

AD-A124 839 AN EXPERIMENTAL ANALYSIS IN MODERN MODAL CONTROL(U) AIR 1/1
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ENGINEERING G F STUDOR DEC 82 AFIT/GA/AA/82D-11

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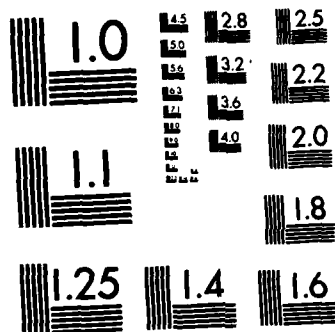
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AN EXPERIMENTAL ANALYSIS
IN HOPERS NODAL CONTROL
THESIS

AFIT/GA/BA/82D-11 George F. Studer, Jr.
Capt USAF

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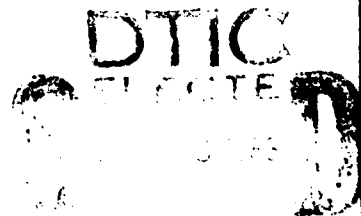
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AN EXPERIMENTAL ANALYSIS
IN MODERN MODAL CONTROL

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology

Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

George F. Studor, Jr.
Capt. USAF

Graduate Astronautical Engineering
December 1982



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PREFACE

I would like to thank my advisor, Dr. Calico, for his calm, assuring direction in the midst of seemingly hopeless times. A special thanks to Capt. Clark Briggs for his diligence and understanding in the digital microcomputer software and hardware development so essential to this thesis. My wife, Anita, has been most understanding and has actively supported me by lifting my spirits, by keeping me healthy, and by even typing the thesis. My desire for the student who resumes this research is that he or she will receive the quality of support I have recieved.

George F. Studor Jr.

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ABSTRACT

Experimental demonstration of modern modal control of a flexible clamped-clamped beam in bending was accomplished. Pole placement techniques in conjunction with a Leuenberger Observer were used for controller development. Available microcomputer computational capabilities drove the reduced order model to a two mode representation. The controllers, designed with varying degrees of robustness, demonstrated the limitations of reduced order controllers in even the simplest of systems. Sensor and actuator position are demonstrated to be of paramount importance in the modern controller LQ design.

↑

INTRODUCTION

The space shuttle is operational. The USSR has a permanent presence in space. Private industry is well on its way to having its own satellite launching facility. These recent developments can only mean one thing: trends towards larger, and more complex space structures are quickly becoming a reality. Demands in pointing, jitter, and surface tolerances for these satellites will require more robust and adaptive controllers due to inaccuracies in the mathematical models and changing mass distribution. Designing a controller for these satellites amounts to attempting to control the minimum number of structural modes in order to maintain desired shape and attitude control requirements. Unfortunately, this reduced order controller is affected by the structure's real modes not included in its model. Their effect on control inputs is called control spillover and their effect on sensor outputs is known as observation spillover. Both can cause structural instabilities which exceed the design requirements.

Calico and Janiszewski (Ref 1) demonstrated that elimination of either observation or control spillover will ensure system stability. The number of modes whose observation spillover can be eliminated is one less than the number of sensors, while the number of modes whose control spillover can be eliminated is one less than the number of actuators. It becomes obvious at this point that the most practical implementation will be elimination of observation

spillover because of the physical limitations of implementing a myriad of actuators.

Computer simulation of this phenomena has been demonstrated repeatedly (Ref 1), and controller design for large space structures has progressed rapidly in recent years. These developments are now available for demonstration of control on physical structures. Schaechter (Ref 2) has demonstrated active shape and dynamic control by using various control law design approaches, including adaptive control, and demonstrated various microprocessor control capabilities on a very flexible clamped-free 12.5 foot beam. However, the requirements for sensor and actuator sensitivity, as well as computational capability preclude the use of such a sophisticated set-up to demonstrate active modal control.

The approach used in this experiment closely parallels a control demonstration by Herrick (Ref 3) on a flexible, 5 foot clamped-clamped beam. This simple case is a reasonable starting point for demonstration of active modal control. Even for this simple case, computer hardware available impacts the structure and complexity of the test significantly. The result is a control design based on a significantly reduced order model and an observer based on only a single measurement.

The objectives of this experiment are to: 1) demonstrate active modal control; 2) demonstrate effects of observation spillover of residual modes not modeled in the controller; and 3) provide a basis for further modal control testing at the Air Force Institute of Technology (AFIT).

EXPERIMENTAL APPARATUS

The laboratory developed to demonstrate active modal control consist of the test bed and beam, modal identification equipment, and control implementation equipment.

The test bed is very massive (over one ton) with rigid beam clamps and rigid actuator mounts. The beam is mounted on edge, and the actuators provide force perpendicular to it in the horizontal direction. It was desireable to keep the first mode of vibration above 10 hz since the lightest accelerometer available (2 gm) was only calibrated down to that frequency. The beam chosen therefore was a 61.5" x 1" x .25" beam of 2024-T-4 aluminum, clamped at both ends. The accelerometer is the piezoelectric type with a preamplifier within, and a selectable gain amplifier also provided. The actuator is a typical classroom shaker employing a voice coil system and has a sizeable shaker core mass(341gm). The test bed is versatile in its ability to reconfigure present equipment and can also accommodate mounting of larger and more complex test structures. The details of the equipment set-up are located in Appendix 1.

The equipment used for modal parameter identification consists of the apparatus used for sine dwell identification and the apparatus used for spectrum analysis. Sine dwell equipment includes a digital frequency counter, two root mean square voltmeters, a storage oscilloscope, and a sine function generator. The spectrum analysis utilizes a band limited white noise generator, a signal correlator, and a spectrum

display. The spectrum display includes storage display of power spectral density and transfer to plotter for hardcopy results.

The sensor and actuator just described were utilized in the system to implement the control algorithm shown in Fig 1.

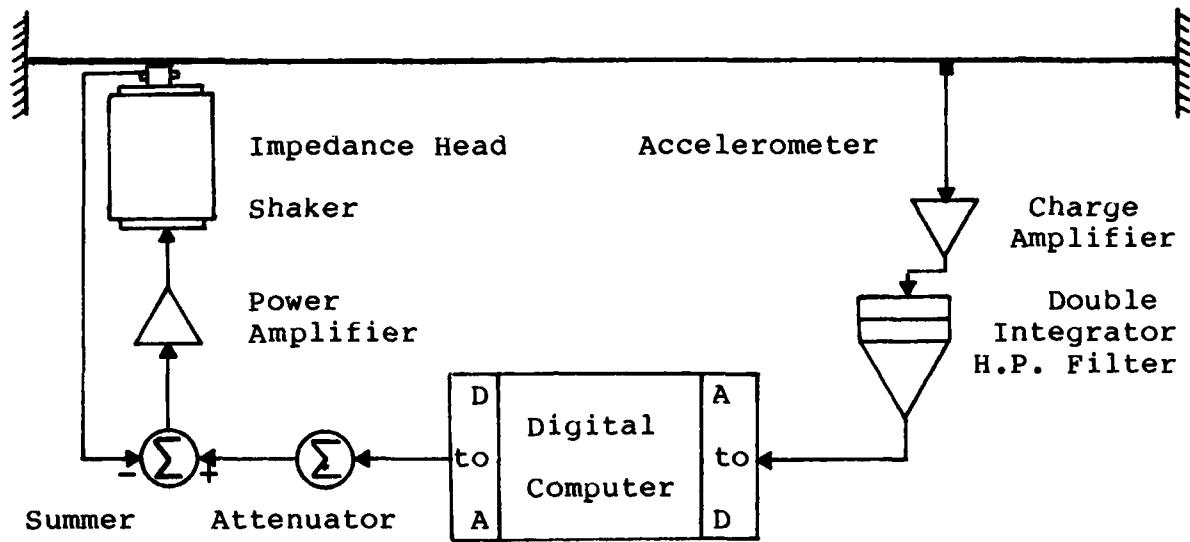


Figure 1. Laboratory Control Components.

The accelerometer is calibrated periodically, including its wires, and the tiny operational amplifier inside also helps guarantee accurate sensitivity and reduced noise. A vibration meter specifically designed for vibration testing incorporates a 5 Hz high pass filter and outputs the desired displacement signal.

The A/D and D/A converters, memory, and single board computer were housed together and access was obtained by a video terminal. Floppy disk program storage was essential to both software development, implementation, and data analysis.

A simple set of potentiometers attenuated the desired

force signal so that a summer could compare it to the force output signal of the impedance head. The pot settings could be very accurately controlled using the analog computer's digital readout in the pot set mode. This became helpful when compensating for the input scale factor in the digital control implementation. In addition, the accelerometer within the impedance head could have provided negative damping to more closely approximate the true beam's dynamics. However, measured beam damping closely matched the light predicted damping in modal identification testing and was therefore not used.

EXPERIMENTAL PROCEDURE

The experimentation consists of modal parameter identification, computer software development, and finally the control experiment.

The beam's modal parameters of concern are natural frequencies and damping. Two methods were used to identify these parameters: swept sine and spectrum analysis.

Swept Sine. Using the set-up described in detail in Appendix 1, a single actuator was driven using a constant root mean square voltage. Then the magnitude of the transfer function between the force in and the acceleration out was calculated for a range of frequencies near each natural frequency. The frequency was determined accurately from the digitally displayed signal period. Then the magnitude of the transfer function was plotted versus frequency, and the peaks were used to identify the first four natural frequencies (ω_i) of vibration. The half power method was then applied to determine the damping ratio (ζ_i).

Spectral Analysis. The shaker was driven by a bandlimited white gaussian noise generator which inputs equal power to all frequencies within its bandwidth. Then a number of samples (on the order of 2×10^5) of the accelerometer output were correlated with a controllable period, T , between samples. The spectrum analyzer takes the Fourier Transform of this autocorrelation and displays the accelerometer signal's power spectral density. The sensitivity of the frequency scale, Δf , displayed on the horizontal axis is a function of the sampling

period, T:

$$\Delta f = 1/(20T) \text{ (Hz/cm)} \quad (1)$$

Typical values for, T, are 10ms, 3.33msec, and 1msec which allow frequency ranges of 0-50Hz, 0-150Hz, and 0-500Hz. Care must be taken that the bandwidth of noise input does not excite beam natural frequencies higher than the sampling ability of the correlator. This would manifest itself in the form of false spectral content in the frequencies within the bandwidth of the spectrum analyzer(aliasing).

The natural frequencies and damping were obtained from the plots of power spectral density in a similar manner as with swept sine except that now the PSD of the output is plotted versus frequency where:

$$\text{PSD } y(t) = |H(j\omega)|^2 \times \text{PSD } f(t) \quad (2)$$

In Eq 2, $f(t)$ is the force input signal, $y(t)$ is the accelerometer output signal, and $|H(j\omega)|$ is the magnitude of the transfer function.

Background noise was also examined in this manner to determine the significance of its effect on the system. A coherence and Modal Assurance Criteria analysis was not required because the beam natural frequencies were expected to be widely separated and lightly damped.

Software Development. Computer software was developed to improve the speed of the single board computer (on the S-100 bus) from 2.5 MHz to 5.0 MHz operation. Logic was then implemented in machine code to obtain accurate time

measurement from the computer's 5 MHz system clock. Next, the machine language program for operation of the analog to digital board and the digital to analog board was developed. The boards were calibrated and then checked using simple multiple channel input-output routines. A first attempt at a control algorithm was written in Fortran, but was found to be much too slow to obtain the desired sampling rate of 200 Hz. This rate was chosen to obtain approximately six samples per cycle of the second vibrational mode of the beam.

A number of techniques should be noted here which can quickly reduce the computation time for real time data processing beyond hardware improvements:

- 1) Use integer arithmetic where it is possible to do so and still obtain the desired accuracy.
- 2) Avoid inefficient computation logic and divides.
- 3) Use the assembly language version of the higher order language program to identify ineffective and redundant commands created by the compiler.
- 4) Avoid the excessive use of subroutine calls, data storage look-ups, and unnecessary 16-bit loads.

After optimization, however, the control algorithm became specific to the number of modes controlled, the number of sensors, the number of actuators, and the scaling factors required to avoid signed 16-bit overflow. Future experimentation will require scheduled events to occur in an intricate manner. A series of programs for control implementation were developed for this purpose and can be found, along with a number of test programs, in the laboratory

as documented in Appendix 8. The control implementation program and its subroutines are contained in Appendix 5.

The Control Experiment. The control was applied and evaluated for two cases: initial condition input and continuous vibration input. The initial condition applied was a step input using a static deflection of the beam center of approximately one third of an inch. A digitized temporal estimate of the first two modal amplitudes was the analysis tool used to compare modal response parameters without control, with only the force loop around the shaker active, and with control applied (for details, see Appendix 1).

The continuous vibration applied was white gaussian noise limited to , 50Hz, 150Hz, and 500Hz at RMS voltage levels of .1, .2, and .3 volts. This was applied through a second shaker positioned at the end opposite to the control shaker and equidistant from the beam center. Incorporating the results of previous analysis by Hungerford (Ref 4), care was taken not to place either actuator near a node of the first four mode shapes to avoid diminished control authority. Also to avoid large actuator deflections which might cause nonlinearities, the actuators were not centrally located. The sensor was also located away from the nodes to avoid a theoretically infinite response time. Controlled modes and observation spillover terms from the third and fourth modes were then examined by spectral analysis for the various cases, and compared to theoretical calculations' expected root migration due to the control applied.

THEORETICAL DEVELOPMENT

The development of the control algorithm, its elements, and its effects on other system components must begin with the test beam. The controller is then designed, and problems involving its implementation are also addressed here. Finally the equipment sensitivities are calibrated and matched.

The Test Beam. Physical properties are identified below:

Material: 2024 T-4 Aluminum

Length: 61.5" = 1 Nondimensional Length = 1 NL

Actuator Position: $x_a = 4.9170/61.5 = 0.079956$ NL

Sensor Position: $x_s = 48.468/61.5 = 0.788106$ NL

Cross-Section: 1.0" x 0.25"

Density: $\rho = 0.097$ lbm/in³

Modulus of Elasticity: $E = 10.1 \times 10^6$ lbf/in²

Area Moment of Inertia: $I = bh^3/12 = .001302$ in⁴

Mass per unit length: $m = \rho A/(12g)$
 $= 0.097(.25)/32.2(12)$
 $= 6.27588 \times 10^{-5}$ lbf-sec/in²

Natural Modes. It was first necessary to determine the natural modes and frequencies for a uniform clamped-clamped beam in bending. The general equation of motion for a beam in bending is:

$$\frac{\partial^2}{\partial x^2} \left[EI \frac{\partial^2 v}{\partial x^2} \right] = -m \frac{\partial^2 v}{\partial t^2} \quad (3)$$

where the form of $v(x,t)$ using the assumed modes technique is:

$$v(x,t) = \sum_{i=1}^n V_i(x) v_i(t) \quad (4)$$

For a uniform beam the spatial coordinates $v_i(t)$ satisfy:

$$V_i'''' - \omega_i^2 (\rho A/EI) V_i = 0 \quad (5)$$

The solution to this homogeneous equation is:

$$V_i(x) = C_1 \sin(\beta_i x) + C_2 \cos(\beta_i x) + C_3 \sinh(\beta_i x) + C_4 \cosh(\beta_i x) \quad (6)$$

$$\text{where } \omega_i^2 = A \beta_i^4 / EI \quad (7)$$

Boundary conditions for the clamped-clamped case are:

$$V_i(0) = V_i'(0) = V_i(L) = V_i'(L) = 0 \quad (8)$$

Applying the boundary conditions, we have:

$$\begin{aligned} V_i(0) = 0 &= C_2 + C_4 \\ V_i'(0) = 0 &= C_3 + C_4 \\ V_i(L) = 0 &= C_1 \sin(\beta_i L) + C_2 \cos(\beta_i L) + C_3 \sinh(\beta_i L) + C_4 \cosh(\beta_i L) \\ V_i'(L) = 0 &= [C_1 \cos(\beta_i L) - C_2 \sin(\beta_i L) + C_3 \cosh(\beta_i L) + C_4 \sinh(\beta_i L)] \end{aligned} \quad (9)$$

Combining these relationships gives:

$$\begin{bmatrix} [\sin(\beta_i L) - \sinh(\beta_i L)] & [\cos(\beta_i L) - \cosh(\beta_i L)] \\ [\cos(\beta_i L) - \cosh(\beta_i L)] & [-\sin(\beta_i L) - \sinh(\beta_i L)] \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (10)$$

Zeroing the determinant is equivalent to:

$$\cos(\beta_i L) \cosh(\beta_i L) = 1 \quad (11)$$

From Eq (7) we find the solutions to Eq (11) to be:

$$\omega_i = (\beta_i L)^2 [EI/mL]^{\frac{1}{2}} \quad (12)$$

where

$$(\beta_1 L) = 4.730$$

$$(\beta_2 L) = 7.853$$

$$(\beta_3 L) = 10.996$$

$$(\beta_4 L) = 14.137$$

and for larger values of i :

$$(\beta_i L) = (2i+1)\pi/2$$

Assuming lengths will now be thought of in terms of beam lengths, the theoretical values for the beam's natural frequencies are for $L = 1$ NL:

$$\beta_1 = 4.73: \quad \omega_1 = 85.6278 \text{ rad/sec or } 13.6281 \text{ Hz}$$

$$\beta_2 = 7.853: \quad \omega_2 = 236.028 \text{ rad/sec } 37.565 \text{ Hz}$$

$$\beta_3 = 10.996: \quad \omega_3 = 462.767 \text{ rad/sec } 73.652 \text{ Hz}$$

$$\beta_4 = 14.1372 \quad \omega_4 = 764.922 \text{ rad/sec } 121.740 \text{ Hz}$$

