slope with respect to velocity, which, of course, can be expected from the form of the control law ($F = -Q\dot{y}$). Furthermore, the width of the envelope is clearly indicative of the contribution of measurements taken at other locations along the beam; again a feature which can be deduced from the specific attributes of the gain matrix. Finally, the velocity-displacement trajectory plots, found in Fig. 4.8, are also very interesting. Features to be found include the initial response of the structure to the disturbance source, and the subsequent effects of the controller. Particularly noteworthy, is the spiral-like pattern of these curves. This observation plus the realization that the equation for a spiral ($r = \sqrt{y^2 + \dot{y}^2} = a\,\theta$) in this instance essentially describes the energy in the system, permits the determination of the rate of change in the angle θ. A relatively simple calculation shows that this has a value of ~-.16 π, clearly demonstrating that the controller dissipates energy.

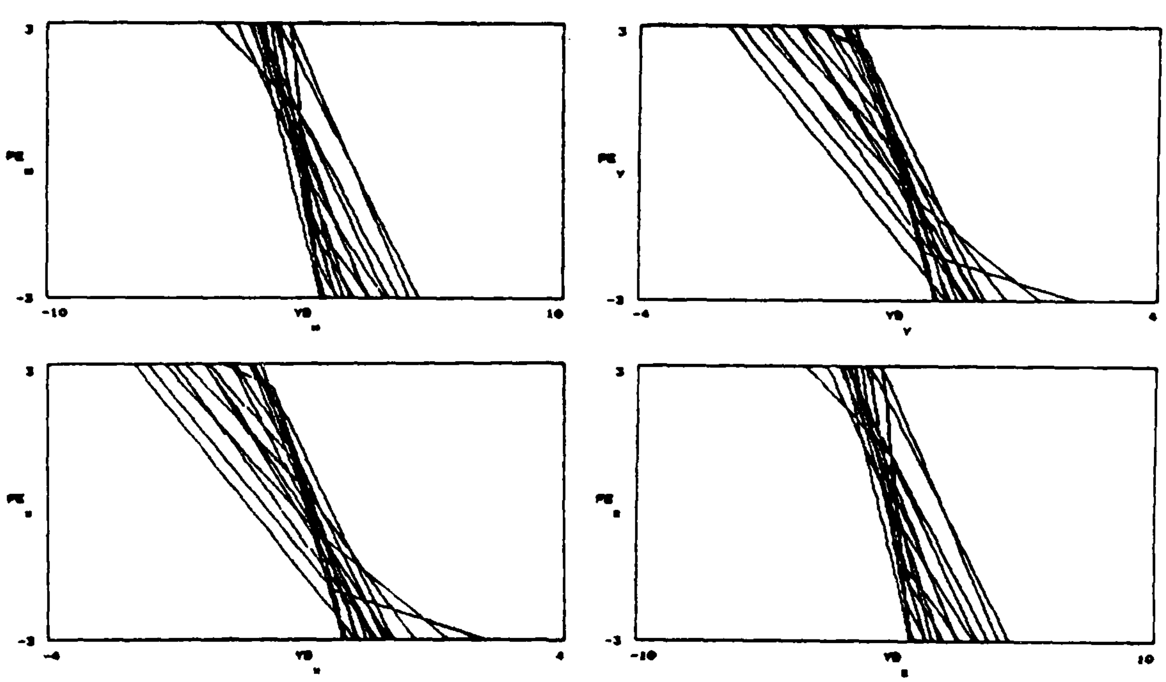


Figure 4.7. Typical Force-Velocity Correlation

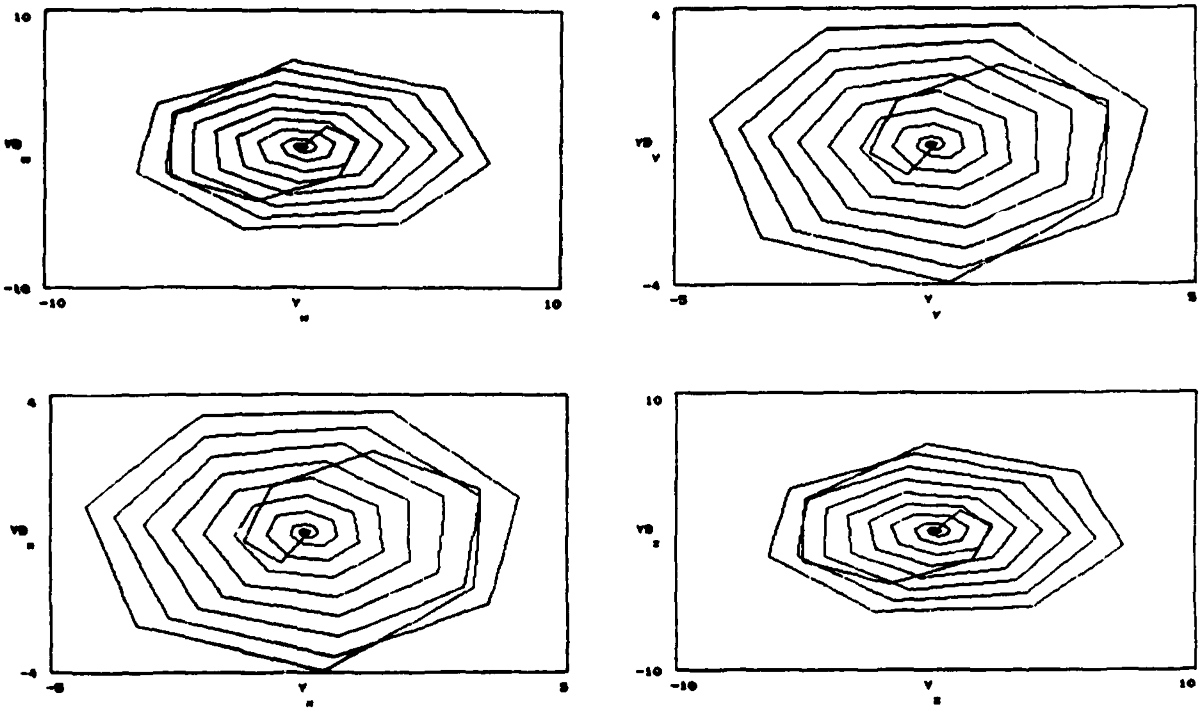


Figure 4.8. DVFB Displacement-Velocity Trajectory (Typical)

4.3 INDEPENDENT MODAL SPACE CONTROL

4.3.1 Theory

The implementation of the Independent Modal Space Control (IMSC) technique starts by first characterizing the system in question by a partial differential equation, and then converting this into an ordinary differential equation. This equation is then rewritten as a summation of space dependent eigenfunctions multiplied by time-dependent modal functions. A set of solutions for the modal functions are obtained, using a control law such as optimal proportional control. When implementing this control, "modal filters" are used, which convert the sensor displacement outputs into modal displacements and modal velocities. The calculation of the modal control forces is of a simple form:

$$f_r = f_{r21}\, \omega_r\, u_r + f_{r22}\, \dot{u}_r$$

where the modal control force, f_r, has feedback on the modal displacements, u_r, the modal velocities, $\dot{u}_r$, and the natural frequency, ω_r. The f_{rij} are control gain functions. These modal control forces f_r are now converted into real control forces, and the process is complete.

The reference structure is a simply supported beam, 10 meters long. There are four actuators, evenly spaced at

$$x_j^a = 2j \qquad\qquad j=1,..,4$$

and similarly, there are nine sensors, evenly spaced at

$$x_j^s = 5(j-1)/4 \qquad\qquad j=1,...,9$$

As noted earlier, the eigenfunctions are given by

$$\phi_r(x) = (1/\sqrt{5}) \sin(r\pi x/10) \qquad r=1,..,4$$

and the eigenvalues by

$$\omega_r = (r\pi/10)^2 \qquad\qquad r=1,..,4$$

The next step in the control problem is to formulate the specific control laws. For this system, a linear proportional optimal control has been chosen. The details of the optimal control formulation will not be covered here, but can be found in the reference by Meirovitch and Baruh. The resulting Riccati equation yields the final optimal generalized modal control equations,

$$f_r(t) = \omega_r \left(\omega_r - \sqrt{\omega_r^2 + R_{\eta r}^{*-1}}\right) u_r(t)$$

$$- \left[2\omega_r \left(-\omega_r + \sqrt{\omega_r^2 + R_{\eta r}^{*-1}}\right) + R_{\eta r}^{*-1}\right]^{1/2} \dot{u}_r(t)$$

$$r=(1,..,4)$$

where,

$f_r(t)$	= modal control forces
ω_r	= eigenvalues as described above
$u_r(t)$	= modal displacements
$\dot{u}_r(t)$	= modal velocities
$R_{\eta r}^{*}$	= optimal control gain parameters

The modal displacements and modal velocities, u_r and $\dot{u}_r$ are calculated by the use of modal filters,

$$u_r = (1/\sqrt{5}) \int_0^{10} y(x) \sin(r\pi x/10)\, dx$$

$$u_r = (1/\sqrt{5}) \int_0^{10} \dot{y}(x) \sin(r\pi x/10)\, dx$$

where $y(x)$ and $\dot{y}(x)$ are the actual displacements and velocities as determined by the nine sensors. The optimal control gain parameters, $R_{\eta r}^{*}$, $r=1,..,4$ are determined in order to obtain a 15% damping factor for the closed loop system. Using a trial and error approach, we obtain the following:

$$R_{\eta 1}^* = 2268.088$$
$$R_{\eta 2}^* = 141.784$$
$$R_{\eta 3}^* = 28.003$$
$$R_{\eta 4}^* = 8.8620$$

Note that the above equations can now be rewritten in the final form,

$$f_r = f_{r21}\,\omega_r\,u_r + f_{r22}\,u_r \qquad r=1,..,4$$

where,

$$f_{r21} = \omega_r - \sqrt{\omega_r^2 + R_{\eta r}^{*-1}}$$

$$f_{r22} = -[2\omega_r\,(-\omega_r + \sqrt{\omega_r^2 + R^*_{\eta r}{}^{-1}}) + R_{\eta r}^{*-1}]^{1/2}$$

It can be clearly seen that the final form of the modal control has feedback on the modal velocity and modal amplitude. Once we have determined the modal control force for each of the four modes to be controlled, we must then convert these into actual control forces which will be applied to the structure by the four actuators:

$$f(x,t) = \sum_{r=1}^{4} \phi_r\,(x)\,f_r(t)$$

$$= \sum_{r=1}^{4} \left(1/\sqrt{5}\right) \sin\left(r\pi x/10\right) \cdot f_r(t)$$

then, the final actuator forces become

$$F_1 = f(x_1, t)$$
$$F_2 = f(x_2, t)$$
$$F_3 = f(x_3, t)$$
$$F_4 = f(x_4, t)$$

4.3.2 Performance

The performance of the IMSC method is presented as the response of the reference structure and IMSC controller to the following four cases:

Case A:	1 N Standing Wave at 0.14 Hz
Case B:	1 N Impulse applied at x = 6.3 meters
Case C:	25 cm Traveling Wave with λ = 2.5625 meters
Case D:	Wideband Disturbance

plots of which can be found at the end of this section.

Much like the DVFB displacement-velocity curves, the IMSC set in Fig. 4.9 exhibit the same spiral-like pattern. Again, to be observed is the initial response of the structure to the disturbance and the subsequent control actions. Inspection of the curves (whose form is $r = a\,\theta$), allows one to determine the rate of change in the angle θ, which in this situation is about -0.12 π. Thus, this negative value clearly demonstrates that the IMSC methodology dissipates energy.

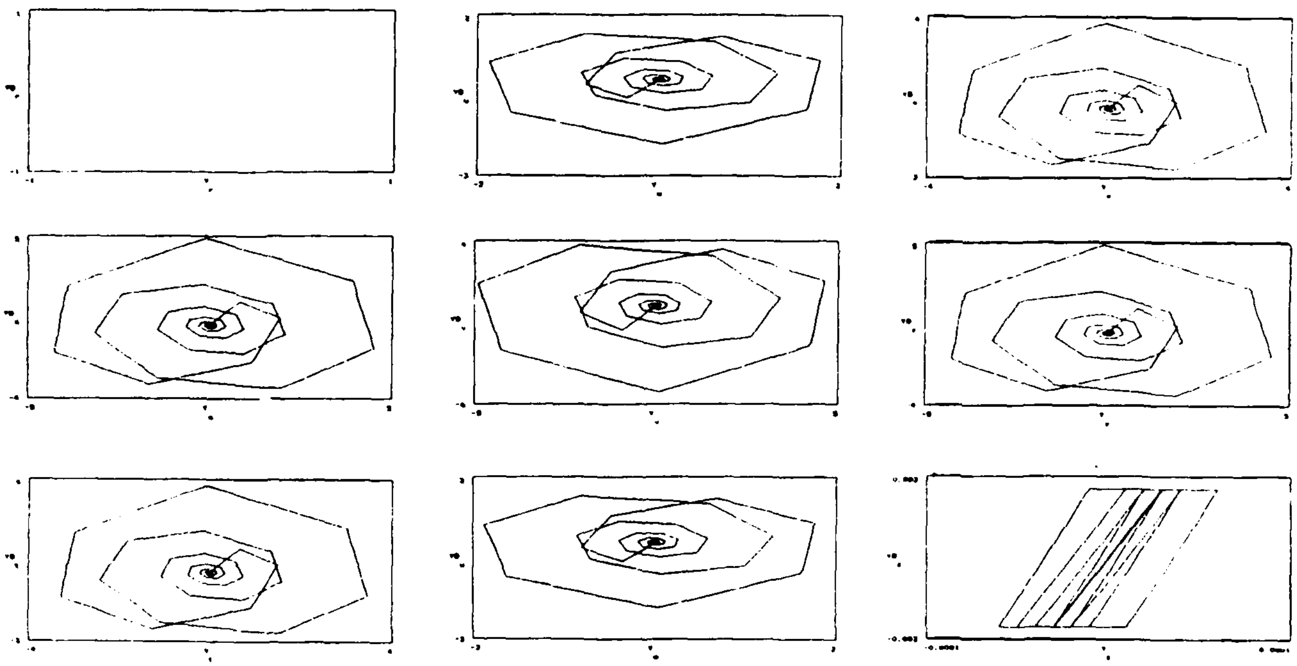
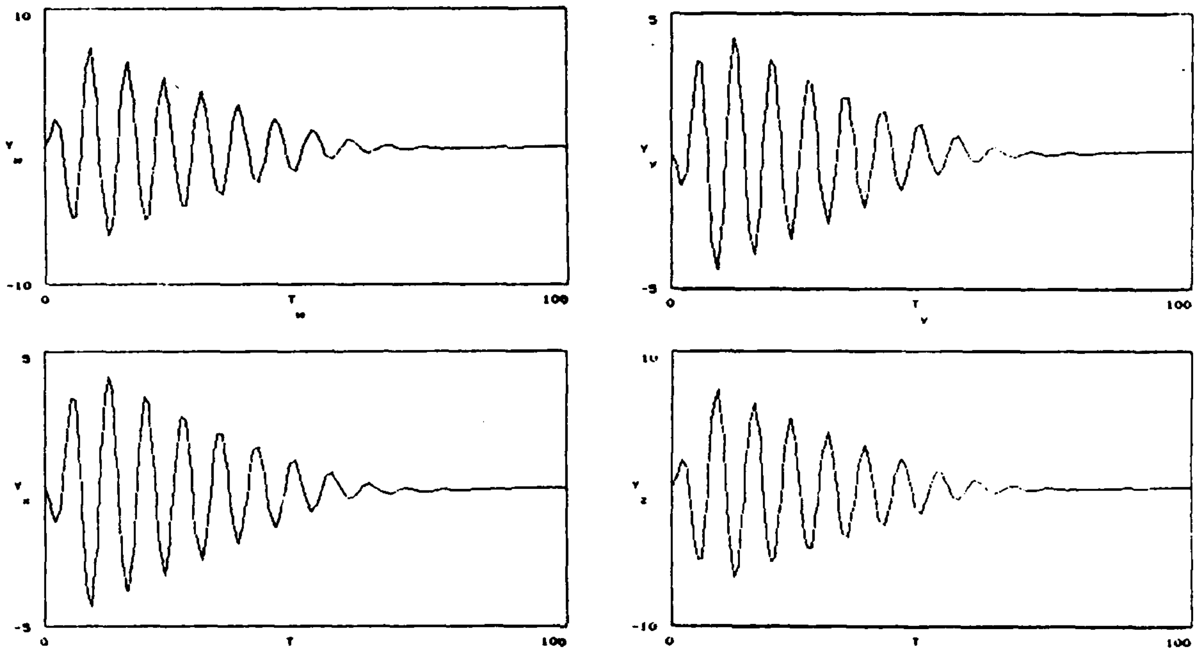


Figure 4.9. IMSC Displacement-Velocity Trajectory (Typical)

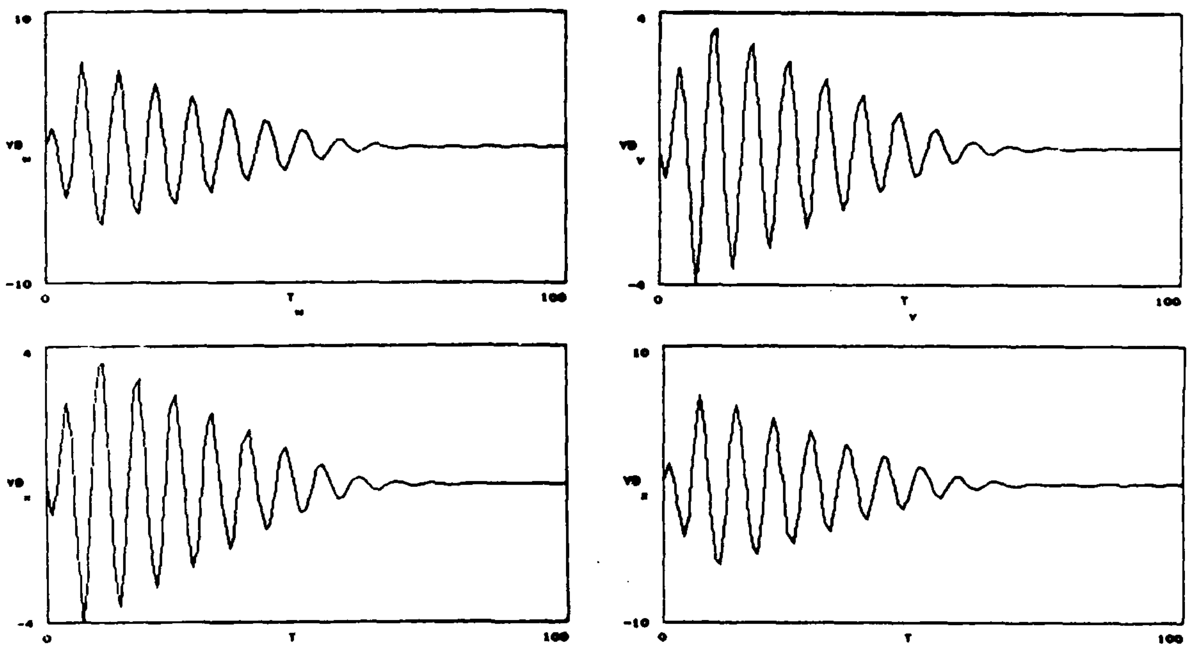
4.4 DIRECT VELOCITY FEEDBACK PERFORMANCE EXAMPLES

4.4.1 Case A: 1 Newton Harmonic Wave with a Frequency of 0.14 Hz

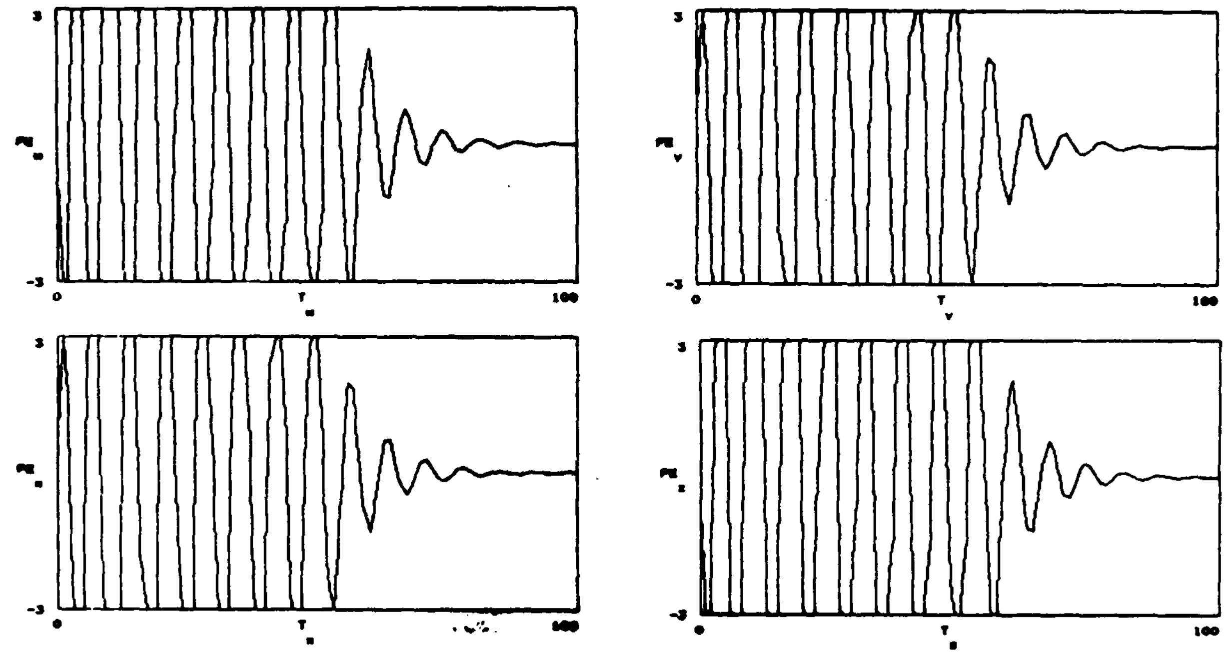
SOURCE: 1 Nt AT 0.14 Hz DISPLACEMENTS



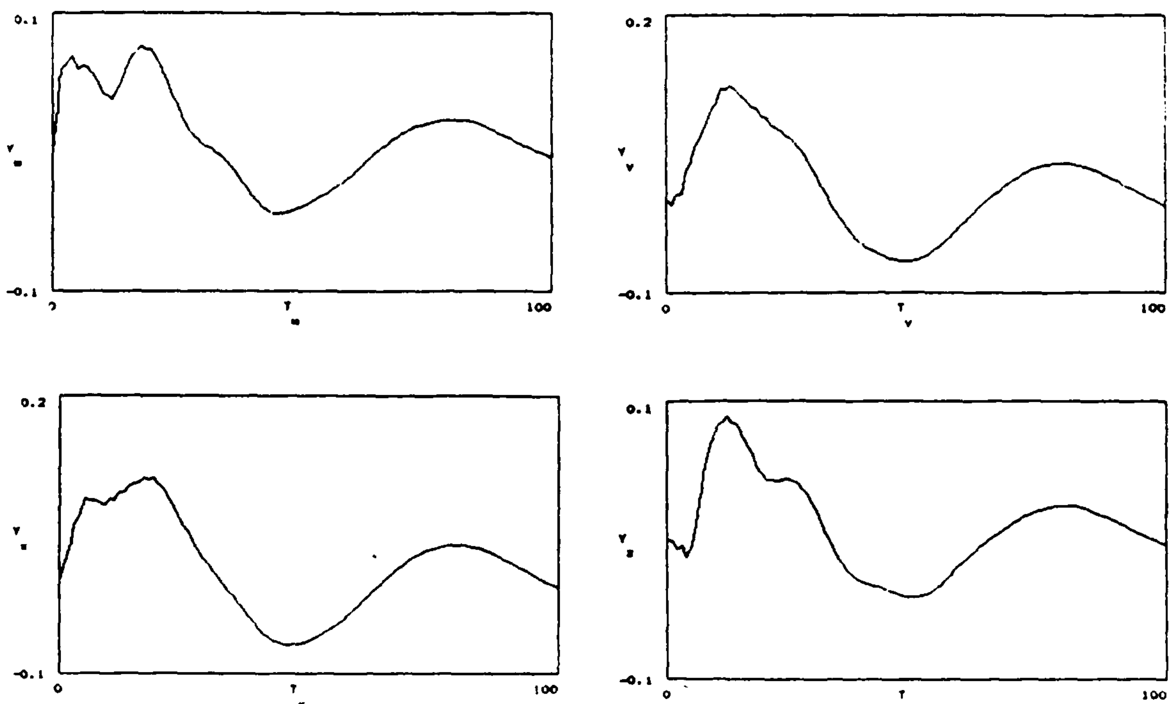
VELOCITIES



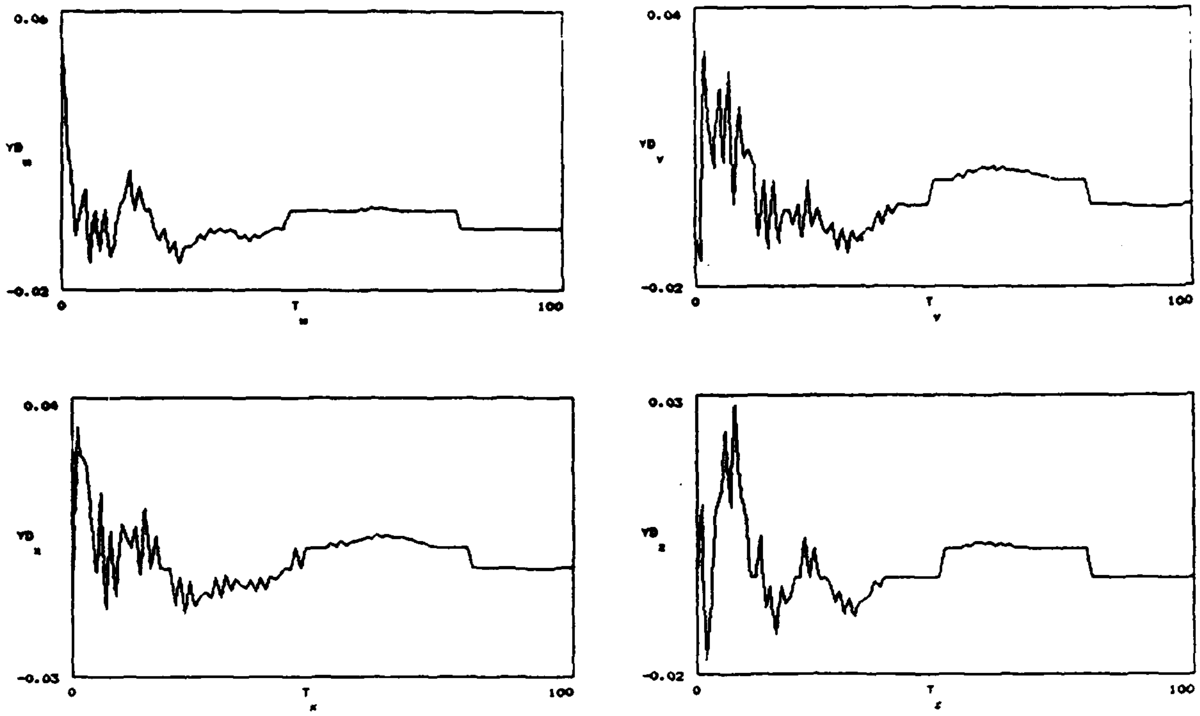
CONTROL FORCES



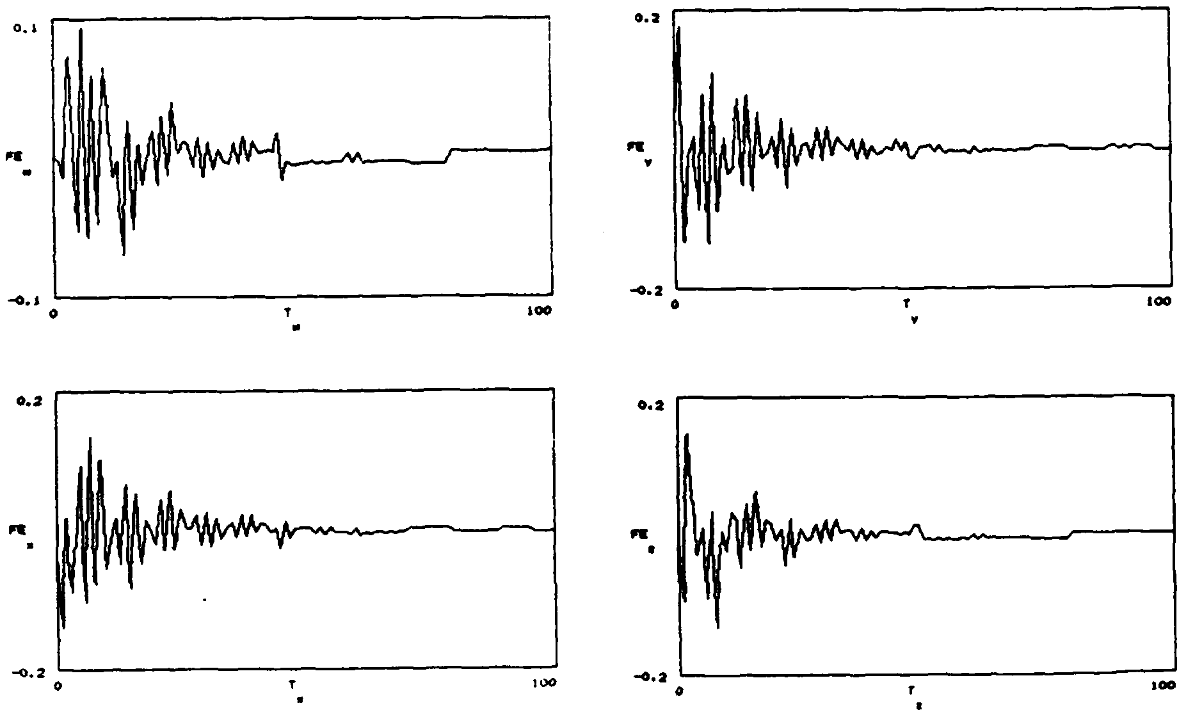
4.4.2 Case B: 1 Newton Impulse at x = 2.5 m



Displacements **Impulse 1 Nt @ 2.5 m**

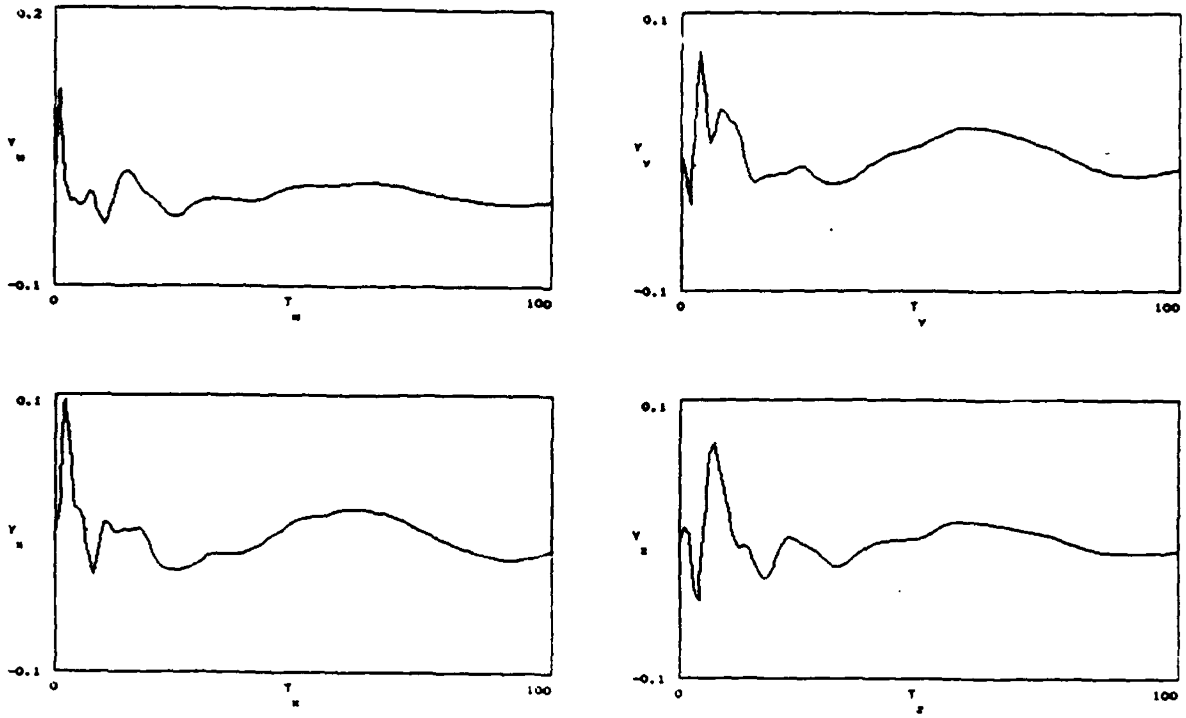


Velocities

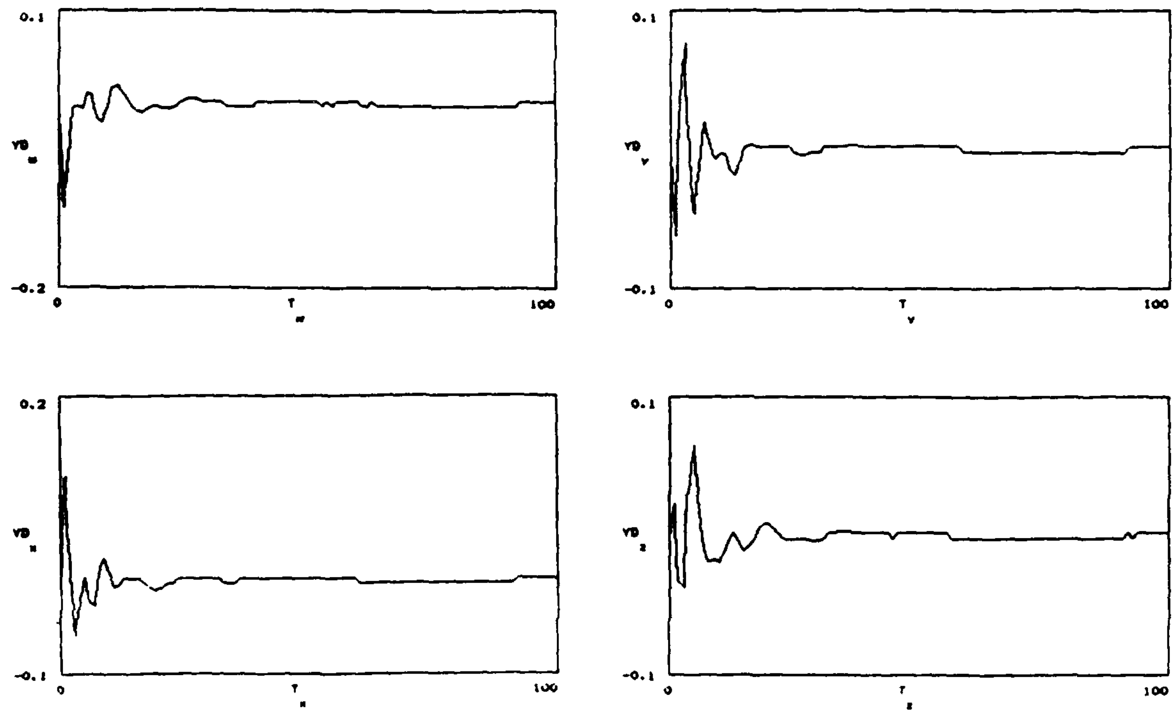


Forces

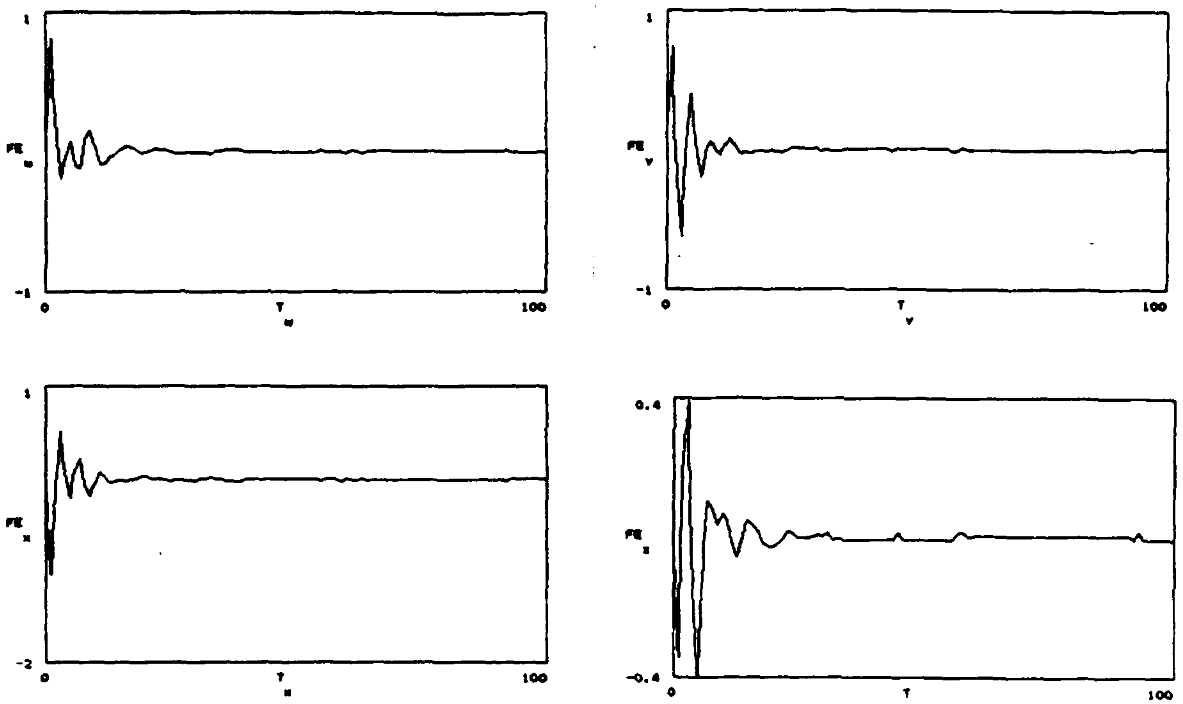
4.4.3 Case C: Traveling Wave with 25 cm Amplitude and a Wavelength of $\sqrt{2}$ meters