Normalizing The Eigenvectors. Common practice is to normalize with respect to the mass. This requires:

$$\int_0^L m V_i^2(x) = 1 \quad i=1,2,3,\dots,n \quad (13)$$

So,

$$V_i(x) = C_{i1} \sin(\beta_i x) - C_{i1} \sinh(\beta_i x) + \sum C_{i2} \cos(\beta_i x) - \sum C_{i2} \cosh(\beta_i x) \quad (14)$$

where

$$C_{i2} = \sum C_{i1} \quad (15)$$

Solving for C_{i1} and C_{i2} from Eq (8) and Eq (13) (in Appendix 2):

$$\begin{aligned} \text{For } i=1: \quad C_{11} &= .80452 \quad \text{and} \quad C_{12} = -.81885 \\ \text{For } i=2: \quad C_{21} &= .81926 \quad \text{and} \quad C_{22} = -.81862 \end{aligned} \quad (16)$$

So that

$$V_1(x) = .80452[\sin(4.730x) - \sinh(4.730x)] + .81885[\cosh(4.730x) - \cos(4.730x)] \quad (17)$$

$$V_2(x) = .81926[\sin(7.853x) - \sinh(7.853x)] + .81862[\cosh(7.853x) - \cos(7.853x)] \quad (18)$$

LQG Regulator Development. Under the assumptions of linear models, quadratic cost criterion, and white Gaussian noise inputs, the design of the optimal controller can be completely separated from the design of the estimator. Using

Hungerford's development of the beam model developed by Balas (Ref 6), the optimal control problem can be expressed by the state equations:

$$\begin{aligned}\dot{\bar{X}}_c &= [A_c] \bar{X}_c + [B_c] \bar{U} \\ \dot{\bar{X}}_r &= [A_r] \bar{X}_r + [B_r] \bar{U}\end{aligned}\quad (19)$$

where

$$\begin{aligned}\bar{X}_c^T &= (v_1 \quad v_2 \quad \dot{v}_1 \quad \dot{v}_2) \\ \bar{X}_r^T &= (v_3 \quad v_4 \quad \dot{v}_3 \quad \dot{v}_4)\end{aligned}\quad (20)$$

and where

$$[A_c] = \left[\begin{array}{cc|cc} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \hline & 2 & & \\ -\omega_i & & -2i\omega_i & \end{array} \right] \quad i = 1, 2 \quad (21)$$

$$[B_c] = [0 \ 0 \ v_1(x)_a \ v_2(x)_a]^T \quad (22)$$

and where

$$[A_r] = \left[\begin{array}{cc|cc} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \hline & 2 & & \\ -\omega_i & & -2i\omega_i & \end{array} \right] \quad i = 3, 4 \quad (23)$$

$$[Br] = \begin{bmatrix} 0 & 0 & V_1(x) & V_2(x) \\ & & a & a \end{bmatrix}^T \quad (24)$$

In addition, the output equations are given by

$$\bar{Y} = [Cc] \bar{X}_c + [Cr] \bar{X}_r \quad (25)$$

where

$$[Cc] = \begin{bmatrix} V_1(x) & V_2(x) & 0 & 0 \\ & s & s & \end{bmatrix} \quad (26)$$

$$[Cr] = \begin{bmatrix} V_3(x) & V_4(x) & 0 & 0 \\ & s & s & \end{bmatrix} \quad (27)$$

The quadratic cost function to be minimized is:

$$J = \frac{1}{2} \int_0^\infty (\bar{X}^T [Q] \bar{X} + \bar{U}^T [R] \bar{U}) dt \quad (28)$$

The local matrix Riccati equation solving package OPTCON (Ref 5) solves for the feedback matrix [G] so that Eq (28) is minimized, within the constraints of Eq (27), by the control applied $\bar{U}$:

$$\bar{U} = - [G] \bar{X} \quad (29)$$

where

$$[G] = [R]^{-1} [B]^T [S] \quad (30)$$

[S] is the solution to the steady-state Ricatti equation:

$$[S][Ac] + [Ac]^T [S] - [S][Bc][R]^{-1} [Bc]^T [S] + [Q] = [0] \quad (31)$$

The OPTCON package solves the Ricatti equation with the appropriate values for $[A_c]$, $[B_c]$, $[Q]$, and $[R]$. Four cases were considered for $[Q]$: $[Q] = 20, 200, 500$, and 6000 . For now, we will consider:

$$[Q] = 200[I] \quad \text{and} \quad [R] = [I] \quad (32)$$

If full state feedback is to be implemented, a state estimator will be required to produce an estimate of $\bar{X}_c$ from the output Y . The deterministic state estimator is of the form:

$$\hat{\bar{X}}(t)_c = [A_c] \hat{\bar{X}}(t)_c + [B_c]U(t) + [K][Y(t) - \hat{Y}(t)] \quad (33)$$

$\hat{\bar{X}}(t)_c$ is the state vector estimate, $Y(t)$ is the sensor output, and $\hat{Y}(t)$ the output corresponding to the estimated state. $U(t)$ is the actuator input. The optimum observer gain matrix $[K]$, can be solved for by the same OPTCON package with the following substitutions:

$$\begin{array}{l} \text{Replace } [A_c] \text{ with } [A_c]^T \\ [B_c] \text{ with } [C_c]^T \end{array}$$

The output is the matrix of estimator gains, $[K]$, transposed.

The resulting regulator in Figure 2 is reduced to a precomputable set of gains to be applied to the output $Y(t)$ to obtain the desired input to the shaker $U(t)$.

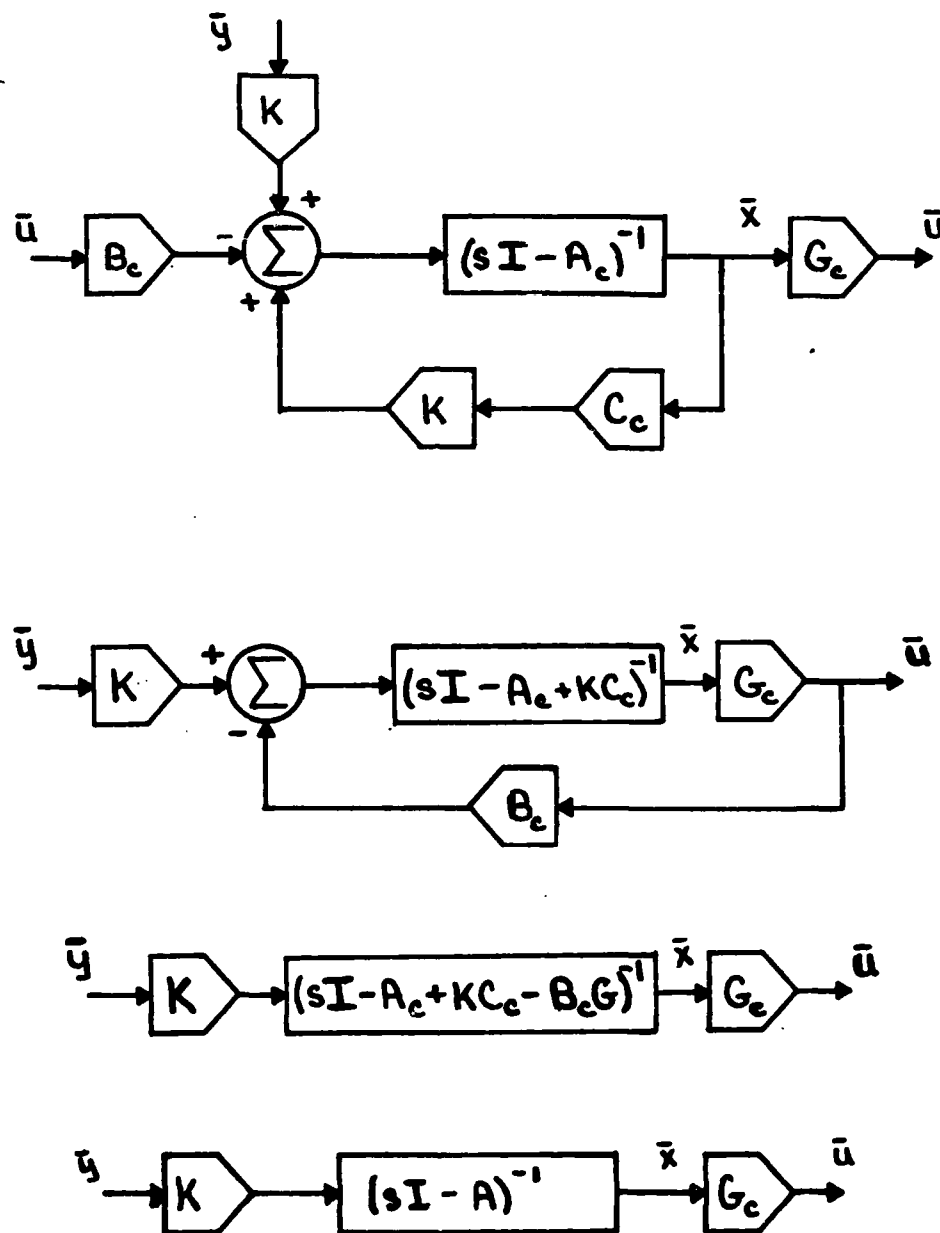


Figure 2. Control Block Diagram

Therefore, the desired control to apply is:

$$U(t) = [G][s[I] - [A_c] - [B_c][G] + [K][C_c]]^{-1} [K] Y(t) \quad (34)$$

The stability of the controller is therefore governed by

the eigenvalues of the matrix [A]. Where [A] is given by

$$[A] = [[Ac] + [Bc][G] - [K][Cc]] \quad (35)$$

The computed natural frequencies, ω_i , which are slightly higher than the measured, are used for the formulation of [Ac]:

$$[Ac] = \left[\begin{array}{cc|cc} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \hline -7332.12 & 0 & -.8563 & 0 \\ 0 & -55709.0 & 0 & -2.3603 \end{array} \right] \quad (36)$$

$$[Bc] = [0 \ 0 \ .10262 \ .25397]^T \quad (37)$$

$$[Cc] = [.307124 \ -.694532 \ 0 \ 0] \quad (38)$$

$$[G] = [-2.3698 \ 7.2801 \ 8.0764 \ 7.6288] \quad (39)$$

$$[K] = [11.6250 \ -11.145 \ -23.573 \ -19.485]^T \quad (40)$$

and, as computed (details are also in Appendix 3) [A] is:

$$[A] = \left[\begin{array}{cc|cc} -3.572 & 8.077 & 1.000 & 0 \\ 3.424 & -7.744 & 0 & 1.000 \\ \hline -7325. & -15.62 & -.0275 & .7829 \\ 15.384 & -55720 & 2.051 & -.4228 \end{array} \right] \quad (41)$$

[A] has eigenvalues: $-1.800 \ +/- \ J \ 85.63$
 $-4.083 \ +/- \ J \ 235.9$

The system eigenvalues are represented by the eigenvalues of $[[Ac] + [Bc][G]]$ and, as computed in Appendix 3, are:

$-.8426 \ +/- \ 85.624$
 $-2.149 \ +/- \ 236.02$

As developed by Calico and Janiszewski in Ref 1, the overall system stability with residual modes present is represented in Eq (42). Note that the off-diagonal terms represented by $[K][Cr]$ from Eq (27), are due to observation spillover, and those represented by $[Br][G]$, from Eq (24), are due to control spillover. The actual matrix elements and matrix eigenvalues for various $[Q]$ values are in Appendix 3.

$$\bar{z} = \begin{bmatrix} [[Ac]+[Bc][G]] & [[Bc][G]] & [0] \\ [0] & [[Ac]-[K][Cc]] & [[K][Cr]] \\ [[Br][G]] & [[Br][G]] & [Ar] \end{bmatrix} \bar{z} \quad (42)$$

and the augmented state vector, $\bar{z}$ is:

$$\bar{z} = \left\{ \bar{v}_c^T, \bar{e}, \bar{v}_r^T \right\} \quad (43)$$

where

$$\bar{e}(t) = \hat{\bar{v}}_c(t) - \bar{v}_c(t) \quad (44)$$

For the sensor and actuator locations chosen, $[Cr]$ and $[Br]$ are given by:

$$[Cr] = [1.0172 \quad -1.2294 \quad 0 \quad 0] \quad (45)$$

$$[Br] = [0 \quad 0 \quad .4485 \quad .6627] \quad (46)$$

and [Ar] is:

$$[Ar] = \left[\begin{array}{cc|cc} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \hline -214153 & 0 & -4.6277 & 0 \\ 0 & -585106 & 0 & -7.6492 \end{array} \right] \quad (47)$$

The equations for the estimator and controller are thus:

$$\frac{\Delta}{X} = [A] \frac{\Delta}{X} + [K] Y \quad (48)$$

$$U = [G] \frac{\Delta}{X} \quad (49)$$

where Y is the measurement, and U is the control to apply.

Control Implementation. To obtain a discrete form of Eq (34), we first integrate both sides:

$$\frac{\Delta}{X}(t) = e^{[A]t} \frac{\Delta}{X}(0) + \int_0^t e^{[A](t-\tau)} [K] Y(\tau) d\tau \quad (50)$$

Or, as derived in Appendix 4,

$$\frac{\Delta}{X}(T) = e^{[A]T} \frac{\Delta}{X}(0) + [A]^{-1} [e^{[A]T} - [I]] [K] Y(0) \quad (51)$$

The result of expanding the exponential into a series, is:

$$\frac{\Delta}{X}(T) = e^{[A]T} \frac{\Delta}{X}(0) + [A]^{-1} \left[[A]T + \frac{([A]T)^2}{2!} + \dots \right] [K] Y(0) \quad (52)$$

In general, for the kth sample period,

$$\begin{aligned} \hat{X}(T)_k &= [[I] + [A]T + \frac{([A]T)^2}{2!} + \dots] \hat{X}(T)_{k-1} \\ &+ T[[I] + \frac{[A]T}{2!} + \frac{([A]T)^2}{3!} + \dots] [K] Y(T)_{k-1} \end{aligned} \quad (53)$$

The discrete control to be implemented by the computer is:

$$\hat{X}(T)_k = [H(T)] \hat{X}(T)_{k-1} + [F(T)] Y(T)_{k-1} \quad (54)$$

Or simply,

$$\hat{X}_{i+1} = [H] \hat{X}_i + [F] Y_i \quad (55)$$

$$U_{i+1} = [G] \hat{X}_{i+1} \quad (56)$$

where

$$[H(T)] = [I] + [A]T + \frac{([A]T)^2}{2!} + \frac{([A]T)^3}{3!} + \dots \quad (57)$$

and

$$[F(T)] = T[[I] + \frac{[A]T}{2!} + \frac{([A]T)^2}{3!} + \dots] [K] \quad (58)$$

Using a sample period of 16 clock ticks (clicks) or about

$$T = .008 \text{ sec}$$

For the two mode model,

$$[H] = \begin{bmatrix} .7513 & .02427 & .007287 & .0001933 \\ .01078 & -.3220 & .0001208 & .003964 \\ -53.38 & -2.316 & .7765 & -.001432 \\ -4.493 & -220.9 & -.005108 & -.2936 \end{bmatrix} \quad (59)$$

$$[F] = \begin{bmatrix} .08209 \\ -.04310 \\ -2.688 \\ 14.14 \end{bmatrix} \quad (60)$$

Due to the limited floating point capacity of the single board computer, these matrix multiplications must be carried out in integer arithmetic to adequately follow the arriving frequencies at the sensor. Note that [H] contains a broad range of values among its elements. The range is so broad that to use the matrices as is would cause the computed values to exceed the maximum value allowed in signed 16-bit integer arithmetic. Thus Eq (55) is carefully scaled:

$$\begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix} = \begin{bmatrix} 10 x_1 \\ 10 x_2 \\ .1 x_3 \\ .1 x_4 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \end{bmatrix} = \begin{bmatrix} 10 f_1 \\ 10 f_2 \\ .1 f_3 \\ .1 f_4 \end{bmatrix} = \begin{bmatrix} .8209 \\ -.4310 \\ -.2688 \\ -1.414 \end{bmatrix} \quad (61)$$

Where $\bar{\xi}$ can be thought of as a new "pseudostate" vector.

Now Eqs (55) and (56) become:

$$\begin{bmatrix} .1\xi_1 \\ .1\xi_2 \\ 10\xi_3 \\ 10\xi_4 \end{bmatrix}_{i+1} = \begin{bmatrix} .7513 & .0243 & .0073 & .0002 \\ .0108 & -.3220 & .0001 & .0040 \\ -53.38 & -2.316 & .7765 & -.0014 \\ -4.493 & -220.9 & -.0051 & -.2936 \end{bmatrix} \begin{bmatrix} .1\xi_1 \\ .1\xi_2 \\ 10\xi_3 \\ 10\xi_4 \end{bmatrix}_i + \begin{bmatrix} .1\eta_1 \\ .1\eta_2 \\ 10\eta_3 \\ 10\eta_4 \end{bmatrix}_i \quad Y \quad (62)$$

$$U_{i+1} = [-2.3698 \quad 7.2801 \quad 8.0764 \quad 7.6288] \begin{bmatrix} .1\xi_1 \\ .1\xi_2 \\ 10\xi_3 \\ 10\xi_4 \end{bmatrix}_{i+1} \quad (63)$$

Or,

$$\begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}_{i+1} = \begin{bmatrix} .7513 & .0243 & .7287 & .0193 \\ .0108 & -.3220 & .0121 & .3964 \\ -.5338 & -.0232 & .7765 & -.0014 \\ -.0449 & -2.209 & -.0051 & -.2936 \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}_i + \begin{bmatrix} .8209 \\ -.4310 \\ -.2688 \\ 1.414 \end{bmatrix}_i \quad Y \quad (64)$$

$$U_{i+1} = [-.2370 \quad .7280 \quad 80.76 \quad 76.24] \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}_{i+1} \quad (65)$$

To make these equations integer valued, multiply [H] and [F] by a factor of 128, and divide $\bar{\xi}_{i+1}'$ by 128 when complete. Thus we define a new pseudostate vector, $\bar{\xi}'$:

$$\begin{bmatrix} \bar{\xi}_1 \\ \bar{\xi}_2 \\ \bar{\xi}_3 \\ \bar{\xi}_4 \end{bmatrix}_{i+1}' = \begin{bmatrix} 96 & 3 & 93 & 2 \\ 1 & -41 & 2 & 51 \\ -68 & -3 & 99 & 0 \\ -6 & -283 & -1 & -38 \end{bmatrix} \begin{bmatrix} \bar{\xi}_1 \\ \bar{\xi}_2 \\ \bar{\xi}_3 \\ \bar{\xi}_4 \end{bmatrix}_i + \begin{bmatrix} 105 \\ -55 \\ -34 \\ 181 \end{bmatrix} y_i \quad (66)$$

Now the original pseudostate vector is:

$$\begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}_{i+1} = \frac{1}{128} \begin{bmatrix} \bar{\xi}_1 \\ \bar{\xi}_2 \\ \bar{\xi}_3 \\ \bar{\xi}_4 \end{bmatrix}_{i+1}' \quad (67)$$

and the control to apply over the next interval is:

$$U_{i+1} = [0 \quad 1 \quad 81 \quad 76] \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}_{i+1} \quad (68)$$

Thus the control calculations reduce to a fairly simple set of multiplies and divides in the actual algorithm (Appendix 5).

Sensitivity Analysis. Sample calculations indicate that these equations will not exceed the maximum integer value of 2^{15} as long as the measurement range is constrained to integers with $Y_i: -100 < Y_i < +100$.

The analog to digital converter is set up such that a linear relationship exists over the range $V_{in}: -10v < V_{in} < +10v$ where:

V_{in} = Voltage to the A/D board

D_{in} = Digitized value of input voltage

so that

$$D_{in} = (V_{in} + 10) \times 204.8 \quad (69)$$

Thus for:

$$\begin{aligned} V_{in} = -10 & \Rightarrow D_{in} = 0 \\ V_{in} = 0 & \Rightarrow D_{in} = 2048 \\ V_{in} = +10 & \Rightarrow D_{in} = 4096 \end{aligned} \quad (70)$$

Now defining $In = D_{in} - 2048$ (71)

The relationship between V_{in} and In is:

$$In = 204.8 \times V_{in} \quad (72)$$

In our digital calculations, Y_i is the measurement represented by In . Since $Y_i: -100 < Y_i < +100$, the range of In

is $I_n: -100 < I_n < +100$. This restricts V_{in} to:

$$V_{in}: -.4883v < V_{in} < +.4883v \quad (73)$$

Note that $Y_i=100$ represents some scaling factor(SF) times the position in nondimensional length units ($NL=61.5"$). The maximum measured deflection is $|.0615"|$ yielding:

$$100 \longleftrightarrow .0615" \text{ or } .001 \text{ NL}$$
$$SF = 10 \exp 5 \quad (74)$$

So using the maximum voltage of .4883v we obtain a desired sensitivity of:

$$\begin{aligned} .4883/.001 \text{ (V/NL)} &= 488.3 \text{ (V/NL)} \\ 488.3 \text{ (V/NL)} \times 1000 \text{ (mv/V)} &= 4.883 \times 10 \exp 5 \text{ (mv/NL)} \\ 4.883 \times 10 \exp 5 \text{ (mv/NL)} / 61.5 \text{ (in/NL)} & \\ 7939.84 \text{ peakmv/in} & \quad (75) \end{aligned}$$

The accelerometer sensitivity is calibrated as:

$$\begin{aligned} 11.69 \text{ mv/g at } 10 \text{ hz} \\ 11.99 \text{ mv/g at } 30 \text{ hz} \end{aligned} \quad (76)$$

Since the first and second natural frequencies have the same order of magnitude contributions at the chosen sensor location, a sensitivity of 11.84 peak millivolts per g will be assumed. The acceleration signal is fed to the vibration

meter. Since the meter requires an input sensitivity of 10 mv(rms) per g(rms), a gain of 1.194 is applied to the acceleration signal before the integration takes place. After proper calibration, the meters display acceleration, velocity, and displacement, and the peak to peak displacement signal is displayed on an rms voltmeter. The desired sensitivity of 5614 mv(rms) per inch (peak displacement) was obtained by attenuating the displacement signal by .1671.

The output of the digital to analog board is proportional to the integer value sent to it (Vout). The linear relationship is the same as for the analog input. We recall that since the scale factor is 10×10^5 and therefore the output is internally divided by 128 to keep within the allowable analog output integer range $OUT: -2048 < OUT < +2048$, the force desired is in lbf $\times 781.25$. Therefore, if the value (OUT) computed is 78, the desired force is 0.1 lbf. A desired force of .00128 lbf corresponds directly to 10/2048 volts, or 4.8828 mv. The D/A board output sensitivity is therefore:

$$\frac{4.8828 \text{ mv}}{.00128 \text{ lbf}} \quad \text{or} \quad 3814.7 \text{ mv/lbf} \quad (77)$$

The impedance head between the shaker and beam measures force with a sensitivity of 557 mv(peak)/lbf. The following diagram functionally depicts the sensitivity matching which must occur prior to force input to the beam after being attenuated by a factor of PS3 (potentiometer #3 setting).

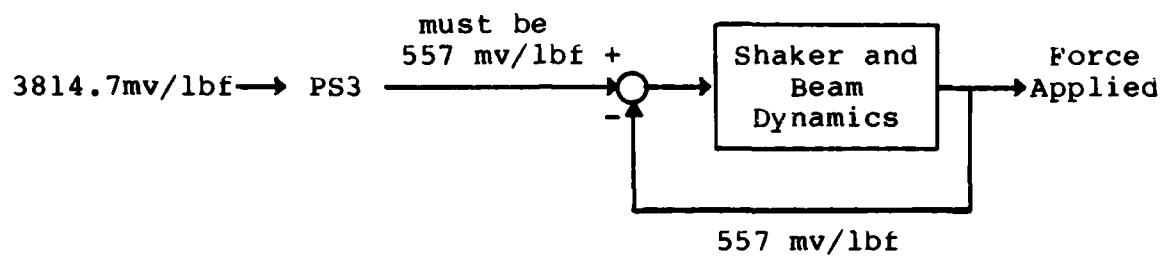


Figure 3. Actuator Sensitivity Matching.

From Figure 3 it is clear that the output force signal must be attenuated by:

$$PS3 = \frac{557}{3814.7} = 0.1460 \quad (78)$$

RESULTS/CONCLUSIONS

Modal Identification. The results of the sine dwell modal identification (Figures 4 through 7) and the spectrum analysis (Figures 8 through 10) are compared to the computed values in Table I. The ability to consistently excite the beam's first mode, using the sine dwell technique, was limited by the frequency drift in the function generator. Also, nonlinearities were discovered when too much force was applied by the shaker. As expected, when over excited, the response peak is no longer symmetric. Also, Figure 11 graphically depicts how approaching the natural frequency from lower frequencies yields drastically different results than when approached from above when nonlinearities are present.

There are basically four modeling errors: the unmodelled accelerometer mass (2gm), shaker core mass (341gm), the inability to obtain perfectly fixed end conditions, and the passive damping due to the shaker. The first three will lower the measured natural frequencies as shown in Table I. The damping due to the shaker supports, however was not noticeable until the control experiment results were examined.

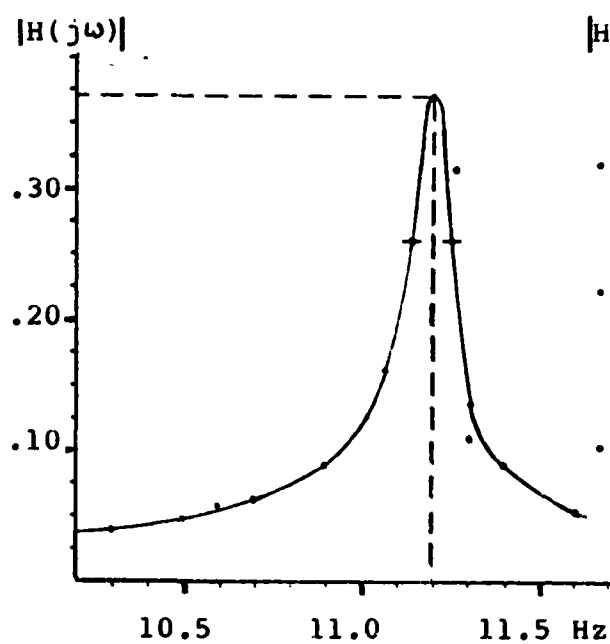


Figure 4. Mode 1
Sine Dwell Identification.

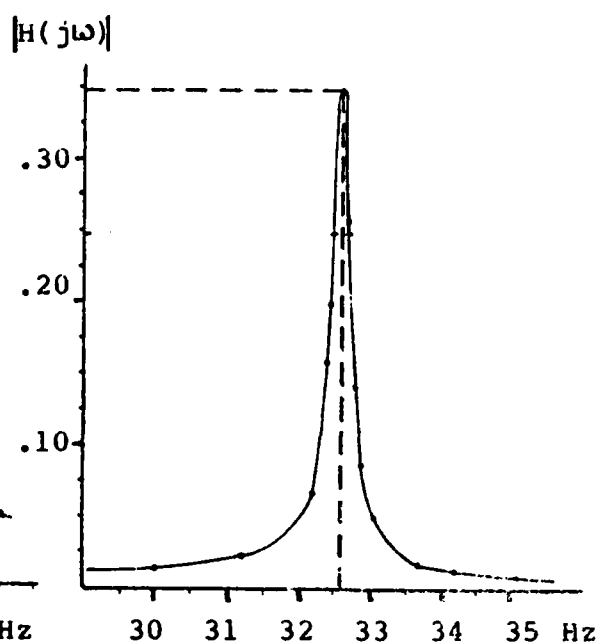


Figure 5. Mode 2
Sine Dwell Identification.

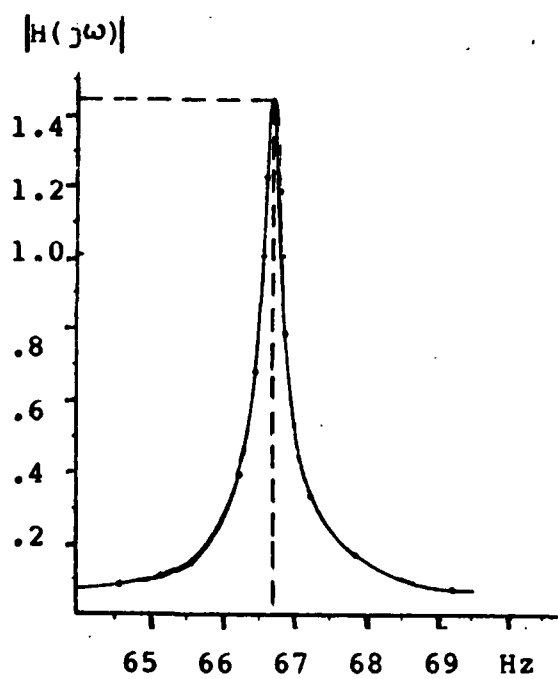


Figure 6. Mode 3
Sine Dwell Identification.

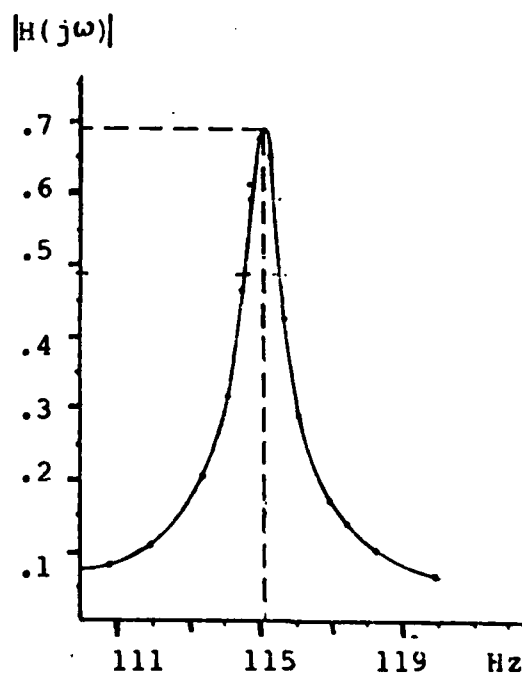


Figure 7. Mode 4
Sine Dwell Identification.

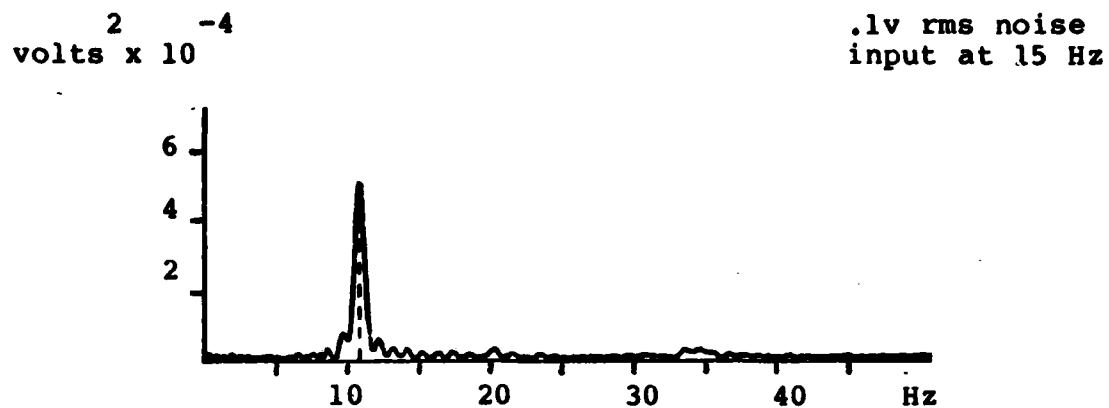


Figure 8. Mode 1 Output Spectrum.

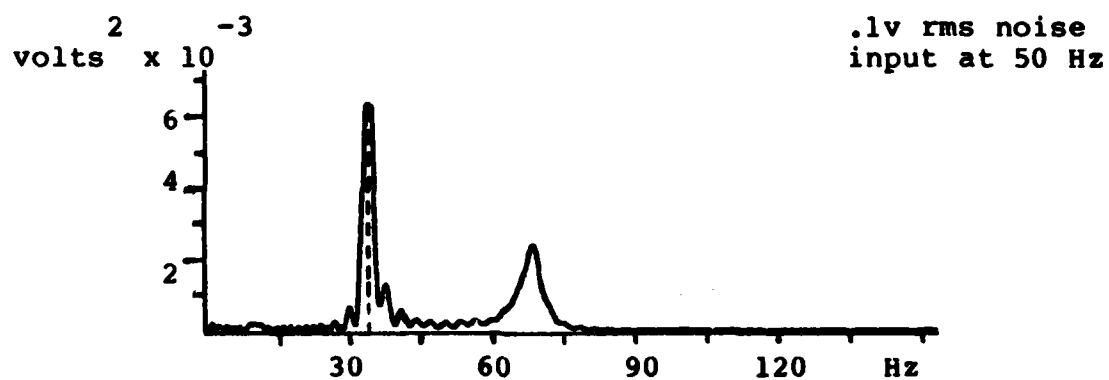


Figure 9. Mode 2 Output Spectrum.

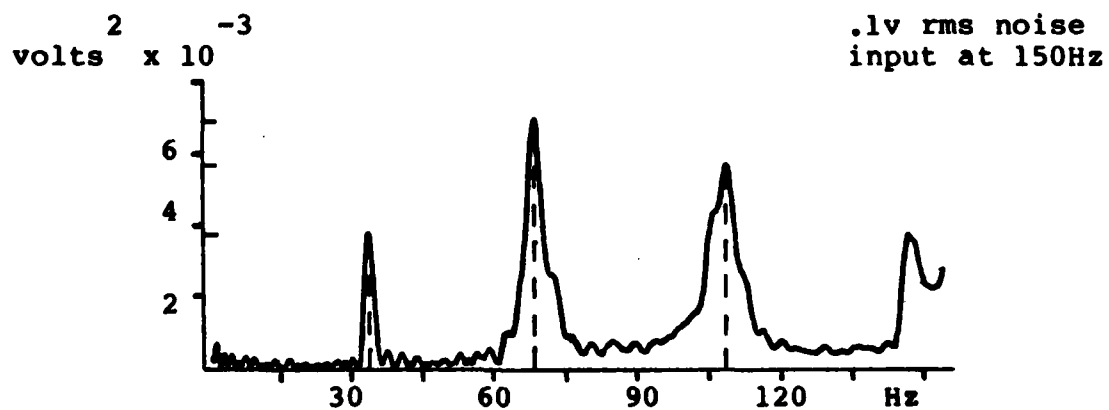


Figure 10. Output Spectrum
Modes 2,3, and 4 Identified.