Displacements

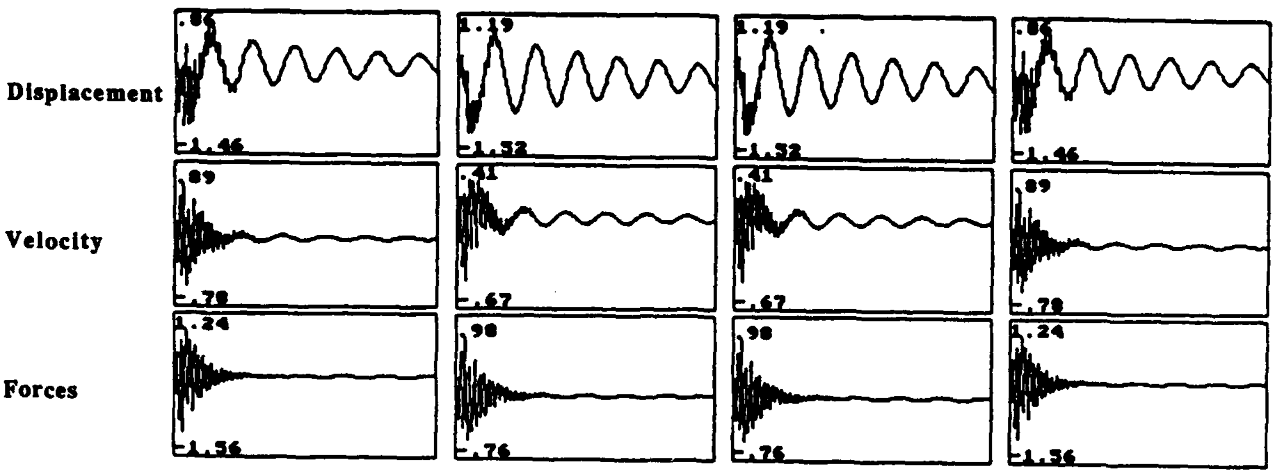


Velocities



Forces

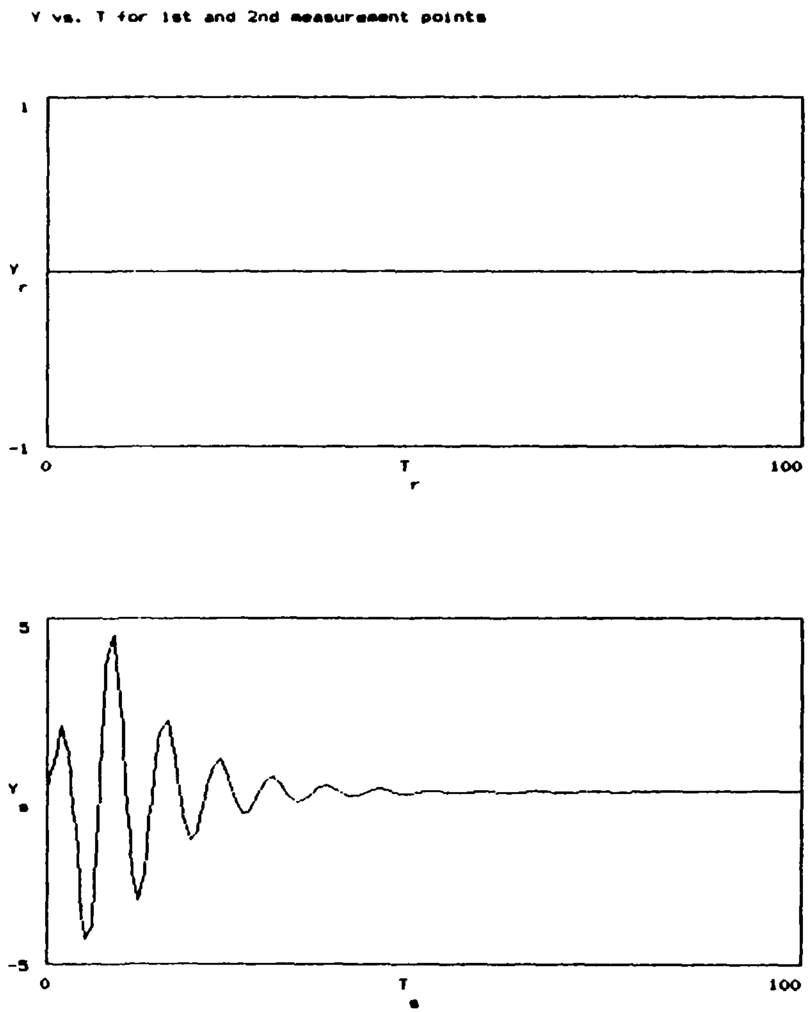
4.4.4 Case D: Wideband PSD Disturbance



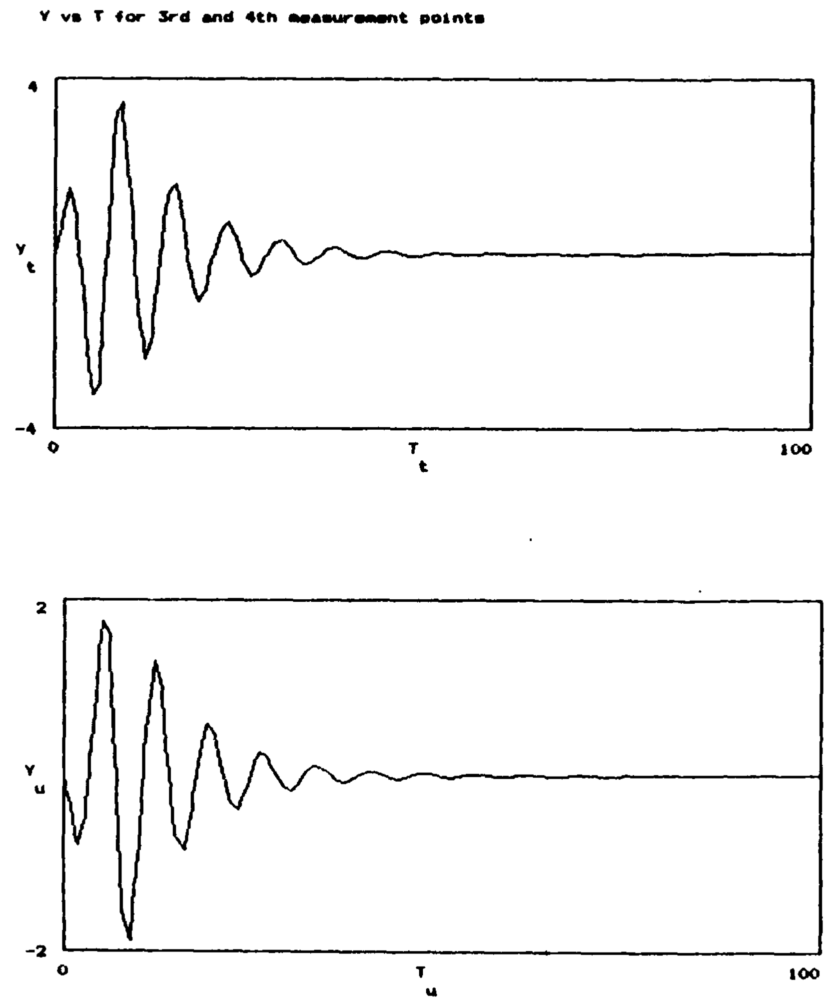
Wideband Disturbance
400 seconds simulation

4.5 INDEPENDENT MODAL SPACE CONTROL PERFORMANCE EXAMPLES

<u>Case A Plots</u>
Standing Wave, 1 N @ 0.14 Hz

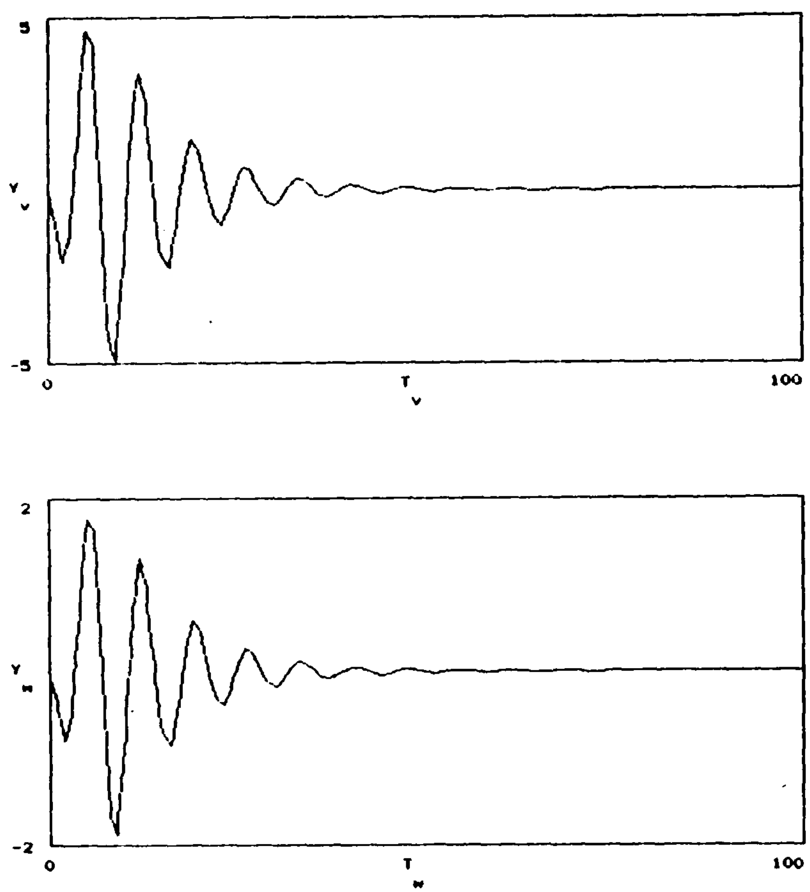


Y vs. T for 1st and 2nd measurement points
1
Y r
-1
0
T r
100
5
Y s
-5
0
T s
100

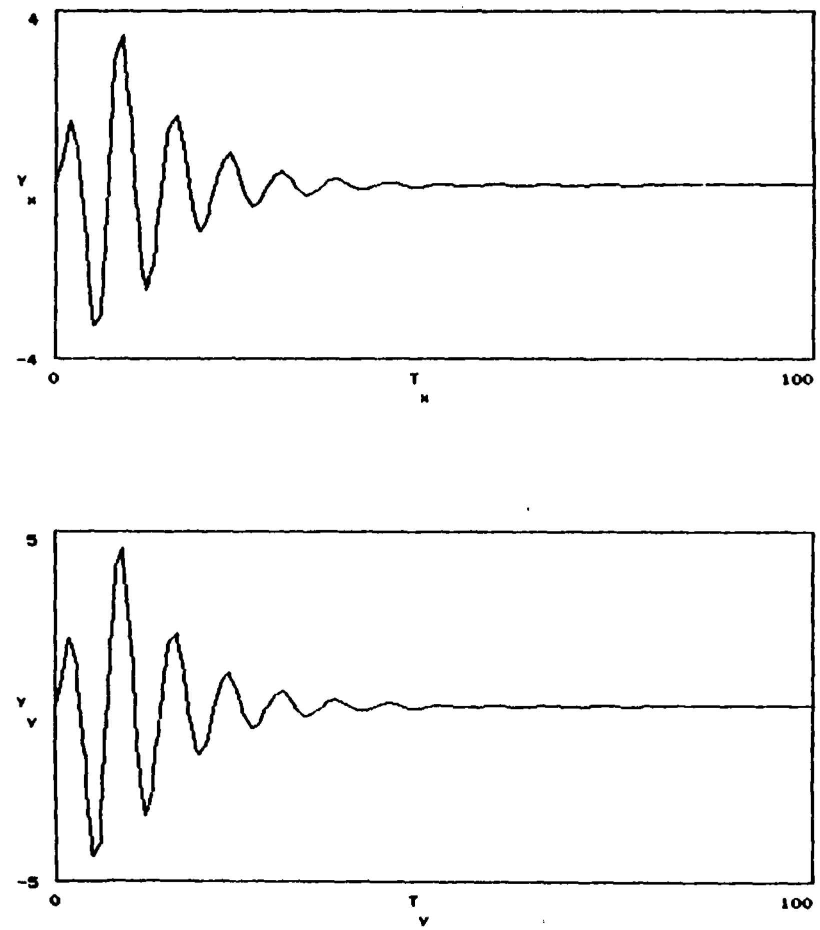


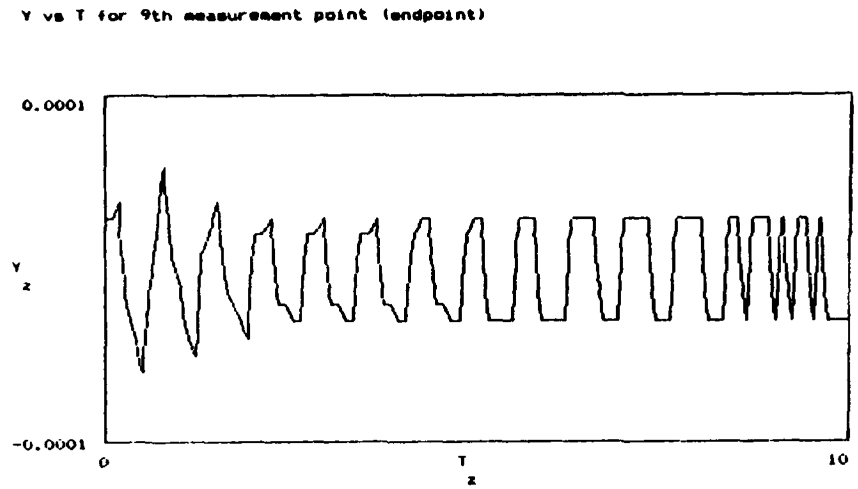
Y vs T for 3rd and 4th measurement points
4
Y t
-4
0
T t
100
2
Y u
-2
0
T u
100

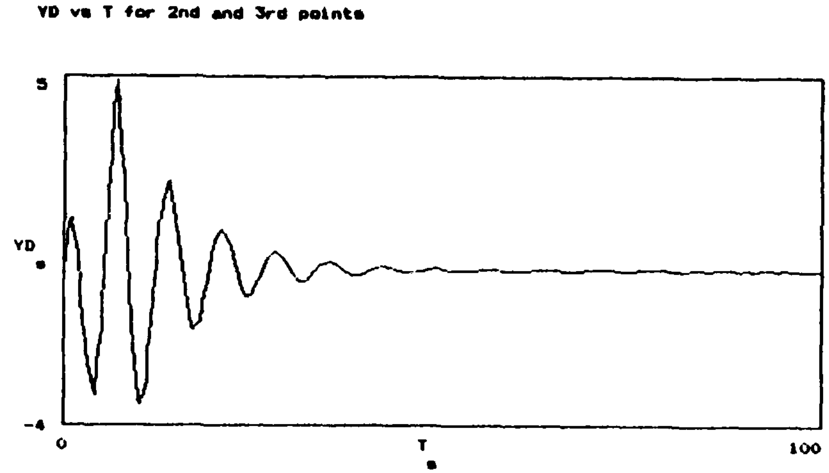
Y vs T for 5th and 6th measurement points

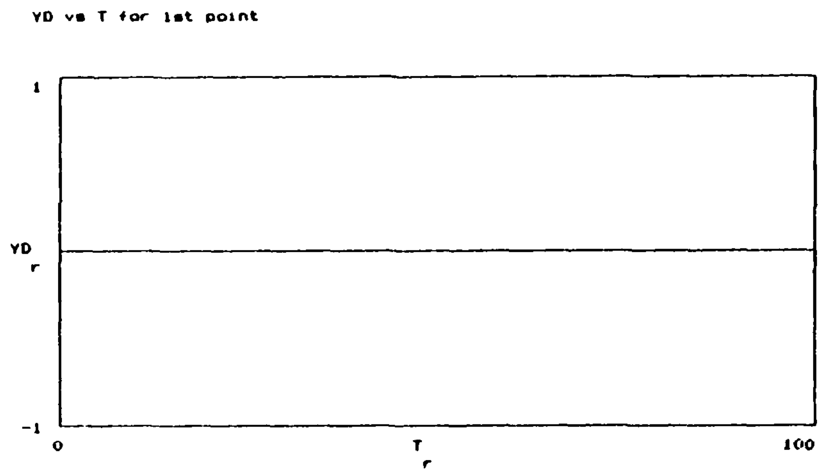


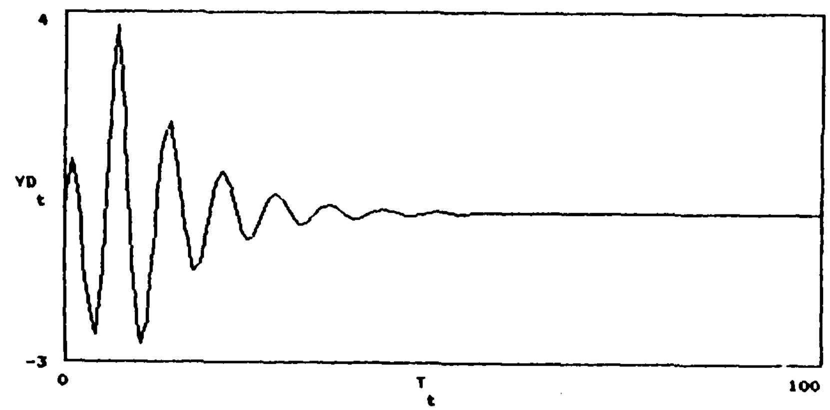
Y vs T for 7th and 8th measurement points



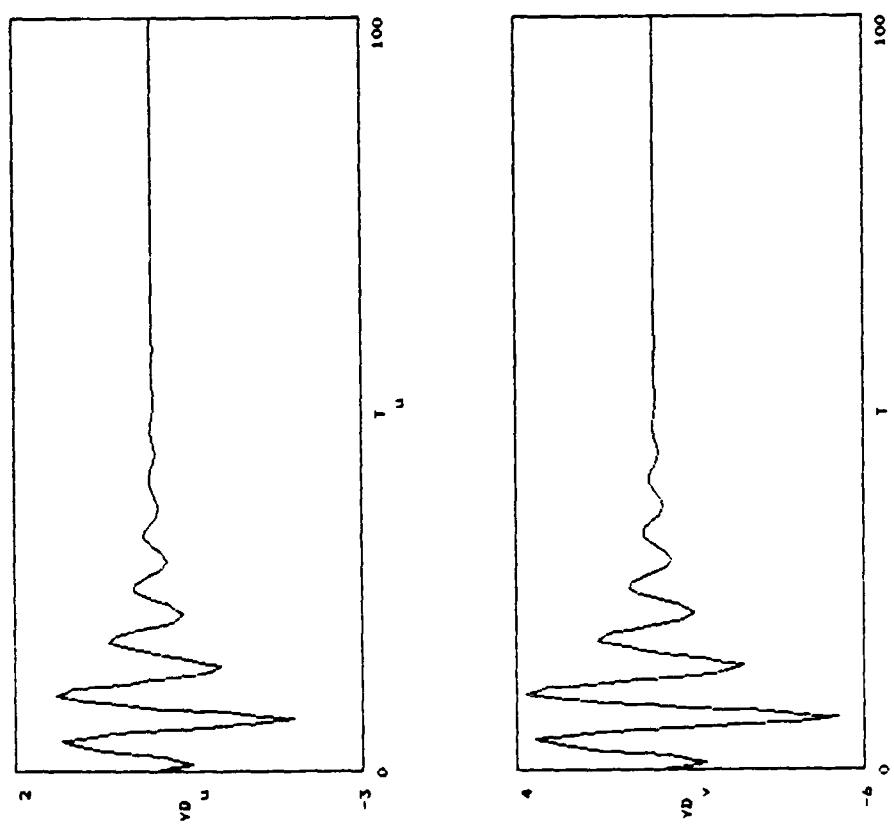

Y vs T for 9th measurement point (endpoint)
0.0001
Y
z
-0.0001
0
T
z
10


YD vs T for 2nd and 3rd points
5
YD
s
-4
0
T
s
100

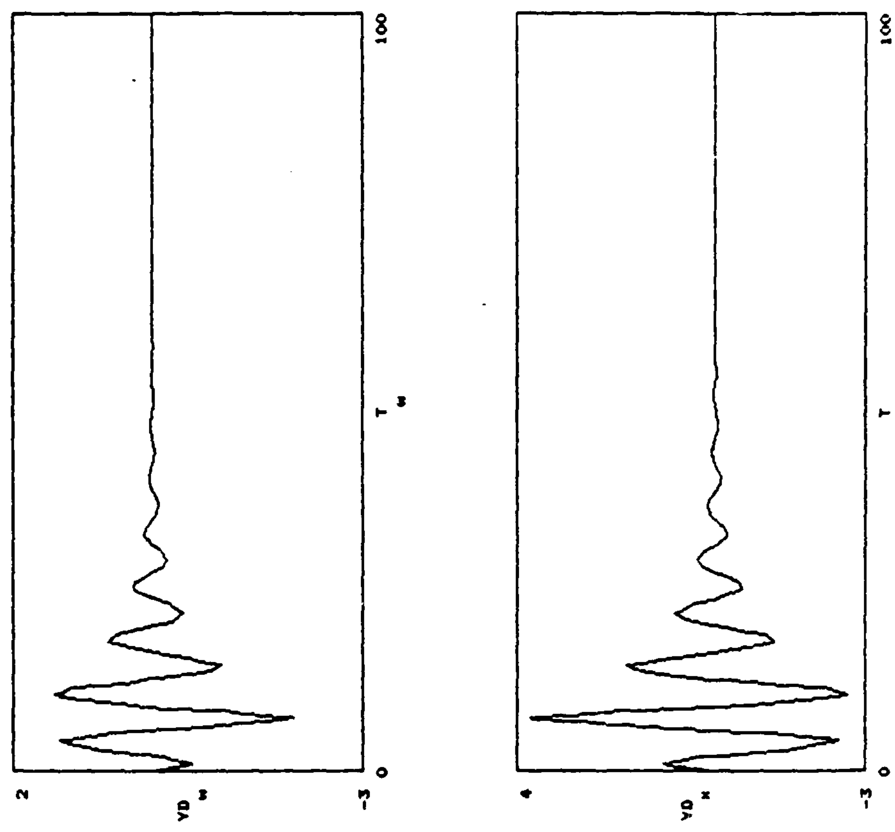

YD vs T for 1st point
1
YD
r
-1
0
T
r
100

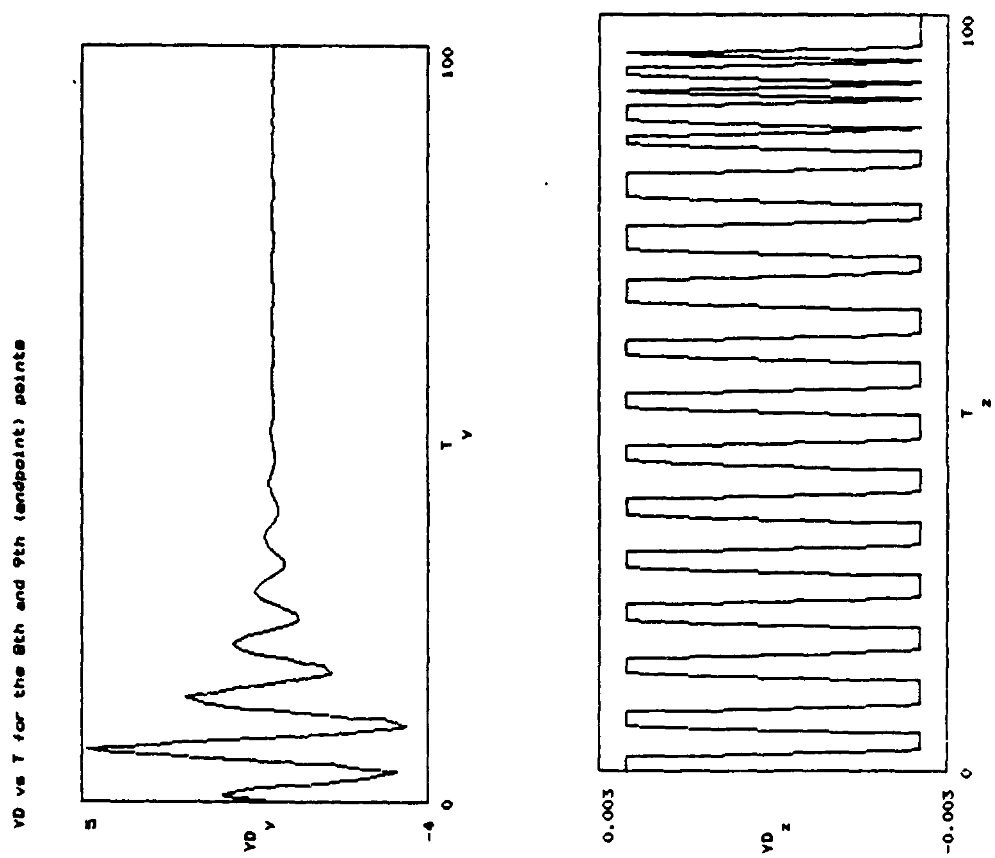

4
YD
t
-3
0
T
t
100

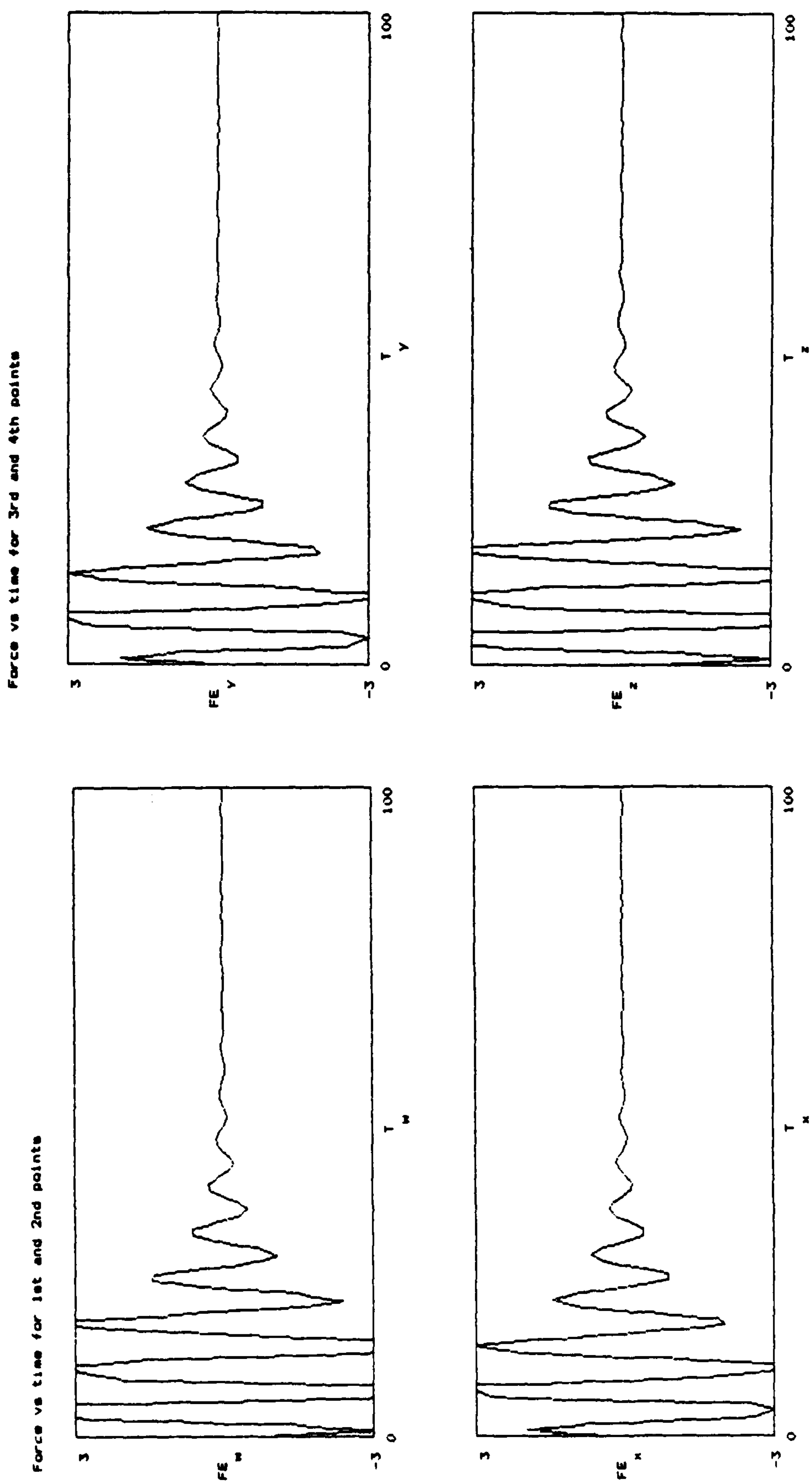
YD vs T for 4th and 5th points



YD vs T for the 6th and 7th points

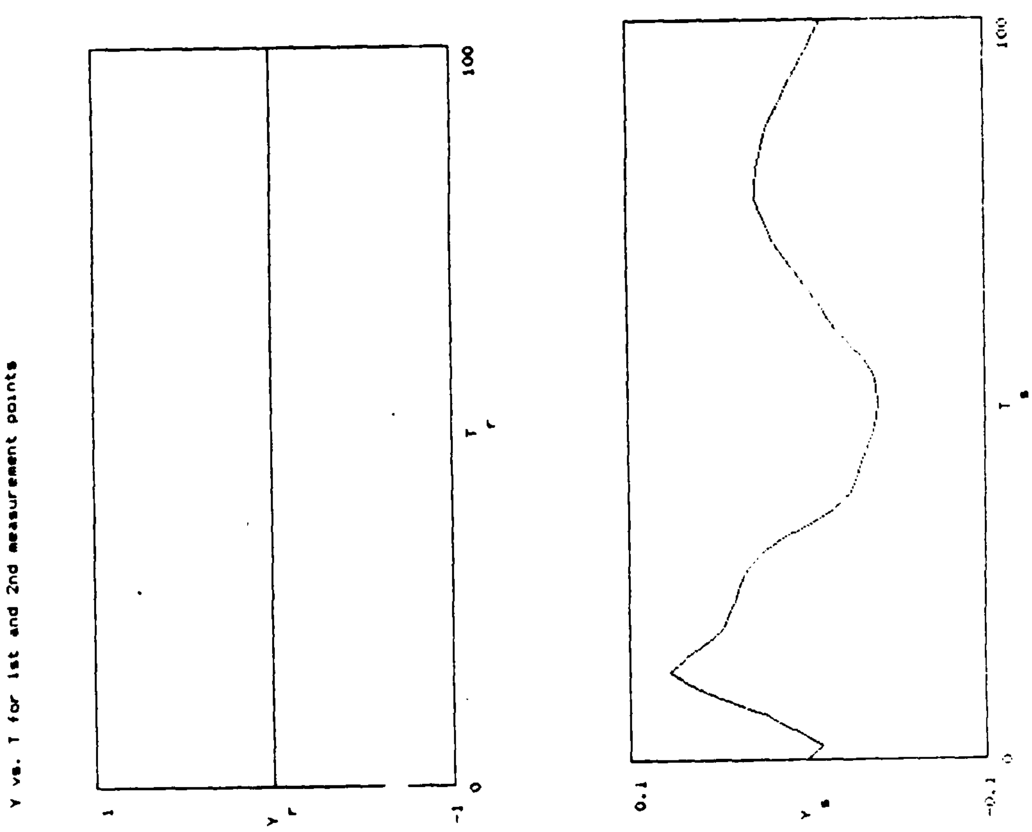


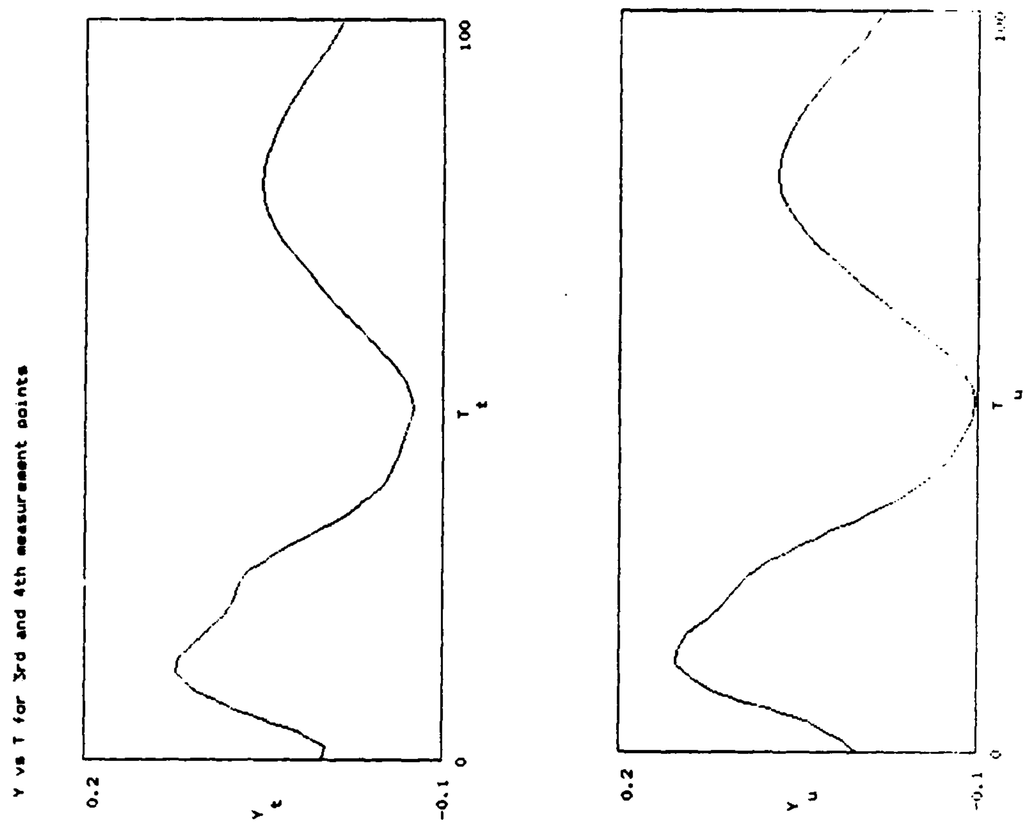

YD vs T for the 8th and 9th (endpoint) points
5
-4
YD
y
0
100
T
y
0.003
-0.003
YD
z
0
100
T
z


Force vs time for 1st and 2nd points
Force vs time for 3rd and 4th points
FE w
FE x
FE y
FE z
T w
T x
T y
T z
3
-3
0
100

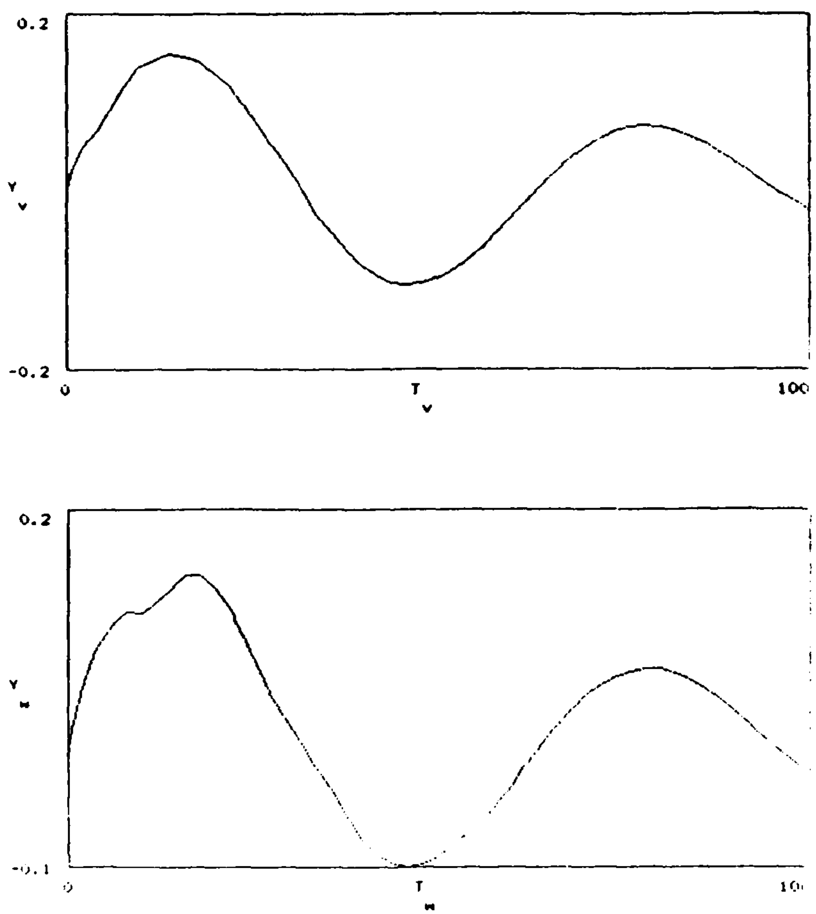
Case B Plots

1 N Impulse @ 6.3 meters

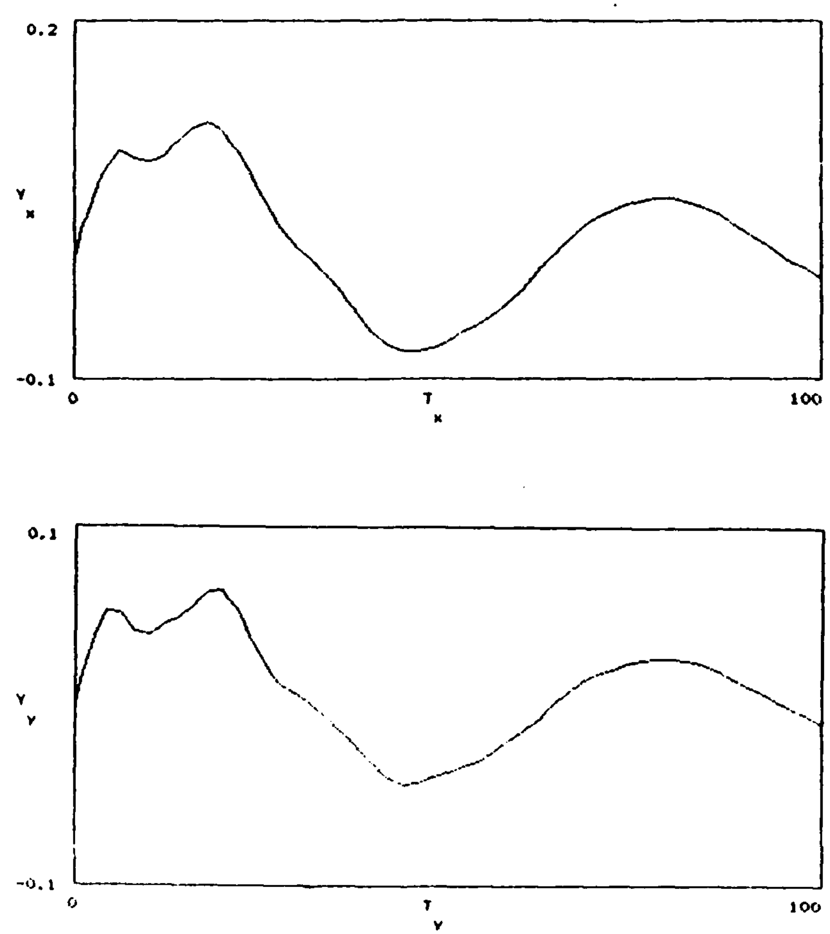

Y vs. T for 1st and 2nd measurement points
1
Y r
-1
0
T r
100
0.1
Y s
-0.1
0
T s
100