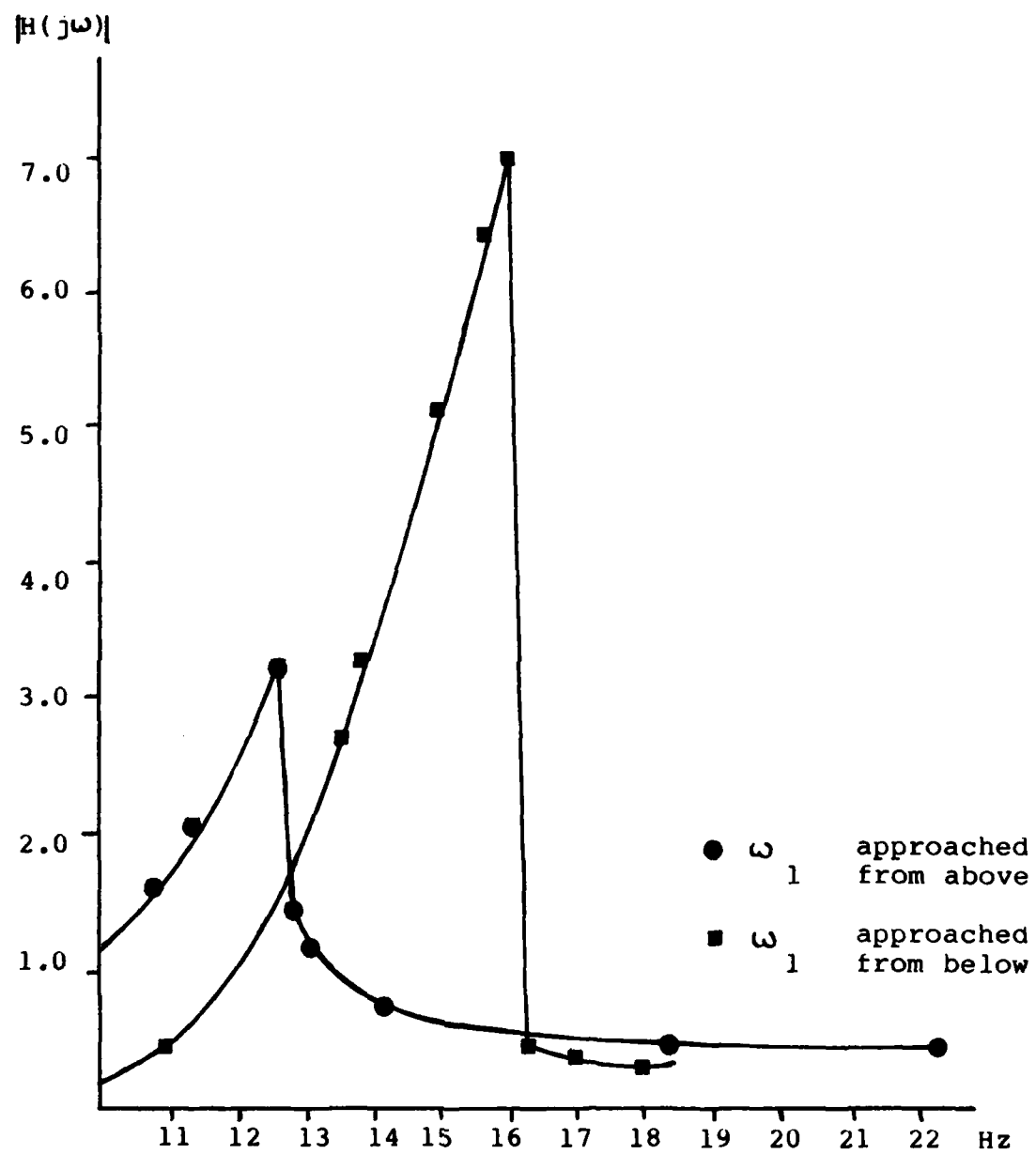


Figure 11. Mode 1 Nonlinear Beam Response.

Table I. Modal Parameters.

Natural Frequencies- ω_i (Hz)	Mode 1	Mode 2	Mode 3	Mode 4
Computed	13.63	37.57	73.65	121.74
Sine Dwell	11.2	32.55	66.7	115.1
Spectral Analysis	11.2	35.3	69	109
Assumed in Model	13.63	37.57	73.65	121.74
Damping Ratio (ζ_i)				
Sine Dwell	.0053	.0031	.0019	.0043
Assumed in Model	.005	.005	.005	.005

Software Development. The main emphasis in the software developed was decreasing the cycle time for each control output. Both the measurement sampling and the control output were performed in the same program loop. Thus, sampling rate drove both the observer and controller sensitivity. For a two mode model, it was desired to obtain at least 5 samples per cycle. Signed 16 bit integer arithmetic kept the computation time down. The system was upgraded from 2.5mHz to 5mHz operation and assembly language instructions were optimized. Only four samples per cycle on the second mode were achieved at a sampling rate of 125Hz on the optimized assembly language subroutine (Appendix 5). When it was determined that the sampling rate could not be increased further without obtaining another processor or going to a single mode approximation, the two mode control was attempted.

The Control Experiment. The data obtained from the static deflection testing was stored on disk, then plotted (as in Figures 19 through 22) and tabulated in Appendix 5. The spectral analyzer output a plot of the acceleration PSD. The half power method was used again to compute the measured damping for each mode. The expected pole migration, obtained from the eigenvalues of Eq 42, and the pole migration actually obtained is presented in Figures 12 and 13. The differences in measured natural frequencies seen in Figures 14 through 18 as compared to those calculated in the modal parameter section are due to the additional shaker used to input the noise the noise disturbance. The passive damping by the shaker is evident in the root migration for each mode. The computed movement, including the effect of the residuals, produced only slightly stable roots, while the actual roots became more highly damped with the force loop closed around the shaker. Note that no change occurred for the first mode between the force loop closed condition and the control applied condition. The second mode became more lightly damped however. The residual modes were expected to cause a more lightly damped set of modes of vibration, but their actual effect is masked by this passive damping. The third mode damping increased slightly, and the fourth mode was significantly damped. The damping of the third and fourth modes was not due to the control applied, and Figures 14, 15 and 16 clearly demonstrate that it was due to the shaker dynamics.

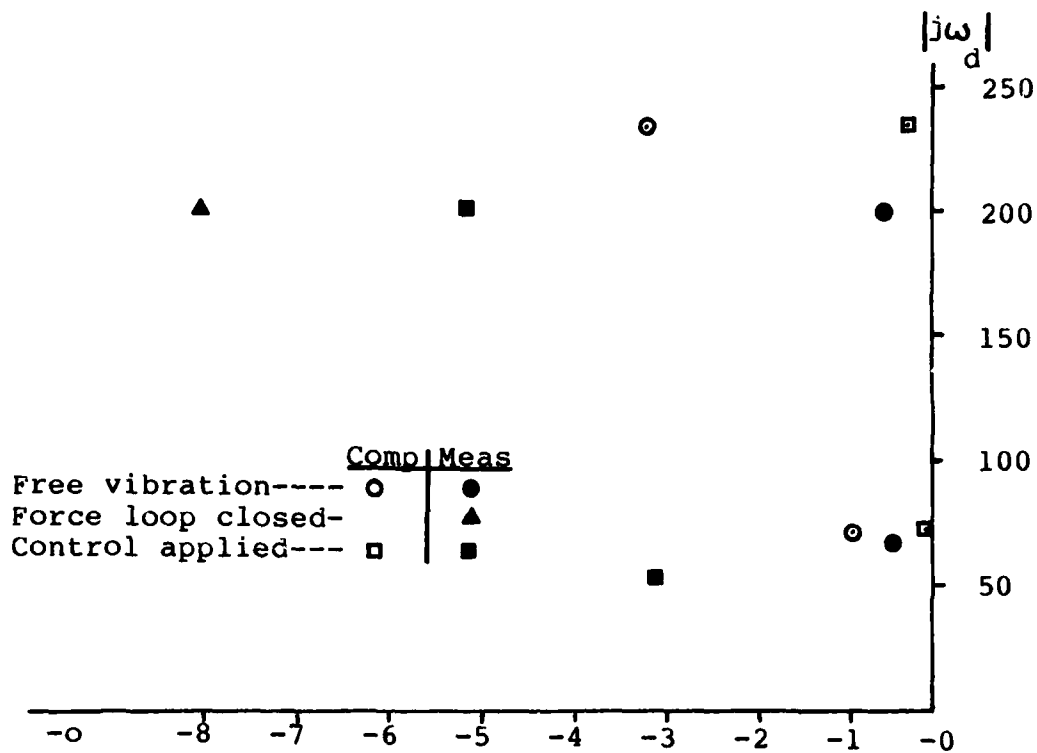


Figure 12. System Pole Movement
Modes 1 and 2.

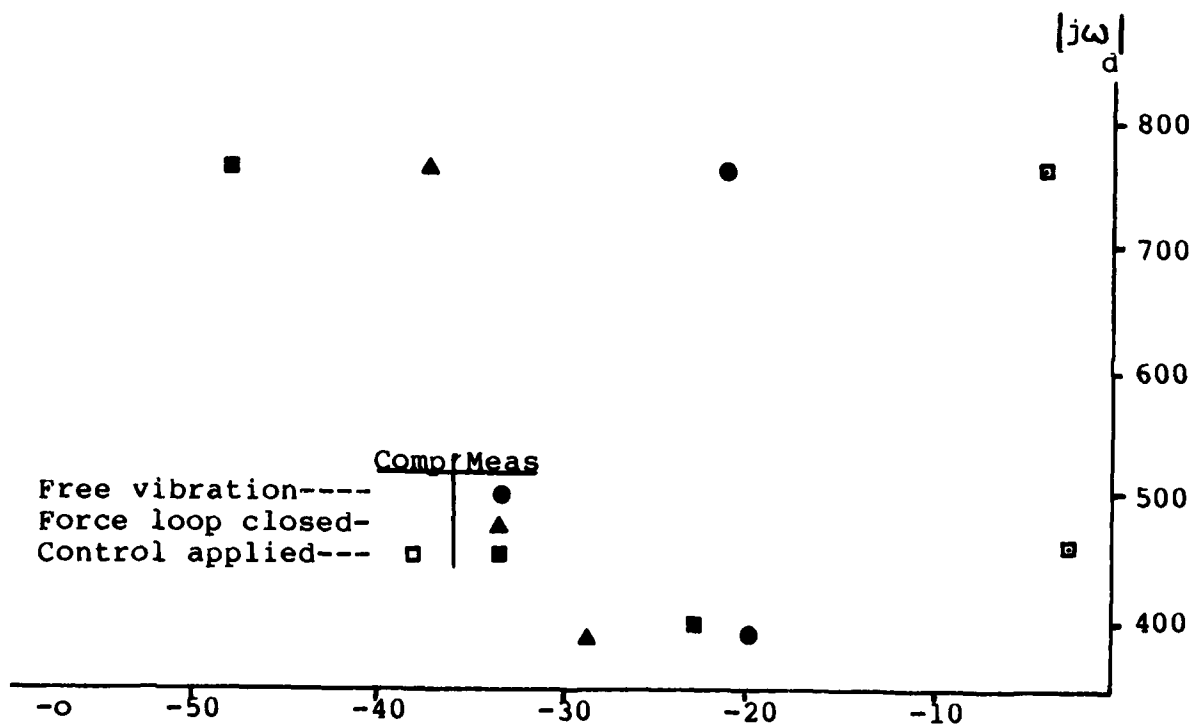


Figure 13. System Pole Movement
Modes 3 and 4.

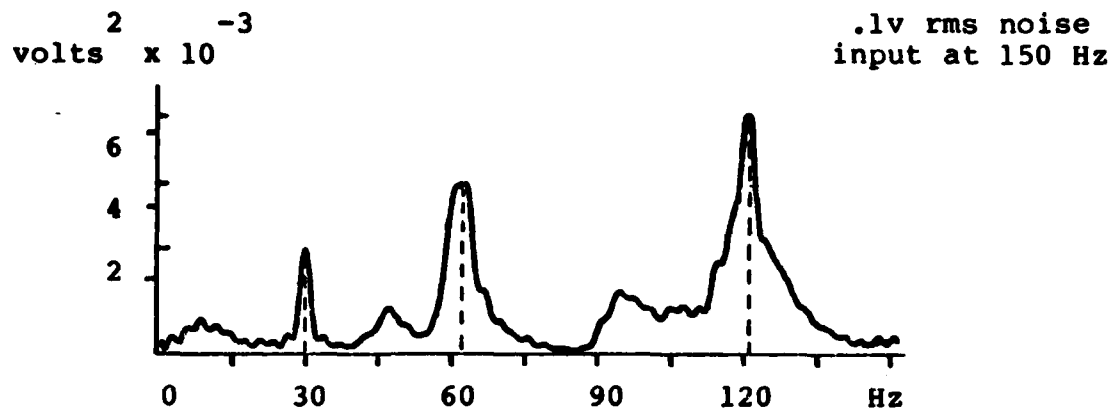


Figure 14. Modes 2,3, and 4
Free Vibration.

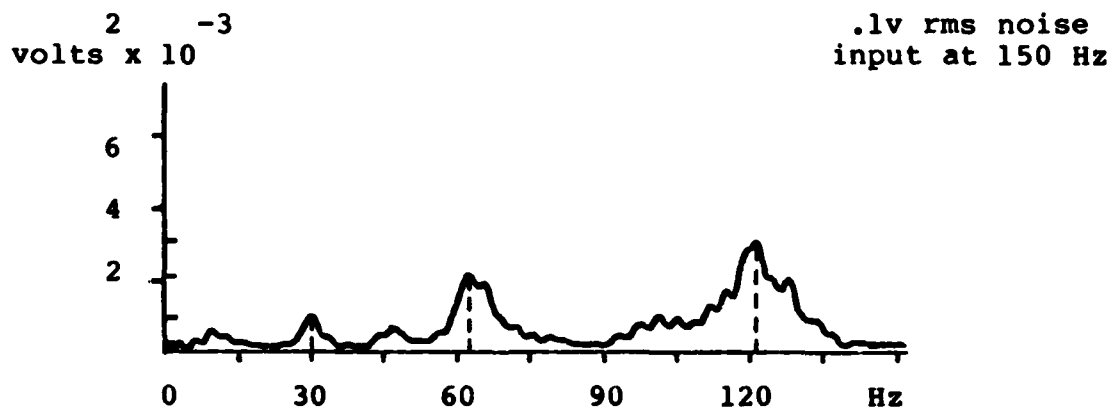


Figure 15. Modes 2,3, and 4
Force Loop Closed.

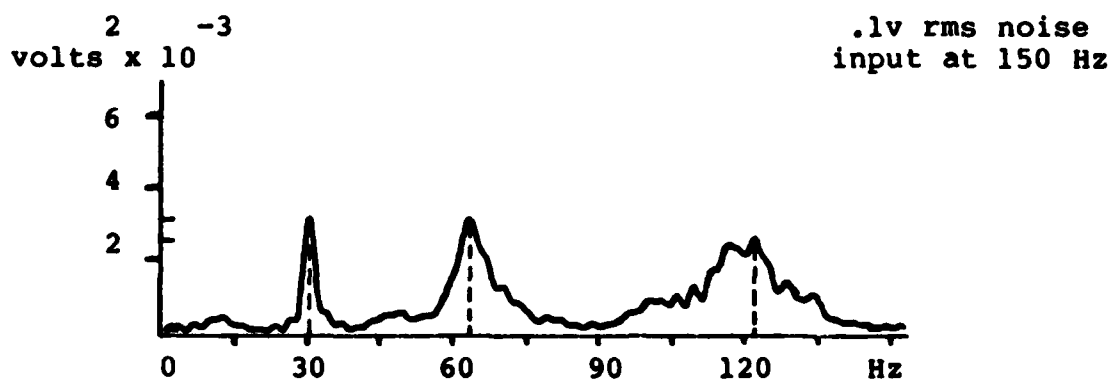


Figure 16. Modes 2,3, and 4
Control Applied.

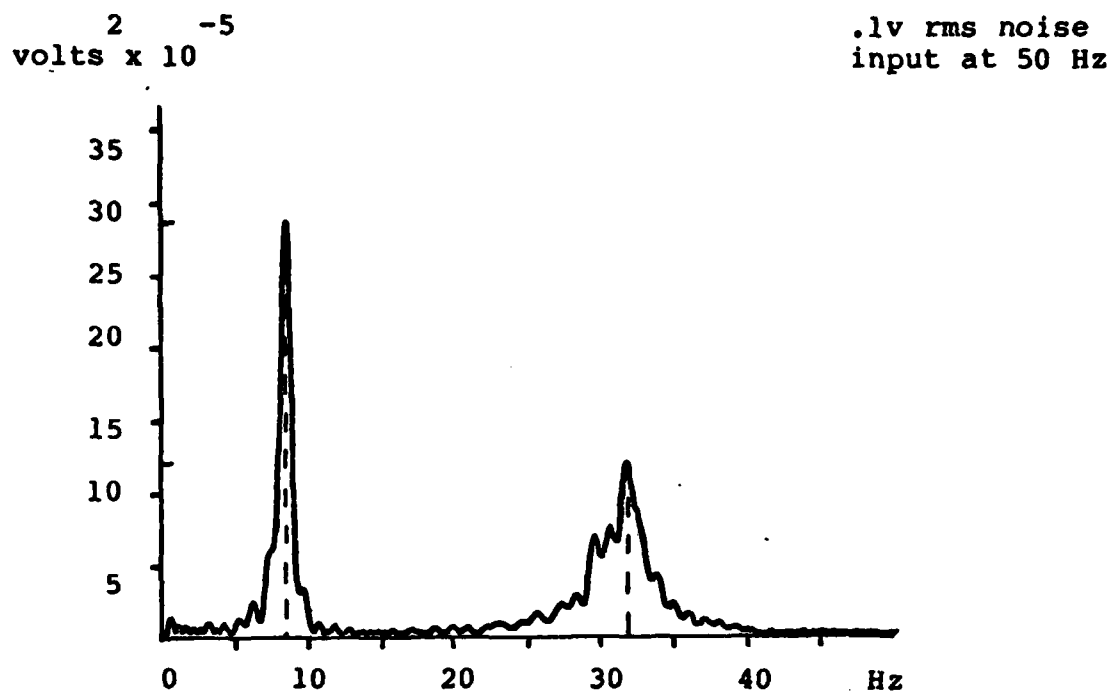


Figure 17. Modes 1 and 2
Force Loop Closed.

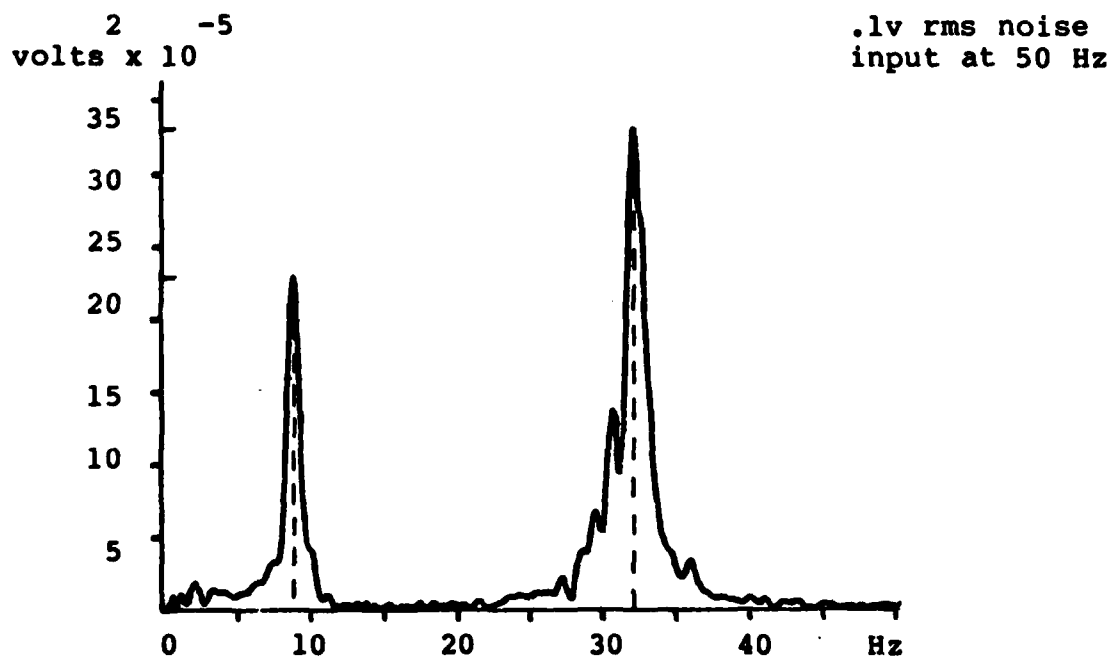


Figure 18. Modes 1 and 2
Control Applied.

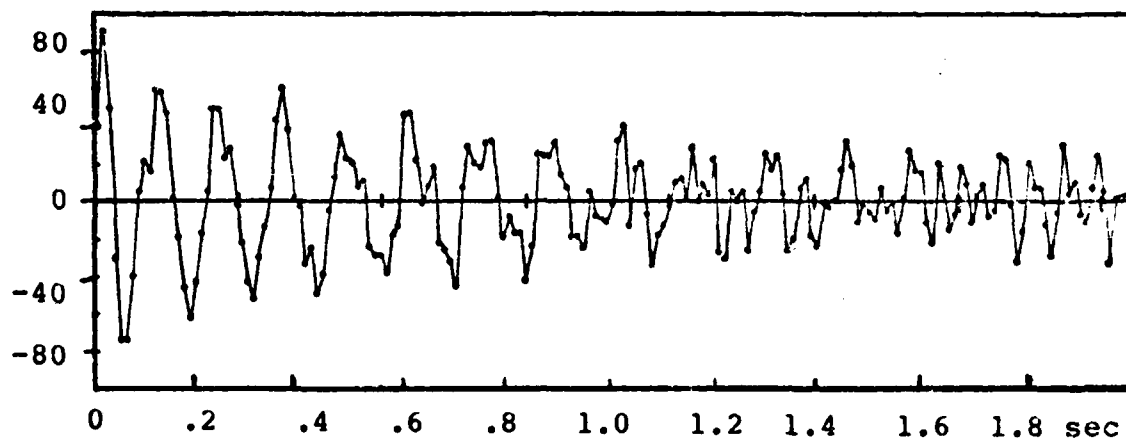


Figure 19. Mode 1 Estimate Force Loop Closed.

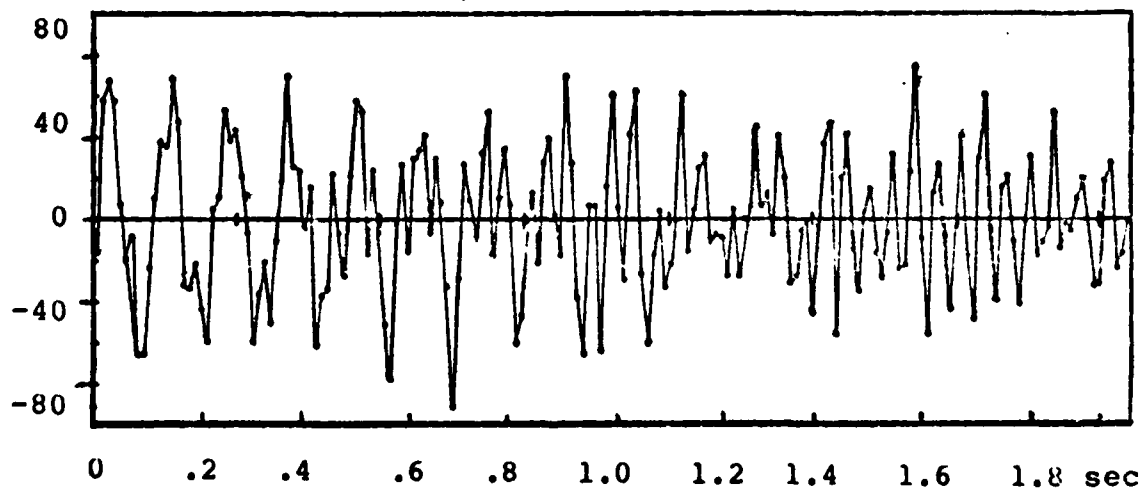


Figure 20. Mode 1 Estimate Control Applied.

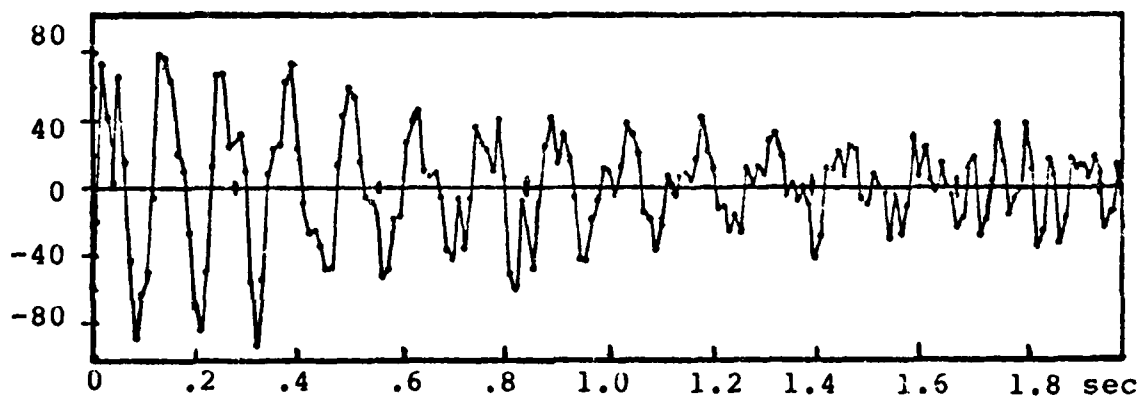


Figure 21. Mode 2 Estimate Force Loop Closed.

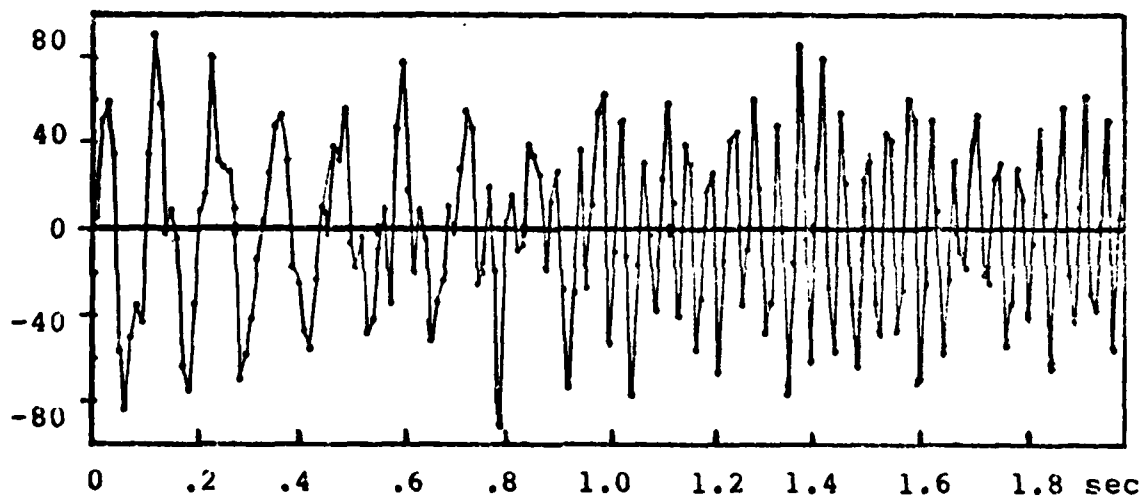


Figure 22. Mode 2 Estimate Control Applied.

The damping of the third and fourth modes was anticipated as Herrick (Ref 3) discovered similar problems where the shaker acted as a passive dashpot when used in this capacity. He found this to be the result of the shaker's flexure supports and restored the beam's resonant behavior by a positive velocity feedback loop around the shaker.

The time responses of the estimate of mode 1 (Fig 19 and 20) for $Q=200$ show that the more lightly damped higher modes predominate shortly after control is applied. Similarly, for the estimate of mode 2 (Fig 21 and 22), the second mode quickly predominates and a much cleaner estimate of the modal amplitudes is produced for this reason.

In summary, the effect of this controller was to slightly damp the first mode and negatively damp the second. The third and fourth modes were damped, however this is attributed to the passive damping of the shaker. Limitations on the control applied include sampling rate, truncation errors due to scaling and use of integer arithmetic, a lack of a positive velocity feedback loop around the shaker, and a lack of phase compensation.

RECOMMENDATIONS

The experience gained in implementation of optimal control algorithms in this experiment has helped to identify some sensitive areas which may affect performance.

The sensor and actuator locations are very important. Although the sensor did well at the location chosen, the actuator did poorly due to its lack of control authority over the first mode. The optimum actuator position is dependent on the relative cost associated with not controlling each mode. Therefore, for this experiment the actuator should be located nearer the center of the beam. In addition, the diagonal elements of $[Q]$ should be weighted to reflect these costs when calculating the optimum controller and observer gain matrices.

Shaker damping was a significant factor in the degraded controller performance and should be compensated for using a velocity feedback path around the shaker. An impedance head which outputs both acceleration and force simultaneously is ideal for this implementation.

The need for faster computation speed is obvious; however no matter what hardware constraints are imposed, the control algorithm will have to be optimized to yield acceptable computation rates and accuracy. A working knowledge of the specific machine code utilized will be required for this.

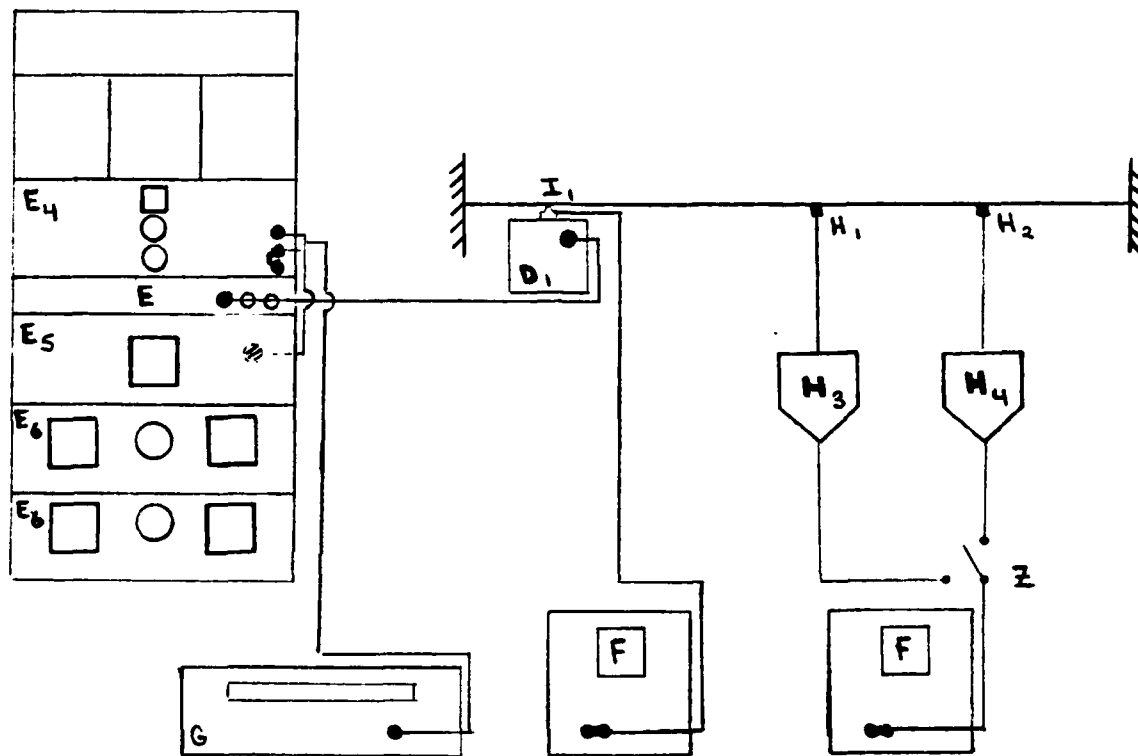
Finally, new methods for exciting the beam without the addition of a second actuator, such as acoustic vibration and the use of a load cell equipped hammer, should be examined.

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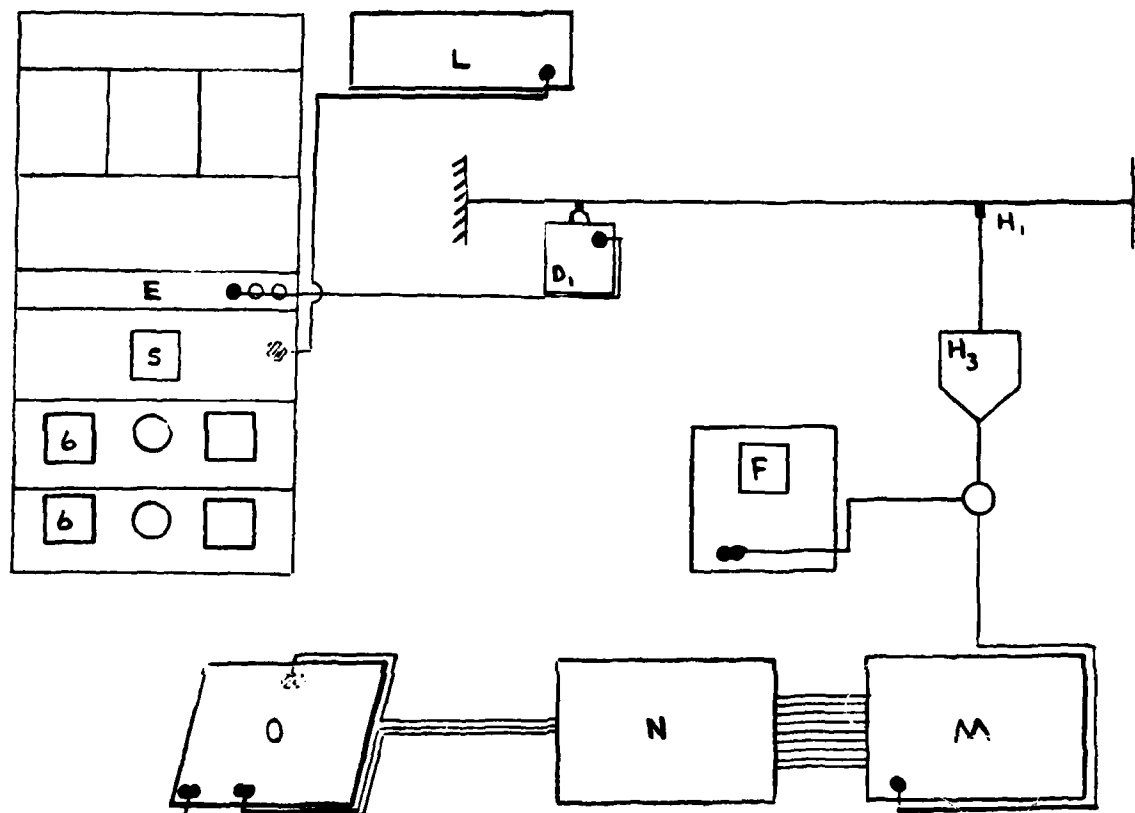
APPENDICES

Appendix 1
Equipment Configurations



- D1 - Shaker.....Detune Clip-Full Up.
- E4 - Low Frequency Function Generator...Function-Sine, Amp<10.
- E5 - Power Amplifier.....Cathode-1.
- E6 - DC Power Supply.....H.V.-ON, DC Amps=200.
- F - True RMS Voltmeters.....Use, Meter.
- G - Universal Counter-Timer.....AC Input, Func.-Period
Time- $N=10\exp 2$.
- H1 - Accelerometer.....&Elect.Iso. Mechanism.
- H3 - Battery Power Unit.....Gain=100.
- I - Impedance Head.....Use Force Output.
- Z - Electrical Connection.....Beam Center-Modes 1&3.
Offset-Modes 2&4.

Figure 23. Sine Dwell
Modal Parameter Identification



D1, F, F, H1, H3.....Same as for Figure 23.
 L - Noise Generator.....Seq.Length-Infinite, Gaussian Output.
 M - Correlator.....Func.-Autocor., Averaging-Exponential.
 Dither-ON, Delay Offset-0, Interpolation-On, Input-A-AC.
 N - Spectrum Display.....Input-1, Disp-Spectrum, Real, Window-Off
 Gain-5, Interpolation-Auto, Marker-Off, Vertical-Modulus
 Horizontal-Freq., Phase Shift-0, Cal-Off, Record-scan.
 O - X-Y Recorders.....Time Base-Off, Sweep Rate-5, Line-On,
 Pen-lift, Servo-On; Polarity-X:+RT, Y:+UP; Reponse-X:Slow
 Y:Slow; Range-X:1v/in, Y:.5v/in.