Y vs T for 3rd and 4th measurement points
0.2
Y t
-0.1
0
T t
100
0.2
Y u
-0.1
0
T u
100

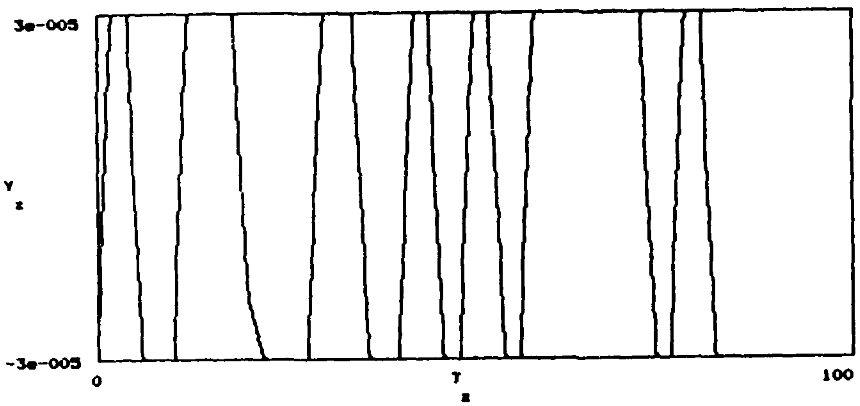
Y vs T for 5th and 6th measurement points



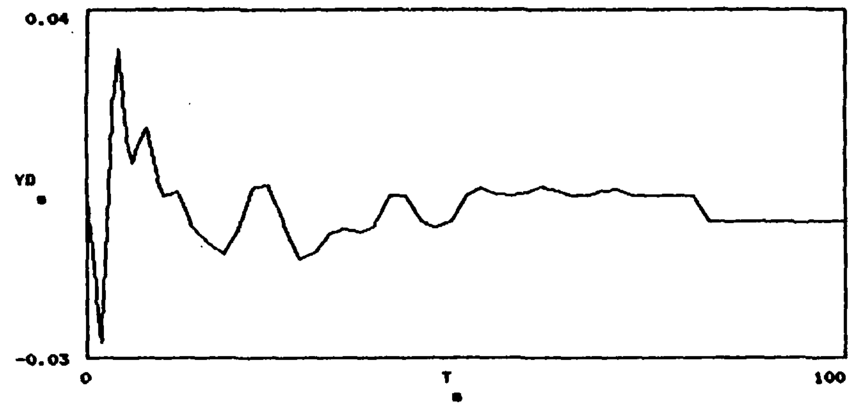
Y vs T for 7th and 8th measurement points



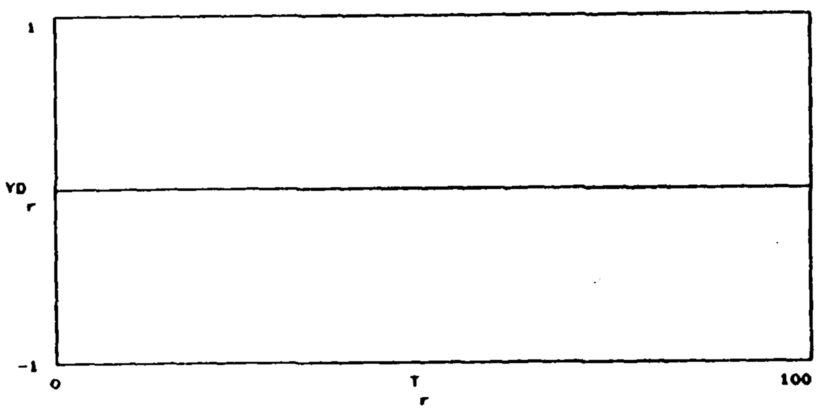
Y vs T for 9th measurement point (endpoint)

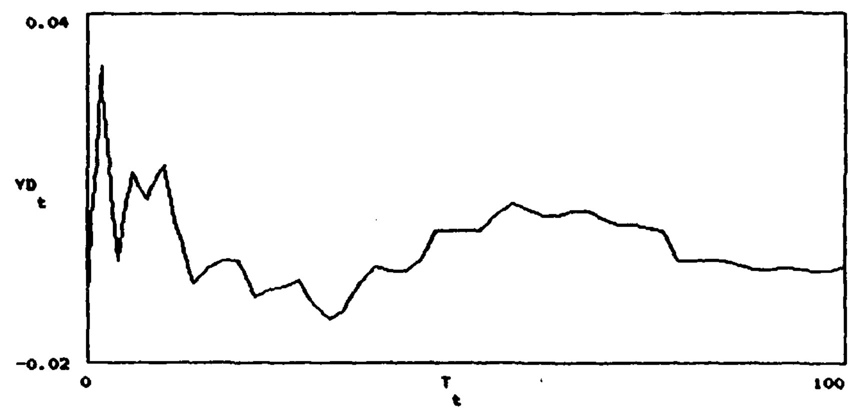


YD vs T for 2nd and 3rd points

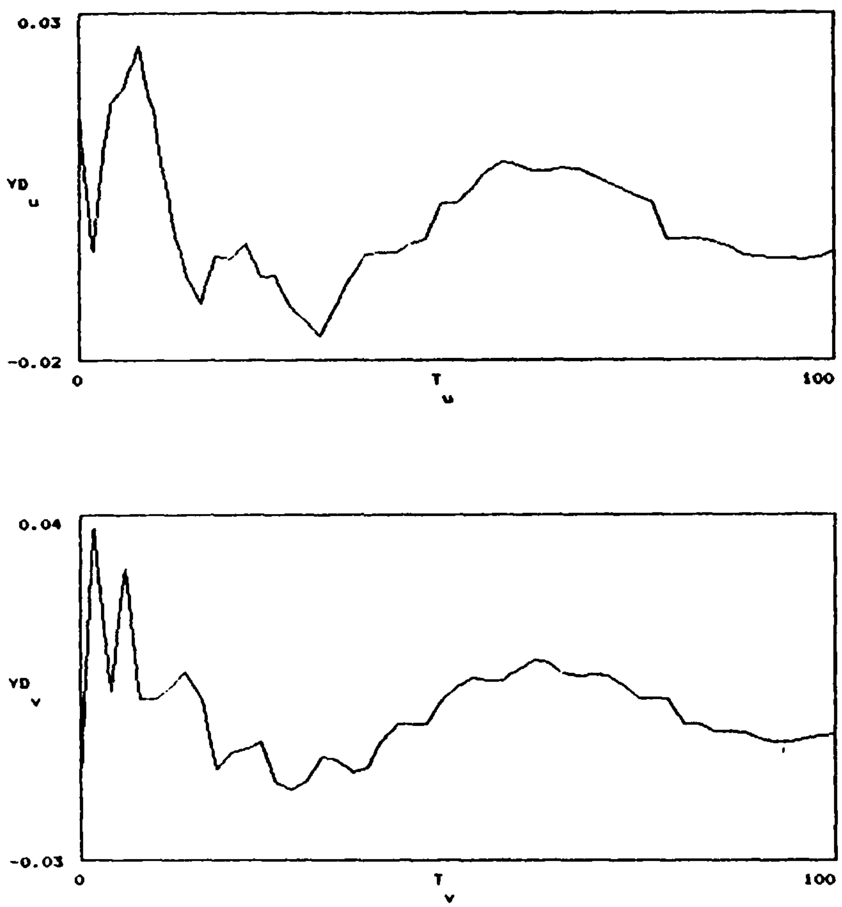


YD vs T for 1st point

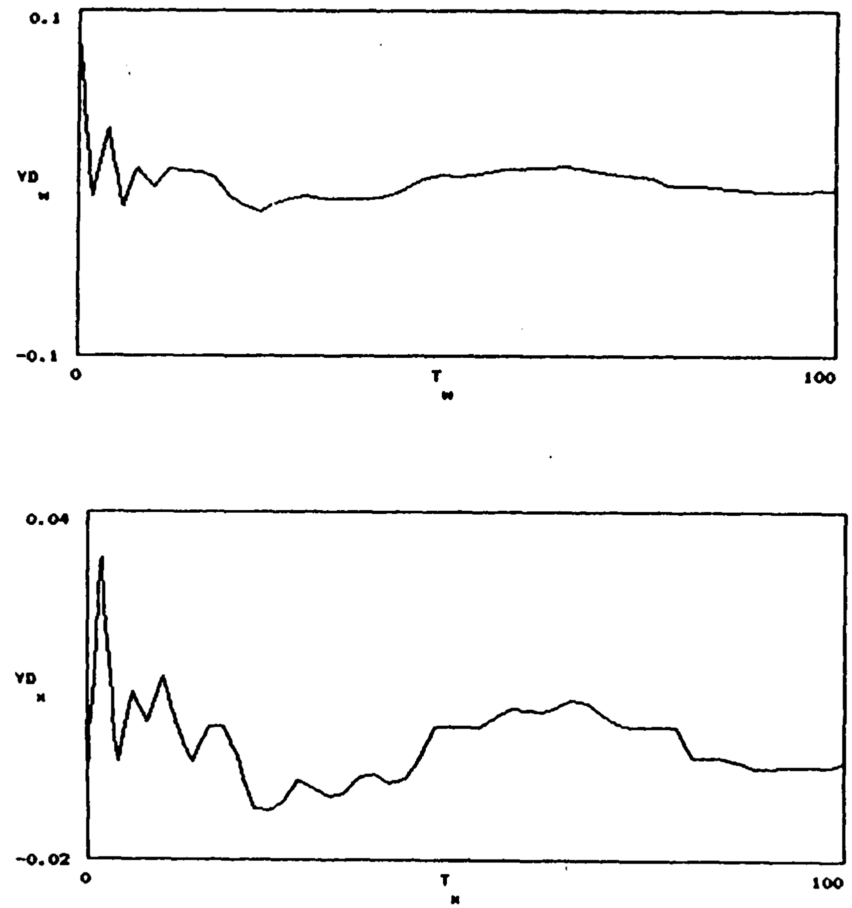


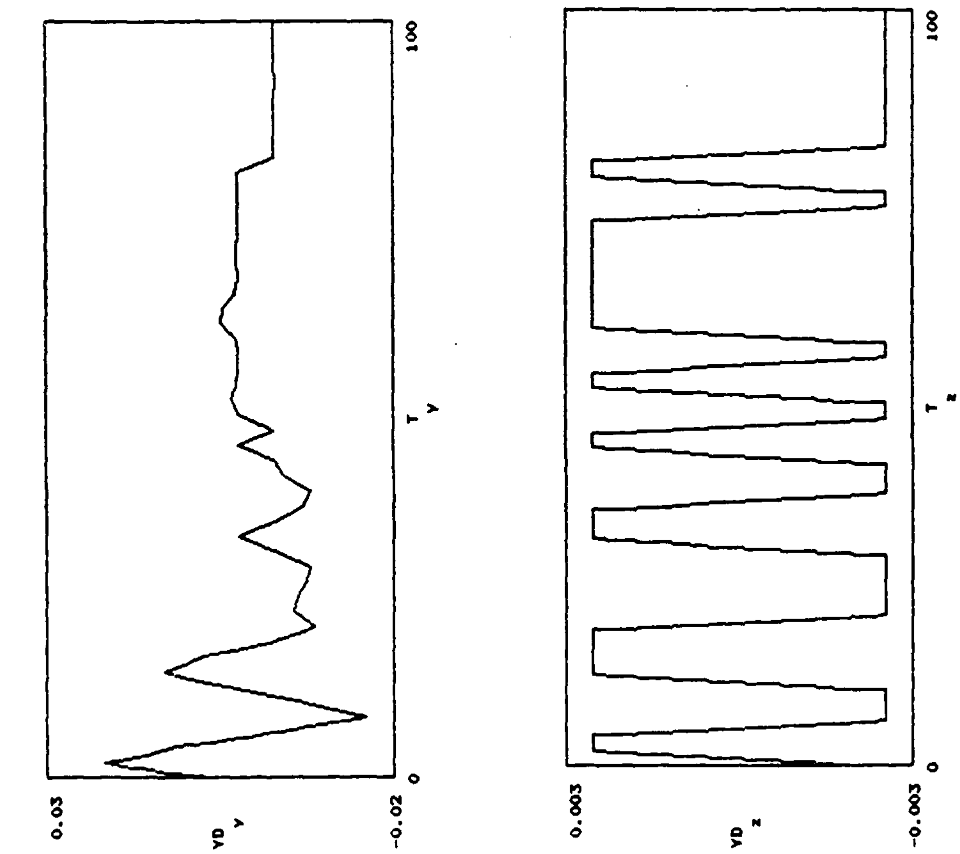


YD vs T for 4th and 5th points

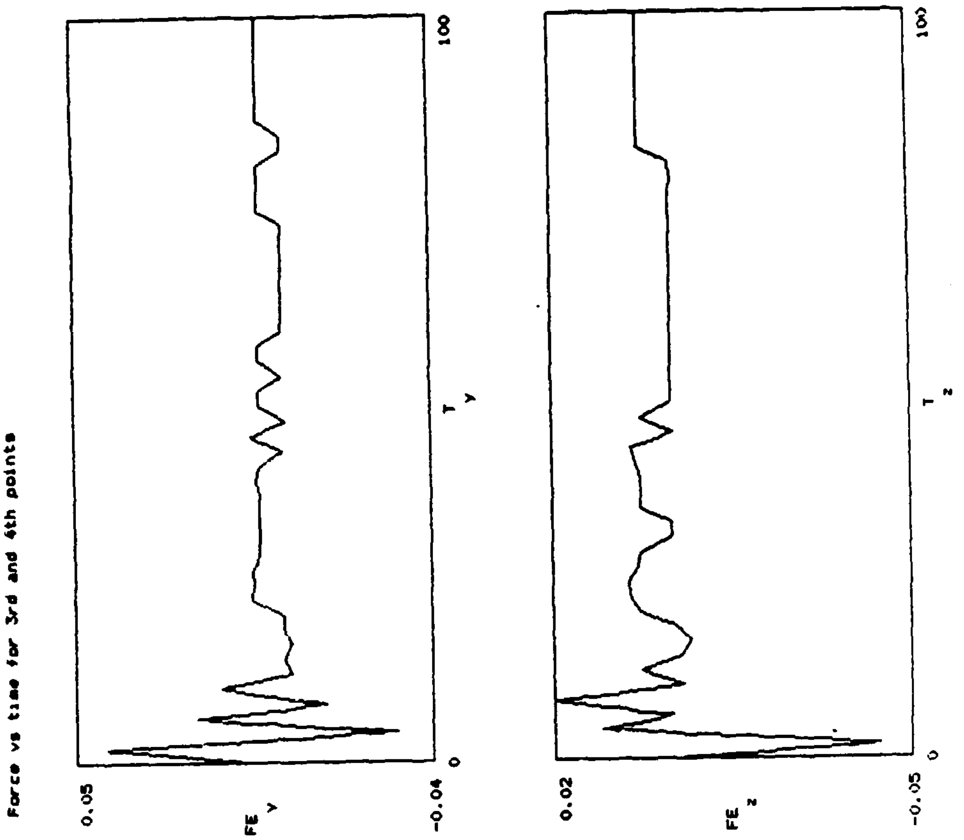


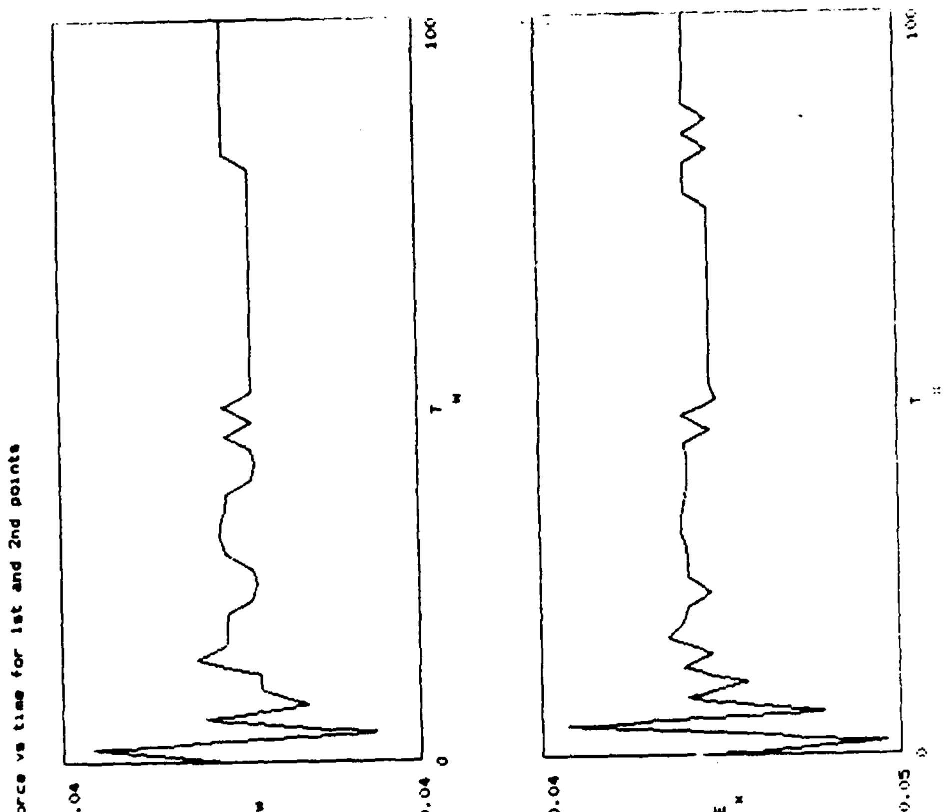
YD vs T for the 6th and 7th points





YD vs T for the 8th and 9th (endpoint) points

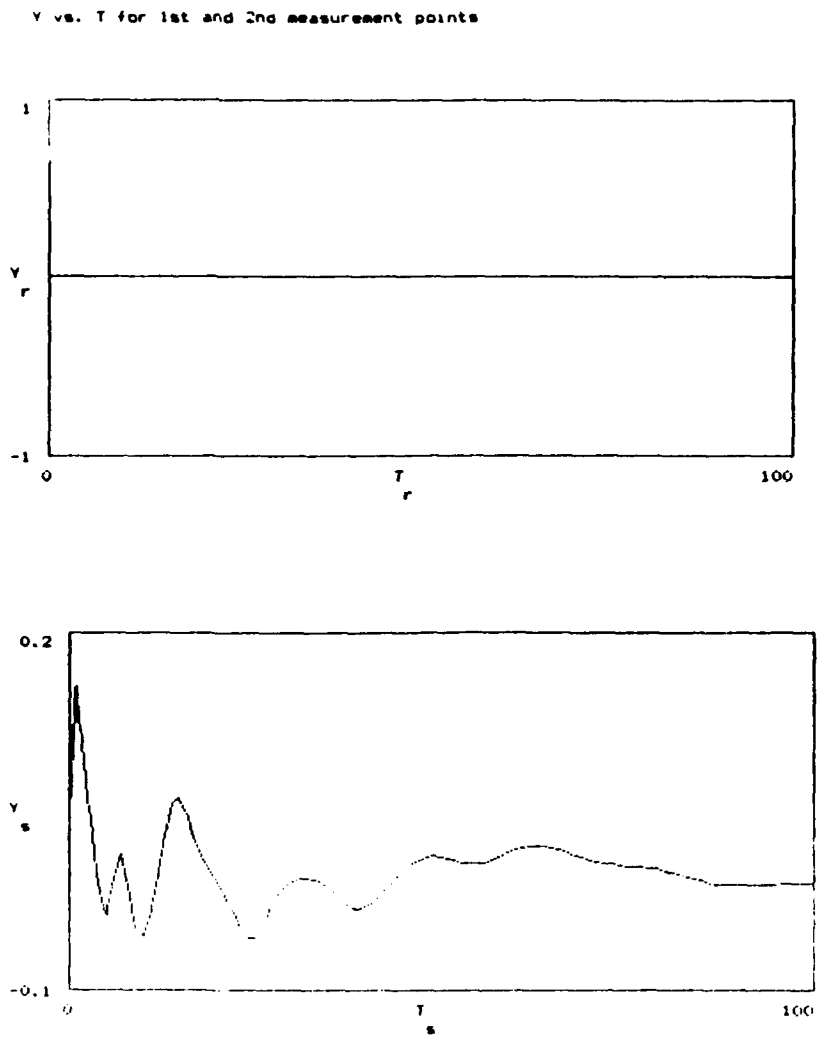

Force vs time for 3rd and 4th points
0.05
FE y
-0.04
0
T y
100
0.02
FE z
-0.05
0
T z
100

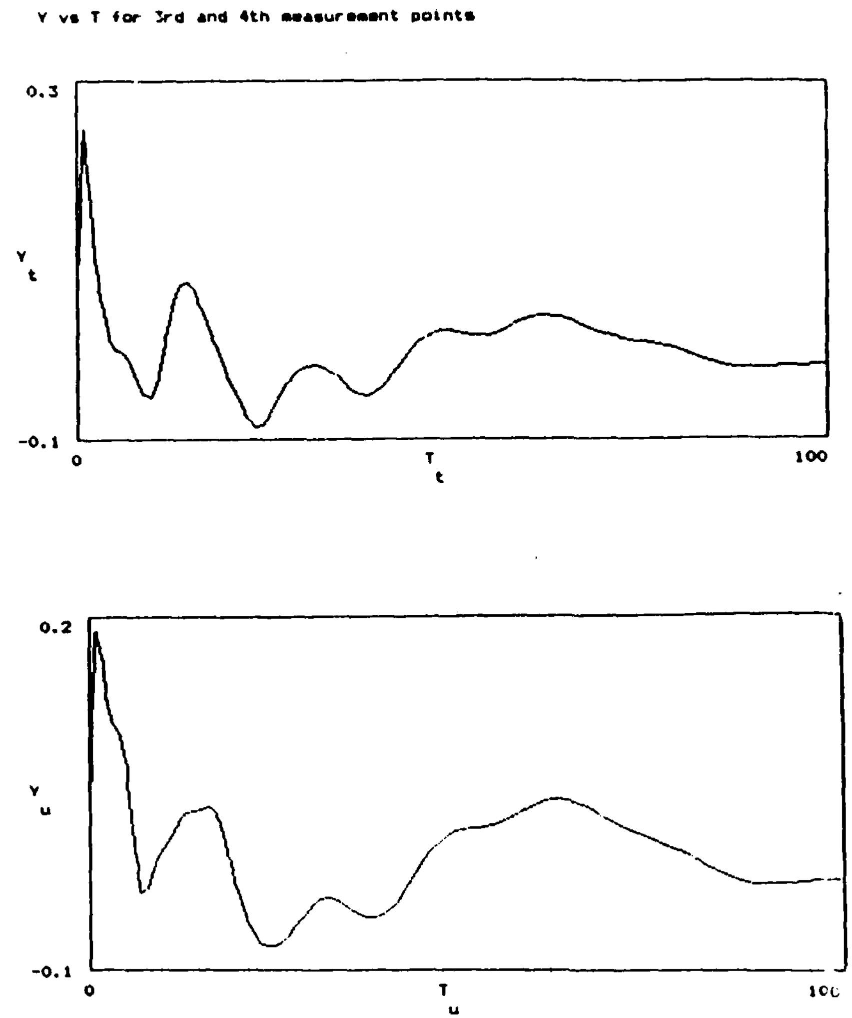

Force vs time for 1st and 2nd points
0.04
FE w
-0.04
0
T w
100
0.04
FE x
-0.05
0
100

Case C Plots

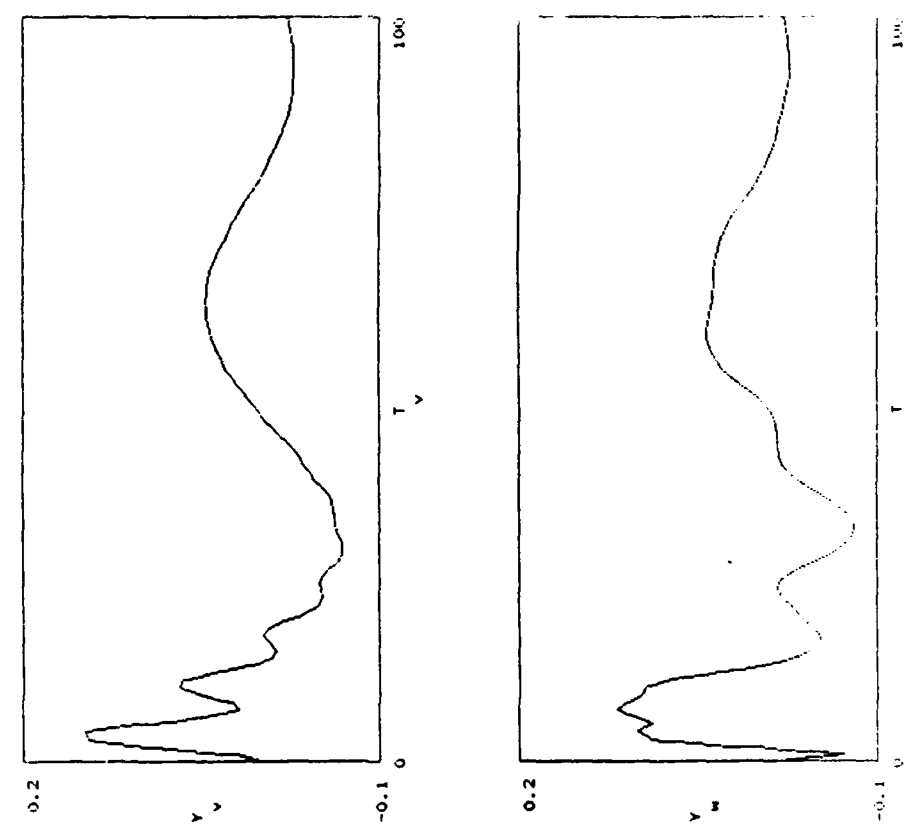
Traveling Wave, 25 cm Amplitude

$\lambda = 2.5625$ meters

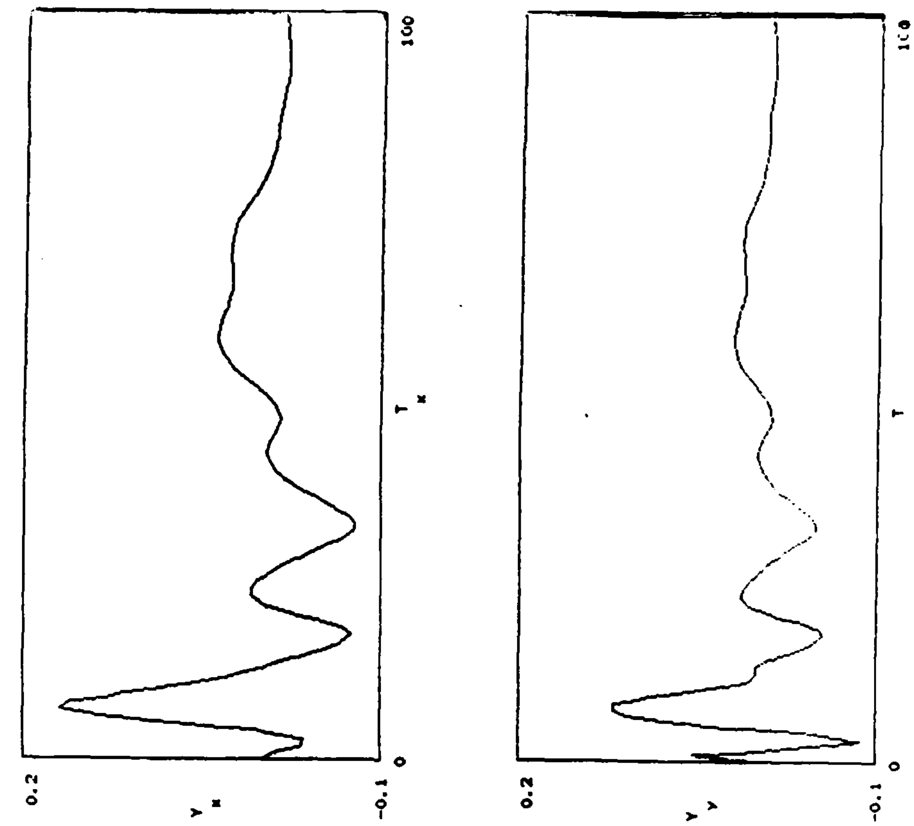

Y vs. T for 1st and 2nd measurement points
1
Y r
-1
0
T r
100
0.2
Y s
-0.1
0
T s
100

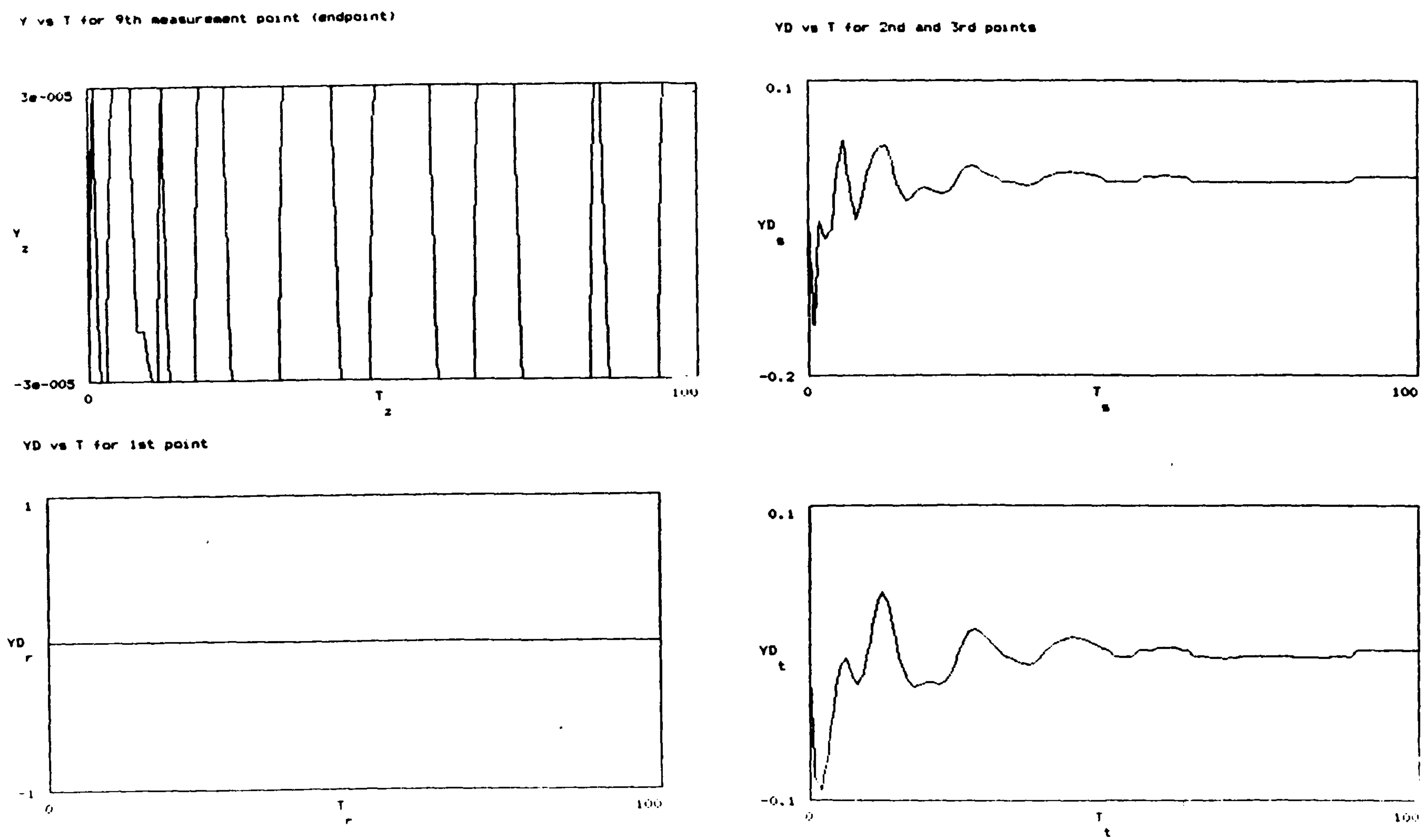

Y vs T for 3rd and 4th measurement points
0.3
Y t
-0.1
0
T t
100
0.2
Y u
-0.1
0
T u
100

Y vs T for 5th and 6th measurement points

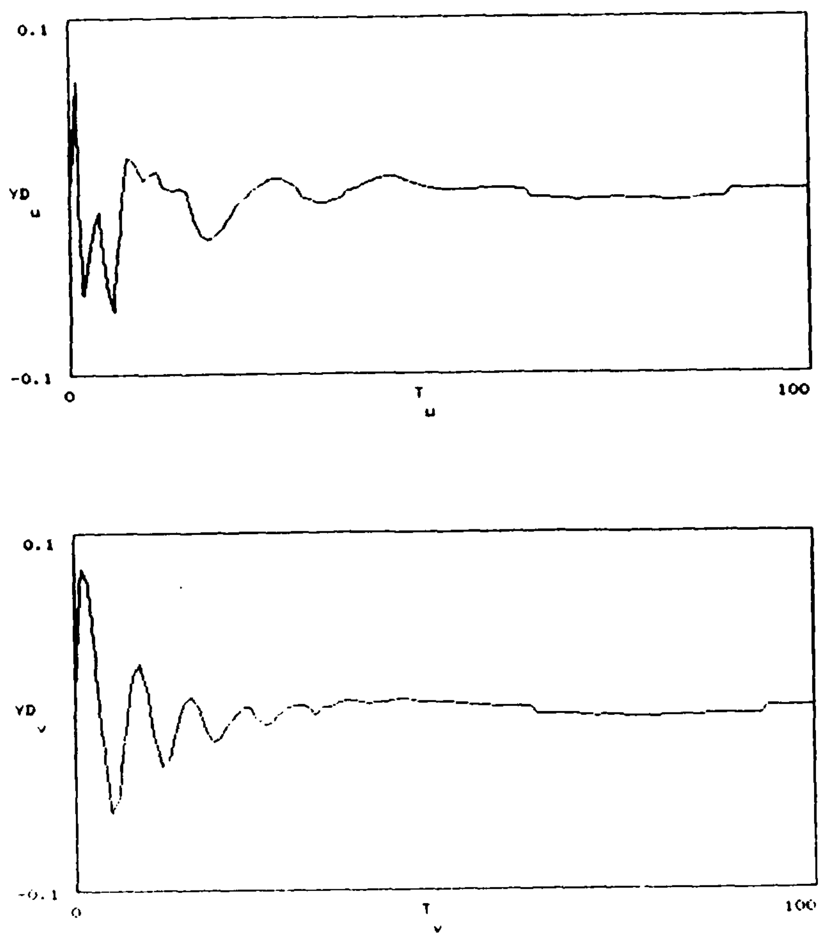


Y vs T for 7th and 8th measurement points

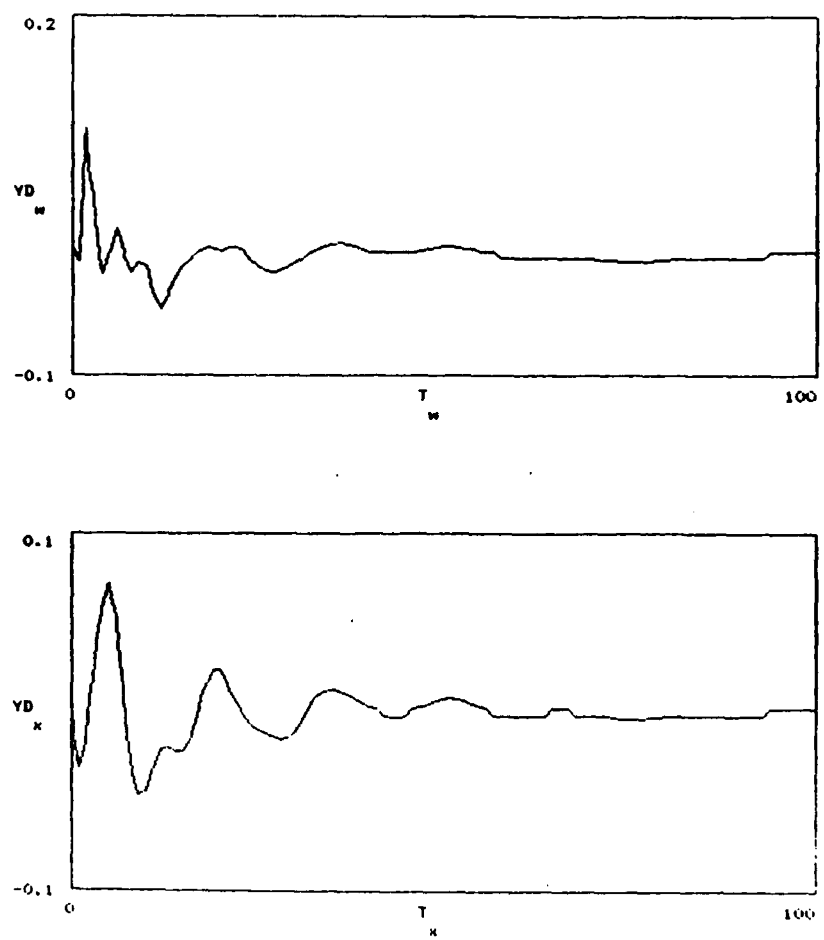



Y vs T for 9th measurement point (endpoint)
3e-005
-3e-005
Y
z
0
T
z
100
YD vs T for 2nd and 3rd points
0.1
-0.2
YD
s
0
T
s
100
YD vs T for 1st point
1
-1
YD
r
0
T
r
100
0.1
-0.1
YD
t
0
T
t
100