Figure 24. Spectrum Analysis
 Modal Parameter Identification

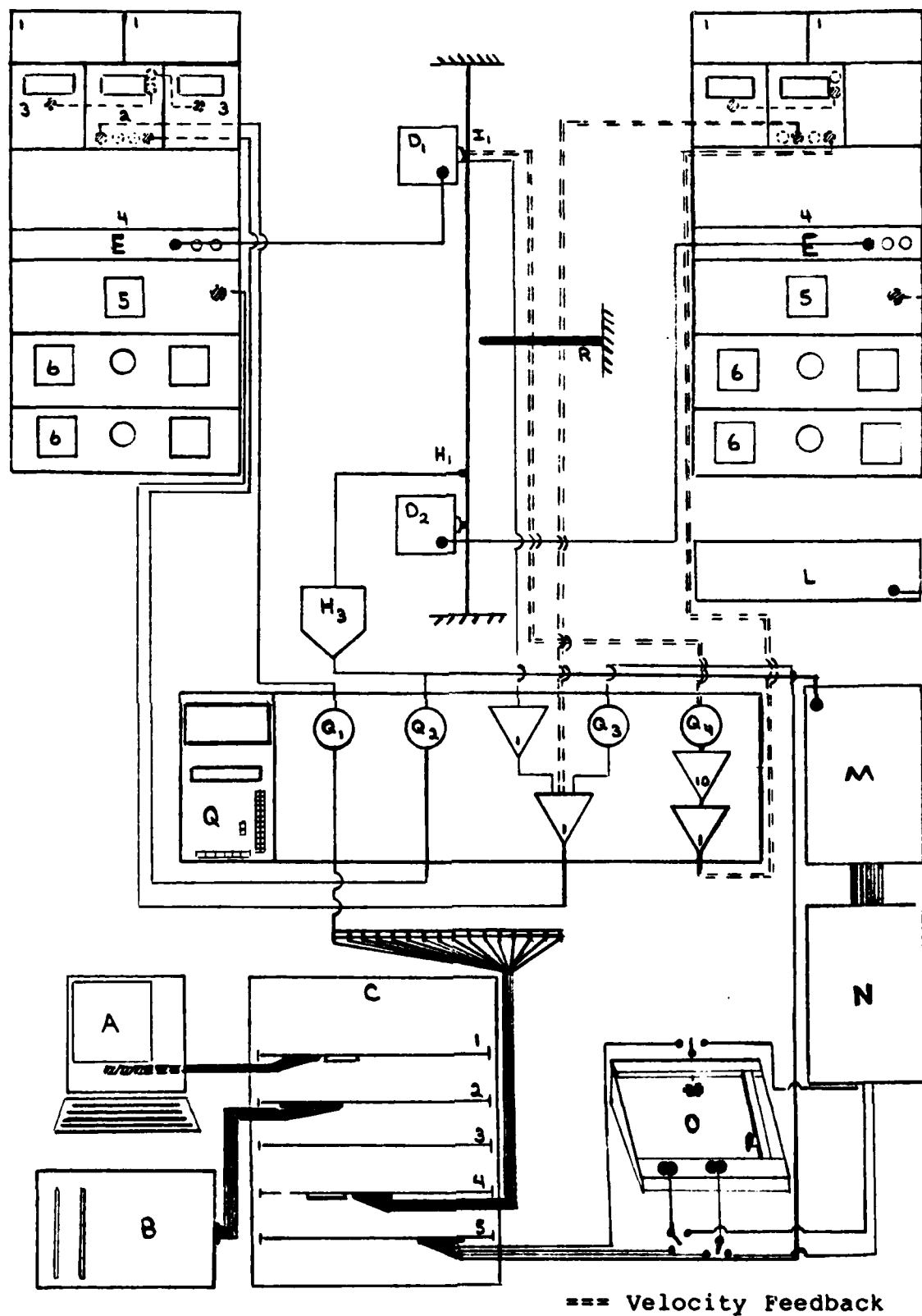


Figure 26. Control Experiment.
(Legend Next Page)

Figure 25 Legend.

A - Video Terminal.
 B - 8" Floppy Disk Drive.
 C - S-100 Mainframe: 1 - SBC-100: Serial Input/Output to A.
 2 - Disk Drive Board.
 3 - Memory Board.
 4 - A/D Board: Input on Chan 0 from Q1.
 5 - D/A Board: Chan 0 - Q3.
 Chan 1 - X on plotter.
 Chan 2 - Y on plotter.
 Chan 3 - PenUp on plotter.
 D(1&2) - Shaker.....Same as Figure 23.
 E- Portable Cabinet: Same as Figure 23, except E2-Input from Q2
 Out Disp.->Q1
 Connect to Q3

 H1 - Accelerometer.
 H3 - Battery Power Unit.....Gain=10.
 I - Impedance Head.
 L - Noise Generator.....Same as Figure 24.
 M - Correlator.....Same " " "
 N - Spectrum Display.....Same " " "
 O - X-Y Recorder: Continuous Vibration Input - Input from N.
 Initial Displacement Input - Input from C5.
 Q - Analog/Hybrid Computer: Pot. Settings: Q1= .1671
 Q2= .1194
 Q3= .1460
 Q4= .2571

 R - Initial Condition Displacement Mechanism: Rod w/wall pivot

LABORATORY EQUIPMENT

A. Heathkit Terminal(#5):Model H19-A - SN 17-43722.

B. Tarbell Floppy Disk Drive:Model VDS-TTD - SN 2267/0482.

C. ECT(Electronic Control Technology)Mainframe MB -10.

1. SBC-100 Single Board Computer - SD Systems
2. Single Density Floppy Disk Interface Board
Tarbell - SN 10867.
3. Expandoram III-Expandable Random Access Memory-
SD Systems - SN AW 0100160.
4. AIM-12, 12 bit Analog Input Module-Dual Systems
Corporation.
5. AOM-12,12 bit 4 Channel S-100 Digital to Analog
Converter - Dual Systems Corporation - SN 1039.

D. Shakers - MB Electronics Vibration Test Equipment

1. Model SAC - SN 186.
2. Model SDA - SN 271.

E. Portable Cabinet

1. Accelerometer Integrator/Amplifier
MBElectronics-Model N504-SN PS4110 and PS4111.
2. Vibration Meter - MB Electronics - Model N499
SN 168 and SN 151.
3. Vibration Indicator- MB Electronics- Model N497
SN 162 and SN 173.
4. Low Freq Function Generator - Hewlett Packard
Model 202A - SN 325-13268 and 4156.
5. 125VA Power Amplifier - MB Electronics Model
2120MB - SN 904 and 913.

- 6. DC Power Supply - Hewlett Packard - Model 1712B
SN 002-05035 and SN 002-05037.
SN 002-05082 and SN 002-05083.
- F. True RMS Meters - Ballantine Laboratories - Model 320
 - 1. SN 1537 (EE Lab).
 - 2. SN 1538 (EE Lab).
- G. Universal Counter-Timer - Computer Measurements Co.
Model 726C - SN 49300/4H5581.
- H. I.C.P. Accelerometer-PCB Piezotronics Inc.
 - 1. Model 303A - SN 1935.
 - 2. Model 303A - SN 1934.
 - 3. Battery Power Unit - PCB - Model 480C06 - SN 1247.
 - 4. Battery Power Unit - PCB - Model 480D06 - SN 2062.
- I. Impedance Head - Wilcoxon Research
 - 1. Model Z11 - SN 900.
 - 2. Model Z11 - SN 802.
- J. Oscilloscope - Tektronics Inc. - Model 116E - SN 002800.
- K. DC Power Supply - H.P. - Model 6205B - SN 1949A16663.
- L. Noise Generator - H.P. - Model 3722A - SN 1722U01822.
- M. Correlator - H.P. - Model 3721A - SN 1112A00104.
- N. Spectrum Display - H.P. - Model 3720A - SN 1215U00120.
- O. X-Y Recorders - H.P. - Model 7045B - SN 2129A00481.
- P. S-100 Bus Extender Board - Bob Mullen Computer Products
Model TB4 - SN 0281.
- Q. TR-48 Analog/Hybrid Computer - EAI - Model 45.117 - SN 568.
- R. Initial Condition Displacement Mechanism: Rod.

Appendix 2

Normalizing the Eigenvectors

$$\int_0^L v_i^2(x) dx = 1 \quad (13)$$

where

$$v_i(x) = C_{i1} \sin(\beta_i x) - C_{i2} \sinh(\beta_i x) + Z_{i1} C_{i1} [\cos(\beta_i x) - \cosh(\beta_i x)] \quad (14)$$

For $L = 1$, and $\beta_1 = 4.73 \Rightarrow Z_1 = -1.017809$

$$\Rightarrow C_1 = .80452$$

$$\Rightarrow C_2 = -.81885$$

$$\beta_2 = 7.853 \Rightarrow Z_2 = -.99922$$

$$\Rightarrow C_1 = .819261$$

$$\Rightarrow C_2 = -.818622$$

$$\beta_3 = 10.996 \Rightarrow Z_3 = -1.00003$$

$$\Rightarrow C_1 = .818953$$

$$\Rightarrow C_2 = -.81898$$

$$\beta_4 = 14.1372 \Rightarrow Z_4 = -.999998$$

$$\Rightarrow C_1 = .827169$$

$$\Rightarrow C_2 = -.827168$$

So that the normalized eigenvectors are:

$$\begin{aligned} V_1(x) = & .80452[\sin(4.73x) - \sinh(4.73x)] \\ & + .81885[\cosh(4.73x) - \cos(4.73x)] \end{aligned} \quad (17)$$

$$\begin{aligned} V_2(x) = & .81926[\sin(7.853x) - \sinh(7.853x)] \\ & + .81862[\cosh(7.853x) - \cos(7.853x)] \end{aligned} \quad (18)$$

$$\begin{aligned} V_3(x) = & .81895[\sin(10.996x) - \sinh(10.996x)] \\ & + .81898[\cosh(10.996x) - \cos(10.996x)] \end{aligned} \quad (13c)$$

$$\begin{aligned} V_4(x) = & .82717[\sin(14.1372x) - \sinh(14.1372x)] \\ & + .82717[\cosh(14.1372x) - \cos(14.1372x)] \end{aligned} \quad (13d)$$

The values of these mode shapes are then:

$$\text{Sensor}(x_s) = .852698 \text{ NL} \quad \text{Actuator}(x_a) = .079956 \text{ NL}$$

$V_1(x)$	.3071239	.1026195
$V_2(x)$	-.6945324	.2539699
$V_3(x)$	1.0171641	.448457
$V_4(x)$	-1.229404	.6626658

Appendix 3

Pole Placement Generation and System Eigenvalues

This appendix contains for $Q = 20, 200, 500, 6000$:

- A. OPTCON generated controller and observer gains $[G]$ and $[K]^T$ (labeled feedback matrix in computer output).
- B. Closed loop system matrices $[[Ac]+[Bc][G]-[k][Cc]]$ without residuals present and their eigenvalues.
- C. Eigenvalues of the closed loop system matrices (with residuals present) of the form:

$$\begin{bmatrix} [[Ac]+[Bc][G]] & [Bc][G] & [0] \\ [0] & [[Ac]-[K][Cc]] & [K][Ccr] \\ [Bcr][G] & [Bcr][G] & [Acr] \end{bmatrix}$$

- D. Computed $[H]$, $[F]$, and $[G]$ matrices for computer

implementation of $\hat{X}_{i+1} = [H]\hat{X}_i + [F]Y_i$ and

$$U_{i+1} = [G] \hat{X}_{i+1}.$$

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

$$\dot{X}/\dot{t} = A*X + B*U$$

$$2J = \text{INTEGRAL OF } X'*Q*X + U'*R*U$$

WHERE

A

0.	0.	1.0000E+00	0.
0.	0.	0.	1.0000E+00
-7.3321E+03	0.	-8.5630E-01	0.
0.	-5.5709E+04	0.	-2.3603E+00

B

0.
0.
1.0262E-01
2.5397E-01

Q

2.0000E+01	0.	0.	0.
0.	2.0000E+01	0.	0.
0.	0.	2.0000E+01	0.
0.	0.	0.	2.0000E+01

R

1.0000E+00

RICCATI SOLUTION

8.0238E+04	-7.1770E-01	1.3637E-03	-1.7360E-01
-7.1770E-01	2.2375E+05	1.3190E+00	1.7934E-04
1.3637E-03	1.3190E+00	1.0943E+01	-3.5887E-05
-1.7360E-01	1.7934E-04	-3.5887E-05	4.0164E+00

FEEDBACK MATRIX

-4.3949E-02	1.3540E-01	1.1230E+00	1.0200E+00
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CLOSED-LOOP EIGENVALUES

REAL	IMAGINARY
------	-----------

-.48577E+00	-.85626E+02
-.48577E+00	.85626E+02
-.13097E+01	-.23602E+03
-.13097E+01	.23602E+03

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

$$\dot{X}/\dot{t} = A \cdot X + B \cdot U$$

$$2J = \text{INTEGRAL OF } X' \cdot Q \cdot X + U' \cdot R \cdot U$$

WHERE

A

0.	0.	-7.3320E+03	0.
0.	0.	0.	-5.5709E+04
1.0000E+00	0.	-8.5630E-01	0.
0.	1.0000E+00	0.	-2.3603E+00

B

3.0712E-01
-6.9453E-01
0.
0.

Q

2.0000E+01	0.	0.	0.
0.	2.0000E+01	0.	0.
0.	0.	2.0000E+01	0.
0.	0.	0.	2.0000E+01

R

1.0000E+00

RICCATI SOLUTION

8.0830E+00	2.7947E-04	-6.9191E+00	-6.3415E+00
2.7947E-04	3.1945E+00	8.3428E-01	-7.5389E+00
-6.9191E+00	8.3428E-01	5.9252E+04	8.7636E+00
-6.3415E+00	-7.5389E+00	8.7636E+00	1.7794E+05

FEEDBACK MATRIX

2.4823E+00 -2.2186E+00 -2.7045E+00 3.2884E+00

CLOSED-LOOP EIGENVALUES

REAL IMAGINARY

-.80934E+00	-.85623E+02
-.80934E+00	.85623E+02
-.19506E+01	-.23602E+03
-.19506E+01	.23602E+03

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

$$DX/DT = A*X + B*U$$

$$2J = \text{INTEGRAL OF } X'*Q*X + U'*R*U$$

WHERE

A

0.	0.	1.0000E+00	0.
0.	0.	0.	1.0000E+00
-7.3321E+03	0.	-8.5630E-01	0.
0.	-5.5709E+04	0.	-2.3603E+00

B

0.
0.
1.0262E-01
2.5397E-01

Q

2.0000E+02	0.	0.	0.
0.	2.0000E+02	0.	0.
0.	0.	2.0000E+02	0.
0.	0.	0.	2.0000E+02

R

1.0000E+00

RICCATI SOLUTION

5.7709E+05	-6.4313E+01	1.3256E-02	-9.3362E+00
-6.4313E+01	1.6735E+06	7.0939E+01	1.3194E-03
1.3256E-02	7.0939E+01	7.8710E+01	-3.3003E-03
-9.3362E+00	1.3194E-03	-3.3003E-03	3.0039E+01

FEEDBACK MATRIX

-2.3690E+00	7.2801E+00	8.0764E+00	7.6280E+00
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CLOSED-LOOP EIGENVALUES

REAL	IMAGINARY
------	-----------

-.21489E+01	-.23602E+03
-.21489E+01	.23602E+03
.04256E+00	.05624E+02
.04256E+00	.05624E+02

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

$$\dot{X}/DT = A*X + B*U$$

$$2J = \text{INTEGRAL OF } X'*Q*X + U'*R*U$$

WHERE

A

0.	0.	-7.3321E+03	0.
0.	0.	0.	-5.5709E+04
1.0000E+00	0.	-8.5630E-01	0.
0.	1.0000E+00	0.	-2.3603E+00

B

3.0712E-01
-6.9453E-01
0.
0.

Q

2.0000E+02	0.	0.	0.
0.	2.0000E+02	0.	0.
0.	0.	2.0000E+02	0.
0.	0.	0.	2.0000E+02

R

1.0000E+00

RICCATI SOLUTION

3.7890E+01	1.7737E-02	-3.2434E+01	-1.4915E+02
1.7737E-02	1.6054E+01	1.9598E+01	-3.7899E+01
-3.2434E+01	1.9598E+01	2.7751E+05	4.0954E+02
-1.4915E+02	-3.7899E+01	4.0954E+02	8.9448E+05

FEEDBACK MATRIX

1.1625E+01 -1.1145E+01 -2.3573E+01 -1.9485E+01

CLOSED-LOOP EIGENVALUES

REAL	IMAGINARY
-.22134E+01	-.85599E+02
-.22134E+01	.85599E+02
-.50501E+01	-.23597E+03
-.50501E+01	.23597E+03

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

$$DX/DT = A*X + B*U$$

$$2J = \text{INTEGRAL OF } X'*Q*X + U'*R*U$$

WHERE

A

0.	0.	1.0000E+00	0.
0.	0.	0.	1.0000E+00
-7.3321E+03	0.	-8.5630E-01	0.
0.	-5.5709E+04	0.	-2.3603E+00

B

0.
0.
1.0262E-01
2.5397E-01

Q

5.0000E+02	0.	0.	0.
0.	5.0000E+02	0.	0.
0.	0.	5.0000E+02	0.
0.	0.	0.	5.0000E+02

R

1.0000E+00

RICCATI SOLUTION

1.1092E+06	-3.4741E+02	2.8685E-02	-3.5088E+01
-3.4741E+02	3.2737E+06	2.6663E+02	-2.2315E-03
2.8685E-02	2.6663E+02	1.5130E+02	-1.7958E-02
-3.5088E+01	-2.2315E-03	-1.7958E-02	5.8757E+01

FEEDBACK MATRIX

-8.9084E+00	2.7361E+01	1.5522E+01	1.4921E+01
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CLOSED-LOOP EIGENVALUES

REAL	IMAGINARY
------	-----------

-.12246E+01	-.85619E+02
-.12246E+01	.85619E+02
-.30748E+01	-.23601E+03
-.30748E+01	.23601E+03

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

$$DX/DT = A*X + B*U$$

$$2J = \text{INTEGRAL OF } X'*Q*X + U'*R*U$$

WHERE

A

0.	0.	-7.3321E+03	0.
0.	0.	0.	-5.5709E+04
1.0000E+00	0.	-8.5630E-01	0.
0.	1.0000E+00	0.	-2.3603E+00

B

3.0712E-01
-6.9453E-01
0.
0.