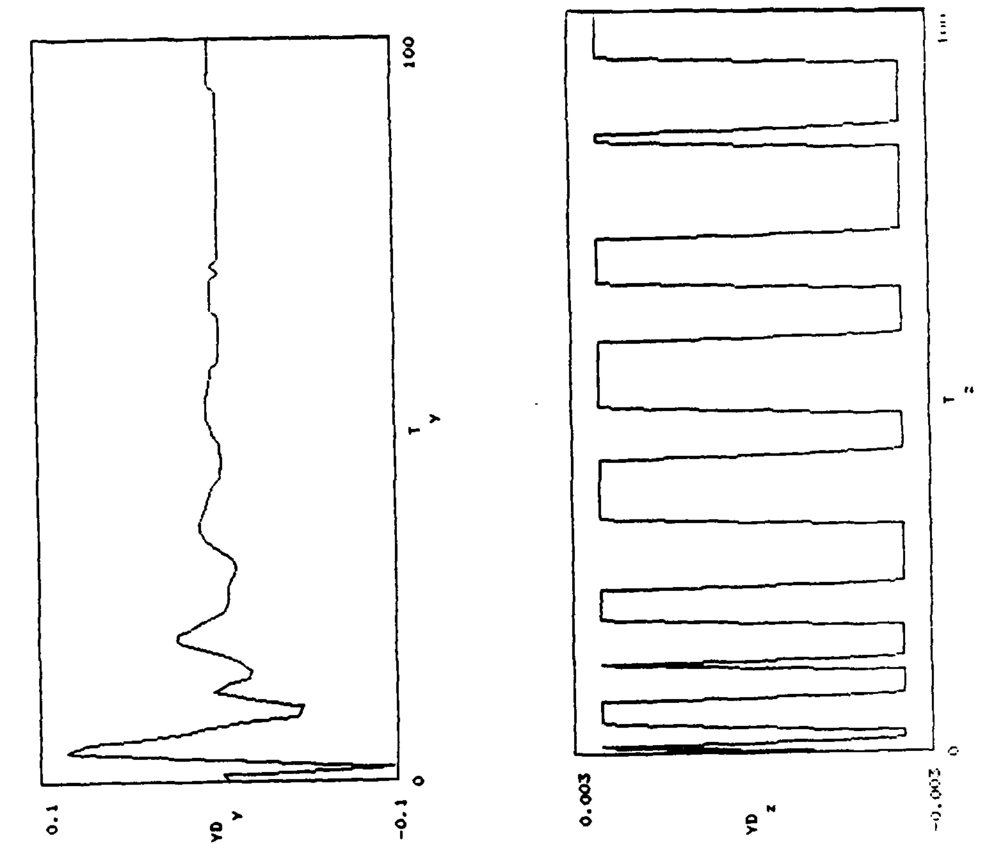
YD vs T for 4th and 5th points



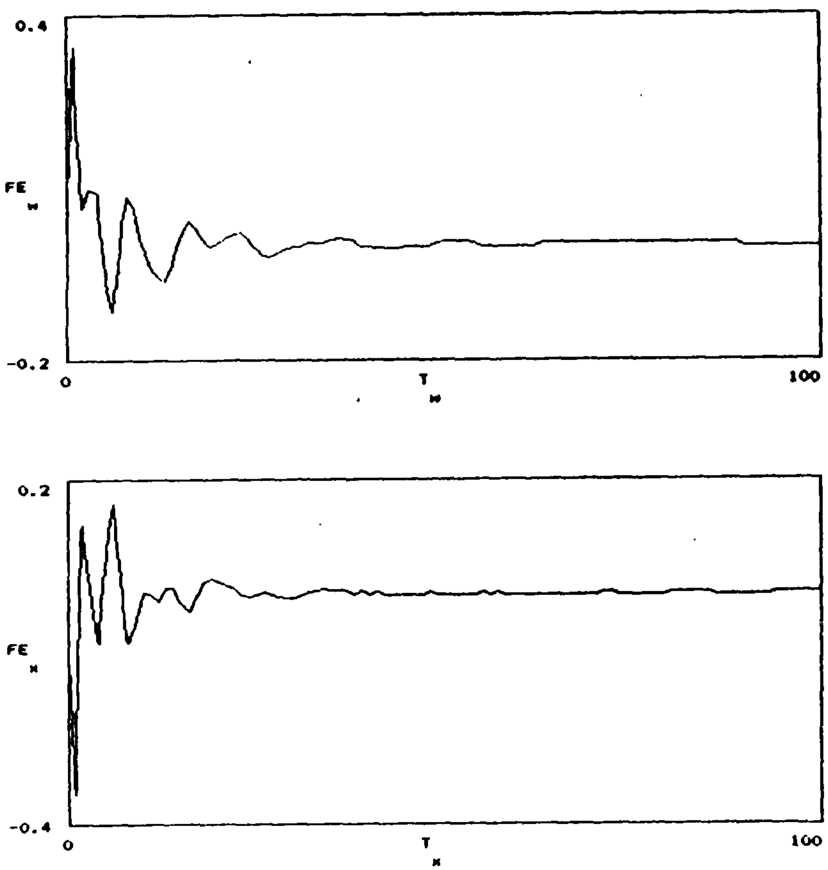
YD vs T for the 6th and 7th points



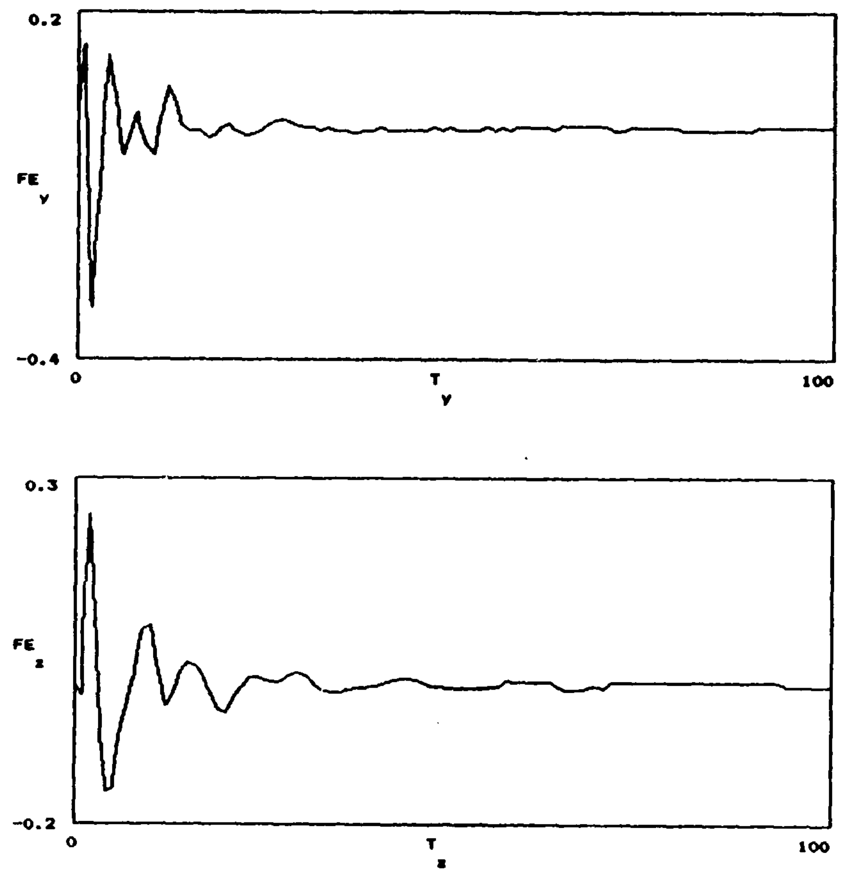
YD vs T for the 8th and 9th (endpoint) points



Force vs time for 1st and 2nd points

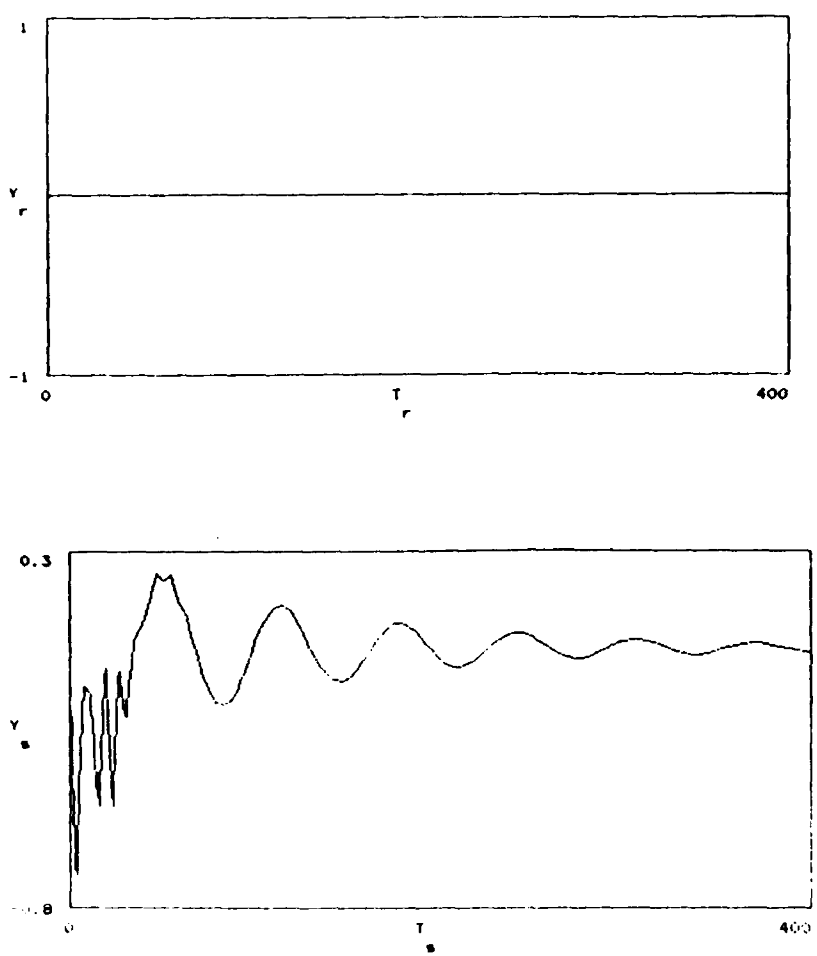


Force vs time for 3rd and 4th points

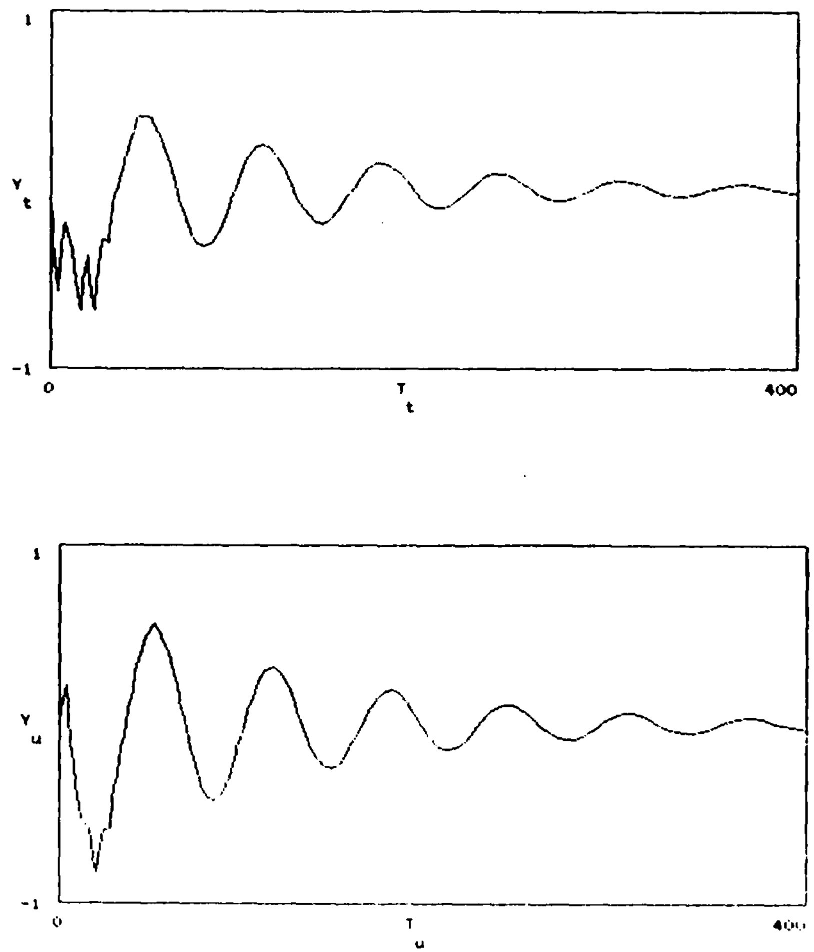


Case D Plots
Wideband Disturbance

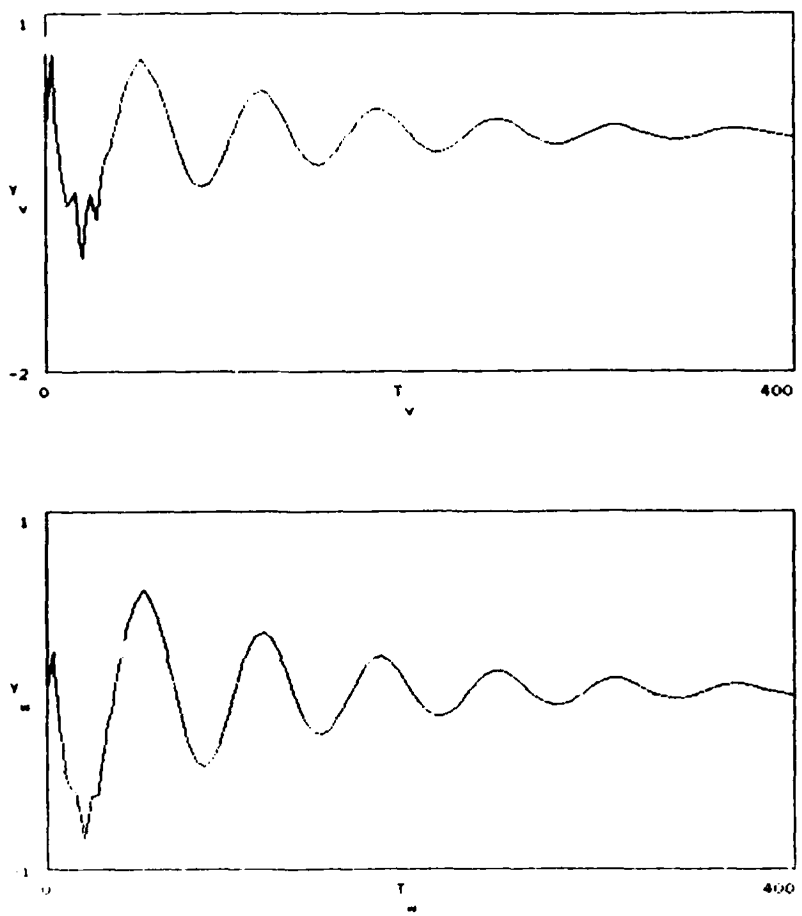
Y vs. T for 1st and 2nd measurement points



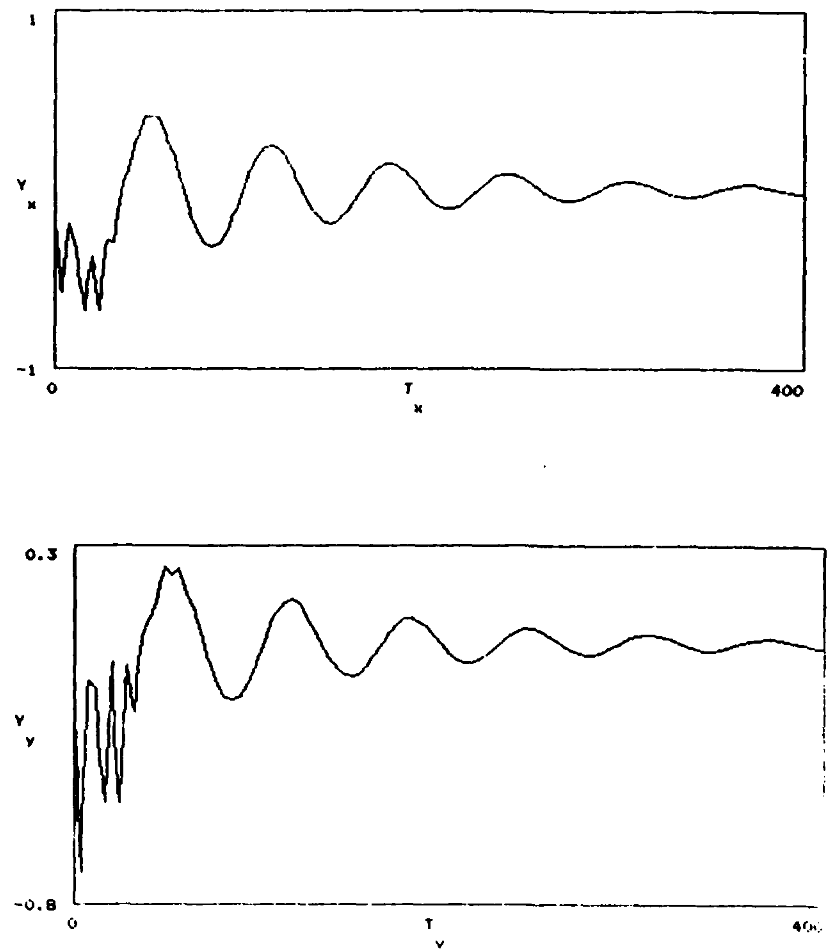
Y vs T for 3rd and 4th measurement points

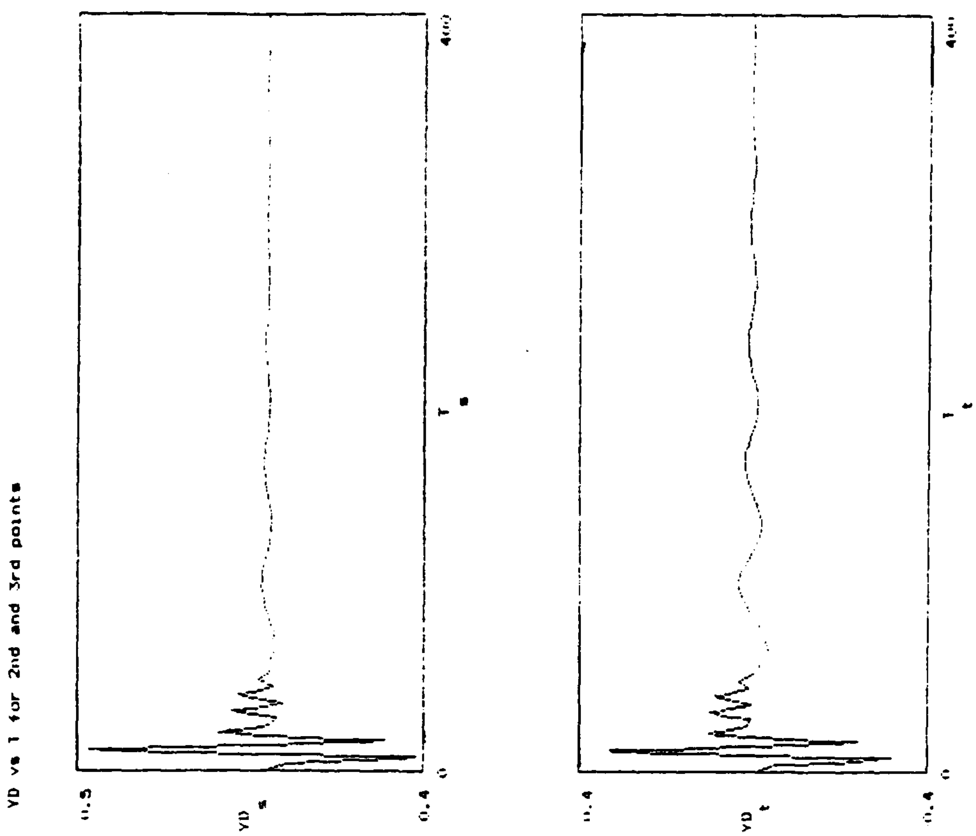


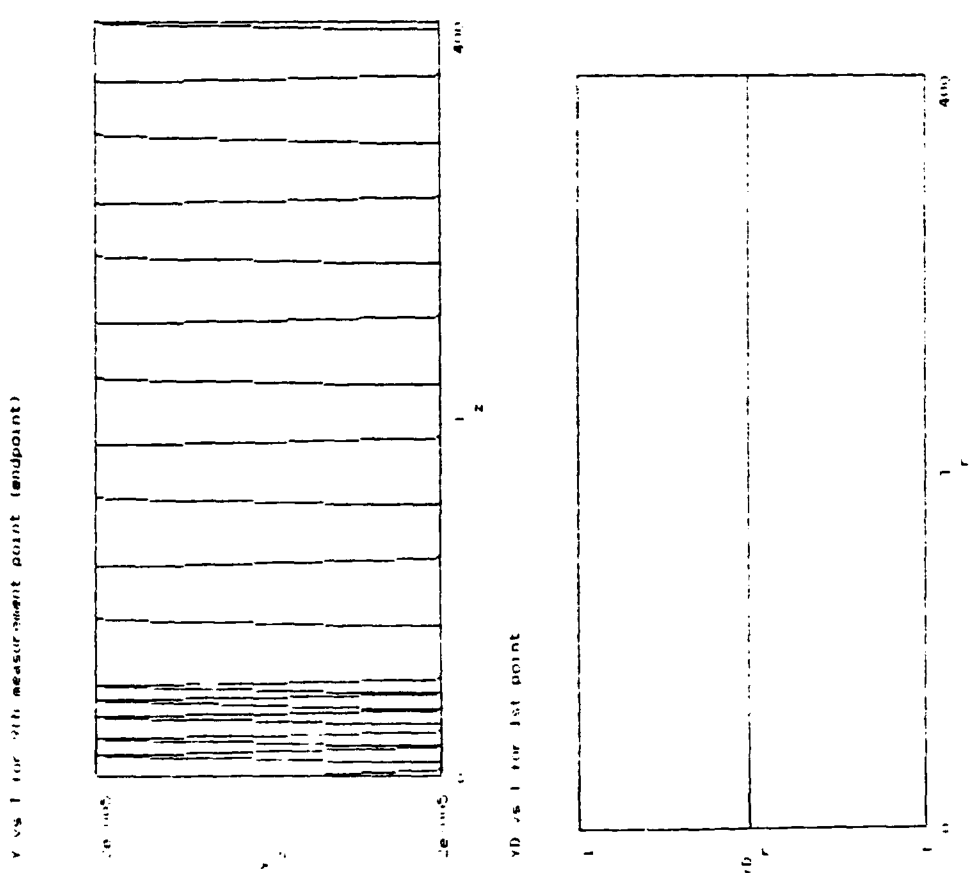
Y vs T for 5th and 6th measurement points

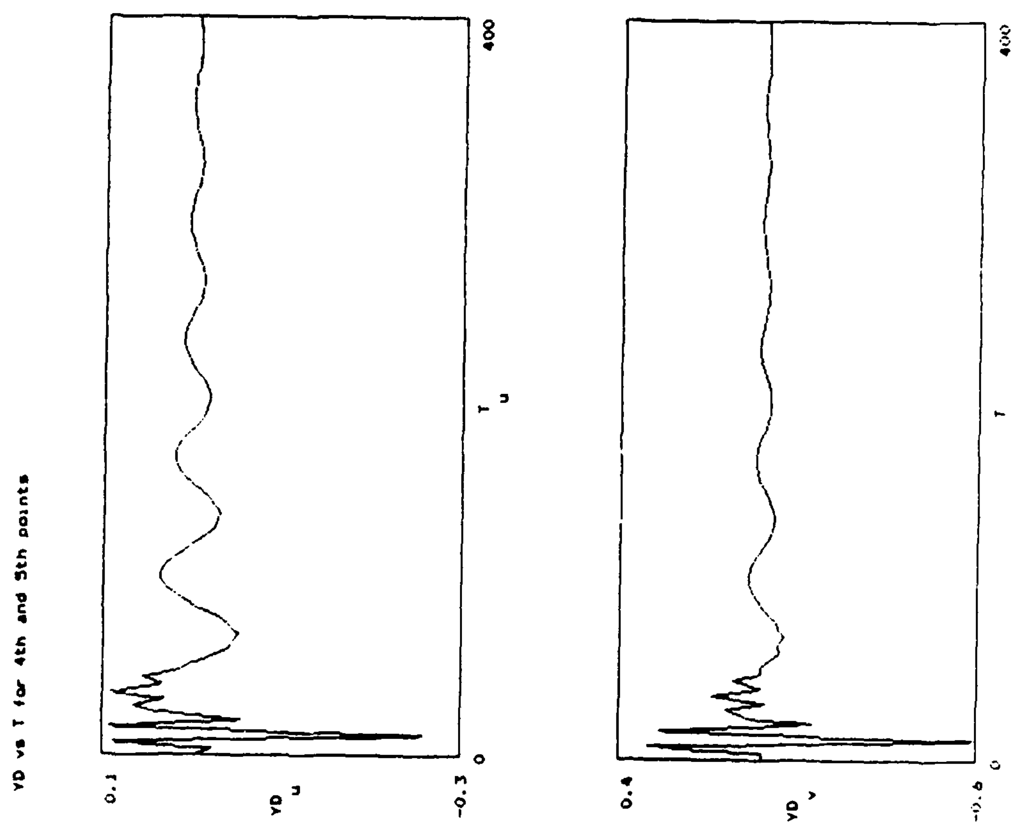


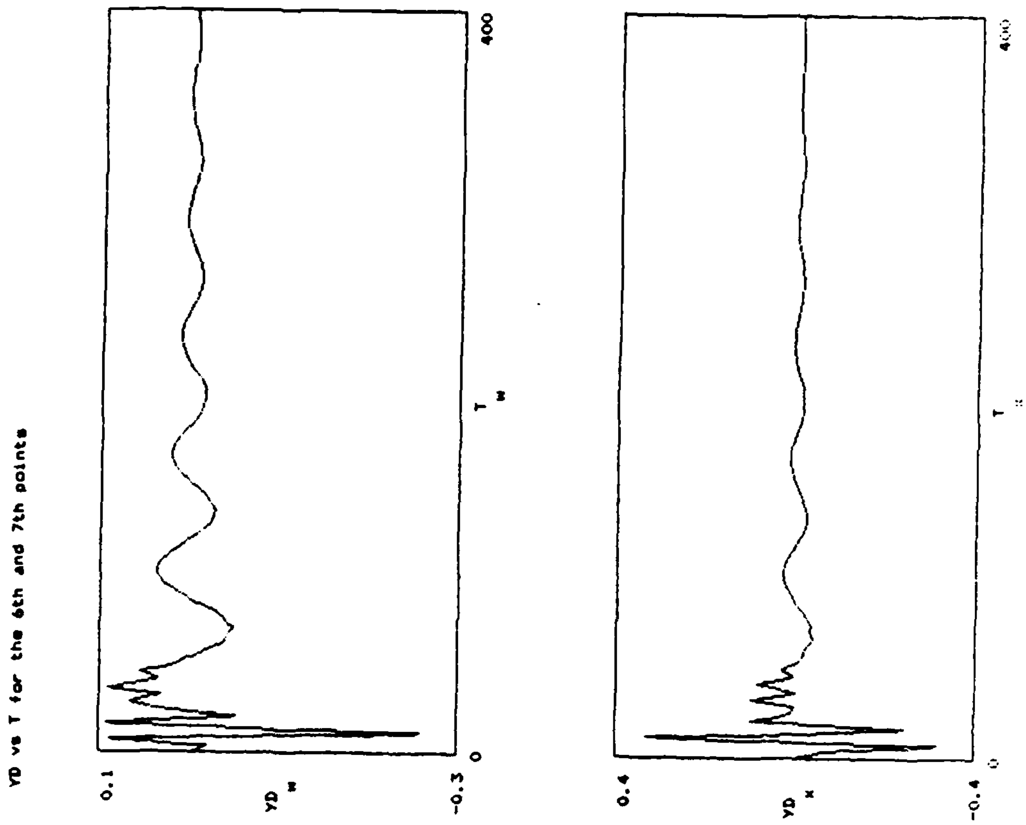
Y vs T for 7th and 8th measurement points

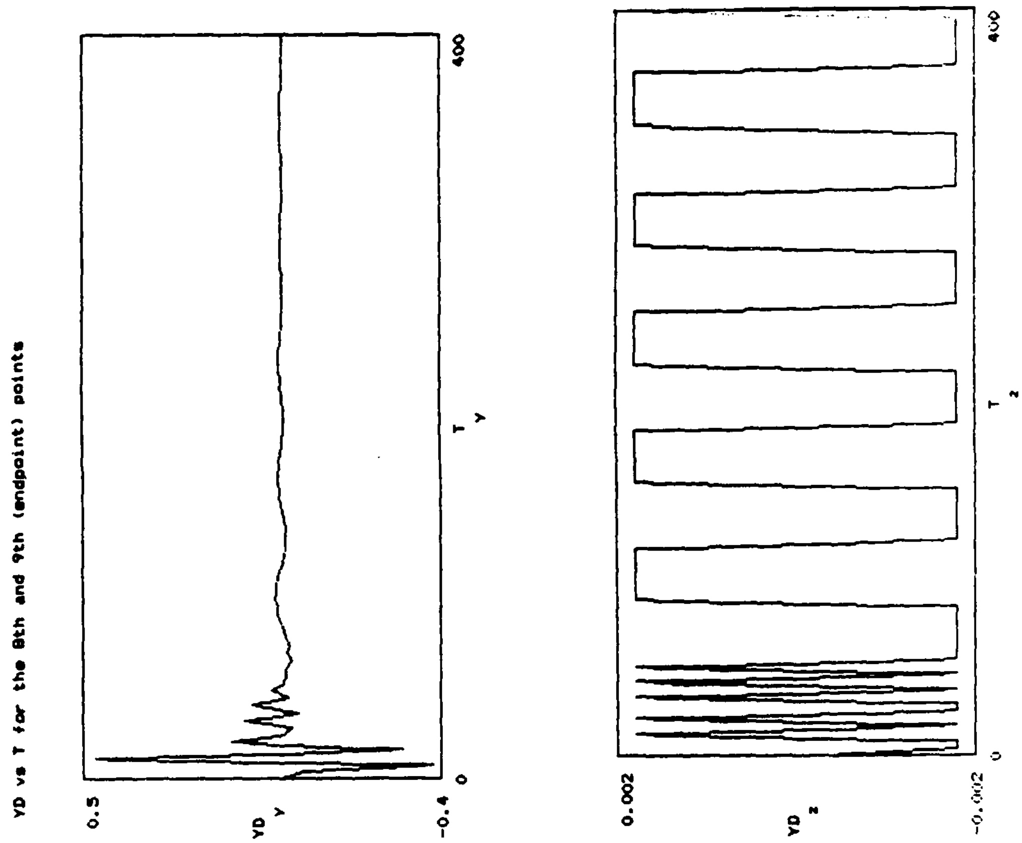



YD vs T for 2nd and 3rd points
0.4
400
0


Y vs T for 9th measurement point (endpoint)
YD vs T for 1st point
400
0

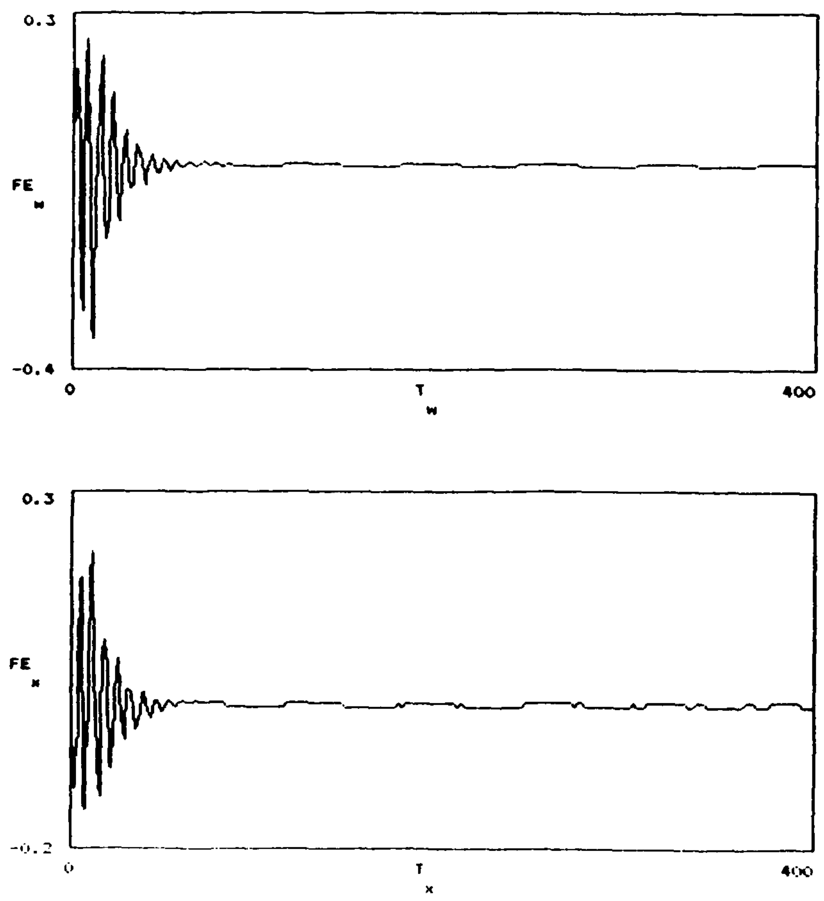

YD vs T for 4th and 5th points
0.1
YD_u
-0.3
0
T_u
400
0.4
YD_v
-0.6
0
T_v
400


YD vs T for the 6th and 7th points
0.1
YD_w
-0.3
0
T_w
400
0.4
YD_x
-0.4
0
T_x
400

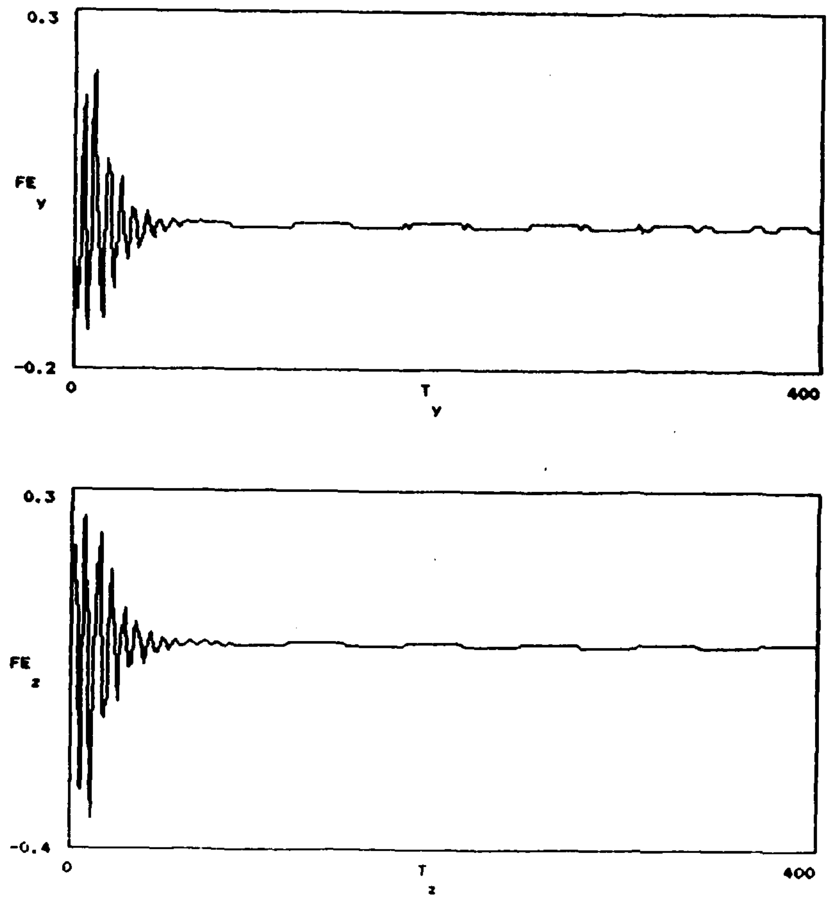


YD vs T for the 8th and 9th (endpoint) points
0.5
YD y
-0.4
0
T y
400
0.002
YD z
-0.002
0
T z
400

Force vs time for 1st and 2nd points



Force vs time for 3rd and 4th points



4.6 REFERENCES

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L. Meirovitch and H. Baruh, "Control of Self-Adjoint Distributed-Parameter Systems," Journal of Guidance and Control, Vol. 5, pp. 60-66, June-February 1982.

L. Meirovitch and H. Baruh, "Robustness of the Independent Modal-Space Control Method," Journal of Guidance and Control, Vol. 6, No. 1, pp. 20-25, January-February 1983.

CHAPTER 5
LOGIC-BASED CONTROL IMPLEMENTATION

5.0 INTRODUCTION

The logic based control system referred to as the Expert System Controller (ESC) is described in this section, including a description of the underlying methodology, specific design features, and performance results. Logic based systems differ from numerical control systems in the method that the actuator force is derived. The numerical control systems are strictly algorithmic, where the force is derived from an equation with velocities and structure mass and weight variables, as described in Chapter 4. In contrast, the logic based system is dependent on a set of rules, where the force is derived from the relation of the input case to the set of rules. For this study, the inputs are the simulated sensor velocities, and the mass and weight are implicitly contained in the rule set, i.e., significantly different structural variables would require a different set of rules.

The logic based control system was developed with a PC-based expert system application generator named TIMM, The Intelligent Machine Model. TIMM provided the framework for specifying the logic based controller, and the algorithm for implementation. The TIMM implementation software was extended to handle more input factors, output factors, and rules for this study.

TIMM was selected because of its unique methodology for interpreting its rules. It is an example or data-driven system that requires no a priori knowledge about underlying data distributions. Representative data can be used to create the rule base for usage with extended sets of data. TIMM's strength lies in the fact that it can infer conclusions from the representative set of rules, and furthermore, infer conclusions when the input set is not completely specified, e.g., sensor degradation, or dropout.

5.1 EXPERT SYSTEM CONTROLLER DEVELOPMENT

The components of a logic based system include the (1) decision structure which is the definition of the inputs and outputs, (2) knowledge base which contains the rules that map the inputs to the outputs, and (3) inference engine which is the software program that interprets the knowledge base, i.e., determines the optimal output(s) given a specific input case.

5.1.1 Decision Structure

TIMM works on bounded decision (or classification) problems. This type of problem has an input list, an output list, and the knowledge which maps the input to the output. A bounded problem has finite lists. That is, it does not allow dynamic creation of new input parameters, or dynamic generation of new output decisions.

In relation to this project, we wanted to determine the appropriate force to apply to a large space structure to regain its stability after it had been disturbed. This problem is a decision problem, in that the optimal force is determined. It is also bounded by the current technology for structure monitoring and controlling devices, and the physical constraints of these devices, i.e., the set of values the sensors can report and the set of forces that the actuators can apply is fixed.

In TIMM, the input list is represented as factors with corresponding factor values. Factor types can be numeric, or symbolic. Factors are further defined as linearly ordered, unordered, or circularly ordered. An example to illustrate the different types follows--if you wanted to discriminate between different types of disturbances over a thirty second time period, some candidate input factors (and corresponding values) may be: SIGNAL VARIANCE (low, medium, high), PEAK FREQUENCY (0 to 100), and MAXIMUM ABSOLUTE VALUE (1:9).

The actuators and sensors are simulated by the same equations given for the DVFB controller in Chapter 4.2.1. In addition, the same assumptions are made: (1) the number of sensors is equal to the number of actuators; (2) only velocity measurements are available; and (3) the sensors and actuators are collocated.

Four logic based controllers were developed, one for each actuator. They all have the same decision structure definitions but contain different rule sets. The simulator in conjunction with the DVFB controller was used to generate data for determination of the inputs, outputs, and rules for all of the logic based controllers. Essentially, the ESC models the behavior of the DVFB controller.

The ESC inputs are the four simulated sensor velocities at each location, and the ESC output is the force to be applied by the corresponding actuator. Since TIMM requires bounded inputs and outputs, the velocities and forces were divided into ranges falling between the anticipated data upper and lower values of 3.0 and -3.0. The resolution of these ranges directly affects the resulting accuracy of TIMM's output, and the computing time to derive an output. For this study, emphasis was placed on accuracy. Based on preliminary ESC test runs, the minimum resolution of 0.02 was adequate to achieve good performance. To keep the number of ranges at least reasonable, this resolution was relaxed beyond the values of 0.70 and -0.70 (see Table 5.1.).

TABLE 5.1
SELECTED RULE BASE RANGES

-9.99	-3.01
-3.01	-2.99
-2.99	-1.50
-1.50	-1.40
-1.40	-1.30
-1.30	-1.20
-1.20	-1.10
-1.10	-1.00
-1.00	-0.90
-0.90	-0.80
-0.80	-0.70
-0.70	-0.68
-0.68	-0.66
-0.66	-0.64
-0.64	-0.62
-0.62	-0.60
-0.60	-0.58
-0.58	-0.56
-0.56	-0.54
-0.54	-0.52

TABLE 5.1 (CONT.)
SELECTED RULE BASE RANGES

-0.52	-0.50
-0.50	-0.48
-0.48	-0.46
-0.46	-0.44
-0.44	-0.42
-0.42	-0.40
-0.40	-0.38
-0.38	-0.36
-0.36	-0.34
-0.34	-0.32
-0.32	-0.30
-0.30	-0.28
-0.28	-0.26
-0.26	-0.24
-0.24	-0.22
-0.22	-0.20
-0.20	-0.18
-0.18	-0.16
-0.16	-0.14
-0.14	-0.12
-0.12	-0.10
-0.10	-0.08
-0.08	-0.06
-0.06	-0.04
-0.04	-0.02
-0.02	-.003
-.003	.003
.003	0.02
0.02	0.04
0.04	0.06
0.06	0.08
0.08	0.10
0.10	0.12
0.12	0.14
0.14	0.16
0.16	0.18
0.18	0.20
0.20	0.22
0.22	0.24
0.24	0.26
0.26	0.28
0.28	0.30
0.30	0.32
0.32	0.34
0.34	0.36
0.36	0.38
0.38	0.40
0.40	0.42
0.42	0.44
0.44	0.46
0.46	0.48
0.48	0.50
0.50	0.52
0.52	0.54

TABLE 5.1 (CONT.)
SELECTED RULE BASE RANGES

0.54	**0.56**
0.56	**0.58**
0.58	**0.60**
0.60	**0.62**
0.62	**0.64**
0.64	**0.66**
0.66	**0.68**
0.68	**0.70**
0.70	**0.80**
0.80	**0.90**
0.90	**1.00**
1.00	**1.10**
1.10	**1.20**
1.20	**1.30**
1.30	**1.40**
1.40	**1.50**
1.50	**2.99**
2.99	**3.01**
3.01	**9.99**

5.1.2 Knowledge Base

Once the decision structure has been defined, the logic based system's knowledge base can be developed or trained. Training is the incorporation of the knowledge required to map inputs to the output(s). Initial training can be performed in two ways: (1) the expert can explicitly state specific or general cases and the corresponding decision(s), or (2) the expert can allow TIMM to present cases, and respond with the decision s/he would advise. Either way, TIMM represents the cases externally to the user in a production rule (if...then...) format.

The rules consist of the factor values, and the corresponding decision or series of decisions. Multiple input values have associated certainties, and multiple output decisions are reported with corresponding likelihood(s). An example of a specific rule is:

IF	SIGNAL VARIANCE	is HIGH
and	PEAK FREQUENCY	is 3
and	MAXIMUM VELOCITY	is 2

THEN disturbance type is WIDEBAND	(90% likelihood)
STANDING WAVE	(10% likelihood)

A general rule allows factor values to cover ranges of values, e.g., PEAK FREQUENCY is between 3 and 9, or cases where a subset of the inputs is relevant for decision making, e.g., if MAXIMUM VELOCITY is greater than 2 then disturbance type is STANDING WAVE (ignoring any values of signal variance and peak frequency).

In a sense, training is similar to setting up a table of possible input cases and correpsonding output(s) allowing special situations (factor value ranges, allowing cases where only relevant information is used, stating impossible cases, etc.). However, not all cases need to be specified. TIMM's power lies in its ability to infer an output or distribution of outputs where there is no exact match (missing table entry) and/or when it is given an incomplete set of inputs. In addition, TIMM assesses the reliability of its own decision in relation to the known cases. This reliability measure is a self contained indicator for knowing when the logic based system requires tuning.

In addition, TIMM offers training tools for reporting input cases that are inconsistent (i.e., there exists more than one decision for a given input situation), and gaps in its decision space (i.e., cases where TIMM cannot make a reliable decision). TIMM also has the ability of suggesting general rules based on specific cases in its knowledge base. This is instrumental in reducing the number of rules it has to look at when reaching a decision, and thus increasing its efficiency.

The rules were generated from data (see Fig. 5.1 for examples) obtained from multiple DVFB simulation runs set up with the following disturbance types:

(a) Two 1 Newton harmonic waves with frequencies of 0.04, and 0.14 hertz.
(b) Five 1 Newton impulses applied at x = 2, 4, 5, 6.3, and 8 meters.
(c) One traveling wave of amplitude = 50 cm, wavelength of 1 meter.
(d) Wideband power spectral density function.

Note that more impulse disturbances were required to capture its behavior. This was because unlike the other disturbance types, the impulse disturbance causes non-linear structural behavior which is dependent on the impulse arrival position.

As noted, TIMM represents the rules in a production rule format. The "if" portion are the inputs, the "then" portion is the output(s). For the ESC, the inputs are the four velocity ranges corresponding to the velocity values from the simulator, and the output is force range corresponding to the force value reported by the DVFB controller. Two examples follow:

Example 1 - Rule generated from a wideband disturbance

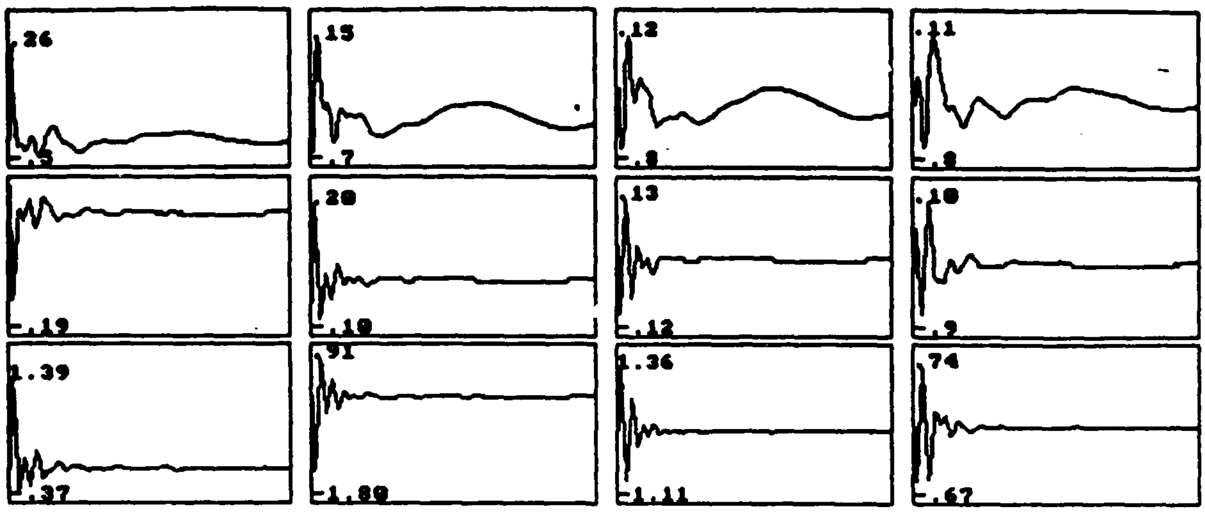
```
IF    SENSOR 1 is    0.44 : 0.46
      SENSOR 2 is   -0.24 :-0.22
      SENSOR 3 is   -0.24 :-0.22
      SENSOR 4 is    0.44 : 0.46

THEN FORCE 1 is -0.80:-0.70   (100)
```

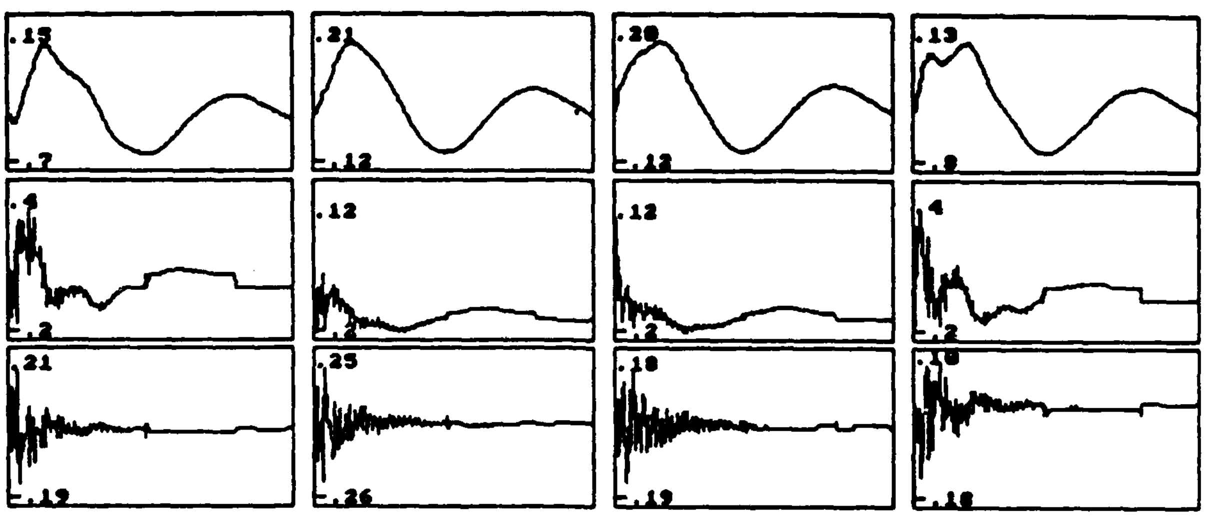
Example 2 - Rule generated from an impulse disturbance

```
IF    SENSOR 1 is   -0.22 :-0.003
      SENSOR 2 is   -0.04 :-0.02
      SENSOR 3 is    0.02 : 0.04
      SENSOR 4 is    0.04 : 0.06

THEN FORCE 1 is -0.06:-0.04   (100)
```

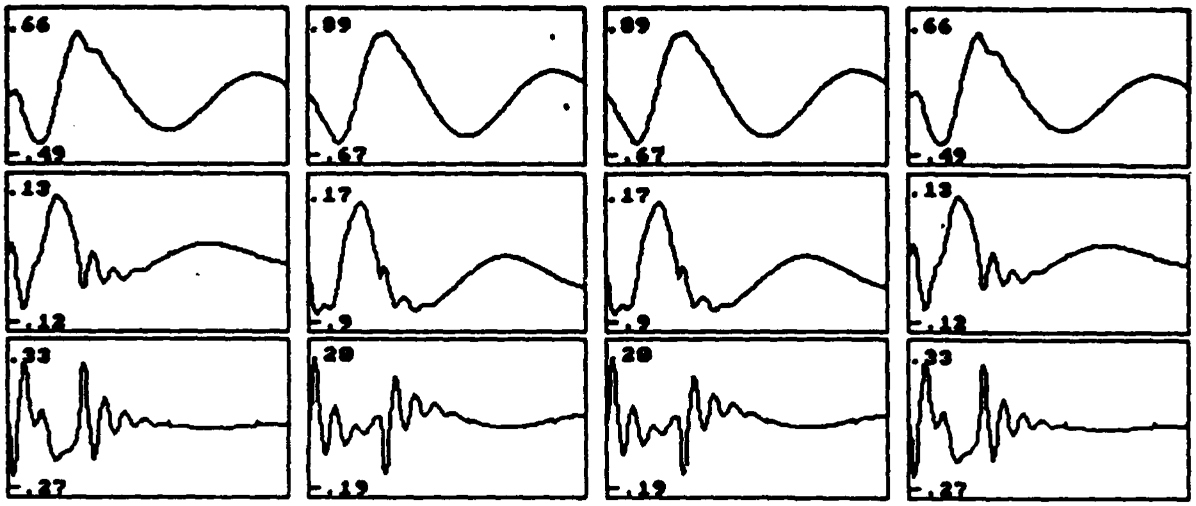


Traveling Wave: 50 cm 100 seconds at 0.5 second intervals; (LSS.TW2: 202 pts.)

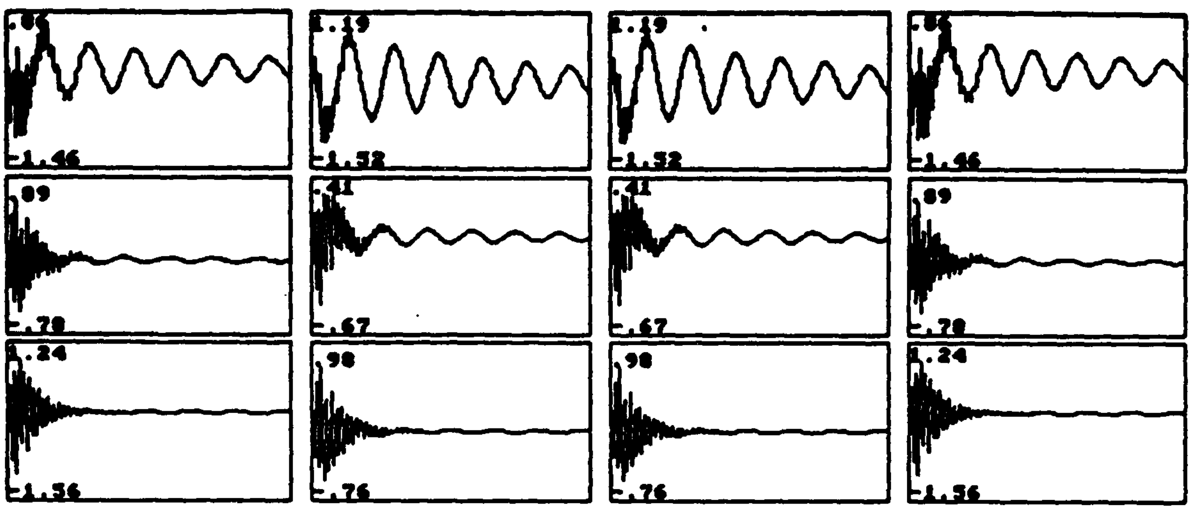


Impulse: 1N at 6.3m 100 seconds at 0.5 second intervals; (LSS.IMP: 202 pts.)

Figure 5.1. Representative Training Data



Standing Wave: 1N @ 0.04Hertz   100s @ 0.5s intervals;   (LSS.SW: 202 pts.)



Wideband Disturbance: 400s at 2s intervals   (LSS.WD2: 201pts)

Figure 5.1. Representative Training Data (Cont.)

different output values. In this case, TIMM consolidates the forces into one output by calculating the relative ratio among the output force values and assigning weights to each unique force value based upon a denominator of 100. An example rule follows:

Example 3 - Rule generated from multiple disturbances

```
IF      SENSOR 1 is  48 (0.003 to 0.02)
        SENSOR 2 is  48 (0.003 to 0.02)
        SENSOR 3 is  48 (0.003 to 0.02)
        SENSOR 4 is  46 (-0.02 to -0.003)

THEN FORCE 1 is 46.     -0.02 to -0.003  (25)
                48.     0.003 to 0.02  (50)
                49.     0.02 to 0.04  (25)
```

Each of the four knowledge bases has 239 rules (listed in Sec. 5.4).

Internally, TIMM represents rules as a state space, where each rule is a point or region in a universe of n-dimensions (n = number of input factors). This cannot be easily represented in figures. However, a 2-dimensional plot gives an idea of how the cases are represented internally to TIMM. The scatterplot in Fig. 5.2 shows the rules base in 2-dimensions: output force for actuator 1 vs. velocity value at sensor 1.

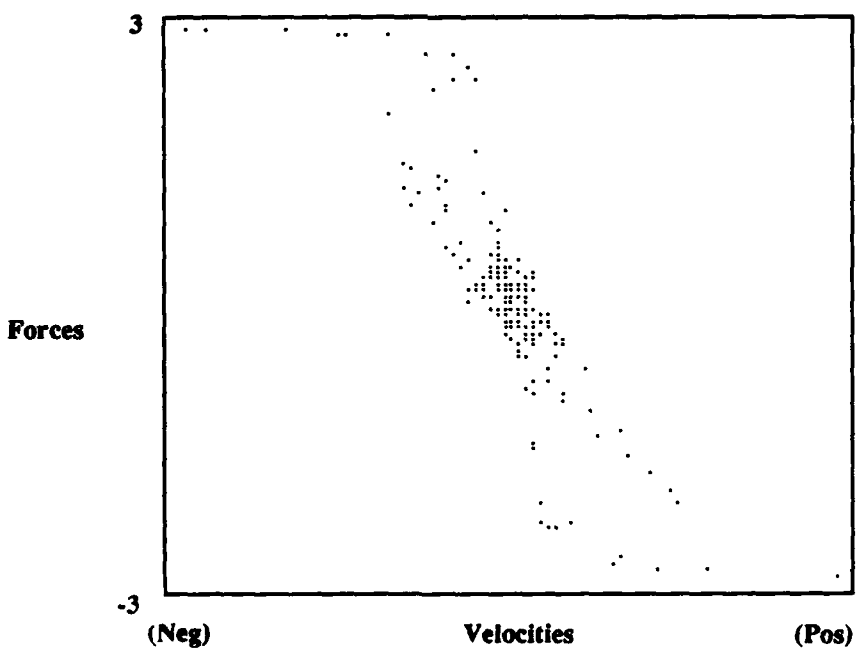


Figure 5.2. Training Data Scatter Plot

5.1.3 Inference Engine

Forces are derived by polling all rules in the rule base and producing a distribution of forces. That is, given an incoming case, TIMM finds the if-then rule(s) that most closely matches the incoming case and adopts the rule output(s) as its recommended answer. If more than one rule is found, and their output decisions are different, TIMM reports a distribution of decisions.

This method is referred to as analogical partial matching. It is analogical in the sense that the closest match is found and a relative measure of correctness, termed reliability, is given for every decision. An exact match has a reliability of 100 percent, inexact matches will have reliabilities less than 100 percent depending on their closeness. The process of partial matching allows conclusions without requiring values for all of the input factors--arriving at the best solution given the information at hand.

The measure for closeness is based on a modified euclidean distance metric. The distance metric is modified in two manners: (1) the metric "non-linearizes" the distance differences between ordered factors, i.e., it rewards similarity, and (2) it normalizes dimensions, i.e., the distance between the maximum and the minimum values for each factor is considered to be the same, and intervening values are distributed evenly.

The distance metric used to determine the distance between an incoming factor value, and the corresponding rule factor value is shown below:

$$d(x) = \frac{(1-C)^x}{(1-C)}$$

where x is the difference between the two specific values being considered divided by the maximum distance between the two most distant values for that factor (normalization), and C is a constant which is less than one.

The overall distance, D, between the incoming case and the rules in the knowledge base is calculated by the following equation:

$$D = [\sum_i d^2(x_i)]^{1/2}$$

TIMM output reliability is calculated as 100.0 (1 - d1/d2) where d1 is the average distance between the incoming case and all of the most similar rules in the knowledge base, and d2 is the distance between the two most dissimilar rules in the knowledge base.

Some actual ESC examples illustrating the ways that TIMM arrives at a resultant force value follow:

Case 1: Exact Match - If the input velocity ranges match the "if" portion of a rule, then the output of that rule is the recommended force with 100 percent likelihood, and 100 percent reliability.

Example 1 - If the simulation output data is:

0.07256 (range # 50) for sensor 1,
-0.08078 (range #41) for sensor 2,
-0.08078 (range # 41) for sensor 3, and
0.07256 (range # 50) for sensor 4;

then recommended actuator 1 force range is -0.14 to -0.12 with 100% likelihood, and a reliability of 100 percent.

The following rule is found as the exact match to the input case.

Rule 110

SENSOR 1 VELOCITY RANGE #	IS 50
SENSOR 2 VELOCITY RANGE #	IS 41
SENSOR 3 VELOCITY RANGE #	IS 41
SENSOR 4 VELOCITY RANGE #	IS 50

ACTUATOR 1 FORCE RANGE # IS   40. -0.14 -0.12 (100
(Reliability = 100)

The actuator 1 force reported by the ESC to the simulation software is the mean of range number 40 which is -0.13 Newtons.

Case 2: Inexact Match - If the input factor values do not match any rules, then the output of the closest rule(s) is the recommended force as in Example 1 but the reliability is less than 100 percent.

Example 2 - If the simulation output data is:

-0.47881 (range # 23) for sensor 1,
0.39582 (range # 66) for sensor 2,
0.39582 (range # 66) for sensor 3, and
-0.47881 (range # 23) for sensor 4;

then the recommended actuator 1 force range is 2.99 to 3.01 with 100% likelihood, and a reliability of 95 percent.

The rule shown below was found to be closest to this case:

Rule 209

If:

SENSOR 1 VELOCITY RANGE #	IS 18
SENSOR 2 VELOCITY RANGE #	IS 64
SENSOR 3 VELOCITY RANGE #	IS 64
SENSOR 4 VELOCITY RANGE #	IS 18

ACTUATOR 1 FORCE RANGE # IS   92. 2.99 3.01 (100)
(Reliability = 95)

The actuator 1 force reported by the ESC to the simulation software is the mean of range number 92 which is 3.00 Newtons.

Example 3 - If the simulation output data is:

-0.13742 (range # 40) for sensor 1,
-0.02242 (range # 45) for sensor 2,
-0.02242 (range # 45) for sensor 3, and
-0.13742 (range # 40) for sensor 4;

then the recommended actuator 1 force ranges shown below
with their associated likelihoods, and the reliability is 99 percent.

(a)	55.	0.14	0.16	(33)
(b)	53.	0.10	0.12	(25)
(c)	54.	0.12	0.14	(25)
(d)	56.	0.16	0.18	(17)

In this case, the force reported by the ESC to the simulation software is sum of the weighted means of force ranges:

$$(.33*0.15) + (.25*.11) + (.25*0.13) + (.17*.17) \;=\; 0.1384 \text{ Newtons}$$

The incoming case was equal distance to two rules:

<u>Rule 117</u>

If:
SENSOR 1 VELOCITY RANGE # IS 41
SENSOR 2 VELOCITY RANGE # IS 45
SENSOR 3 VELOCITY RANGE # IS 45
SENSOR 4 VELOCITY RANGE # IS 41

ACTUATOR 1 FORCE RANGE # IS 53. 0.10 0.12 (50)
54. 0.12 0.14 (50)

<u>Rule 124</u>

If:
SENSOR 1 VELOCITY RANGE # IS 40
SENSOR 2 VELOCITY RANGE # IS 46
SENSOR 3 VELOCITY RANGE # IS 46
SENSOR 4 VELOCITY RANGE # IS 40

ACTUATOR 1 FORCE RANGE # IS 55. 0.14 0.16 (67)
56. 0.16 0.18 (33)

5.2 PERFORMANCE

The ESC was developed to emulate the behavior of the DVFB controller. The performance of the ESC is best illustrated by the response of the system to the following disturbances:

(a) A 1 Newton harmonic wave with a frequency of 0.14 hertz.
(b) The wideband power spectral density function.

The plots of these simulations appear in the next section.

As seen in Fig. 5.3, the spiral-like pattern found for the ESC displacement-velocity trajectory shows the distinctive reduction in energy also found for DVFB and IMSC. Careful comparison with Fig. 4.8 shows the result to be a faithful reproduction of the DVFB results demonstrating that ESC can produce similar results.

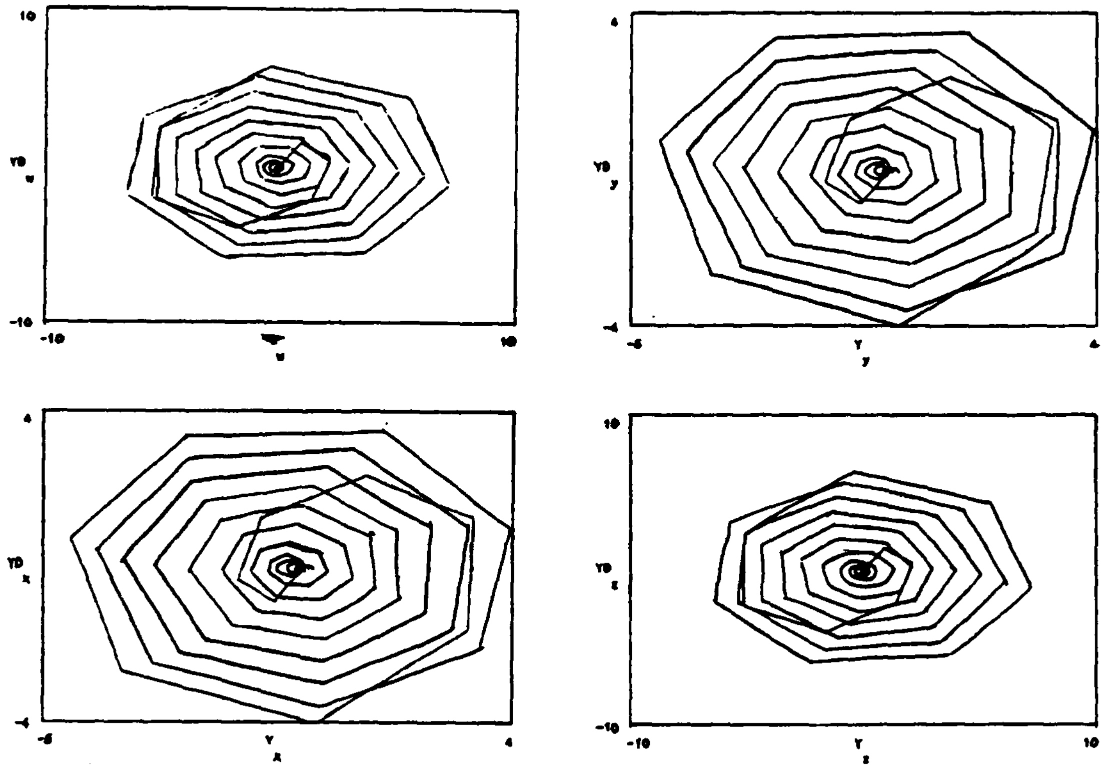
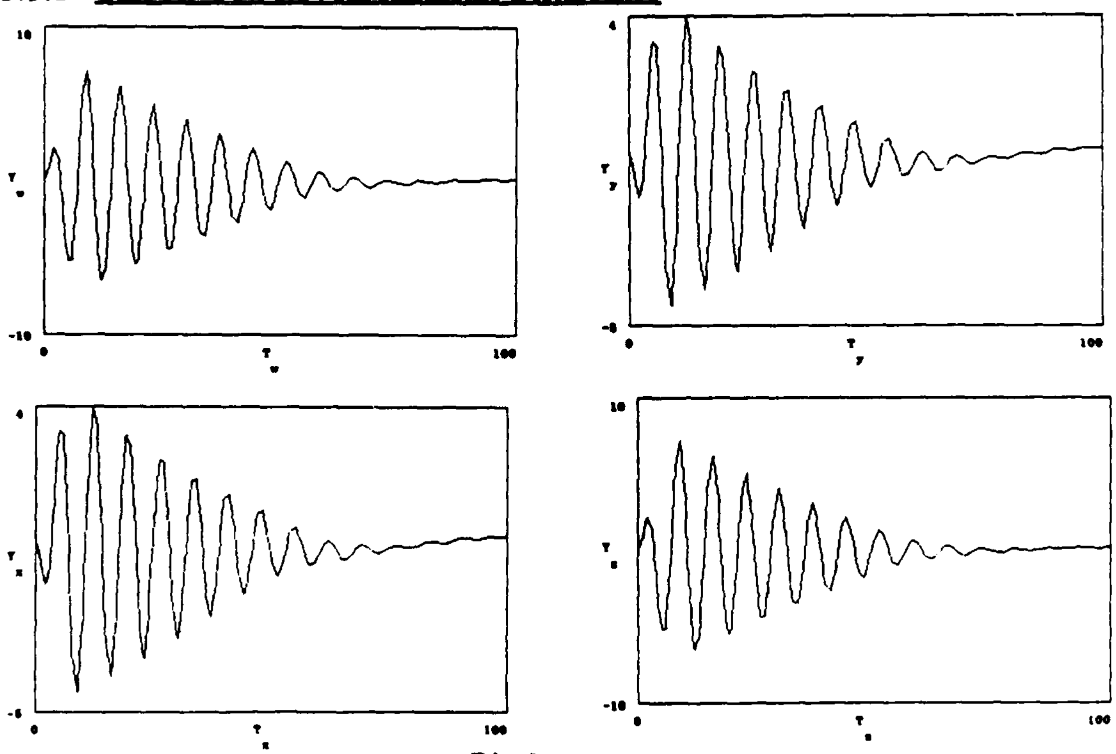


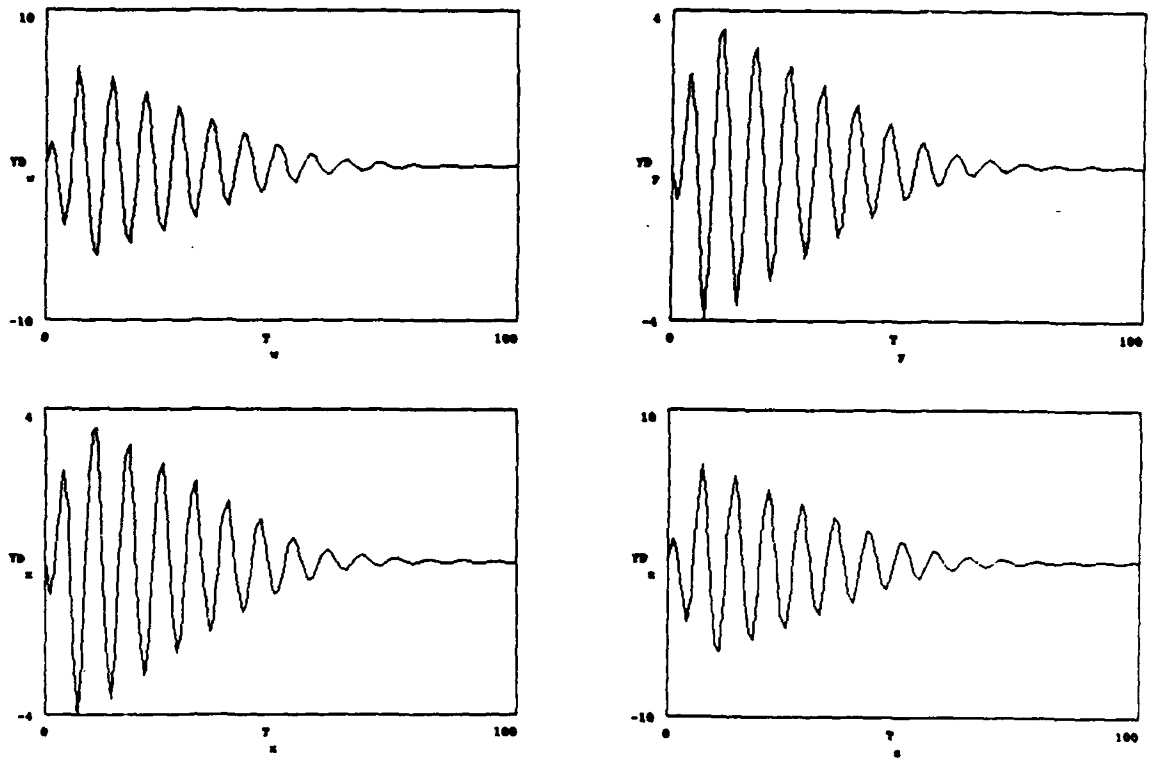
Figure 5.3. ESC Displacement-Velocity Trajectory (Typical)

5.3 EXPERT SYSTEM CONTROLLER PERFORMANCE EXAMPLES

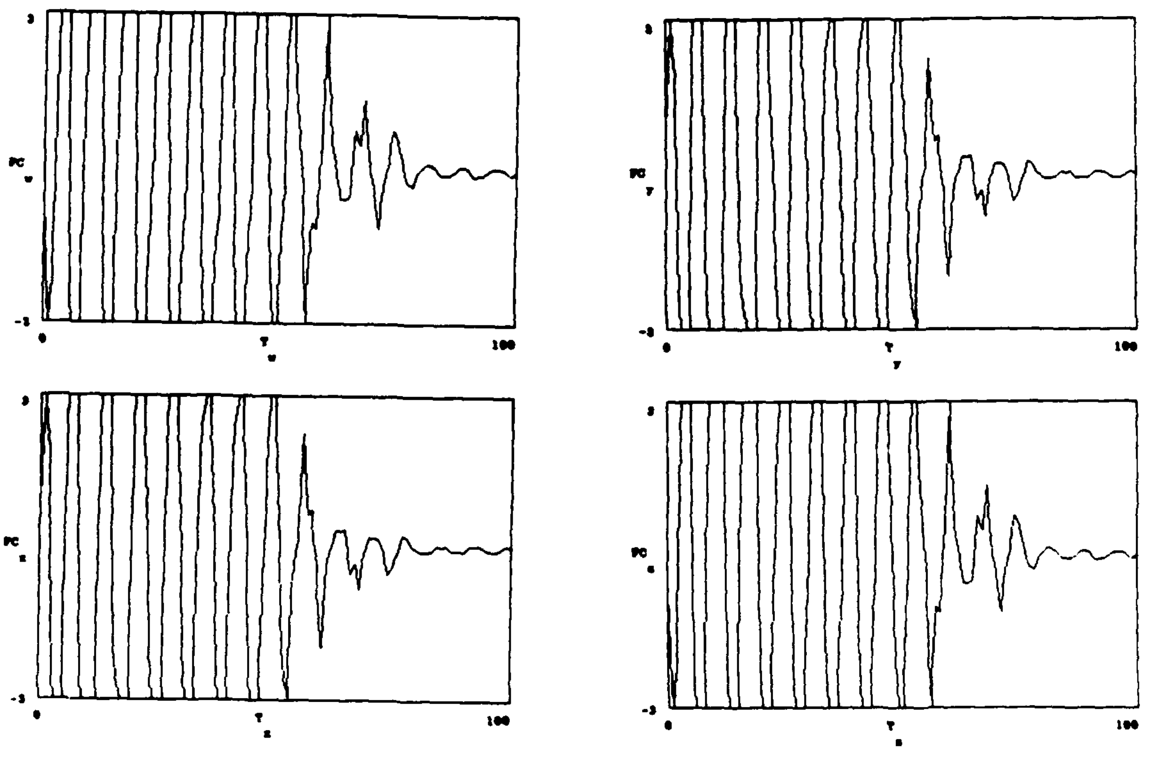
5.3.1 Case A: 1 N, 0.14 Hz Harmonic Disturbance