Q

5.0000E+02	0.	0.	0.
0.	5.0000E+02	0.	0.
0.	0.	5.0000E+02	0.
0.	0.	0.	5.0000E+02

R

1.0000E+00

RICCATI SOLUTION

6.4446E+01	8.0944E-02	-5.5234E+01	-4.3637E+02
8.0944E-02	2.7694E+01	5.7243E+01	-6.5498E+01
-5.5234E+01	5.7243E+01	4.7136E+05	1.7321E+03
-4.3637E+02	-6.5498E+01	1.7321E+03	1.544 E+06

FEEDBACK MATRIX

1.9737E+01 -1.9209E+01 -5.6720E+01 -8.8528E+01

CLOSED-LOOP EIGENVALUES

REAL IMAGINARY

-.34594E+01	-.85558E+02
-.34594E+01	.85558E+02
-.78504E+01	-.23590E+03
-.78504E+01	.23590E+03

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

$$DX/DT = A*X + B*U$$

$$2J = \text{INTEGRAL OF } X'*Q*X + U'*R*U$$

WHERE

A

0.	0.	1.0000E+00	0.
0.	0.	0.	1.0000E+00
-7.3321E+03	0.	-8.5630E-01	0.
0.	-5.5709E+04	0.	-2.3603E+00

B

0.
0.
1.0262E-01
2.5397E-01

Q

6.0000E+03	0.	0.	0.
0.	6.0000E+03	0.	0.
0.	0.	6.0000E+03	0.
0.	0.	0.	6.0000E+03

R

1.0000E+00

RICCATI SOLUTION

4.9752E+06	-2.3089E+04	-1.8803E+00	-7.2070E+02
-2.3089E+04	1.5129E+07	5.4899E+03	-2.7877E+00
-1.8803E+00	5.4899E+03	6.8029E+02	-1.2009E+00
-7.2070E+02	-2.7877E+00	-1.2009E+00	2.7089E+02

FEEDBACK MATRIX

-1.8323E+02	5.6267E+02	6.9507E+01	-6.8671E+01
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CLOSED-LOOP EIGENVALUES

REAL	IMAGINARY
------	-----------

-.39954E+01	-.85535E+02
-.39954E+01	.85535E+02
-.98995E+01	-.23582E+03
-.98995E+01	.23582E+03

$$[[Ac] + [Bc][G] - [K][Cc]]$$

For Q=20:

-0.7624	1.724	1.000	0
.6814	-1.541	0	1.000
-7331.	-1.864	-.7411	.1047
-1.021	-55710	.2852	-2.101

Eigenvalues:

-0.7517	+/- J	85.62
-1.821	+/- J	236.0

For Q=200:

-3.572	8.077	1.000	0
3.424	-7.744	0	1.000
-7325.	-15.62	-.0275	.7829
5.384	-55720	2.051	-.4228

-1.800	+/- J	85.63
-4.083	+/- J	235.9

For Q=500:

-6.062	13.71	1.000	0
5.899	-13.34	0	1.000
-7316.	-36.58	.7366	1.531
24.93	-55760	3.942	1.429

-2.666	+/- J	85.65
-5.952	+/- J	235.8

For Q=6000:

-22.83	51.64	1.000	0
22.62	-51.16	0	1.000
-7157.	-379.7	6.277	7.047
484.6	-56770	17.65	15.08

-8.427	+/- J	86.42
-17.89	+/- J	232.1

The eigenvalues of the closed loop system with residuals present are:

For Q=20:

-.8096	+/-	J	85.6224
-.3706	+/-	J	85.6263
-1.9504	+/-	J	236.0198
-1.0505	+/-	J	236.0251
-2.3139	+/-	J	462.7612
-2.3139	+/-	J	764.9125

For Q=200:

-0.0137	+/-	J	85.6291
-2.2145	+/-	J	85.6019
-0.2115	+/-	J	236.0505
-5.0518	+/-	J	236.9636
-2.3135	+/-	J	462.7740
-3.8249	+/-	J	764.9085

For Q=500:

+0.3684	+/-	J	85.6397
-3.4605	+/-	J	85.5716
+0.7140	+/-	J	235.9869
-7.8489	+/-	J	235.8623
-2.3114	+/-	J	462.8053
-3.8266	+/-	J	764.8986

For Q=6000:

+03.1510	+/-	J	85.8333
-11.9052	+/-	J	84.9542
+07.4927	+/-	J	235.1097
-26.7056	+/-	J	233.8435
-02.1238	+/-	J	463.5620
-03.9725	+/-	J	764.6554

Q=20

$$[H] = \begin{bmatrix} .7697 & .00572 & .007345 & .00004066 \\ .002269 & -.3112 & .00002155 & .004035 \\ -53.85 & -.4197 & .7699 & -.0005213 \\ -.8969 & -224.8 & -.001568 & -.3135 \end{bmatrix}$$

$$[F] = [.01812 \quad -.008787 \quad -.5747 \quad 2.900]^T$$

$$[G] = [-.043949 \quad .1354 \quad 1.123 \quad 1.020]$$

Pseudostate Form:

$$[H]' = \begin{bmatrix} .7697 & .00572 & .7345 & .004066 \\ .002269 & -.3112 & .002155 & .4035 \\ -.5385 & -.004197 & .7699 & -.0005213 \\ -.008969 & -2.248 & -.001568 & -.3135 \end{bmatrix}$$

$$[F]' = [.1812 \quad -.08787 \quad -.05747 \quad .29]^T$$

$$[G] = [-.00439 \quad .01354 \quad 11.23 \quad 10.2]$$

Multiply $[H]'$ and $[F]'$ by 128 and form integer matrices:

$$[H] = \begin{bmatrix} 99 & 1 & 94 & 1 \\ 0 & -40 & 0 & 52 \\ -69 & -1 & 99 & 0 \\ -1 & -288 & 0 & -40 \end{bmatrix}$$

$$[F] = [23 \quad -11 \quad -7 \quad 3]^T$$

$$[G] = [-0 \quad 0 \quad 11 \quad 10]$$

Q=200

$$[H] = \begin{bmatrix} .7513 & .02427 & .007287 & .0001933 \\ .01078 & -.3220 & .0001208 & .003964 \\ -53.38 & -2.316 & .7765 & -.001432 \\ -4.493 & -220.9 & -.005108 & -.2936 \end{bmatrix}$$

$$[F] = [.08209 \quad -.04310 \quad -2.688 \quad 14.14]^T$$

$$[G] = [-2.3698 \quad 7.2801 \quad 8.0764 \quad 7.6288]$$

Pseudostate Form:

$$[H]' = \begin{bmatrix} .7513 & .02427 & .7284 & .01933 \\ .01078 & -.3220 & .01208 & .3964 \\ -.5338 & -.02316 & .7765 & -.001432 \\ -.04493 & -2.209 & -.005108 & -.2936 \end{bmatrix}$$

$$[F]' = [.8209 \quad -.431 \quad -.2688 \quad 1.414]^T$$

$$[G] = [-.23698 \quad .7280 \quad 80.764 \quad 76.288]$$

Multiply [H] and [F] by 128 and form integer matrices:

$$[H] = \begin{bmatrix} 96 & 3 & 93 & 2 \\ 1 & -41 & 2 & 51 \\ -68 & -3 & 99 & 0 \\ -6 & -283 & -1 & -38 \end{bmatrix}$$

$$[F] = [105 \quad -55 \quad -34 \quad 181]^T$$

$$[G] = [0 \quad 1 \quad 81 \quad 76]$$

Q=500

$$[H] = \begin{bmatrix} .7358 & .03832 & .007244 & .0003274 \\ .01788 & -.3320 & .0002152 & .003907 \\ -53.01 & -4.159 & .7834 & -.001706 \\ -7.646 & -217.9 & -.006418 & -.2759 \end{bmatrix}$$

$$[F] = [\begin{matrix} .1353 & -.07268 & -4.551 & 23.74 \end{matrix}]^T$$

$$[G] = [\begin{matrix} -8.9084 & 27.361 & 15.522 & 14.921 \end{matrix}]$$

Pseudostate Form:

$$[H]' = \begin{bmatrix} .7358 & .03832 & .7244 & .03274 \\ .01788 & -.3320 & .02152 & .3907 \\ -.5301 & -.04159 & .7834 & -.001706 \\ -.07646 & -2.179 & -.006418 & -.2759 \end{bmatrix}$$

$$[F]' = [\begin{matrix} 1.353 & -.7268 & -.4551 & 2.374 \end{matrix}]^T$$

$$[G] = [\begin{matrix} -.8908 & 2.7361 & 155.22 & 149.21 \end{matrix}]$$

Multiply [H] and [F] by 128 and form integer matrices:

$$[H]' = \begin{bmatrix} 94 & 5 & 93 & 4 \\ 2 & -42 & 3 & 50 \\ -68 & -5 & 100 & 0 \\ -10 & -279 & -1 & -35 \end{bmatrix}$$

$$[F]' = [\begin{matrix} 173 & -93 & -58 & 304 \end{matrix}]^T$$

$$[G] = [\begin{matrix} -1 & 3 & 155 & 149 \end{matrix}]$$

Q=6000

$$[H] = \begin{bmatrix} .6527 & .09193 & .007073 & .001147 \\ .05591 & -.3879 & .0008353 & .003601 \\ -50.87 & -16.65 & .8357 & -.0007079 \\ -26.19 & -203.9 & .007458 & -.1694 \end{bmatrix}$$

$$[F] = [.4181 \quad -.2429 \quad -16.69 \quad 77.01]^T$$

$$[G] = [-183.23 \quad 562.67 \quad 69.507 \quad 68.671]$$

Pseudostate Form

$$[H]' = \begin{bmatrix} .6527 & .09193 & .7073 & .1147 \\ .05591 & -.3879 & .08353 & .3601 \\ -.5087 & -.1665 & .8357 & -.0007079 \\ -.2619 & -2.039 & .007458 & -.1694 \end{bmatrix}$$

$$[F]' = [4.181 \quad -2.429 \quad -1.669 \quad 7.701]^T$$

$$[G] = [-18.323 \quad 56.267 \quad 695.07 \quad 686.71]$$

Multiply $[H]'$ and $[F]'$ by 128 and form integer matrices

$$[H] = \begin{bmatrix} 84 & 12 & 91 & 15 \\ 7 & -50 & 11 & 46 \\ -65 & -21 & 107 & 0 \\ -34 & -261 & 1 & -22 \end{bmatrix}$$

$$[F] = [535 \quad -311 \quad -214 \quad 986]^T$$

With Gain = 100 at accelerometer amplifier:

$$[F] = [5 \quad -3 \quad -2 \quad 10]^T$$

Divide by 18.323 here, and Multiply by 18.323 outside:

$$[G] = [-1 \quad 3 \quad 38 \quad 37]$$

Appendix 4

Control Implementation Discrete Form Derivation

The details of the discrete form integrations are provided below:

$$\bar{X}(t) = e^{[A]t} \bar{X}(0) + \int_0^t e^{[A](t-\tau)} [K]Y(\tau) d\tau \quad (50)$$

Over one sample period, T,

$$\bar{X}(T) = e^{[A]T} \bar{X}(0) + \int_0^T e^{[A](T-\tau)} [K]Y(\tau) d\tau \quad (50a)$$

Assuming $Y(\tau)$ is constant over the sample period, 0 to T,

$$\bar{X}(T) = e^{[A]T} \bar{X}(0) + e^{[A]T} \int_0^T e^{-[A]\tau} d\tau [K]Y(0) \quad (50b)$$

It can be easily shown that:

$$\int_0^T e^{-[A]\tau} d\tau = -[A]^{-1} e^{-[A]\tau} \Big|_{\tau=0}^T \quad (50c)$$

Which by substitution leaves:

$$\bar{X}(T) = e^{[A]T} \bar{X}(0) + e^{[A]T} [-[A]^{-1} e^{-[A]\tau}]_{\tau=0}^T [K]Y(0) \quad (50d)$$

Or,

$$\bar{X}(T) = e^{[A]T} \bar{X}(0) + [A]^{-1} [e^{[A]T} - I] [K]Y(0) \quad (51)$$

Appendix 5

Control Algorithm Computer Listing

The computer programs used for control implementation are listed below:

1. TASK9. This Fortran 80 main body program incorporates the storage of controller matrices' elements and commands the subroutines to:

- a) Start the system clock counters(STCLK).
- b) Perform the control function(CNTRL2M).
- c) Write the data stored(time response of the estimate of the mode) to a disk file(WRTBUF).
- d) Plot the discretized time response(PLOT).

Support subroutines are:

- a) Analog to Digital and Digital to Analog service routines(AD and DA, contained in ADIO).
- b) A simple time delay routine which allows the plotter time to respond to directed inputs(WAIT).

PROGRAM TASK9

```

PROGRAM TASK9
  IMPLICIT INTEGER(A-Z)
C  DEFAULT IS INTEGER * 2
    DIMENSION F(4),G(4),HX(4),X(4),Y(1000)
    DIMENSION IH(4,4)
    WRITE(1,22)
22   FORMAT(4X,'RUN NUMBER(1,2,3,4)?',/)
    READ(1,24)RUN
24   FORMAT(I1)
C  THE FOLLOWING VALUES COME FROM EQ 66 AND 68 IN THESIS
    F(1)=105
    F(2)=-55
    F(3)=-34
    F(4)=181
    IH(1,1)=96
    IH(1,2)=3
    IH(1,3)=93
    IH(1,4)=2
    IH(2,1)=1
    IH(2,2)=-41
    IH(2,3)=2
    IH(2,4)=51
    IH(3,1)=-68
    IH(3,2)=-3
    IH(3,3)=99
    IH(3,4)=0
    IH(4,1)=-6
    IH(4,2)=-283
    IH(4,3)=-1
    IH(4,4)=-38
    G(1)=0
    G(2)=1
    G(3)=81
    G(4)=76
    DO 90 N=1,1000
90   Y(N)=0
    DO 100 I=1,4
    X(I)=0
    HX(I)=0
100  CONTINUE
    CALL STCLK
    CALL CNTL2M(F(1),G(1),IH(1,1),HX(1),X(1),Y(1))
    CALL WRTBUF(Y(1),1000,RUN)
    CALL PLOT(Y(1))
    STOP
    END

```

SUBROUTINE CNTL2M

ENTRY CNTL2M
EXTERNAL \$AT,\$M9

CSEG

CNTL2M:

;THIS PROOGRAM IS DERIVED FROM THE FORTRAN COMPILER'S
;VERSION OF AN EQUIVALENT SUBROUTINE, USING TECHNIQUES
;AS OUTLINED IN THE THESIS PAGE 8. SOME SUBROUTINES
;ARE MADE PROGRAM SPECIFIC TO REDUCE COMPUTATION TIME.
;COMMENTS ARE DENOTED BY A C IN THE SECOND COLUMN. THE
;EQUIVALENT S/R IN FORTRAN IS NOTED BY AN F IN THE
;SECOND COLUMN:

;F SUBROUTINE CNTL2M(F,G,IH,HX,X,Y)
;F IMPLICIT INTEGER(A-Z)
;F DIMENSION Y(1000),HX(4),X(4),F(4),G(4)
;F DIMENSION IH(4,4)
;C INITIALIZE PROGRAM

.RADIX 16
SHLD F
XCHG
SHLD G
MVI A,04
LXI H,IH
CALL \$AT

;F DO 300 K=0,253
;C REMOVE THE NEXT SEMI-COLON FOR LONGER RUN TIME

;DOK: SHLD K
;F DO 300 N=1,999,2
LXI H,0001
DON: SHLD N
;F CALL GETTIM(Y(N+1))
LHLD N
DAD H
XCHG
LHLD Y
DAD D
SHLD T00
LHLD T00

.280
IN A,(07AH)
LD (HL),A
IN A,(07BH)
INC HL
LD (HL),A

.8080
;F OUT=0
LXI H,0000
SHLD OUT
;F CALL AD(VIN,0,80)
LXI B,FIFTY
LXI D,ZERO
LXI H,VIN

.280

```

LD      (VALUE),HL
LD      (CHAN),DE
LD      (BASE),BC
EX      DE,HL
LD      A,(HL)
LD      HL,(BASE)
LD      C,(HL)
OUT     (C),A
INC     C
LD      A,0
OUT     (C),A
DEC     C
NRDY:   IN      A,(C)
        AND     080H
        JR      NZ,NRDY
        INC     C
        INC     C
        IN      A,(C)
        LD      E,A
        INC     C
        IN      A,(C)
        AND     0FH
        LD      D,A
        LD      HL,(VALUE)
        LD      (HL),E
        INC     HL
        LD      (HL),D

.8080
;F      IN=VIN-2048
        LHL     VIN
        LXI     D,0F800
        DAD     D
        SHLD    IN
;F      DO 250 I=0,3
        LXI     H,0000
DOI:     SHLD    I
;F      DO 230 J=0,3
        LXI     H,0000
DOJ:     SHLD    J
;F      230 HX(I+1)=IH(I+1,J+1)*X(J+1)+HX(I+1)
        LHL     I
        DAD     H
        SHLD    T00
        XCHG
        LHL     HX
        DAD     D
        SHLD    T01
        LHL     J
        DAD     H
        DAD     H
        DAD     H
        XCHG
        LHL     T00
        DAD     D
        XCHG

```

```

LHLD    IH
DAD     D
SHLD    T02
LHLD    J
DAD     H
XCHG
LHLD    X
DAD     D
MOV     A,M
INX     H
MOV     H,M
MOV     L,A
XCHG
LHLD    T02
MOV     A,M
INX     H
MOV     H,M
MOV     L,A
CALL    $M9
XCHG
LHLD    T01
MOV     A,M
INX     H
MOV     H,M
MOV     L,A
DAD     D
XCHG
LHLD    T01
MOV     M,E
INX     H
MOV     M,D
;C      LOOP J
LHLD    J
INX     H
;C LOAD -(THE NUMBER OF TIMES TO LOOP IN HEX) = -4
LXI     B,-4
MOV     D,H
MOV     E,L
DAD     B
XCHG
JNC     DOJ
;F      X(I+1)=(HX(I+1)+F(I+1)*IN)/128
LHLD    I
DAD     H
SHLD    T00
XCHG
LHLD    X
DAD     D
SHLD    T01
LHLD    T00
XCHG
LHLD    HX
DAD     D
SHLD    T02
LHLD    T00