Displacements

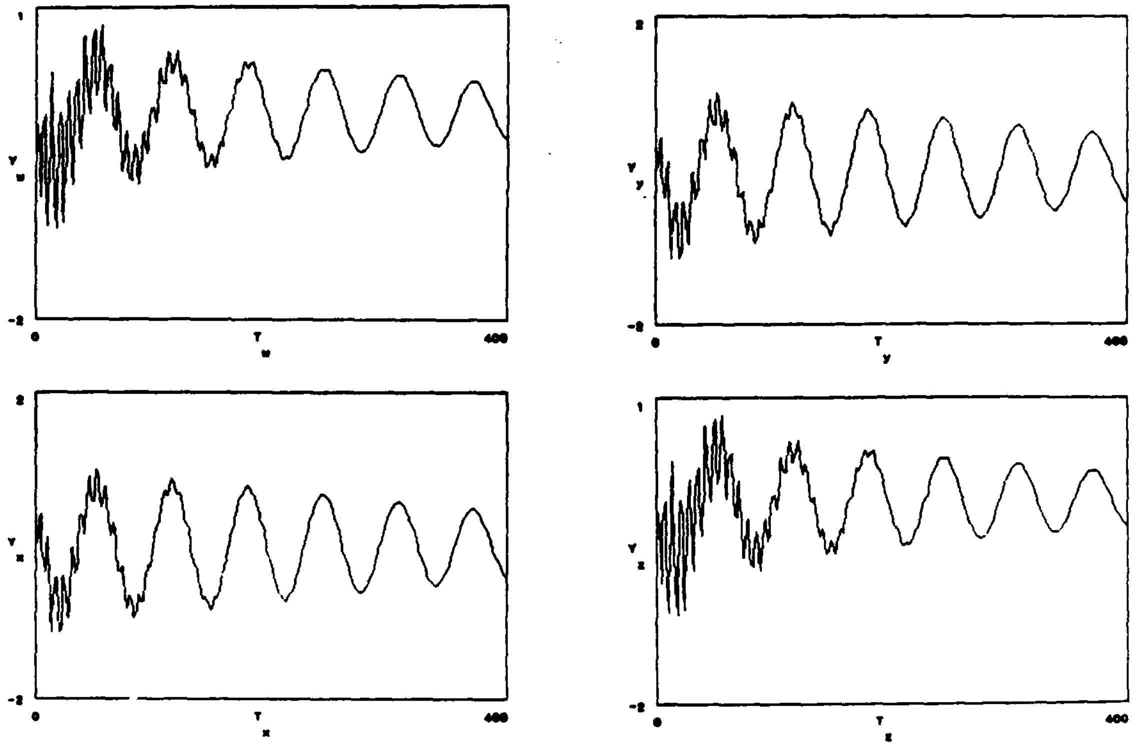


Velocities

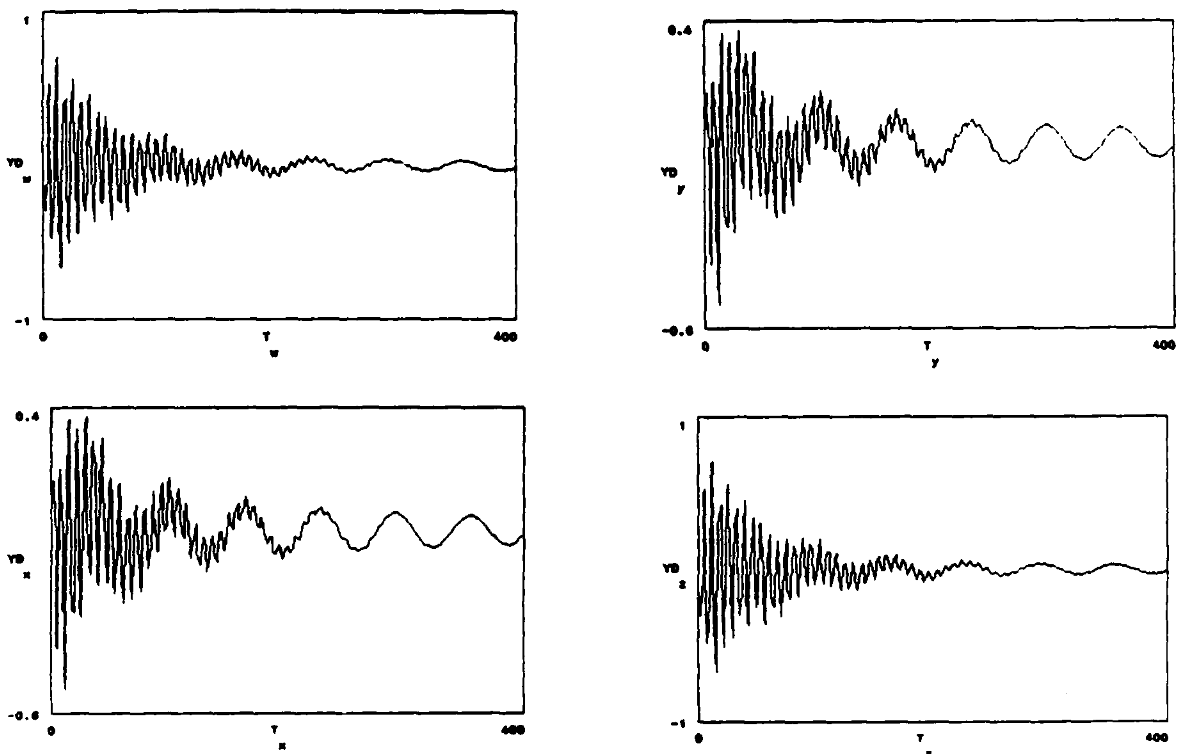


Forces

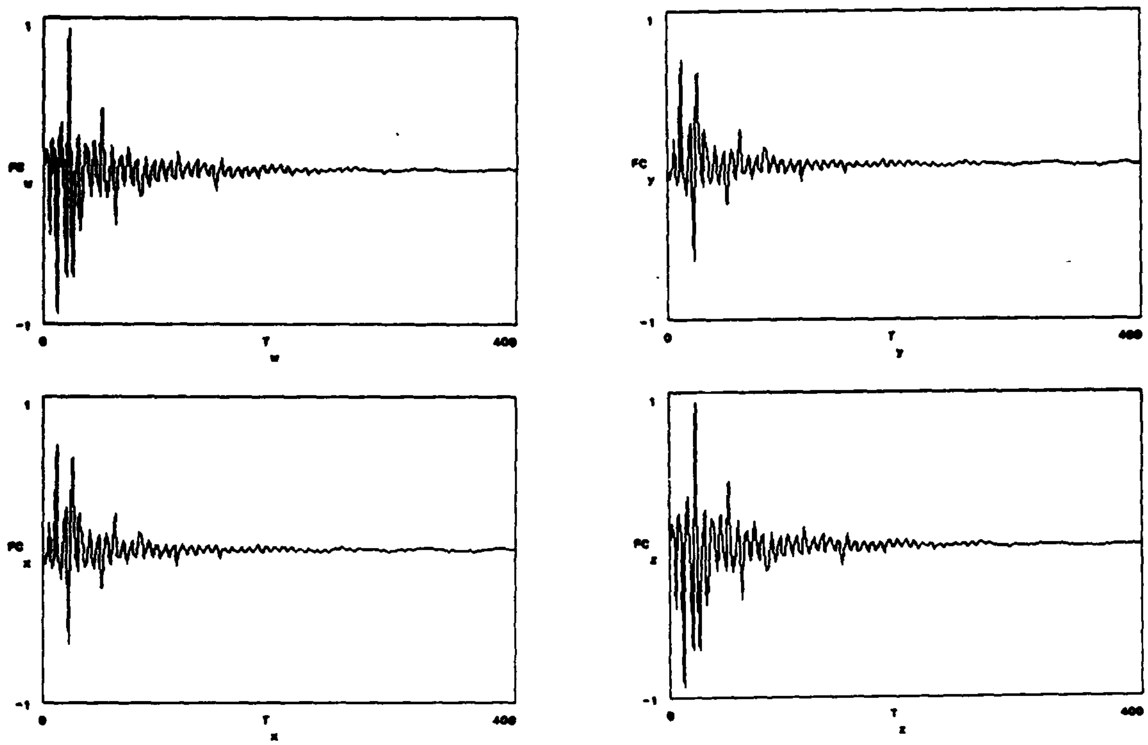
5.3.2 Case B: Wideband PSD Disturbance



Displacements



Velocities



Forces

5.4 ESC RULE BASES

DECISION STRUCTURE FOR THE EXPERT SYSTEM "EXPERT SYSTEM CONTROLLER FOR LARGE SPACE STRUCTURES"

DECISION:

```
      FORCE 1
          Choices:
           01. -9.99 -3.01 (LESS THAN LOWER LIMIT)
           02. -3.01 -2.99 (LOWER LIMIT)
           03. -2.99 -1.50
           04. -1.50 -1.40
           05. -1.40 -1.30
           06. -1.30 -1.20
           07. -1.20 -1.10
           08. -1.10 -1.00
           09. -1.00 -0.90
           10. -0.90 -0.80
           11. -0.80 -0.70
           12. -0.70 -0.68
           13. -0.68 -0.66
           14. -0.66 -0.64
           15. -0.64 -0.62
           16. -0.62 -0.60
           17. -0.60 -0.58
```

18.	-0.58	-0.56
19.	-0.56	-0.54
20.	-0.54	-0.52
21.	-0.52	-0.50
22.	-0.50	-0.48
23.	-0.48	-0.46
24.	-0.46	-0.44
25.	-0.44	-0.42
26.	-0.42	-0.40
27.	-0.40	-0.38
28.	-0.38	-0.36
29.	-0.36	-0.34
30.	-0.34	-0.32
31.	-0.32	-0.30
32.	-0.30	-0.28
33.	-0.28	-0.26
34.	-0.26	-0.24
35.	-0.24	-0.22
36.	-0.22	-0.20
37.	-0.20	-0.18
38.	-0.18	-0.16
39.	-0.16	-0.14
40.	-0.14	-0.12
41.	-0.12	-0.10
42.	-0.10	-0.08
43.	-0.08	-0.06
44.	-0.06	-0.04
45.	-0.04	-0.02
46.	-0.02	-.003
47.	-0.003	.003
48.	0.003	0.02
49.	0.02	0.04
50.	0.04	0.06
51.	0.06	0.08
52.	0.08	0.10
53.	0.10	0.12
54.	0.12	0.14
55.	0.14	0.16
56.	0.16	0.18
57.	0.18	0.20
58.	0.20	0.22
59.	0.22	0.24
60.	0.24	0.26
61.	0.26	0.28
62.	0.28	0.30
63.	0.30	0.32
64.	0.32	0.34
65.	0.34	0.36
66.	0.36	0.38
67.	0.38	0.40
68.	0.40	0.42
69.	0.42	0.44
70.	0.44	0.46
71.	0.46	0.48

```
        72.   0.48   0.50
        73.   0.50   0.52
        74.   0.52   0.54
        75.   0.54   0.56
        76.   0.56   0.58
        77.   0.58   0.60
        78.   0.60   0.62
        79.   0.62   0.64
        80.   0.64   0.66
        81.   0.66   0.68
        82.   0.68   0.70
        83.   0.70   0.80
        84.   0.80   0.90
        85.   0.90   1.00
        86.   1.00   1.10
        87.   1.10   1.20
        88.   1.20   1.30
        89.   1.30   1.40
        90.   1.40   1.50
        91.   1.50   2.99
        92.   2.99   3.01 (UPPER LIMIT)
        93.   3.01   9.99 (GREATER THAN UPPER LIMIT)

FACTORS:
--------
       SENSOR 1
          Type of values: Linearly-Ordered Numbers
          Values:
            Minimum value 0
            Maximum value 95
       SENSOR 2
          Type of values: Linearly-Ordered Numbers
          Values:
            Minimum value 0
            Maximum value 95
       SENSOR 3
          Type of values: Linearly-Ordered Numbers
          Values:
            Minimum value 0
            Maximum value 95
       SENSOR 4
          Type of values: Linearly-Ordered Numbers
          Values:
            Minimum value 0
            Maximum value 95
```

DECISION STRUCTURE FOR THE EXPERT SYSTEM "EXPERT SYSTEM CONTROLLER FOR LARGE SPACE STRUCTURES"

DECISION:

```
FORCE 1
    Choices:
     01. -9.99 -3.01 (LESS THAN LOWER LIMIT)
     02. -3.01 -2.99 (LOWER LIMIT)
     03. -2.99 -1.50
     04. -1.50 -1.40
     05. -1.40 -1.30
     06. -1.30 -1.20
     07. -1.20 -1.10
     08. -1.10 -1.00
     09. -1.00 -0.90
     10. -0.90 -0.80
     11. -0.80 -0.70
     12. -0.70 -0.68
     13. -0.68 -0.66
     14. -0.66 -0.64
     15. -0.64 -0.62
     16. -0.62 -0.60
     17. -0.60 -0.58
     18. -0.58 -0.56
     19. -0.56 -0.54
     20. -0.54 -0.52
     21. -0.52 -0.50
     22. -0.50 -0.48
     23. -0.48 -0.46
     24. -0.46 -0.44
     25. -0.44 -0.42
     26. -0.42 -0.40
     27. -0.40 -0.38
     28. -0.38 -0.36
     29. -0.36 -0.34
     30. -0.34 -0.32
     31. -0.32 -0.30
     32. -0.30 -0.28
     33. -0.28 -0.26
     34. -0.26 -0.24
     35. -0.24 -0.22
     36. -0.22 -0.20
     37. -0.20 -0.18
     38. -0.18 -0.16
     39. -0.16 -0.14
     40. -0.14 -0.12
     41. -0.12 -0.10
     42. -0.10 -0.08
     43. -0.08 -0.06
     44. -0.06 -0.04
     45. -0.04 -0.02
     46. -0.02 -.003
```

DECISION (continued)

47.	-0.003	.003	
48.	0.003	0.02	
49.	0.02	0.04	
50.	0.04	0.06	
51.	0.06	0.08	
52.	0.08	0.10	
53.	0.10	0.12	
54.	0.12	0.14	
55.	0.14	0.16	
56.	0.16	0.18	
57.	0.18	0.20	
58.	0.20	0.22	
59.	0.22	0.24	
60.	0.24	0.26	
61.	0.26	0.28	
62.	0.28	0.30	
63.	0.30	0.32	
64.	0.32	0.34	
65.	0.34	0.36	
66.	0.36	0.38	
67.	0.38	0.40	
68.	0.40	0.42	
69.	0.42	0.44	
70.	0.44	0.46	
71.	0.46	0.48	
72.	0.48	0.50	
73.	0.50	0.52	
74.	0.52	0.54	
75.	0.54	0.56	
76.	0.56	0.58	
77.	0.58	0.60	
78.	0.60	0.62	
79.	0.62	0.64	
80.	0.64	0.66	
81.	0.66	0.68	
82.	0.68	0.70	
83.	0.70	0.80	
84.	0.80	0.90	
85.	0.90	1.00	
86.	1.00	1.10	
87.	1.10	1.20	
88.	1.20	1.30	
89.	1.30	1.40	
90.	1.40	1.50	
91.	1.50	2.99	
92.	2.99	3.01	(UPPER LIMIT)
93.	3.01	9.99	(GREATER THAN UPPER LIMIT)

```
FACTORS:
--------
       SENSOR 1
          Type of values: Linearly-Ordered Numbers
          Values:
            Minimum value 0
            Maximum value 95
       SENSOR 2
          Type of values: Linearly-Ordered Numbers
          Values:
            Minimum value 0
            Maximum value 95
       SENSOR 3
          Type of values: Linearly-Ordered Numbers
          Values:
            Minimum value 0
            Maximum value 95
       SENSOR 4
          Type of values: Linearly-Ordered Numbers
          Values:
            Minimum value 0
            Maximum value 95

VERBOSE VERSIONS
----------------

       ***None***

HELP INFORMATION
----------------

       ***None***
```

KNOWLEDGE BASE FOR THE EXPERT SYSTEM 1 AT ACTUATOR 1

```
Rule 1
------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(31)
                  47. -0.003 .003(19)
                  48.  0.003 0.02(50)

Rule 4
------
   If:
      SENSOR 1 IS 36
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 36
   Then:
      FORCE 1  IS 64.  0.32  0.34(100)

Rule 5
------
   If:
      SENSOR 1 IS 32
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 32
   Then:
      FORCE 1  IS 71.  0.46  0.48(100)

Rule 7
------
   If:
      SENSOR 1 IS 30
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 30
   Then:
      FORCE 1  IS 74.  0.52  0.54(100)
```

```
Rule 9
------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 51.  0.06  0.08(50)
                  52.  0.08  0.10(50)

Rule 11
-------
   If:
      SENSOR 1 IS 66
      SENSOR 2 IS 32
      SENSOR 3 IS 32
      SENSOR 4 IS 66
   Then:
      FORCE 1  IS 15. -0.64 -0.62(100)

Rule 13
-------
   If:
      SENSOR 1 IS 72
      SENSOR 2 IS 28
      SENSOR 3 IS 28
      SENSOR 4 IS 72
   Then:
      FORCE 1  IS 10. -0.90 -0.80(100)

Rule 15
-------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 37. -0.20 -0.18(67)
                  38. -0.18 -0.16(33)

Rule 17
-------
   If:
      SENSOR 1 IS 24
      SENSOR 2 IS 57
      SENSOR 3 IS 57
      SENSOR 4 IS 24
   Then:
      FORCE 1  IS 82.  0.68  0.70(100)
```

```
Rule 19
-------
   If:
      SENSOR 1 IS 25
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 25
   Then:
      FORCE 1  IS 81.  0.66  0.68(100)

Rule 21
-------
   If:
      SENSOR 1 IS 55
      SENSOR 2 IS 37
      SENSOR 3 IS 37
      SENSOR 4 IS 55
   Then:
      FORCE 1  IS 31. -0.32 -0.30(100)

Rule 23
-------
   If:
      SENSOR 1 IS 77
      SENSOR 2 IS 24
      SENSOR 3 IS 24
      SENSOR 4 IS 77
   Then:
      FORCE 1  IS 08. -1.10 -1.00(100)

Rule 25
-------
   If:
      SENSOR 1 IS 75
      SENSOR 2 IS 25
      SENSOR 3 IS 25
      SENSOR 4 IS 75
   Then:
      FORCE 1  IS 09. -1.00 -0.90(100)

Rule 27
-------
   If:
      SENSOR 1 IS 52
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 52
   Then:
      FORCE 1  IS 36. -0.22 -0.20(67)
                  37. -0.20 -0.18(33)
```

```
Rule 29
-------
   If:
      SENSOR 1 IS 25
      SENSOR 2 IS 57
      SENSOR 3 IS 57
      SENSOR 4 IS 25
   Then:
      FORCE 1  IS 80.  0.64  0.66(100)

Rule 31
-------
   If:
      SENSOR 1 IS 15
      SENSOR 2 IS 64
      SENSOR 3 IS 64
      SENSOR 4 IS 15
   Then:
      FORCE 1  IS 86.  1.00  1.10(100)

Rule 33
-------
   If:
      SENSOR 1 IS 27
      SENSOR 2 IS 57
      SENSOR 3 IS 57
      SENSOR 4 IS 27
   Then:
      FORCE 1  IS 78.  0.60  0.62(100)

Rule 35
-------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 53
   Then:
      FORCE 1  IS 37. -0.20 -0.18(100)

Rule 37
-------
   If:
      SENSOR 1 IS 71
      SENSOR 2 IS 31
      SENSOR 3 IS 31
      SENSOR 4 IS 71
   Then:
      FORCE 1  IS 11. -0.80 -0.70(100)
```

```
Rule 39
-------
   If:
      SENSOR 1 IS 64
      SENSOR 2 IS 36
      SENSOR 3 IS 36
      SENSOR 4 IS 64
   Then:
      FORCE 1  IS 18. -0.58 -0.56(100)

Rule 41
-------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 55.  0.14  0.16(100)

Rule 45
-------
   If:
      SENSOR 1 IS 25
      SENSOR 2 IS 62
      SENSOR 3 IS 62
      SENSOR 4 IS 25
   Then:
      FORCE 1  IS 83.  0.70  0.80(100)

Rule 47
-------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 59.  0.22  0.24(100)

Rule 49
-------
   If:
      SENSOR 1 IS 61
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 61
   Then:
      FORCE 1  IS 26. -0.42 -0.40(100)
```

```
Rule 53
-------
   If:
      SENSOR 1 IS 63
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 63
   Then:
      FORCE 1  IS 22. -0.50 -0.48(100)

Rule 55
-------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 57
-------
   If:
      SENSOR 1 IS 32
      SENSOR 2 IS 60
      SENSOR 3 IS 60
      SENSOR 4 IS 32
   Then:
      FORCE 1  IS 74.  0.52  0.54(100)

Rule 59
-------
   If:
      SENSOR 1 IS 31
      SENSOR 2 IS 62
      SENSOR 3 IS 62
      SENSOR 4 IS 31
   Then:
      FORCE 1  IS 76.  0.56  0.58(100)

Rule 61
-------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 55
      SENSOR 3 IS 55
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 58.  0.20  0.22(100)
```

```
Rule 63
-------
    If:
        SENSOR 1 IS 58
        SENSOR 2 IS 45
        SENSOR 3 IS 45
        SENSOR 4 IS 58
    Then:
        FORCE 1  IS 32. -0.30 -0.28(100)

Rule 65
-------
    If:
        SENSOR 1 IS 66
        SENSOR 2 IS 40
        SENSOR 3 IS 40
        SENSOR 4 IS 66
    Then:
        FORCE 1  IS 19. -0.56 -0.54(50)
                    20. -0.54 -0.52(50)

Rule 67
-------
    If:
        SENSOR 1 IS 56
        SENSOR 2 IS 47
        SENSOR 3 IS 47
        SENSOR 4 IS 56
    Then:
        FORCE 1  IS 36. -0.22 -0.20(100)

Rule 69
-------
    If:
        SENSOR 1 IS 42
        SENSOR 2 IS 56
        SENSOR 3 IS 56
        SENSOR 4 IS 42
    Then:
        FORCE 1  IS 59.  0.22  0.24(100)

Rule 71
-------
    If:
        SENSOR 1 IS 34
        SENSOR 2 IS 61
        SENSOR 3 IS 61
        SENSOR 4 IS 34
    Then:
        FORCE 1  IS 71.  0.46  0.48(100)
```

```
Rule 73
-------
   If:
      SENSOR 1 IS 38
      SENSOR 2 IS 58
      SENSOR 3 IS 58
      SENSOR 4 IS 38
   Then:
      FORCE 1  IS 66.  0.36  0.38(100)

Rule 75
-------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 77
-------
   If:
      SENSOR 1 IS 63
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 63
   Then:
      FORCE 1  IS 25. -0.44 -0.42(100)

Rule 79
-------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 54
      SENSOR 3 IS 54
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 55.  0.14  0.16(100)

Rule 83
-------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 56.  0.16  0.18(100)
```

```
Rule 85
-------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 53
   Then:
      FORCE 1  IS 39. -0.16 -0.14(100)

Rule 87
-------
   If:
      SENSOR 1 IS 59
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 59
   Then:
      FORCE 1  IS 29. -0.36 -0.34(50)
                  30. -0.34 -0.32(50)

Rule 89
-------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 53
   Then:
      FORCE 1  IS 38. -0.18 -0.16(100)

Rule 91
-------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 53.  0.10  0.12(100)

Rule 93
-------
   If:
      SENSOR 1 IS 38
      SENSOR 2 IS 54
      SENSOR 3 IS 54
      SENSOR 4 IS 38
   Then:
      FORCE 1  IS 62.  0.28  0.30(50)
                  63.  0.30  0.32(50)
```

```
Rule 97
-------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 42. -0.10 -0.08(50)
                  43. -0.08 -0.06(50)

Rule 99
-------
   If:
      SENSOR 1 IS 55
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 55
   Then:
      FORCE 1  IS 10. -0.90 -0.80(25)
                  11. -0.80 -0.70(25)
                  33. -0.28 -0.26(25)
                  34. -0.26 -0.24(25)

Rule 100
--------
   If:
      SENSOR 1 IS 54
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 54
   Then:
      FORCE 1  IS 35. -0.24 -0.22(100)

Rule 102
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 41. -0.12 -0.10(67)
                  45. -0.04 -0.02(33)
```

```
Rule 103
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 104
--------
   If:
      SENSOR 1 IS 40
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 40
   Then:
      FORCE 1  IS 56.  0.16  0.18(100)

Rule 105
--------
   If:
      SENSOR 1 IS 38
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 38
   Then:
      FORCE 1  IS 59.  0.22  0.24(50)
                  60.  0.24  0.26(50)

Rule 107
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 55.  0.14  0.16(100)

Rule 108
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 50.  0.04  0.06(25)
                  52.  0.08  0.10(25)
                  53.  0.10  0.12(50)
```

```
Rule 109
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 38. -0.18 -0.16(50)
                   44. -0.06 -0.04(50)

Rule 110
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 50
   Then:
      FORCE 1   IS 40. -0.14 -0.12(100)

Rule 112
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 43
   Then:
      FORCE 1   IS 50.  0.04  0.06(43)
                   55.  0.14  0.16(14)
                   56.  0.16  0.18(14)
                   58.  0.20  0.22(29)

Rule 113
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 41
   Then:
      FORCE 1   IS 54.  0.12  0.14(100)

Rule 115
--------
   If:
      SENSOR 1 IS 39
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 39
   Then:
      FORCE 1   IS 58.  0.20  0.22(100)
```

```
Rule 116
--------
   If:
      SENSOR 1 IS 39
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 39
   Then:
      FORCE 1  IS 57.  0.18  0.20(100)

Rule 117
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 53.  0.10  0.12(50)
                  54.  0.12  0.14(50)

Rule 118
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 120
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 39. -0.16 -0.14(100)

Rule 122
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 49.  0.02  0.04(25)
                  51.  0.06  0.08(50)
                  54.  0.12  0.14(25)
```

```
Rule 123
--------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)

Rule 124
--------
   If:
      SENSOR 1 IS 40
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 40
   Then:
      FORCE 1  IS 55.  0.14  0.16(67)
                  56.  0.16  0.18(33)

Rule 125
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 45. -0.04 -0.02(50)
                  46. -0.02 -.003(50)

Rule 126
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 43. -0.08 -0.06(100)

Rule 129
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

```
Rule 130
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 45
   Then:
      FORCE 1   IS 48.   0.003 0.02(33)
                   49.   0.02  0.04(44)
                   50.   0.04  0.06(11)
                   52.   0.08  0.10(11)

Rule 131
--------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 42
   Then:
      FORCE 1   IS 53.   0.10  0.12(100)

Rule 132
--------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 42
   Then:
      FORCE 1   IS 53.   0.10  0.12(50)
                   54.   0.12  0.14(50)

Rule 133
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 43
   Then:
      FORCE 1   IS 52.   0.08  0.10(100)

Rule 134
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 44
   Then:
      FORCE 1   IS 50.   0.04  0.06(100)
```

```
Rule 135
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44. -0.06 -0.04(10)
                  46. -0.02 -.003(20)
                  47. -0.003 .003(10)
                  48.  0.003 0.02(50)
                  49.  0.02  0.04(10)

Rule 136
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 36. -0.22 -0.20(50)
                  44. -0.06 -0.04(50)

Rule 137
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 41. -0.12 -0.10(67)
                  42. -0.10 -0.08(33)

Rule 138
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 38. -0.18 -0.16(20)
                  40. -0.14 -0.12(20)
                  42. -0.10 -0.08(20)
                  44. -0.06 -0.04(20)
                  47. -0.003 .003(20)
```

```
Rule 139
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 140
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 51.  0.06  0.08(33)
                  59.  0.22  0.24(33)
                  62.  0.28  0.30(33)

Rule 141
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)

Rule 142
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 143
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 49.  0.02  0.04(50)
                  51.  0.06  0.08(50)
```

```
Rule 144
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 46. -0.02 -.003(92)
                  47. -0.003 .003(3)
                  49.  0.02  0.04(3)
                  50.  0.04  0.06(3)

Rule 145
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 43. -0.08 -0.06(100)

Rule 146
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 148
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 149
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  47. -0.003 .003(50)
```

```
Rule 150
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 50.  0.04  0.06(50)
                  51.  0.06  0.08(50)

Rule 151
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 152
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 42. -0.10 -0.08(25)
                  43. -0.08 -0.06(25)
                  44. -0.06 -0.04(25)
                  45. -0.04 -0.02(25)

Rule 153
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 27. -0.40 -0.38(25)
                  43. -0.08 -0.06(50)
                  44. -0.06 -0.04(25)
```

```
Rule 154
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 49
   Then:
      FORCE 1   IS 48.   0.003 0.02(100)

Rule 155
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 49.   0.02   0.04(50)
                   50.   0.04   0.06(50)

Rule 156
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 49
   Then:
      FORCE 1   IS 38. -0.18 -0.16(100)

Rule 157
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 37. -0.20 -0.18(33)
                   40. -0.14 -0.12(67)

Rule 158
--------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 42
   Then:
      FORCE 1   IS 59.   0.22   0.24(100)
```

Rule 159

```
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 45
   Then:
      FORCE 1   IS 45.  -0.04  -0.02(12)
                   46.  -0.02  -.003(15)
                   47.  -0.003  .003(8)
                   48.   0.003 0.02(27)
                   49.   0.02  0.04(19)
                   50.   0.04  0.06(15)
                   51.   0.06  0.08(4)
```

Rule 160

```
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1   IS 46.  -0.02  -.003(5)
                   47.  -0.003  .003(7)
                   48.   0.003 0.02(85)
                   49.   0.02  0.04(2)
```

Rule 161

```
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1   IS 49.   0.02   0.04(100)
```

Rule 162

```
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 50.   0.04   0.06(100)
```

```
Rule 163
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 164
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 41. -0.12 -0.10(25)
                  42. -0.10 -0.08(50)
                  43. -0.08 -0.06(25)

Rule 165
--------
   If:
      SENSOR 1 IS 52
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 52
   Then:
      FORCE 1  IS 40. -0.14 -0.12(50)
                  41. -0.12 -0.10(50)

Rule 168
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 169
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 43. -0.08 -0.06(20)
                  46. -0.02 -.003(80)
```

```
Rule 170
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(10)
                  45. -0.04 -0.02(3)
                  46. -0.02 -.003(76)
                  47. -0.003 .003(10)

Rule 171
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(17)
                  46. -0.02 -.003(33)
                  47. -0.003 .003(17)
                  48.  0.003 0.02(33)

Rule 172
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 57.  0.18  0.20(33)
                  59.  0.22  0.24(67)

Rule 173
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 57.  0.18  0.20(100)
```

```
Rule 174
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 53.   0.10   0.12(100)

Rule 175
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 41.  -0.12  -0.10(50)
                  42.  -0.10  -0.08(50)

Rule 176
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44.  -0.06  -0.04(100)

Rule 177
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47.  -0.003  .003(36)
                  48.   0.003 0.02(36)
                  49.   0.02  0.04(27)

Rule 179
--------
   If:
      SENSOR 1 IS 76
      SENSOR 2 IS 33
      SENSOR 3 IS 33
      SENSOR 4 IS 76
   Then:
      FORCE 1  IS 03.  -2.99  -1.50(100)
```

```
Rule 186
--------
   If:
      SENSOR 1 IS 8
      SENSOR 2 IS 83
      SENSOR 3 IS 83
      SENSOR 4 IS 8
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)

Rule 189
--------
   If:
      SENSOR 1 IS 17
      SENSOR 2 IS 70
      SENSOR 3 IS 70
      SENSOR 4 IS 17
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)

Rule 190
--------
   If:
      SENSOR 1 IS 36
      SENSOR 2 IS 58
      SENSOR 3 IS 58
      SENSOR 4 IS 36
   Then:
      FORCE 1  IS 86.  1.00  1.10(100)

Rule 194
--------
   If:
      SENSOR 1 IS 87
      SENSOR 2 IS 10
      SENSOR 3 IS 10
      SENSOR 4 IS 87
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)

Rule 196
--------
   If:
      SENSOR 1 IS 60
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 60
   Then:
      FORCE 1  IS 06. -1.30 -1.20(100)
```

```
Rule 198
--------
   If:
      SENSOR 1 IS 83
      SENSOR 2 IS 20
      SENSOR 3 IS 20
      SENSOR 4 IS 83
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)

Rule 200
--------
   If:
      SENSOR 1 IS 63
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 63
   Then:
      FORCE 1  IS 03. -2.99 -1.50(100)

Rule 202
--------
   If:
      SENSOR 1 IS 9
      SENSOR 2 IS 76
      SENSOR 3 IS 76
      SENSOR 4 IS 9
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)

Rule 203
--------
   If:
      SENSOR 1 IS 67
      SENSOR 2 IS 32
      SENSOR 3 IS 32
      SENSOR 4 IS 67
   Then:
      FORCE 1  IS 03. -2.99 -1.50(100)

Rule 206
--------
   If:
      SENSOR 1 IS 61
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 61
   Then:
      FORCE 1  IS 05. -1.40 -1.30(100)
```

```
Rule 209
--------
   If:
      SENSOR 1 IS 18
      SENSOR 2 IS 64
      SENSOR 3 IS 64
      SENSOR 4 IS 18
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)

Rule 210
--------
   If:
      SENSOR 1 IS 77
      SENSOR 2 IS 27
      SENSOR 3 IS 27
      SENSOR 4 IS 77
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)

Rule 211
--------
   If:
      SENSOR 1 IS 75
      SENSOR 2 IS 29
      SENSOR 3 IS 29
      SENSOR 4 IS 75
   Then:
      FORCE 1  IS 03. -2.99 -1.50(100)

Rule 212
--------
   If:
      SENSOR 1 IS 34
      SENSOR 2 IS 55
      SENSOR 3 IS 55
      SENSOR 4 IS 34
   Then:
      FORCE 1  IS 89.  1.30  1.40(100)

Rule 213
--------
   If:
      SENSOR 1 IS 26
      SENSOR 2 IS 59
      SENSOR 3 IS 59
      SENSOR 4 IS 26
   Then:
      FORCE 1  IS 91.  1.50  2.99(100)
```

```
Rule 214
--------
   If:
      SENSOR 1 IS 58
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 58
   Then:
      FORCE 1  IS 07. -1.20 -1.10(100)

Rule 215
--------
   If:
      SENSOR 1 IS 58
      SENSOR 2 IS 39
      SENSOR 3 IS 39
      SENSOR 4 IS 58
   Then:
      FORCE 1  IS 07. -1.20 -1.10(100)

Rule 216
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 24. -0.46 -0.44(50)
                  27. -0.40 -0.38(50)

Rule 217
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 68.  0.40  0.42(100)

Rule 218
--------
   If:
      SENSOR 1 IS 39
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 39
   Then:
      FORCE 1  IS 83.  0.70  0.80(100)
```

```
Rule 219
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 76.  0.56  0.58(100)

Rule 220
--------
   If:
      SENSOR 1 IS 52
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 52
   Then:
      FORCE 1  IS 23. -0.48 -0.46(100)

Rule 221
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 43. -0.08 -0.06(10)
                  44. -0.06 -0.04(30)
                  45. -0.04 -0.02(30)
                  46. -0.02 -.003(30)

Rule 222
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)

Rule 223
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 52
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 47. -0.003 .003(100)
```

```
Rule 224
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 49
   Then:
      FORCE 1   IS 44. -0.06 -0.04(50)
                   45. -0.04 -0.02(50)

Rule 225
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 51.  0.06  0.08(33)
                   53.  0.10  0.12(33)
                   55.  0.14  0.16(33)

Rule 226
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 52.  0.08  0.10(100)

Rule 227
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1   IS 44. -0.06 -0.04(100)

Rule 228
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 49
   Then:
      FORCE 1   IS 44. -0.06 -0.04(50)
                   45. -0.04 -0.02(50)
```

```
Rule 229
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 46
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 40. -0.14 -0.12(100)

Rule 230
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SFNSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(50)
                  46. -0.02 -.003(50)

Rule 231
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 232
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44. -0.06 -0.04(20)
                  45. -0.04 -0.02(40)
                  46. -0.02 -.003(40)

Rule 233
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

Rule 234

```
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)
```

Rule 235

```
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)
```

Rule 236

```
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)
```

Rule 237

```
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)
```

Rule 238

```
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)
```

```
Rule 239
---------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(25)
                  46. -0.02 -.003(50)
                  48.  0.003 0.02(25)

Rule 240
---------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(50)
                  49.  0.02  0.04(50)

Rule 241
---------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(50)
                  46. -0.02 -.003(50)

Rule 242
---------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(67)
                  45. -0.04 -0.02(33)
```

```
Rule 243
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 244
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 49.  0.02  0.04(67)
                  50.  0.04  0.06(33)

Rule 245
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  49.  0.02  0.04(50)

Rule 246
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 247
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)
```

```
Rule 248
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(33)
                  46. -0.02 -.003(67)

Rule 249
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 250
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 251
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(50)
                  46. -0.02 -.003(50)

Rule 252
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(40)
                  48.  0.003 0.02(60)
```

```
Rule 253
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 48.  0.003 0.02(50)
                   49.  0.02  0.04(50)

Rule 254
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1   IS 46. -0.02 -.003(100)

Rule 255
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 46. -0.02 -.003(10)
                   48.  0.003 0.02(50)
                   49.  0.02  0.04(40)

Rule 256
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1   IS 46. -0.02 -.003(53)
                   47. -0.003 .003(27)
                   48.  0.003 0.02(20)
```

```
Rule 257
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 258
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 45
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 259
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 53
      SENSOR 3 IS 43
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 83.  0.70  0.80(100)

Rule 260
--------
   If:
      SENSOR 1 IS 40
      SENSOR 2 IS 55
      SENSOR 3 IS 42
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 85.  0.90  1.00(100)

Rule 261
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 52
      SENSOR 3 IS 45
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 83.  0.70  0.80(100)
```

```
Rule 262
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 48
      SENSOR 3 IS 50
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 63.  0.30  0.32(100)

Rule 263
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 44
      SENSOR 3 IS 52
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 264
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 43
      SENSOR 3 IS 52
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 33. -0.28 -0.26(100)

Rule 265
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 44
      SENSOR 3 IS 50
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 36. -0.22 -0.20(100)

Rule 266
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 45
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

```
Rule 267
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 44
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 52.  0.08  0.10(50)
                  53.  0.10  0.12(50)

Rule 268
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 44
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 269
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 45
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 40. -0.14 -0.12(100)

Rule 270
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 45
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 37. -0.20 -0.18(100)

Rule 271
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 45
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 38. -0.18 -0.16(100)
```

```
Rule 272
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 43. -0.08 -0.06(100)

Rule 273
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)

Rule 274
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 49
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 56.  0.16  0.18(100)

Rule 275
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 53
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 276
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 56.  0.16  0.18(100)
```

```
Rule 277
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 278
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 279
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 280
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 281
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)
```

```
Rule 282
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 49.  0.02   0.04(33)
                   50.  0.04   0.06(33)
                   51.  0.06   0.08(33)

Rule 283
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 50.  0.04   0.06(100)

Rule 284
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 53
   Then:
      FORCE 1   IS 47. -0.003 .003(100)

Rule 285
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 45
      SENSOR 3 IS 49
      SENSOR 4 IS 50
   Then:
      FORCE 1   IS 44. -0.06 -0.04(100)

Rule 286
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 47
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 55.  0.14   0.16(100)
```

```
Rule 287
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 53.  0.10  0.12(100)

Rule 288
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 289
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44. -0.06 -0.04(33)
                  46. -0.02 -.003(67)

Rule 290
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 291
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)
```

```
Rule 292
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 293
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 294
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  48.  0.003 0.02(50)

Rule 295
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 296
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)
```

```
Rule 297
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 298
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 46. -0.02 -.003(25)
                  48.  0.003 0.02(75)

Rule 299
--------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 300
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 49
      SENSOR 3 IS 45
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 43. -0.08 -0.06(100)

Rule 301
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 47
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)
```

```
Rule 302
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 303
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 304
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 305
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 306
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)
```

```
Rule 307
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 43. -0.08 -0.06(50)
                  45. -0.04 -0.02(50)

Rule 308
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  48.  0.003 0.02(50)

Rule 309
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 310
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 53
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 311
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)
```

```
Rule 312
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)

Rule 313
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 314
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 315
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 316
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)
```

```
Rule 317
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 318
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 319
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 48.  0.003 0.02(50)
                  50.  0.04  0.06(50)

Rule 320
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 321
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

```
Rule 322
--------
   If:
      SENSOR 1 IS 92
      SENSOR 2 IS 2
      SENSOR 3 IS 2
      SENSOR 4 IS 92
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)

Rule 323
--------
   If:
      SENSOR 1 IS 2
      SENSOR 2 IS 92
      SENSOR 3 IS 92
      SENSOR 4 IS 2
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)
```

KNOWLEDGE BASE FOR THE EXPERT SYSTEM 2 AT ACTUATOR 2

```
Rule 3
------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)

Rule 5
------
   If:
      SENSOR 1 IS 32
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 32
   Then:
      FORCE 1  IS 32. -0.30 -0.28(100)

Rule 7
------
   If:
      SENSOR 1 IS 30
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 30
   Then:
      FORCE 1  IS 31. -0.32 -0.30(100)

Rule 9
------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 44. -0.06 -0.04(50)
                  45. -0.04 -0.02(50)

Rule 11
-------
   If:
      SENSOR 1 IS 66
      SENSOR 2 IS 32
      SENSOR 3 IS 32
      SENSOR 4 IS 66
   Then:
      FORCE 1  IS 68.  0.40  0.42(100)
```

```
Rule 13
-------
   If:
      SENSOR 1 IS 72
      SENSOR 2 IS 28
      SENSOR 3 IS 28
      SENSOR 4 IS 72
   Then:
      FORCE 1  IS 75.  0.54  0.56(100)

Rule 15
-------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 53.  0.10  0.12(33)
                  54.  0.12  0.14(67)

Rule 17
-------
   If:
      SENSOR 1 IS 24
      SENSOR 2 IS 57
      SENSOR 3 IS 57
      SENSOR 4 IS 24
   Then:
      FORCE 1  IS 26. -0.42 -0.40(100)

Rule 19
-------
   If:
      SENSOR 1 IS 25
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 25
   Then:
      FORCE 1  IS 27. -0.40 -0.38(100)

Rule 21
-------
   If:
      SENSOR 1 IS 55
      SENSOR 2 IS 37
      SENSOR 3 IS 37
      SENSOR 4 IS 55
   Then:
      FORCE 1  IS 58.  0.20  0.22(100)
```

```
Rule 23
-------
   If:
      SENSOR 1 IS 77
      SENSOR 2 IS 24
      SENSOR 3 IS 24
      SENSOR 4 IS 77
   Then:
      FORCE 1  IS 80.  0.64  0.66(100)

Rule 25
-------
   If:
      SENSOR 1 IS 75
      SENSOR 2 IS 25
      SENSOR 3 IS 25
      SENSOR 4 IS 75
   Then:
      FORCE 1  IS 78.  0.60  0.62(100)

Rule 27
-------
   If:
      SENSOR 1 IS 52
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 52
   Then:
      FORCE 1  IS 54.  0.12  0.14(33)
                  55.  0.14  0.16(67)

Rule 31
-------
   If:
      SENSOR 1 IS 15
      SENSOR 2 IS 64
      SENSOR 3 IS 64
      SENSOR 4 IS 15
   Then:
      FORCE 1  IS 16. -0.62 -0.60(100)

Rule 33
-------
   If:
      SENSOR 1 IS 27
      SENSOR 2 IS 57
      SENSOR 3 IS 57
      SENSOR 4 IS 27
   Then:
      FORCE 1  IS 28. -0.38 -0.36(100)
```

```
Rule 35
-------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 53
   Then:
      FORCE 1  IS 54.  0.12  0.14(100)

Rule 37
-------
   If:
      SENSOR 1 IS 71
      SENSOR 2 IS 31
      SENSOR 3 IS 31
      SENSOR 4 IS 71
   Then:
      FORCE 1  IS 72.  0.48  0.50(100)

Rule 39
-------
   If:
      SENSOR 1 IS 64
      SENSOR 2 IS 36
      SENSOR 3 IS 36
      SENSOR 4 IS 64
   Then:
      FORCE 1  IS 65.  0.34  0.36(100)

Rule 41
-------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 43
-------
   If:
      SENSOR 1 IS 25
      SENSOR 2 IS 61
      SENSOR 3 IS 61
      SENSOR 4 IS 25
   Then:
      FORCE 1  IS 25. -0.44 -0.42(100)
```

```
Rule 45
-------
   If:
      SENSOR 1 IS 25
      SENSOR 2 IS 62
      SENSOR 3 IS 62
      SENSOR 4 IS 25
   Then:
      FORCE 1  IS 24. -0.46 -0.44(100)

Rule 51
-------
   If:
      SENSOR 1 IS 70
      SENSOR 2 IS 35
      SENSOR 3 IS 35
      SENSOR 4 IS 70
   Then:
      FORCE 1  IS 69.  0.42  0.44(100)

Rule 53
-------
   If:
      SENSOR 1 IS 63
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 63
   Then:
      FORCE 1  IS 62.  0.28  0.30(100)

Rule 55
-------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 57
-------
   If:
      SENSOR 1 IS 32
      SENSOR 2 IS 60
      SENSOR 3 IS 60
      SENSOR 4 IS 32
   Then:
      FORCE 1  IS 29. -0.36 -0.34(100)
```

```
Rule 59
-------
   If:
      SENSOR 1 IS 31
      SENSOR 2 IS 62
      SENSOR 3 IS 62
      SENSOR 4 IS 31
   Then:
      FORCE 1   IS 28. -0.38 -0.36(100)

Rule 61
-------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 55
      SENSOR 3 IS 55
      SENSOR 4 IS 42
   Then:
      FORCE 1   IS 39. -0.16 -0.14(100)

Rule 63
-------
   If:
      SENSOR 1 IS 58
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 58
   Then:
      FORCE 1   IS 56.  0.16  0.18(100)

Rule 65
-------
   If:
      SENSOR 1 IS 66
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 66
   Then:
      FORCE 1   IS 63.  0.30  0.32(50)
                   64.  0.32  0.34(50)

Rule 67
-------
   If:
      SENSOR 1 IS 56
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 56
   Then:
      FORCE 1   IS 53.  0.10  0.12(100)
```

```
Rule 69
-------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 38. -0.18 -0.16(100)

Rule 71
-------
   If:
      SENSOR 1 IS 34
      SENSOR 2 IS 61
      SENSOR 3 IS 61
      SENSOR 4 IS 34
   Then:
      FORCE 1  IS 31. -0.32 -0.30(100)

Rule 73
-------
   If:
      SENSOR 1 IS 38
      SENSOR 2 IS 58
      SENSOR 3 IS 58
      SENSOR 4 IS 38
   Then:
      FORCE 1  IS 34. -0.26 -0.24(100)

Rule 75
-------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 44. -0.06 -0.04(25)
                  46. -0.02 -.003(75)

Rule 77
-------
   If:
      SENSOR 1 IS 63
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 63
   Then:
      FORCE 1  IS 60.  0.24  0.26(100)
```

```
Rule 79
-------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 54
      SENSOR 3 IS 54
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)

Rule 83
-------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 40. -0.14 -0.12(100)

Rule 85
-------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 53
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 87
-------
   If:
      SENSOR 1 IS 59
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 59
   Then:
      FORCE 1  IS 58.  0.20  0.22(100)

Rule 89
-------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 53
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)
```

```
Rule 91
-------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 43. -0.08 -0.06(100)

Rule 93
-------
   If:
      SENSOR 1 IS 38
      SENSOR 2 IS 54
      SENSOR 3 IS 54
      SENSOR 4 IS 38
   Then:
      FORCE 1  IS 37. -0.20 -0.18(100)

Rule 99
-------
   If:
      SENSOR 1 IS 55
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 55
   Then:
      FORCE 1  IS 56.  0.16  0.18(40)
                  72.  0.48  0.50(40)
                  74.  0.52  0.54(20)

Rule 101
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)

Rule 102
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 49.  0.02  0.04(33)
                  51.  0.06  0.08(67)
```

```
Rule 103
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 104
--------
   If:
      SENSOR 1 IS 40
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 40
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 105
--------
   If:
      SENSOR 1 IS 38
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 38
   Then:
      FORCE 1  IS 39. -0.16 -0.14(50)
                  40. -0.14 -0.12(50)

Rule 106
--------
   If:
      SENSOR 1 IS 39
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 39
   Then:
      FORCE 1  IS 40. -0.14 -0.12(100)

Rule 108
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 45. -0.04 -0.02(50)
                  46. -0.02 -.003(50)
```

```
Rule 109
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 50.   0.04   0.06(50)
                   54.   0.12   0.14(50)

Rule 110
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 50
   Then:
      FORCE 1   IS 52.   0.08   0.10(100)

Rule 111
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 46
   Then:
      FORCE 1   IS 49.   0.02   0.04(50)
                   53.   0.10   0.12(50)

Rule 112
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 43
   Then:
      FORCE 1   IS 43. -0.08 -0.06(29)
                   44. -0.06 -0.04(14)
                   45. -0.04 -0.02(14)
                   46. -0.02 -.003(43)
```

```
Rule 115
--------
   If:
      SENSOR 1 IS 39
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 39
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)

Rule 116
--------
   If:
      SENSOR 1 IS 39
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 39
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 117
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 43. -0.08 -0.06(50)
                  44. -0.06 -0.04(50)

Rule 118
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 122
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 45. -0.04 -0.02(25)
                  47. -0.003 .003(25)
                  48.  0.003 0.02(50)
```

```
Rule 123
--------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 124
--------
   If:
      SENSOR 1 IS 40
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 40
   Then:
      FORCE 1  IS 42. -0.10 -0.08(33)
                  43. -0.08 -0.06(67)

Rule 125
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 49.  0.02  0.04(50)
                  51.  0.06  0.08(50)

Rule 126
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 127
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 51.  0.06  0.08(50)
                  52.  0.08  0.10(50)
```

```
Rule 129
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 130
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 46. -0.02 -.003(11)
                  48.  0.003 0.02(78)
                  49.  0.02  0.04(11)

Rule 133
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 135
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 48.  0.003 0.02(70)
                  49.  0.02  0.04(20)
                  50.  0.04  0.06(10)
```

```
Rule 136
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 49.  0.02  0.04(50)
                  54.  0.12  0.14(50)

Rule 137
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 50.  0.04  0.06(33)
                  51.  0.06  0.08(67)

Rule 138
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 49.  0.02  0.04(25)
                  50.  0.04  0.06(25)
                  51.  0.06  0.08(25)
                  53.  0.10  0.12(25)

Rule 139
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

```
Rule 140
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 44
   Then:
      FORCE 1   IS 38. -0.18 -0.16(33)
                   39. -0.16 -0.14(33)
                   44. -0.06 -0.04(33)

Rule 141
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 44
   Then:
      FORCE 1   IS 43. -0.08 -0.06(50)
                   44. -0.06 -0.04(50)

Rule 143
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1   IS 44. -0.06 -0.04(50)
                   45. -0.04 -0.02(50)

Rule 144
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 44. -0.06 -0.04(33)
                   45. -0.04 -0.02(33)
                   46. -0.02 -.003(33)
```

Rule 145

```
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)
```

Rule 146

```
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)
```

Rule 147

```
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 49.  0.02  0.04(50)
                  50.  0.04  0.06(50)
```

Rule 148

```
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)
```

Rule 149

```
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)
```

```
Rule 151
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 152
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 153
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 49.  0.02  0.04(75)
                  57.  0.18  0.20(25)

Rule 154
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 43. -0.08 -0.06(50)
                  45. -0.04 -0.02(50)

Rule 155
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(50)
                  45. -0.04 -0.02(50)
```

```
Rule 158
--------
   If:
      SENSOR 1 IS 2
      SENSOR 2 IS 92
      SENSOR 3 IS 92
      SENSOR 4 IS 2
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)

Rule 159
--------
   If:
      SENSOR 1 IS 92
      SENSOR 2 IS 2
      SENSOR 3 IS 2
      SENSOR 4 IS 92
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)

Rule 160
--------
   If:
      SENSOR 1 IS 76
      SENSOR 2 IS 33
      SENSOR 3 IS 33
      SENSOR 4 IS 76
   Then:
      FORCE 1  IS 90.  1.40  1.50(35)
                  91.  1.50  2.99(65)

Rule 161
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 34. -0.26 -0.24(50)
                  35. -0.24 -0.22(50)

Rule 162
--------
   If:
      SENSOR 1 IS 34
      SENSOR 2 IS 55
      SENSOR 3 IS 55
      SENSOR 4 IS 34
   Then:
      FORCE 1  IS 10. -0.90 -0.80(67)
                  11. -0.80 -0.70(33)
```

```
Rule 163
--------
   If:
      SENSOR 1 IS 26
      SENSOR 2 IS 59
      SENSOR 3 IS 59
      SENSOR 4 IS 26
   Then:
      FORCE 1  IS 06. -1.30 -1.20(100)

Rule 164
--------
   If:
      SENSOR 1 IS 83
      SENSOR 2 IS 20
      SENSOR 3 IS 20
      SENSOR 4 IS 83
   Then:
      FORCE 1  IS 91.  1.50  2.99(100)

Rule 165
--------
   If:
      SENSOR 1 IS 63
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 63
   Then:
      FORCE 1  IS 84.  0.80  0.90(23)
                  85.  0.90  1.00(78)

Rule 168
--------
   If:
      SENSOR 1 IS 18
      SENSOR 2 IS 64
      SENSOR 3 IS 64
      SENSOR 4 IS 18
   Then:
      FORCE 1  IS 03. -2.99 -1.50(67)
                  04. -1.50 -1.40(34)

Rule 169
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 60.  0.24  0.26(33)
                  62.  0.28  0.30(67)
```

```
Rule 170
--------
   If:
      SENSOR 1 IS 58
      SENSOR 2 IS 39
      SENSOR 3 IS 39
      SENSOR 4 IS 58
   Then:
      FORCE 1  IS 83.  0.70  0.80(100)

Rule 171
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 45
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 172
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 53
      SENSOR 3 IS 43
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 08. -1.10 -1.00(100)

Rule 173
--------
   If:
      SENSOR 1 IS 40
      SENSOR 2 IS 55
      SENSOR 3 IS 42
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 06. -1.30 -1.20(100)

Rule 174
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 52
      SENSOR 3 IS 45
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 10. -0.90 -0.80(100)
```

```
Rule 175
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 48
      SENSOR 3 IS 50
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 40. -0.14 -0.12(100)

Rule 176
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 44
      SENSOR 3 IS 52
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 71.  0.46  0.48(100)

Rule 177
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 43
      SENSOR 3 IS 52
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 80.  0.64  0.66(100)

Rule 178
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 44
      SENSOR 3 IS 50
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 70.  0.44  0.46(100)

Rule 179
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 45
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)
```

```
Rule 180
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 44
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 32. -0.30 -0.28(50)
                  35. -0.24 -0.22(50)

Rule 181
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 44
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 40. -0.14 -0.12(100)

Rule 182
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 45
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 53.  0.10  0.12(100)

Rule 183
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 45
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 61.  0.26  0.28(100)

Rule 184
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 45
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 61.  0.26  0.28(100)
```

```
Rule 185
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1   IS 54.  0.12  0.14(100)

Rule 186
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 45
   Then:
      FORCE 1   IS 44. -0.06 -0.04(100)

Rule 187
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 49
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1   IS 35. -0.24 -0.22(50)
                   37. -0.20 -0.18(50)

Rule 188
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 49
      SENSOR 3 IS 46
      SENSOR 4 IS 45
   Then:
      FORCE 1   IS 38. -0.18 -0.16(100)

Rule 189
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 45
   Then:
      FORCE 1   IS 44. -0.06 -0.04(100)
```

```
Rule 190
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 191
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 49.  0.02  0.04(50)
                  52.  0.08  0.10(50)

Rule 192
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 193
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 194
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 45
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

```
Rule 195
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 196
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 197
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 198
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 199
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 52
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 47. -0.003 .003(100)
```

```
Rule 200
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 49.  0.02  0.04(50)
                  53.  0.10  0.12(50)

Rule 201
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 37. -0.20 -0.18(33)
                  41. -0.12 -0.10(67)

Rule 202
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 203
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 204
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)
```

```
Rule 205
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 46
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 56.  0.16  0.18(100)

Rule 206
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 48.  0.003 0.02(50)
                  50.  0.04  0.06(50)

Rule 207
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 208
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 46. -0.02 -.003(20)
                  48.  0.003 0.02(40)
                  49.  0.02  0.04(20)
                  50.  0.04  0.06(20)
```

```
Rule 209
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  48.  0.003 0.02(50)

Rule 210
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)

Rule 211
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)

Rule 212
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 213
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 43. -0.08 -0.06(100)
```

```
Rule 214
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 50.   0.04   0.06(100)

Rule 215
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 43. -0.08 -0.06(25)
                   44. -0.06 -0.04(50)
                   45. -0.04 -0.02(25)

Rule 216
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 48.   0.003 0.02(78)
                   49.   0.02  0.04(22)

Rule 217
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 44. -0.06 -0.04(100)

Rule 218
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 48.   0.003 0.02(50)
                   50.   0.04  0.06(50)
```

```
Rule 219
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 50.  0.04  0.06(33)
                  51.  0.06  0.08(67)

Rule 220
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 221
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(33)
                  46. -0.02 -.003(67)

Rule 222
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 223
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)
```

Rule 224

```
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 54.  0.12  0.14(100)
```

Rule 225

```
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 53.  0.10  0.12(67)
                  55.  0.14  0.16(33)
```

Rule 226

```
--------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)
```

Rule 227

```
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 48.  0.003 0.02(27)
                  49.  0.02  0.04(54)
                  50.  0.04  0.06(12)
                  51.  0.06  0.08(8)
```

```
Rule 228
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 45. -0.04 -0.02(5)
                  46. -0.02 -.003(25)
                  47. -0.003 .003(5)
                  48.  0.003 0.02(45)
                  49.  0.02  0.04(15)
                  50.  0.04  0.06(5)

Rule 229
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 230
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 231
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)
```

```
Rule 232
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 45. -0.04 -0.02(50)
                  46. -0.02 -.003(50)

Rule 233
--------
   If:
      SENSOR 1 IS 52
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 52
   Then:
      FORCE 1  IS 45. -0.04 -0.02(63)
                  46. -0.02 -.003(38)

Rule 235
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 236
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 237
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)
```

```
Rule 238
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 46.  -0.02 -.003(17)
                   48.   0.003 0.02(83)

Rule 239
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 48.   0.003 0.02(100)

Rule 240
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 44
   Then:
      FORCE 1   IS 40.  -0.14 -0.12(67)
                   41.  -0.12 -0.10(33)

Rule 241
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 44
   Then:
      FORCE 1   IS 41.  -0.12 -0.10(100)

Rule 242
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 45
   Then:
      FORCE 1   IS 44.  -0.06 -0.04(100)
```

Rule 243

```
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)
```

Rule 244

```
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)
```

Rule 246

```
--------
   If:
      SENSOR 1 IS 3
      SENSOR 2 IS 89
      SENSOR 3 IS 89
      SENSOR 4 IS 3
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)
```

Rule 247

```
--------
   If:
      SENSOR 1 IS 17
      SENSOR 2 IS 70
      SENSOR 3 IS 70
      SENSOR 4 IS 17
   Then:
      FORCE 1  IS 03. -2.99 -1.50(100)
```

Rule 248

```
--------
   If:
      SENSOR 1 IS 36
      SENSOR 2 IS 58
      SENSOR 3 IS 58
      SENSOR 4 IS 36
   Then:
      FORCE 1  IS 12. -0.70 -0.68(100)
```

```
Rule 249
--------
   If:
      SENSOR 1 IS 60
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 60
   Then:
      FORCE 1  IS 83.  0.70  0.80(100)

Rule 250
--------
   If:
      SENSOR 1 IS 67
      SENSOR 2 IS 32
      SENSOR 3 IS 32
      SENSOR 4 IS 67
   Then:
      FORCE 1  IS 89.  1.30  1.40(100)

Rule 251
--------
   If:
      SENSOR 1 IS 61
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 61
   Then:
      FORCE 1  IS 84.  0.80  0.90(100)

Rule 252
--------
   If:
      SENSOR 1 IS 15
      SENSOR 2 IS 71
      SENSOR 3 IS 71
      SENSOR 4 IS 15
   Then:
      FORCE 1  IS 03. -2.99 -1.50(100)

Rule 253
--------
   If:
      SENSOR 1 IS 9
      SENSOR 2 IS 78
      SENSOR 3 IS 78
      SENSOR 4 IS 9
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)
```

```
Rule 254
--------
   If:
      SENSOR 1 IS 77
      SENSOR 2 IS 27
      SENSOR 3 IS 27
      SENSOR 4 IS 77
   Then:
      FORCE 1  IS 91.  1.50  2.99(100)

Rule 257
--------
   If:
      SENSOR 1 IS 39
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 39
   Then:
      FORCE 1  IS 22. -0.50 -0.48(100)

Rule 258
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 29. -0.36 -0.34(100)

Rule 259
--------
   If:
      SENSOR 1 IS 52
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 52
   Then:
      FORCE 1  IS 62.  0.28  0.30(100)

Rule 260
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(13)
                  46. -0.02 -.003(63)
                  47. -0.003 .003(25)
```

Rule 261

```
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)
```

Rule 262

```
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 53
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)
```

Rule 263

```
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 39. -0.16 -0.14(100)
```

Rule 264

```
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)
```

Rule 265

```
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 39. -0.16 -0.14(100)
```

```
Rule 266
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)

Rule 267
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)

Rule 268
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(50)
                  45. -0.04 -0.02(50)

Rule 269
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 42. -0.10 -0.08(33)
                  44. -0.06 -0.04(33)
                  46. -0.02 -.003(33)

Rule 270
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 50.  0.04  0.06(50)
                  51.  0.06  0.08(50)
```

Rule 271

```
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)
```

Rule 272

```
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

Rule 273

```
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  48.  0.003 0.02(25)
                  49.  0.02  0.04(25)
```

Rule 274

```
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(22)
                  46. -0.02 -.003(33)
                  48.  0.003 0.02(44)
```

```
Rule 275
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 46. -0.02 -.003(11)
                  47. -0.003 .003(11)
                  48.  0.003 0.02(33)
                  49.  0.02  0.04(44)

Rule 276
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 277
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 53
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 278
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 45
      SENSOR 3 IS 49
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 56.  0.16  0.18(100)

Rule 279
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 47
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

```
Rule 280
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 281
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 282
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 48.  0.003 0.02(33)
                  49.  0.02  0.04(33)
                  51.  0.06  0.08(33)

Rule 283
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 284
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)
```

```
Rule 285
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 286
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 287
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 49.  0.02   0.04(50)
                  50.  0.04   0.06(50)

Rule 288
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 289
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

```
Rule 290
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 291
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 45. -0.04 -0.02(25)
                  46. -0.02 -.003(25)
                  47. -0.003 .003(25)
                  48.  0.003 0.02(25)

Rule 292
--------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 293
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 49
      SENSOR 3 IS 45
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)

Rule 294
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 47
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)
```

```
Rule 295
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 296
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 50.  0.04  0.06(50)
                  51.  0.06  0.08(50)

Rule 297
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 298
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 299
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)
```

```
Rule 300
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 48.  0.003 0.02(50)
                  50.  0.04  0.06(50)

Rule 301
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44. -0.06 -0.04(50)
                  45. -0.04 -0.02(50)

Rule 302
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 303
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 304
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)
```

```
Rule 305
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 53
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 306
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)

Rule 307
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 308
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 309
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)
```

```
Rule 310
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 43. -0.08 -0.06(100)

Rule 311
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 55.  0.14  0.16(100)

Rule 312
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 51.  0.06  0.08(100)

Rule 313
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 42. -0.10 -0.08(100)

Rule 314
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 43. -0.08 -0.06(50)
                   44. -0.06 -0.04(50)
```

```
Rule 315
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 316
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)
```

KNOWLEDGE BASE FOR THE EXPERT SYSTEM 4 AT ACTUATOR 4

```
Rule 1
------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(31)
                  47. -0.003 .003(19)
                  48.  0.003 0.02(50)

Rule 4
------
   If:
      SENSOR 1 IS 36
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 36
   Then:
      FORCE 1  IS 64.  0.32  0.34(100)

Rule 5
------
   If:
      SENSOR 1 IS 32
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 32
   Then:
      FORCE 1  IS 71.  0.46  0.48(100)

Rule 7
------
   If:
      SENSOR 1 IS 30
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 30
   Then:
      FORCE 1  IS 74.  0.52  0.54(100)
```

```
Rule 9
------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 51.  0.06  0.08(50)
                  52.  0.08  0.10(50)

Rule 11
-------
   If:
      SENSOR 1 IS 66
      SENSOR 2 IS 32
      SENSOR 3 IS 32
      SENSOR 4 IS 66
   Then:
      FORCE 1  IS 15. -0.64 -0.62(100)

Rule 13
-------
   If:
      SENSOR 1 IS 72
      SENSOR 2 IS 28
      SENSOR 3 IS 28
      SENSOR 4 IS 72
   Then:
      FORCE 1  IS 10. -0.90 -0.80(100)

Rule 15
-------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 37. -0.20 -0.18(67)
                  38. -0.18 -0.16(33)

Rule 17
-------
   If:
      SENSOR 1 IS 24
      SENSOR 2 IS 57
      SENSOR 3 IS 57
      SENSOR 4 IS 24
   Then:
      FORCE 1  IS 82.  0.68  0.70(100)
```

```
Rule 19
-------
   If:
      SENSOR 1 IS 25
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 25
   Then:
      FORCE 1  IS 81.  0.66  0.68(100)

Rule 21
-------
   If:
      SENSOR 1 IS 55
      SENSOR 2 IS 37
      SENSOR 3 IS 37
      SENSOR 4 IS 55
   Then:
      FORCE 1  IS 31. -0.32 -0.30(100)

Rule 23
-------
   If:
      SENSOR 1 IS 77
      SENSOR 2 IS 24
      SENSOR 3 IS 24
      SENSOR 4 IS 77
   Then:
      FORCE 1  IS 08. -1.10 -1.00(100)

Rule 25
-------
   If:
      SENSOR 1 IS 75
      SENSOR 2 IS 25
      SENSOR 3 IS 25
      SENSOR 4 IS 75
   Then:
      FORCE 1  IS 09. -1.00 -0.90(100)

Rule 27
-------
   If:
      SENSOR 1 IS 52
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 52
   Then:
      FORCE 1  IS 36. -0.22 -0.20(67)
                  37. -0.20 -0.18(33)
```

```
Rule 29
-------
   If:
      SENSOR 1 IS 25
      SENSOR 2 IS 57
      SENSOR 3 IS 57
      SENSOR 4 IS 25
   Then:
      FORCE 1   IS 80.   0.64   0.66(100)

Rule 31
-------
   If:
      SENSOR 1 IS 15
      SENSOR 2 IS 64
      SENSOR 3 IS 64
      SENSOR 4 IS 15
   Then:
      FORCE 1   IS 86.   1.00   1.10(100)

Rule 33
-------
   If:
      SENSOR 1 IS 27
      SENSOR 2 IS 57
      SENSOR 3 IS 57
      SENSOR 4 IS 27
   Then:
      FORCE 1   IS 78.   0.60   0.62(100)

Rule 35
-------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 53
   Then:
      FORCE 1   IS 37. -0.20 -0.18(100)

Rule 37
-------
   If:
      SENSOR 1 IS 71
      SENSOR 2 IS 31
      SENSOR 3 IS 31
      SENSOR 4 IS 71
   Then:
      FORCE 1   IS 11. -0.80 -0.70(100)
```

```
Rule 39
-------
   If:
      SENSOR 1 IS 64
      SENSOR 2 IS 36
      SENSOR 3 IS 36
      SENSOR 4 IS 64
   Then:
      FORCE 1  IS 18. -0.58 -0.56(100)

Rule 41
-------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 55.  0.14  0.16(100)

Rule 45
-------
   If:
      SENSOR 1 IS 25
      SENSOR 2 IS 62
      SENSOR 3 IS 62
      SENSOR 4 IS 25
   Then:
      FORCE 1  IS 83.  0.70  0.80(100)

Rule 47
-------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 59.  0.22  0.24(100)

Rule 49
-------
   If:
      SENSOR 1 IS 61
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 61
   Then:
      FORCE 1  IS 26. -0.42 -0.40(100)
```

```
Rule 53
-------
   If:
      SENSOR 1 IS 63
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 63
   Then:
      FORCE 1  IS 22. -0.50 -0.48(100)

Rule 55
-------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 57
-------
   If:
      SENSOR 1 IS 32
      SENSOR 2 IS 60
      SENSOR 3 IS 60
      SENSOR 4 IS 32
   Then:
      FORCE 1  IS 74.  0.52  0.54(100)

Rule 59
-------
   If:
      SENSOR 1 IS 31
      SENSOR 2 IS 62
      SENSOR 3 IS 62
      SENSOR 4 IS 31
   Then:
      FORCE 1  IS 76.  0.56  0.58(100)

Rule 61
-------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 55
      SENSOR 3 IS 55
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 58.  0.20  0.22(100)
```

```
Rule 63
-------
   If:
      SENSOR 1 IS 58
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 58
   Then:
      FORCE 1  IS 32. -0.30 -0.28(100)

Rule 65
-------
   If:
      SENSOR 1 IS 66
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 66
   Then:
      FORCE 1  IS 19. -0.56 -0.54(50)
                  20. -0.54 -0.52(50)

Rule 67
-------
   If:
      SENSOR 1 IS 56
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 56
   Then:
      FORCE 1  IS 36. -0.22 -0.20(100)

Rule 69
-------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 56
      SENSOR 3 IS 56
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 59.  0.22  0.24(100)

Rule 71
-------
   If:
      SENSOR 1 IS 34
      SENSOR 2 IS 61
      SENSOR 3 IS 61
      SENSOR 4 IS 34
   Then:
      FORCE 1  IS 71.  0.46  0.48(100)
```

```
Rule 73
-------
   If:
      SENSOR 1 IS 38
      SENSOR 2 IS 58
      SENSOR 3 IS 58
      SENSOR 4 IS 38
   Then:
      FORCE 1  IS 66.  0.36  0.38(100)

Rule 75
-------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 77
-------
   If:
      SENSOR 1 IS 63
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 63
   Then:
      FORCE 1  IS 25. -0.44 -0.42(100)

Rule 79
-------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 54
      SENSOR 3 IS 54
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 55.  0.14  0.16(100)

Rule 83
-------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 56.  0.16  0.18(100)
```

```
Rule 85
-------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 53
   Then:
      FORCE 1  IS 39. -0.16 -0.14(100)

Rule 87
-------
   If:
      SENSOR 1 IS 59
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 59
   Then:
      FORCE 1  IS 29. -0.36 -0.34(50)
                  30. -0.34 -0.32(50)

Rule 89
-------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 53
   Then:
      FORCE 1  IS 38. -0.18 -0.16(100)

Rule 91
-------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 53.  0.10  0.12(100)

Rule 93
-------
   If:
      SENSOR 1 IS 38
      SENSOR 2 IS 54
      SENSOR 3 IS 54
      SENSOR 4 IS 38
   Then:
      FORCE 1  IS 62.  0.28  0.30(50)
                  63.  0.30  0.32(50)
```

```
Rule 97
-------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 50
   Then:
      FORCE 1   IS 42.  -0.10 -0.08(50)
                   43.  -0.08 -0.06(50)

Rule 99
-------
   If:
      SENSOR 1 IS 55
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 55
   Then:
      FORCE 1   IS 10.  -0.90 -0.80(25)
                   11.  -0.80 -0.70(25)
                   33.  -0.28 -0.26(25)
                   34.  -0.26 -0.24(25)

Rule 100
--------
   If:
      SENSOR 1 IS 54
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 54
   Then:
      FORCE 1   IS 35.  -0.24 -0.22(100)

Rule 102
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 41.  -0.12 -0.10(67)
                   45.  -0.04 -0.02(33)
```

```
Rule 103
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 104
--------
   If:
      SENSOR 1 IS 40
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 40
   Then:
      FORCE 1  IS 56.  0.16  0.18(100)

Rule 105
--------
   If:
      SENSOR 1 IS 38
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 38
   Then:
      FORCE 1  IS 59.  0.22  0.24(50)
                  60.  0.24  0.26(50)

Rule 107
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 55.  0.14  0.16(100)

Rule 108
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 50.  0.04  0.06(25)
                  52.  0.08  0.10(25)
                  53.  0.10  0.12(50)
```

```
Rule 109
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 38. -0.18 -0.16(50)
                  44. -0.06 -0.04(50)

Rule 110
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 40. -0.14 -0.12(100)

Rule 112
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 50.  0.04  0.06(43)
                  55.  0.14  0.16(14)
                  56.  0.16  0.18(14)
                  58.  0.20  0.22(29)

Rule 113
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 54.  0.12  0.14(100)

Rule 115
--------
   If:
      SENSOR 1 IS 39
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 39
   Then:
      FORCE 1  IS 58.  0.20  0.22(100)
```

```
Rule 116
--------
   If:
      SENSOR 1 IS 39
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 39
   Then:
      FORCE 1  IS 57.  0.18  0.20(100)

Rule 117
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 53.  0.10  0.12(50)
                  54.  0.12  0.14(50)

Rule 118
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 120
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 39. -0.16 -0.14(100)

Rule 122
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 49.  0.02  0.04(25)
                  51.  0.06  0.08(50)
                  54.  0.12  0.14(25)
```

Rule 123

```
--------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)
```

Rule 124

```
--------
   If:
      SENSOR 1 IS 40
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 40
   Then:
      FORCE 1  IS 55.  0.14  0.16(67)
                  56.  0.16  0.18(33)
```

Rule 125

```
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 45. -0.04 -0.02(50)
                  46. -0.02 -.003(50)
```

Rule 126

```
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 43. -0.08 -0.06(100)
```

Rule 129

```
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

```
Rule 130
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 48.  0.003 0.02(33)
                  49.  0.02  0.04(44)
                  50.  0.04  0.06(11)
                  52.  0.08  0.10(11)

Rule 131
--------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 53.  0.10  0.12(100)

Rule 132
--------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 53.  0.10  0.12(50)
                  54.  0.12  0.14(50)

Rule 133
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)

Rule 134
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)
```

```
Rule 135
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44. -0.06 -0.04(10)
                  46. -0.02 -.003(20)
                  47. -0.003 .003(10)
                  48.  0.003 0.02(50)
                  49.  0.02  0.04(10)

Rule 136
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 45
      SENSOR 3 IS 45
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 36. -0.22 -0.20(50)
                  44. -0.06 -0.04(50)

Rule 137
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 41. -0.12 -0.10(67)
                  42. -0.10 -0.08(33)

Rule 138
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 38. -0.18 -0.16(20)
                  40. -0.14 -0.12(20)
                  42. -0.10 -0.08(20)
                  44. -0.06 -0.04(20)
                  47. -0.003 .003(20)
```

```
Rule 139
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 140
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 51.  0.06  0.08(33)
                  59.  0.22  0.24(33)
                  62.  0.28  0.30(33)

Rule 141
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)

Rule 142
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 143
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 49.  0.02  0.04(50)
                  51.  0.06  0.08(50)
```

```
Rule 144
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 46. -0.02 -.003(92)
                  47. -0.003 .003(3)
                  49.  0.02  0.04(3)
                  50.  0.04  0.06(3)

Rule 145
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 43. -0.08 -0.06(100)

Rule 146
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 148
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 149
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  47. -0.003 .003(50)
```

```
Rule 150
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 50.  0.04  0.06(50)
                  51.  0.06  0.08(50)

Rule 151
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 152
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 42. -0.10 -0.08(25)
                  43. -0.08 -0.06(25)
                  44. -0.06 -0.04(25)
                  45. -0.04 -0.02(25)

Rule 153
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 27. -0.40 -0.38(25)
                  43. -0.08 -0.06(50)
                  44. -0.06 -0.04(25)
```

Rule 154

```
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 48.   0.003 0.02(100)
```

Rule 155

```
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 49.   0.02   0.04(50)
                  50.   0.04   0.06(50)
```

Rule 156

```
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 38. -0.18 -0.16(100)
```

Rule 157

```
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 37. -0.20 -0.18(33)
                  40. -0.14 -0.12(67)
```

Rule 158

```
--------
   If:
      SENSOR 1 IS 42
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 42
   Then:
      FORCE 1  IS 59.   0.22   0.24(100)
```

```
Rule 159
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 45. -0.04 -0.02(12)
                  46. -0.02 -.003(15)
                  47. -0.003 .003(8)
                  48.  0.003 0.02(27)
                  49.  0.02  0.04(19)
                  50.  0.04  0.06(15)
                  51.  0.06  0.08(4)
Rule 160
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 46. -0.02 -.003(5)
                  47. -0.003 .003(7)
                  48.  0.003 0.02(85)
                  49.  0.02  0.04(2)
Rule 161
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)
Rule 162
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)
```

```
Rule 163
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 164
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 41. -0.12 -0.10(25)
                  42. -0.10 -0.08(50)
                  43. -0.08 -0.06(25)

Rule 165
--------
   If:
      SENSOR 1 IS 52
      SENSOR 2 IS 53
      SENSOR 3 IS 53
      SENSOR 4 IS 52
   Then:
      FORCE 1  IS 40. -0.14 -0.12(50)
                  41. -0.12 -0.10(50)

Rule 168
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 169
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 43. -0.08 -0.06(20)
                  46. -0.02 -.003(80)
```

```
Rule 170
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(10)
                  45. -0.04 -0.02(3)
                  46. -0.02 -.003(76)
                  47. -0.003 .003(10)

Rule 171
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(17)
                  46. -0.02 -.003(33)
                  47. -0.003 .003(17)
                  48.  0.003 0.02(33)

Rule 172
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 57.  0.18  0.20(33)
                  59.  0.22  0.24(67)

Rule 173
--------
   If:
      SENSOR 1 IS 44
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 57.  0.18  0.20(100)
```

Rule 174
```
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 53.  0.10  0.12(100)
```

Rule 175
```
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 41. -0.12 -0.10(50)
                  42. -0.10 -0.08(50)
```

Rule 176
```
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)
```

Rule 177
```
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(36)
                  48.  0.003 0.02(36)
                  49.  0.02  0.04(27)
```

Rule 179
```
--------
   If:
      SENSOR 1 IS 76
      SENSOR 2 IS 33
      SENSOR 3 IS 33
      SENSOR 4 IS 76
   Then:
      FORCE 1  IS 03. -2.99 -1.50(100)
```

Rule 186

```
--------
   If:
      SENSOR 1 IS 8
      SENSOR 2 IS 83
      SENSOR 3 IS 83
      SENSOR 4 IS 8
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)
```

Rule 189

```
--------
   If:
      SENSOR 1 IS 17
      SENSOR 2 IS 70
      SENSOR 3 IS 70
      SENSOR 4 IS 17
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)
```

Rule 190

```
--------
   If:
      SENSOR 1 IS 36
      SENSOR 2 IS 58
      SENSOR 3 IS 58
      SENSOR 4 IS 36
   Then:
      FORCE 1  IS 86.  1.00  1.10(100)
```

Rule 194

```
--------
   If:
      SENSOR 1 IS 87
      SENSOR 2 IS 10
      SENSOR 3 IS 10
      SENSOR 4 IS 87
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)
```

Rule 196

```
--------
   If:
      SENSOR 1 IS 60
      SENSOR 2 IS 43
      SENSOR 3 IS 43
      SENSOR 4 IS 60
   Then:
      FORCE 1  IS 06. -1.30 -1.20(100)
```

```
Rule 198
--------
   If:
      SENSOR 1 IS 83
      SENSOR 2 IS 20
      SENSOR 3 IS 20
      SENSOR 4 IS 83
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)

Rule 200
--------
   If:
      SENSOR 1 IS 63
      SENSOR 2 IS 41
      SENSOR 3 IS 41
      SENSOR 4 IS 63
   Then:
      FORCE 1  IS 03. -2.99 -1.50(100)

Rule 202
--------
   If:
      SENSOR 1 IS 9
      SENSOR 2 IS 76
      SENSOR 3 IS 76
      SENSOR 4 IS 9
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)

Rule 203
--------
   If:
      SENSOR 1 IS 67
      SENSOR 2 IS 32
      SENSOR 3 IS 32
      SENSOR 4 IS 67
   Then:
      FORCE 1  IS 03. -2.99 -1.50(100)

Rule 206
--------
   If:
      SENSOR 1 IS 61
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 61
   Then:
      FORCE 1  IS 05. -1.40 -1.30(100)
```

```
Rule 209
--------
   If:
      SENSOR 1 IS 18
      SENSOR 2 IS 64
      SENSOR 3 IS 64
      SENSOR 4 IS 18
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)

Rule 210
--------
   If:
      SENSOR 1 IS 77
      SENSOR 2 IS 27
      SENSOR 3 IS 27
      SENSOR 4 IS 77
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)

Rule 211
--------
   If:
      SENSOR 1 IS 75
      SENSOR 2 IS 29
      SENSOR 3 IS 29
      SENSOR 4 IS 75
   Then:
      FORCE 1  IS 03. -2.99 -1.50(100)

Rule 212
--------
   If:
      SENSOR 1 IS 34
      SENSOR 2 IS 55
      SENSOR 3 IS 55
      SENSOR 4 IS 34
   Then:
      FORCE 1  IS 89.  1.30  1.40(100)

Rule 213
--------
   If:
      SENSOR 1 IS 26
      SENSOR 2 IS 59
      SENSOR 3 IS 59
      SENSOR 4 IS 26
   Then:
      FORCE 1  IS 91.  1.50  2.99(100)
```

```
Rule 214
--------
   If:
      SENSOR 1 IS 58
      SENSOR 2 IS 40
      SENSOR 3 IS 40
      SENSOR 4 IS 58
   Then:
      FORCE 1  IS 07. -1.20 -1.10(100)

Rule 215
--------
   If:
      SENSOR 1 IS 58
      SENSOR 2 IS 39
      SENSOR 3 IS 39
      SENSOR 4 IS 58
   Then:
      FORCE 1  IS 07. -1.20 -1.10(100)

Rule 216
--------
   If:
      SENSOR 1 IS 51
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 24. -0.46 -0.44(50)
                  27. -0.40 -0.38(50)

Rule 217
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 50
      SENSOR 3 IS 50
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 68.  0.40  0.42(100)

Rule 218
--------
   If:
      SENSOR 1 IS 39
      SENSOR 2 IS 52
      SENSOR 3 IS 52
      SENSOR 4 IS 39
   Then:
      FORCE 1  IS 83.  0.70  0.80(100)
```

```
Rule 219
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 51
      SENSOR 3 IS 51
      SENSOR 4 IS 41
   Then:
      FORCE 1  IS 76.  0.56  0.58(100)

Rule 220
--------
   If:
      SENSOR 1 IS 52
      SENSOR 2 IS 44
      SENSOR 3 IS 44
      SENSOR 4 IS 52
   Then:
      FORCE 1  IS 23. -0.48 -0.46(100)

Rule 221
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 43. -0.08 -0.06(10)
                  44. -0.06 -0.04(30)
                  45. -0.04 -0.02(30)
                  46. -0.02 -.003(30)

Rule 222
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)

Rule 223
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 52
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 47. -0.003 .003(100)
```

```
Rule 224
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 41. -0.12 -0.10(50)
                  44. -0.06 -0.04(50)

Rule 225
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 42. -0.10 -0.08(33)
                  53.  0.10  0.12(33)
                  55.  0.14  0.16(33)

Rule 226
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 49
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)

Rule 227
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 228
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 42. -0.10 -0.08(50)
                  44. -0.06 -0.04(50)
```

```
Rule 229
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 46
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 40. -0.14 -0.12(100)

Rule 230
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  50.  0.04  0.06(50)

Rule 231
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 232
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 45. -0.04 -0.02(40)
                  46. -0.02 -.003(40)
                  51.  0.06  0.08(20)

Rule 233
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(50)
                  48.  0.003 0.02(50)
```

```
Rule 234
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 235
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 236
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 237
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 238
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)
```

```
Rule 239
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 44. -0.06 -0.04(25)
                   45. -0.04 -0.02(25)
                   46. -0.02 -.003(25)
                   48.  0.003 0.02(25)

Rule 240
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 45. -0.04 -0.02(50)
                   49.  0.02  0.04(50)

Rule 241
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 46. -0.02 -.003(50)
                   48.  0.003 0.02(50)

Rule 242
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 44. -0.06 -0.04(33)
                   45. -0.04 -0.02(33)
                   46. -0.02 -.003(33)
```

```
Rule 243
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 50.  0.04  0.06(100)

Rule 244
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 43. -0.08 -0.06(33)
                   45. -0.04 -0.02(33)
                   49.  0.02  0.04(33)

Rule 245
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 46. -0.02 -.003(50)
                   49.  0.02  0.04(50)

Rule 246
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 49.  0.02  0.04(100)

Rule 247
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1   IS 45. -0.04 -0.02(50)
                   49.  0.02  0.04(50)
```

```
Rule 248
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(33)
                  48.  0.003 0.02(33)
                  50.  0.04  0.06(33)

Rule 249
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 250
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 251
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(50)
                  48.  0.003 0.02(50)

Rule 252
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(20)
                  48.  0.003 0.02(80)
```

```
Rule 253
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 47. -0.003 .003(50)
                   49.  0.02  0.04(50)

Rule 254
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1   IS 46. -0.02 -.003(50)
                   49.  0.02  0.04(50)

Rule 255
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1   IS 46. -0.02 -.003(40)
                   47. -0.003 .003(30)
                   48.  0.003 0.02(30)

Rule 256
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1   IS 46. -0.02 -.003(33)
                   47. -0.003 .003(7)
                   48.  0.003 0.02(33)
                   49.  0.02  0.04(27)
```

```
Rule 257
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  49.  0.02  0.04(50)

Rule 258
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 45
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 259
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 53
      SENSOR 3 IS 43
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 83.  0.70  0.80(100)

Rule 260
--------
   If:
      SENSOR 1 IS 40
      SENSOR 2 IS 55
      SENSOR 3 IS 42
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 85.  0.90  1.00(100)

Rule 261
--------
   If:
      SENSOR 1 IS 41
      SENSOR 2 IS 52
      SENSOR 3 IS 45
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 83.  0.70  0.80(100)
```

```
Rule 262
--------
   If:
      SENSOR 1 IS 43
      SENSOR 2 IS 48
      SENSOR 3 IS 50
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 63.  0.30  0.32(100)

Rule 263
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 44
      SENSOR 3 IS 52
      SENSOR 4 IS 43
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 264
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 43
      SENSOR 3 IS 52
      SENSOR 4 IS 44
   Then:
      FORCE 1  IS 33. -0.28 -0.26(100)

Rule 265
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 44
      SENSOR 3 IS 50
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 36. -0.22 -0.20(100)

Rule 266
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 45
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

```
Rule 267
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 44
      SENSOR 4 IS 51
   Then:
      FORCE 1  IS 52.  0.08  0.10(50)
                  53.  0.10  0.12(50)

Rule 268
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 44
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 269
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 45
      SENSOR 3 IS 46
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 40. -0.14 -0.12(100)

Rule 270
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 45
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 37. -0.20 -0.18(100)

Rule 271
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 45
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 38. -0.18 -0.16(100)
```

```
Rule 272
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 43. -0.08 -0.06(100)

Rule 273
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 52.  0.08  0.10(100)

Rule 274
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 49
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 56.  0.16  0.18(100)

Rule 275
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 53
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 276
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 41. -0.12 -0.10(100)
```

```
Rule 277
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 278
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 279
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 280
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 281
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)
```

```
Rule 282
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 47
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(33)
                  46. -0.02 -.003(67)

Rule 283
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 284
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 53
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 285
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 45
      SENSOR 3 IS 49
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 43. -0.08 -0.06(100)

Rule 286
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 47
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)
```

```
Rule 287
--------
   If:
      SENSOR 1 IS 45
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 288
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 289
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 49.  0.02  0.04(33)
                  50.  0.04  0.06(33)
                  51.  0.06  0.08(33)

Rule 290
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 291
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)
```

```
Rule 292
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 293
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 294
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  48.  0.003 0.02(50)

Rule 295
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 296
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 47. -0.003  .003(33)
                  49.  0.02   0.04(33)
                  50.  0.04   0.06(33)
```

```
Rule 297
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 298
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 47. -0.003 .003(50)
                  48.  0.003 0.02(50)

Rule 299
--------
   If:
      SENSOR 1 IS 53
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 300
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 49
      SENSOR 3 IS 45
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 301
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 47
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 55.  0.14  0.16(100)
```

```
Rule 302
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 53.  0.10  0.12(100)

Rule 303
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 47
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 304
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 48.  0.003 0.02(100)

Rule 305
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 47
      SENSOR 4 IS 49
   Then:
      FORCE 1  IS 42. -0.10 -0.08(100)

Rule 306
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)
```

```
Rule 307
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 46. -0.02 -.003(50)
                  48.  0.003 0.02(50)

Rule 308
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 46
      SENSOR 3 IS 46
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 309
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 53
      SENSOR 3 IS 47
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 47. -0.003 .003(100)

Rule 310
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 49
      SENSOR 4 IS 45
   Then:
      FORCE 1  IS 56.  0.16  0.18(100)

Rule 311
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)
```

```
Rule 312
--------
   If:
      SENSOR 1 IS 49
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 313
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 46. -0.02 -.003(100)

Rule 314
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 49
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 45. -0.04 -0.02(100)

Rule 315
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 51.  0.06  0.08(100)

Rule 316
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 47
      SENSOR 3 IS 49
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)
```

```
Rule 317
--------
   If:
      SENSOR 1 IS 46
      SENSOR 2 IS 48
      SENSOR 3 IS 48
      SENSOR 4 IS 48
   Then:
      FORCE 1  IS 44. -0.06 -0.04(100)

Rule 318
--------
   If:
      SENSOR 1 IS 47
      SENSOR 2 IS 48
      SENSOR 3 IS 46
      SENSOR 4 IS 47
   Then:
      FORCE 1  IS 45. -0.04 -0.02(50)
                  46. -0.02 -.003(50)

Rule 319
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 48
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 50.  0.04  0.06(100)

Rule 320
--------
   If:
      SENSOR 1 IS 48
      SENSOR 2 IS 46
      SENSOR 3 IS 47
      SENSOR 4 IS 46
   Then:
      FORCE 1  IS 49.  0.02  0.04(100)

Rule 321
--------
   If:
      SENSOR 1 IS 2
      SENSOR 2 IS 92
      SENSOR 3 IS 92
      SENSOR 4 IS 2
   Then:
      FORCE 1  IS 92.  2.99  3.01 (UPPER LIMIT)(100)
```

```
Rule 322
--------
   If:
      SENSOR 1 IS 92
      SENSOR 2 IS 2
      SENSOR 3 IS 2
      SENSOR 4 IS 92
   Then:
      FORCE 1  IS 02. -3.01 -2.99 (LOWER LIMIT)(100)

Rule 323
--------
   If:
      SENSOR 1 IS 50
      SENSOR 2 IS 42
      SENSOR 3 IS 42
      SENSOR 4 IS 50
   Then:
      FORCE 1  IS 40. -0.14 -0.12(100)
```

5.5 REFERENCES

W. Clancy, "Classification Problem Solving," Proceedings of AAAI-84, Austin, TX, August 1984.

TIMM User's Manual, General Research Corporation, 1986.

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CHAPTER 6
NUMERICAL AND LOGIC BASED CONTROLLER PERFORMANCE COMPARISONS

6.0 INTRODUCTION

In this section of the final report a comparison of the performance of the three control implementations, Direct Velocity Feedback (DVFB), Independent Modal Space Contrl (IMSC) and Expert System Control (ESC), will be presented. Topics to be examined will include a comparison under a typical disturbance, and an examination of how each fare under a system failure condition. First, however, we must establish the common measures of performance.

6.1 PERFORMANCE MEASURES

In order to make a meaningful comparison of the three control implementations examined, there must be a justifiable means to measure the ultimate performance of each. Regardless of the manner in which one designs a controller, there are two fundamental evaluation criteria. The first of these is a global control evaluation functional, S, which is a measure of the total quadratic cost expended on an infinite dimensional distributed parameter system. As will be discussed, this characteristic is highly dependent upon the control technique. The second measure, is the power dissipated by damping the vibrations; the value of which is in principle only dependent upon the design goal.

As formulated by Oz et al., the global control evaluation functional for an infinite dimension distributed parameter system takes the form

$$S = \int_0^\infty \int_D m^{-1}(p)\, f^T(p,t)\, f(p,t)\, dDdt \qquad (1)$$

which represents the average power consumed by the control design over the control period. This equation, however, is a global quantity. Similarly, a global modal control cost functional is defined as

$$S_\infty = \sum_{r=1}^{M\infty} \int_0^\infty f_r^2(t)dt \qquad (2)$$

which can be shown to be identical to the previous result. Furthermore, this relation can be decomposed into the controlled modes and the uncontrolled modes, being written as

$$S_\infty = \sum_{r=1}^{M\,N} \int_0^\infty f_r^2(t)dt + \sum_{r=N+1}^{\infty} \int_0^\infty f_r^2(t)dt \qquad (3)$$

which from the earlier statement can be written as

$$S = S_c^M + S_u^M \quad (4)$$

where the definitions of S_c^M and S_u^M are evident. A feature of a "good" controller would be to minimize not only the global control cost, but also to have as little spillover control cost as practical. These relations can also be used to estimate a controller efficiency, which is a basic measure of how much control energy is going into the controlled modes, as compared to the global cost value. This last possibility was not measured in this research. It must be noted that the particular value which S takes depends on the following factors:

(a) the number, type, and locations of localized actuator inputs

(b) the particular control design technique chosen

(c) the order of the control design model and the closed-loop eigenvalues

(d) structural parameters

(e) the initial disturbance.

Another measure of a controller's performance is directly related to the overall goals, which in this instance is added damping. The work performed by the controller is given by

$$\Delta U = \int F dx \quad (5)$$

per cycle. As an example, each of the control laws take the form F = -Hx, consequently for a sine wave disturbance with an amplitude X and a frequency ω_f, the total power is of the form

$$\Delta U = \pi H \omega_f X^2 \quad (6)$$

Consequently, it can be expected that each of the three controllers should exhibit the same value after one cycle; that is they should all have the same asympotic performance.

6.2 PERFORMANCE COMPARISONS

In order to compare the performance characteristics of each controller, simulations of their specific responses were obtained from the FLEXSIM program. The use of the simulator allowed for the recording of the time evolution of not only control cost and power, but also the residual displacements and velocities. The case considered was a 1 N impact at 6.3 m along the beam. As noted in Secs. 4 and 5 of the report, all controllers dissipate energy. Consequently, it is expected that similar residual displacements and velocities can be expected. As is evident in Figs. 6.1 and 6.2, this is indeed what occurs; in all examples, the values reached after 100 s differ only slightly.

However, it is the control cost and power behavior that is more interesting. As noted earlier, it can be expected that control cost will be different for each control implementation. As seen in Fig. 6.3, the IMSC implementation yields a significantly lower cost as compared to DVFB and ESC. Furthermore, it can be seen that the DVFB controller expends about 90% of the control cost in the first 30 seconds of operation. The ESC approach has a similar pattern, which is to be expected as the ESC is based upon simulations of the DVFB controller. The differences between these three approaches clearly demonstrates the dependency of the global control cost functional on the number and location of actuators, and the specific technique chosen.

The last point to examine is control power. As was stated earlier, it can be expected that the total power for all should have approximately the same value in an asymoptic sense. Furthermore, it can also be surmised that the power time evolution should have the same pattern as the cost functional. As is seen in Fig. 6.4, these points are indeed what occurs. That is, after 100 s, the difference in power between all three implementations is of little or no consequence.

Thus we have seen that under nominal conditions all control implementations are able to successfully add damping to the structure, with each attaining essentially the same result. There is, as can be expected, some differences in the control cost to attain the design goal.

What needs to be examined in further detail is the behavior of each when faced with an off-nominal situation, such as the failure of a sensor. This situation was examined by instructing the simulator FLEXSIM to consider the sensor at or nearest 2 m to be producing "null" values. The disturbance in this case was a 1 N harmonic wave with a frequency of 0.04 Hz. Table 6.1 summarizes the nominal performance of the controllers after 100 s for this disturbance. As can be seen, the DVFB and ESC approaches have about the same control cost and power, with IMSC using much less control cost to add damping. There is nothing particularly unusual about this result. However, this situation is considerably different under the system failure mode.

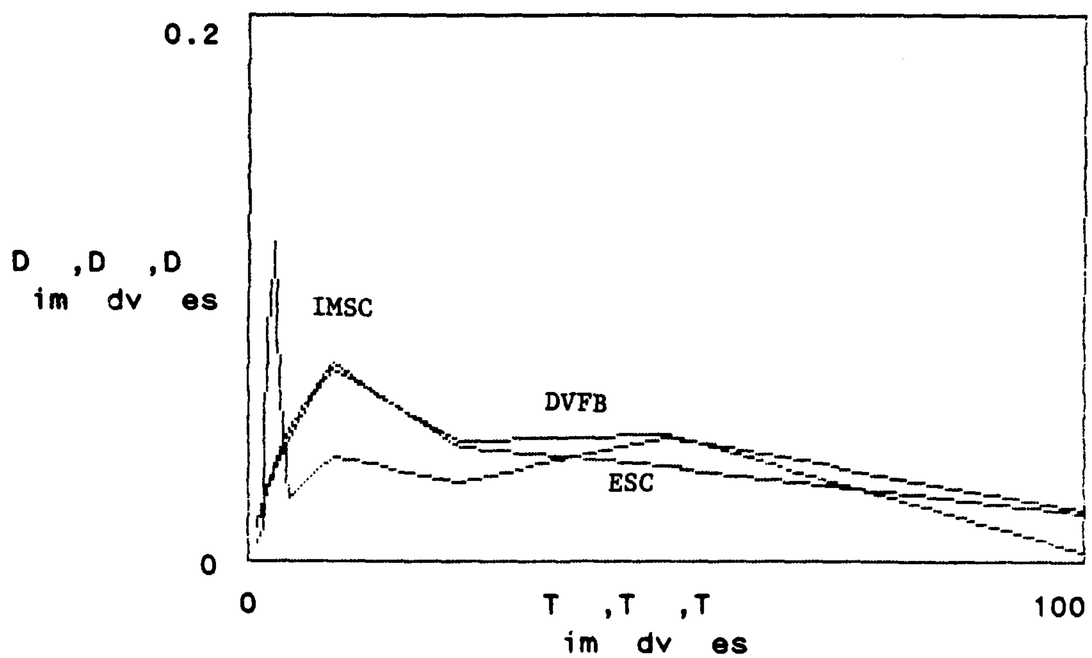

Figure 6.1. Residual Displacements

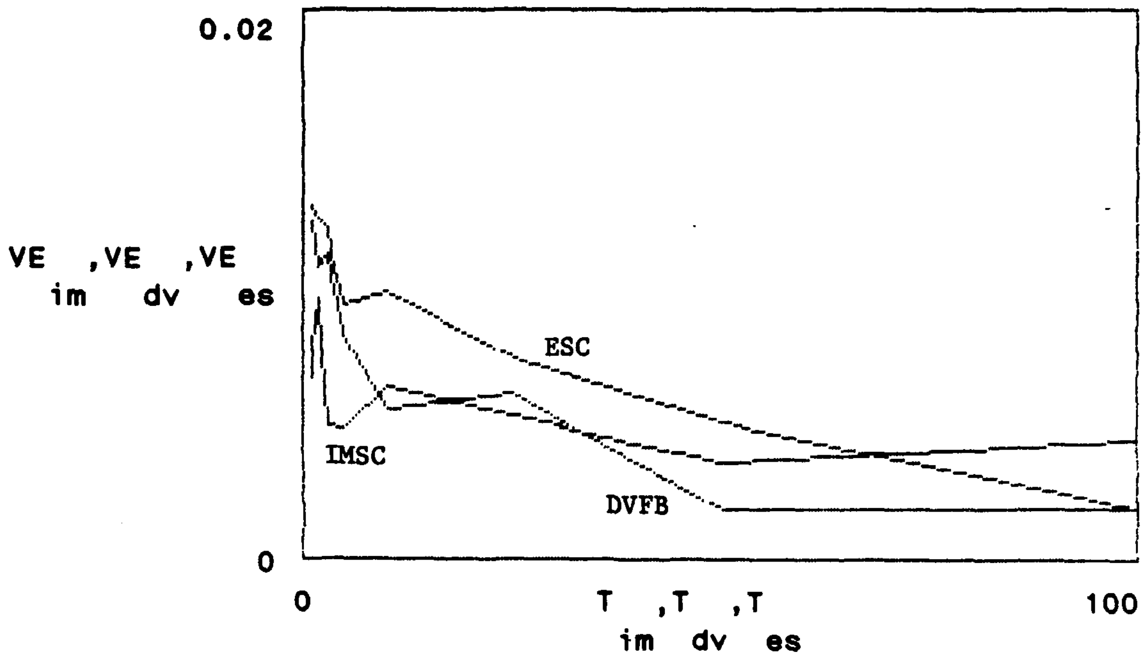

Figure 6.2. Residual Velocities

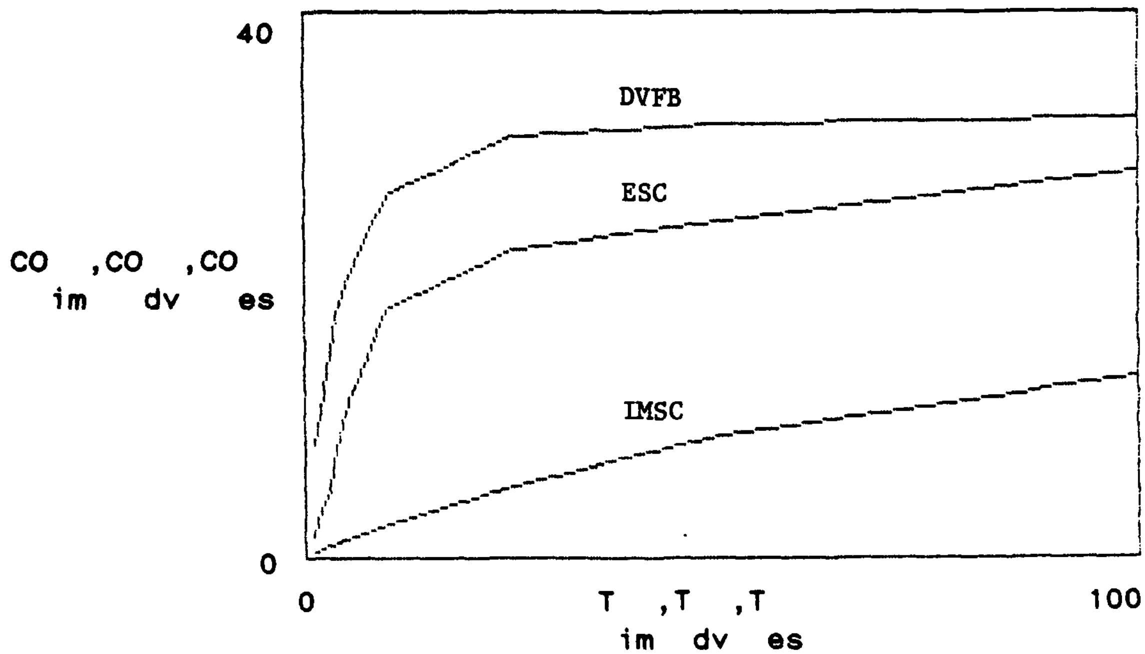

Figure 6.3. Cumulative Cost

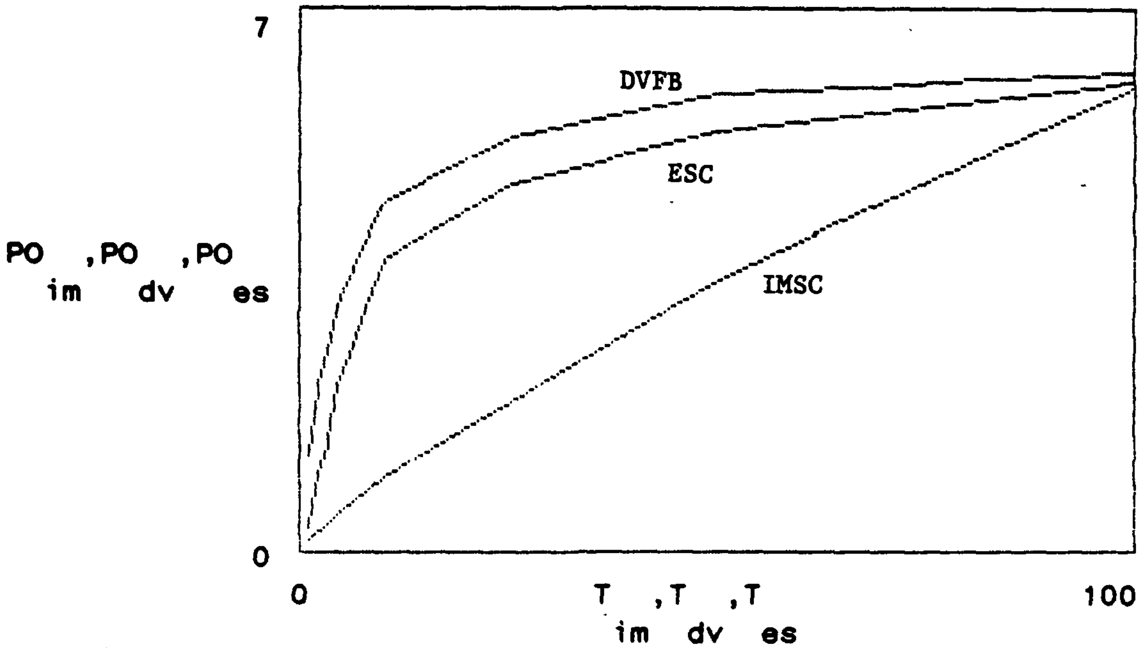

Figure 6.4. Cumulative Power

TABLE 6.1
PERFORMANCE SUMMARY NOMINAL*

	DVFB	ESC	IMSC
ELAPSED TIME (sec)	100	100	100
CONTROL COST (N^2)	126.3	123.8	24.8
CONTROL POWER (W)	60.9	62.9	27.0
RSS DISPLACEMENT (m)	0.079	0.086	0.098
RSS VELOCITY (m/s)	0.012	0.0071	0.017

*1 N Disturbance at 0.04 Hz.

Presented in Table 6.2 is the performance summary for each of the three controllers when the sensor at or nearest x = 2 m is producing "null" values. In this instance while each attains roughly the same residual displacement and velocity, the cost and power to do this is very different. Both DVFB and IMSC use about 4 times as much control cost and 2-3 times greater power as compared to the Expert System Control approach. Furthermore, when compared to nominal conditions, the differences are even more dramatic. The DVFB controller has its control cost more than double and the power increase by nearly 50 percent. IMSC, on the other hand, has control cost increase by about a factor of twelve and power by a factor of 4. Conversely, the ESC technique actually has a decrease in cost and power. The dramatic differences are further explained by examining Fig. 6.5, which shows the major differences in the signatures for each controller under these circumstances.

Thus, it can be concluded that this demonstration has shown that the ESC is capable of not only producing similar results to the numerical approaches under normal conditions, but is more effective than these under off-nominal conditions. This, then, is the attractiveness of a logic-based controller--the ability to be a robust controller regardless of the source of change, be it parameter changes, disturbances outside it's experience base, or system failures.

6.3 REFERENCES

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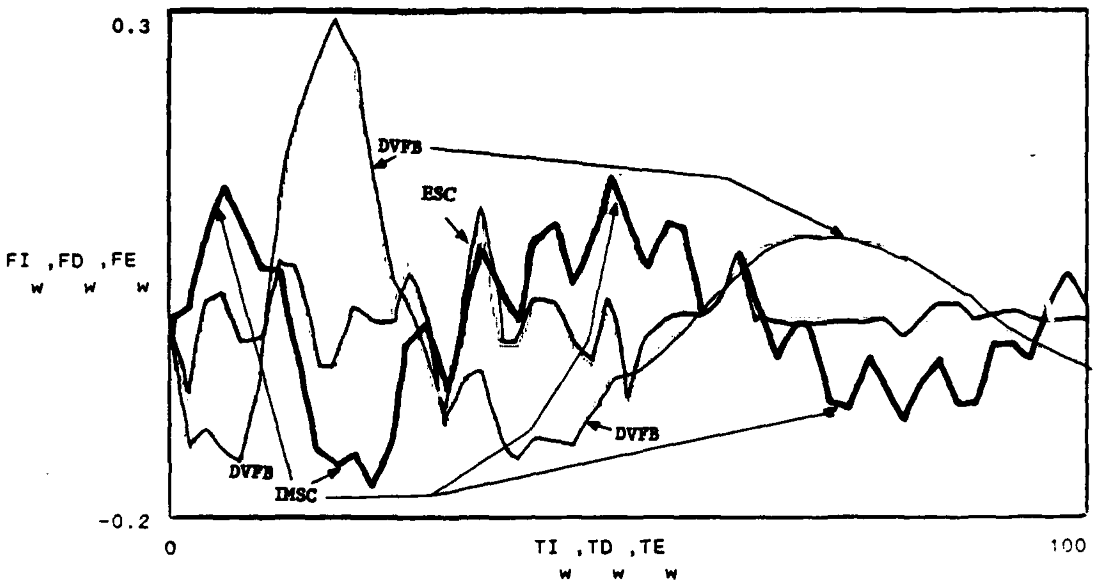
TABLE 6.2
PERFORMANCE SUMMARY SENSOR LOSS*

	DVFB	ESC	IMSC
ELAPSED TIME (sec)	100	100	100
CONTROL COST (N^2)	332.6	76.5	317.4
CONTROL POWER (W)	90.2	43.8	140.5
RSS DISPLACEMENT (m)	0.078	0.082	0.118
RSS VELOCITY (m/s)	0.012	0.0084	0.015

*1 N Disturbance at 0.04 Hz.

Actuator 1



Actuator 2

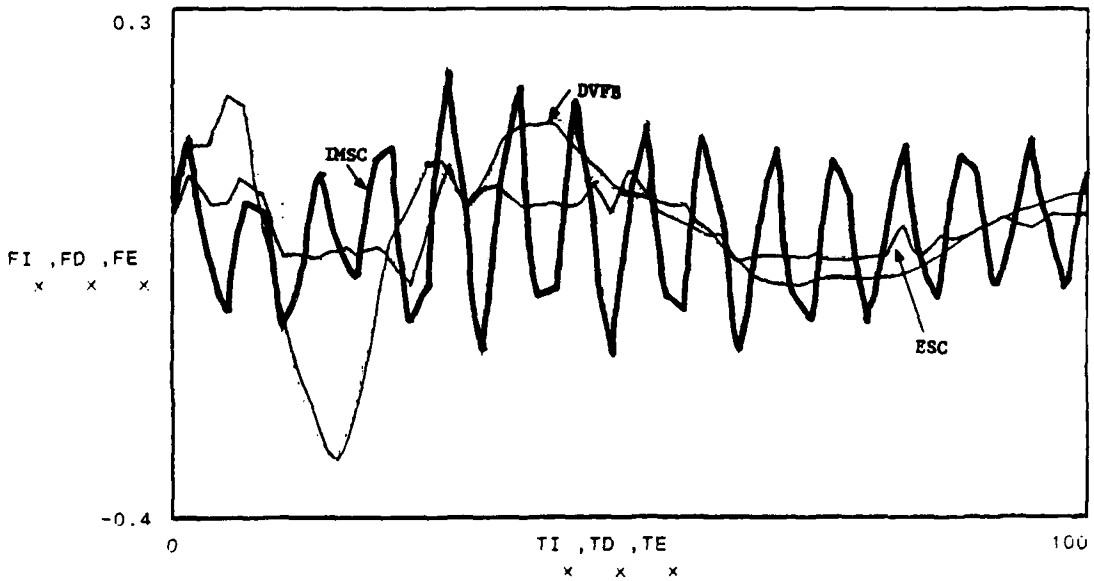
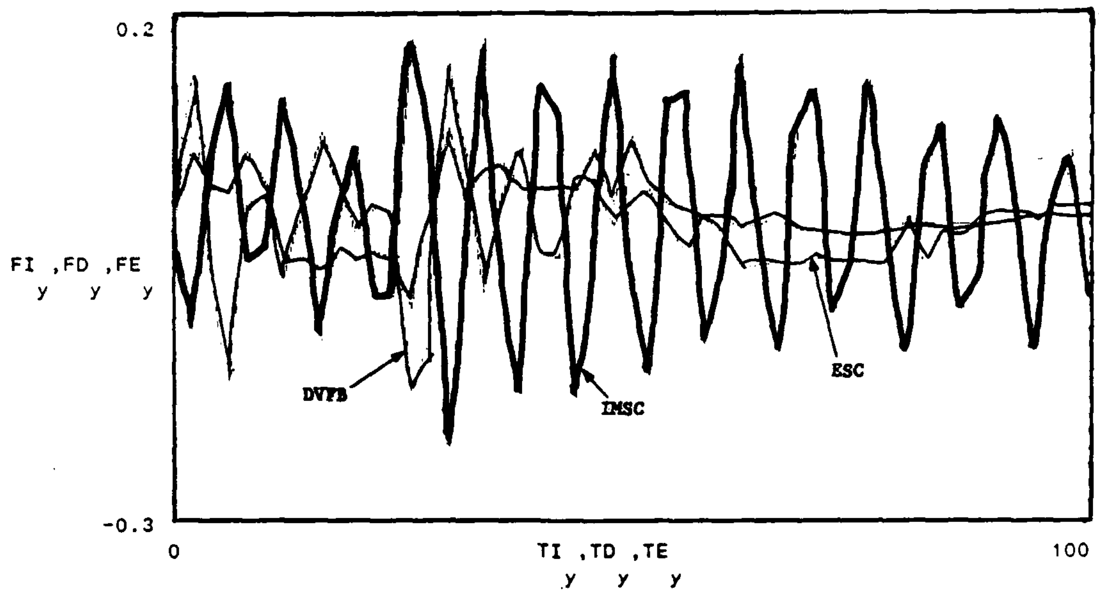


Figure 6.5. Actuator Signals

Actuator 3



Actuator 4

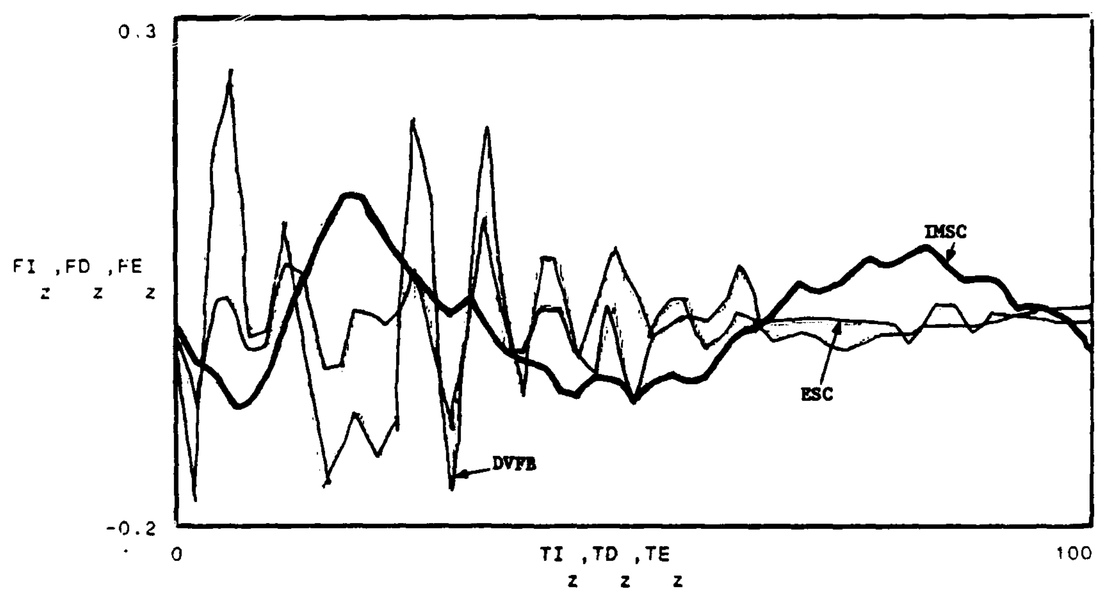


Figure 6.5. Actuator Signals (Cont.)