```

```

XCHG
LHLD    F
DAD     D
MOV     A,M
INX     H
MOV     H,M
MOV     L,A
XCHG
LHLD    IN
CALL    $M9
XCHG
LHLD    T02
MOV     A,M
INX     H
MOV     H,M
MOV     L,A
DAD     D
;C      DIVIDE BY 128
.280
        RL      L
        RL      H
        LD      L,H
        LD      A,0
        SBC     A,0
        LD      H,A
;C      SAVE VALUE OF X(I)
.8080
        LDA     I
;C      FOR MODE1: X(1),CMP 0; FOR MODE 2: X(2),CMP 1
        CMP     0
        JZ      DWN
.280
        LD      (XSAVE),HL
.8080
DWN:
XCHG
LHLD    T01
MOV     M,E
INX     H
MOV     M,D
;F      250  OUT=OUT-G(I+1)*X(I+1)
        LHLD    I
        DAD     H
        SHLD    T00
XCHG
LHLD    G
DAD     D
SHLD    T01
LHLD    T00
XCHG
LHLD    X
DAD     D
MOV     A,M
INX     H
MOV     H,M
MOV     L,A

```

```

XCHG
LHLD    T01
MOV     A,M
INX     H
MOV     H,M
MOV     L,A
CALL    $M9
XCHG
LHLD    OUT
MOV     A,E
SUB     L
MOV     L,A
MOV     A,D
SBB     H
MOV     H,A
XRA     A
SUB     L
MOV     L,A
SBB     H
SUB     L
MOV     H,A
SHLD    OUT
;C      LOOP I
LHLD    I
INX     H
;C LOAD: -(THE NUMBER OF TIMES TO LOOP IN HEX) = -4
LXI     B,-4
MOV     D,H
MOV     E,L
DAD     B
XCHG
JNC     DOI
;F      OUT=OUT/128
LHLD    OUT
;C      DIVIDE BY 128
.280
RL       L
RL       H
LD       L,H
LD       A,0
SBC     A,0
LD       H,A
.8080
;F      VOUT=OUT+2048
SHLD    OUT
LXI     D,0800
DAD     D
SHLD    VOUT
;F      CALL DA(VOUT,0,72)
LXI     B,FORTY8
LXI     D,ZERO
LXI     H,VOUT
.280
LD       A,(DE)
ADD     A,A

```

```

INC      A
PUSH     HL
PUSH     BC
POP      HL
LD       C,(HL)
ADD      A,C
LD       C,A
POP      HL
LD       A,(HL)
OUT      (C),A
DEC      C
INC      HL
LD       A,(HL)
OUT      (C),A

.8080
;F      300 Y(N)=IN
        LHL D      N
        DAD      H
        DCX      H
        DCX      H
        XCHG
        LHL D      Y
        DAD      D
        SHLD     T00
;C      LHL D      IN (USE IF WANT Y(N)=IN)
;C Y(N) = XSAVE = X(1) OR X(2) DEPENDING ON ABOVE INFO
        LHL D      XSAVE
        XCHG
        LHL D      T00
        MOV      M,E
        INX      H
        MOV      M,D
;C      LOOP N
        LHL D      N
        INX      H
        INX      H
;C LOAD -(THE NUMBER OF TIMES TO LOOP(1000) IN HEX)
        LXI      B,-03E8
        MOV      D,H
        MOV      E,L
        DAD      B
        XCHG
        JNC      DON
;C LOOP K REMOVE SEMI-COLONS FOR LONGER RUN TIME
;      LHL D      K
;      INX      H
;C LOAD -(THE NUMBER OF TIMES TO LOOP(254) IN HEX)
;      LXI      B,-0FE
;      MOV      D,H
;      MOV      E,L
;      DAD      B
;      XCHG
;      JNC      DOK
;F      RETURN
        RET

```

DSEG

F:	DW	0
G:	DW	0
IH:	DW	0
HX:	DW	0
X:	DW	0
Y:	DW	0
I:	DW	0
J:	DW	0
K:	DW	0
N:	DW	0
OUT:	DW	0
T00:	DW	0
VIN:	DW	0
IN:	DW	0
T01:	DW	0
T02:	DW	0
VOUT:	DW	0
FIFTY:	DW	50
FORTY8:	DW	48
ZERO:	DW	0
VALUE:	DW	0
CHAN:	DW	0
BASE:	DW	0
XSAVE:	DW	0
END		

SUBROUTINE ADIO

.Z80

```

ENTRY AD
; A/D SERVICE ROUTINE - CAPT BRIGGS(AFIT/ENY, WPAFB,OH)
; FORTRAN CALLABLE: CALL AD(VALUE,CHAN,BASE)
; GET ONE SAMPLE FROM THE CHAN'TH CHANNEL
; ON THE A/D BOARD WITH BASE ADDRESS 'BASE'
AD: LD (VALUE),HL
LD (CHAN),DE
LD (BASE),BC
EX DE,HL ;HL->CHAN
LD A,(HL) ;GET CHAN NO.
LD HL,(BASE)
LD C,(HL) ;GET BASE I/O ADDRESS TO C REG FOR OUTING
OUT (C),A ;MODE 0 TO CHAN NO.
;USES BASE ADDRESS IN C REG
;POINT TO START CONVERSION PORT
INC C
LD A,0
OUT (C),A ;START CONVERSION
DEC C ;POINT TO BASE REGISTER
NRDY: IN A,(C) ;GET STATUS
AND 080H ;BIT 7 IS STATUS, =1 IS BUSY
JR NZ,NRDY ;NOT ALL 0'S => BUSY
INC C ;POINT TO BASE ADD+1
INC C ;POINT TO DRL
IN A,(C) ;LOW BYTE OF VALUE
LD E,A
INC C ;POINT TO DRH
IN A,(C) ;HIGH BYTE OF VALUE
AND 0FH ;MASK OUT HIGH NIBBLE
LD D,A ;DE=VALUE
LD HL,(VALUE) ;HL->WHERE TO PUT VALUE
LD (HL),E ;PUT LOW BYTE OF VALUE
INC HL
LD (HL),D ;THAT GIVES THE CALLER THE VALUE
RET
VALUE: DW 0 ;STORAGE FOR ADDRESS OF VALUE
CHAN: DW 0 ;STORAGE FOR ADDRESS OF CHANNEL NO
BASE: DW 0 ;STORAGE FOR ADDRESS OF BASE ADDRESS

```

.Z80

```

ENTRY DA
; CALL DA(VAL,CHAN,BASE)
; CHAN IS 0
; BASE IS 72(BASE 10)
DA: LD A,(DE) ;GET CHAN
ADD A,A ;DOUBLE IT
INC A ;ADD ONE
PUSH HL ;SAVE VAL
PUSH BC
;
POP HL ;HL=>BASE
LD C,(HL) ;C=LOW BYTE OF BASE
ADD A,C
;

```

LD	C,A	;C=LOW BYTE VALUE OF PORT
POP	HL	;GET VAL
LD	A,(HL)	;GET LOW BYTE
OUT	(C),A	;PUT LOW BYTE
DEC	C	;C=HIGH BYTE PORT
INC	HL	;HL=>HI BYTE
LD	A,(HL)	;GET HI BYTE
OUT	(C),A	;PUT HI BYTE
RET		
END		

SUBROUTINE PLOT

```

SUBROUTINE PLOT(Y)
  IMPLICIT INTEGER(A-Z)
  DIMENSION Y(1000)
  EXTERNAL DA, WAIT
C  PLOT THE VALUES IN ARRAY(Y(N))
  YMX=0
  DO 200 N=1,399,2
    Y(N+1)=(Y(N+1))/2
    IF(Y(N).GT.0) GO TO 110
    YCOMP=-Y(N)
    GO TO 115
110  YCOMP=Y(N)
115  CONTINUE
    IF (YCOMP.LT.YMX) GO TO 120
    YMX=YCOMP
120  YMAX=2048+YMX+YMX/10
    YMIN=2048-YMX-YMX/10
    Y(N)=2048+Y(N)
    Y(N+1)=2048-Y(N+1)
    M=3
C  PEN UP
    CALL DA(3500,3,72)
C  WAIT FOR PEN TO COME UP
    CALL WAIT(M)
C  GO TO Y-VALUE
    CALL DA(Y(N),2,72)
C  GO TO X-VALUE
    CALL DA(Y(N+1),1,72)
C  WAIT FOR PEN TO STOP MOVING
    CALL WAIT(M)
C  PEN DOWN
    CALL DA(2048,3,72)
    CALL WAIT(M)
200  CONTINUE
C  WHEN DONE PLOTTING,DRAW BOUNDARIES
C  GO TO THE ORIGIN
    CALL DA(3500,3,72)
    CALL WAIT(M)
    CALL DA(2048,1,72)
    CALL DA(2048,2,72)
    CALL DA(2048,3,72)
    CALL WAIT(M)
C  GO AROUND TWICE
    DO 220 I=1,2
      CALL DA(YMAX,2,72)
      CALL WAIT(M)
      CALL DA(Y(N+1),1,72)
      CALL WAIT(M)
      CALL DA(YMIN,2,72)
      CALL WAIT(M)
      CALL DA(2048,1,72)
220  CALL WAIT(M)

```

```

CALL DA(2048,2,72)
XM=2048
V=(YMAX-2048)/30
PV=2048+V
MV=2048-V
U=(YMAX-2048)/5
DO 240 I=1,7
C INCREMENT X-AXIS
CALL WAIT(M)
CALL DA(2048,3,72)
XM=XM+200
CALL WAIT(M)
CALL DA(XM,1,72)
CALL WAIT(M)
CALL DA(PV,2,72)
CALL WAIT(M)
CALL DA(MV,2,72)
CALL WAIT(M)
240 CALL DA(2048,2,72)
C RETURN TO ORIGIN
CALL WAIT(M)
CALL DA(Y(N+1),1,72)
CALL WAIT(M)
CALL DA(2048,1,72)
CALL WAIT(M)
CALL DA(2048,2,72)
YM=2048-6*U
C INCREMENT THE Y-AXIS
DO 270 I=1,10
YM=YM+U
CALL WAIT(M)
CALL DA(YM,2,72)
CALL WAIT(M)
CALL DA(2055,1,72)
CALL WAIT(M)
270 CALL DA(2048,1,72)
CALL WAIT(M)
CALL DA(YMAX,2,72)
CALL WAIT(M)
CALL DA(2048,2,72)
CALL WAIT(M)
CALL DA(3500,3,72)
RETURN
END

```

SUBROUTINE WRTBUF

```

SUBROUTINE WRTBUF(BUF,NS2,RUN)
IMPLICIT INTEGER(A-Z)
DIMENSION BUF(1)
DIMENSION ZBUF(8)
ST=0
WRITE(1,50)
50  FORMAT(3X,'MODE 1',5X,'TIME',3(5X,'MODE 1',4X,'TIME'))
N=NS2/8
R=RUN+5
DO 800 JA=1,N
DO 90 C=1,8
P=ST+C
90  ZBUF(C)=BUF(P)
WRITE(1,100)(ZBUF(K),K=1,8)
WRITE(R,100)(ZBUF(K),K=1,8)
100  FORMAT(/,4(2X,I7,3X,I6))
ST=ST+8
800  CONTINUE
NT=NS2-N*8
IF(NT.EQ.0) GO TO 910
DO 890 D=1,NT
P=ST+D
890  ZBUF(D)=BUF(P)
WRITE(1,900)(ZBUF(M),M=1,NT)
WRITE(R,900)(ZBUF(M),M=1,NT)
900  FORMAT(/,4(2X,I7,3X,I6))
910  CONTINUE
RETURN
END

```

SUBROUTINE STCLK

```

ENTRY STCLK
.Z80
STCLK:
LD A,017H ; CHANNEL 1 CTRL WD =TIME/16
OUT (079H),A
LD A,09AH ;TIME CONSTANT
OUT (079H),A
LD A,057H ;CHANNEL 2 CNTRL WD=CTR
OUT (07AH),A
LD A,0FFH ;TIME CONSTANT=256(BASE 10)
OUT (07AH),A
LD A,057H ;CHANNEL 3 CNTRL WD=CTR
OUT (07BH),A
LD A,0FFH ;TIME CONSTANT
OUT (07BH),A
RET
END

```

Appendix 6
Experiment Checklist

1. Turn on all equipment - leave High Voltage Dc (HVDC) off.
2. Check accelerometer firmly in place.
3. Check all connections (especially micro dot) secure.
4. Assure HVDC dials are fully CCW and turn on.
5. Select operate on analog computer/check potentiometers.
6. Simultaneously set both HVDC dials at 200 ma.
7. Turn plotter on, center/check.
8. Set beam initial displacement or white noise generator.
9. Place disk #3(operating system) in drive A (label faces right).
10. Place disk #5 (program) in drive B (label faces right).
11. "Boot up" the system by pressing reset button.
12. Type: B: (return).
13. Type: TASK91 (return) for mode 1 output, and TASK92 for mode 2 output. TASK91 is just TASK9 linked with CNTL2M which outputs the estimate of mode 1. TASK92 is formed similarly using CNTL2M which outputs the estimate of mode 2. Both give discrete time response. For the continuous case use TASK91N or TASK92N which are formed by deleting the appropriate ; in CNTL2M.
14. Enter run number, push return, and release the initial displacement mechanism, or push RUN for noise input.
15. Data will appear on screen and in a disk file, Fort0(run number plus five).Dat, as four pairs of value and time (1 clock cycle = .00005013 sec.).

Appendix 7

Library

This file contains a list of the information stored in room 147 pertaining to Dr. Calico's Flexible Beam Experiment. Vol. I.

A. Microsoft Fortran-80 Documentation - Microsoft.

1. Fortran-80 Reference Manual - statements, functions, syntax.
2. Fortran-80 User's Manual - compiler commands and error messages.
3. Microsoft Utility Software Manual - Macro-80 assembler, LINK-80 Linker Loader, LIB-80 Lib Manager.

B. MC 5.16 Vibrations Laboratory Experiments - Winter 1982.

1. Oscilloscope, RMS meter, Oscillator.
2. Shaker, Power Supply, Power Amplifier, Freq Counter.
3. Accelerometers, Accelerometer Amplifiers.
4. Unknown Accelerometer Calibration.
5. Cantilever Beam Response.
6. Measure Resistance, Output Impedance.
7. Oscillograph, Galvanometer Operation.
8. Vibration Decay Experiment.

C. CP/M Seminar Lecture Notes.

Vol II EE 6.87 Microcomputer Lab - Alan Ross

A. Course Notes and Assignments.

- B. ZCPR Documentation.
- C. SID Symbolic Intruction Debugger User's Guide.
- D. ZSID Command Summary.
- E. MACRO-80 Assembler Reference Manual.
- F. WM Screen-Oriented Text Editor User's Manual
- E. Manual 0: S-100 Bus.
- F. Manual 1: Z80 CPU Technical Manual.
- G. Manual 2: Z80 CPU Technical Manual and Applica-
tions Note (8251 Specification Sheets contained
within).
- H. Manual 3: Z80 PIO Technical Manual.
- I. Manual 4: Z80 CTC Product Specification.
- J. Manual 5: Z80 Family Interrupt Structure
Tutorial.
- K. Manual 6: SBC-100 Single Board Computer.

Vol III. Mainframe Hardware.

- A. Model 910 Terminal - Televideo.
- B. S-100 Bus Mainframe - Electronic Control
Technology.
 - 1. Expandoram II - Random Access Memory
SD Systems.
 - 2. SD Monitor -Instructional Publication.
 - 3. SBC-100 Single Board Computer.
 - 4. Mostek 3882 CTC Technical Manual - Mostek.
 - 5. S-100 Bus Extender Board/Logic Probe Kit.
 - 6. S-100 D/A Converter Board - Techmar Inc.
 - 7. S-100 A/D Converter Board - Techmar Inc.
 - 8. AIM- 12 Analog Input Module - Dual Systems

Control.

9. AOM- 12 S-100 D/A Converter - Dual Systems
Control.

10. HP3721A Correlator Documentation.

11. HP3720A Spectrum Display Documentation.

Vol IV. Background Information.

A. PACOSS - Statement of Work - Passive and Active
Control of Space Structures.

B. DTIC (Defense Technical Information Center)
Literature Search.

C. ASIAC (Aerospace Structures Information and
Analysis Center) Literature Search.

D. User's Guide to DTIC.

E. Control of a Flexible Satellite Via Elimination
of Observation Spillover - Janiszewski/Calico -
AFIT.

F. Hardware Demonstration of Flexible Beam Control
Schaechter JPL, California Institute of
Technology.

G. An Experimental Investigation of Modern Modal
Control-Herrick, Canavin, Strunce - Draper Labs.

Vol V. Tarbell Disk Control/Digital Research CP/M Pubs.

A. Tarbell Basic - Tarbell Electronics.

B. Tarbell Basic 15.4 Improvements and Changes.

C. Tarbell CP/M 2.0 (BIOS)/User's Guide.

D. Tarbell Double Density Floppy Disk Interface-
Owner's Manual.

E. Intro to CP/M Features and Facilities- Digital

Research.

- F. ED: Context Editor for the CP/M Disk System User's Manual.
- G. CP/M Dynamic Debugging Tool (DDT) - User's Guide.
- H. CP/M Assembler (ASM) - User's Guide.
- I. CP/M 2 User's Guide.
- J. CP/M 2 Alteration Guide.
- K. CP/M 2 Interface Guide.

Vol VI Additional Software/Studor's Thesis

- A. TOTAL USERS MANUAL - An interactive computer-aided design program for digital and continuous control system analysis and synthesis.
- B. OPTCON - Solution of Linear Quadratic Optimal Control Problem - Witt, Mirmak, & Ray March 1982
- C. Thesis
- D. Disk Programs
 - 1. Used in thesis
 - 2. Future applications

VITA

George Frederick Studor, Jr. was born in Syracuse, New York on November 22, 1954. Soon after high school graduation in 1972 he began his Air Force service as a cadet at the USAF Academy. Graduating in 1976 with a Bachelor of Science in Astronautical Engineering, Lieutenant Studor went on to USAF Undergraduate Pilot Training which he completed successfully in August, 1977. He was assigned to the 41st TAS, Pope Air Force Base, North Carolina, and was upgraded to C-130 aircraft commander. In June 1981, Captain Studor was assigned to the School of Engineering, Air Force Institute of Technology, to enter the Masters Degree Program in Astronautical Engineering.

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18. SUPPLEMENTARY NOTES Approved for public release; LAW AFR 190-17. LYNN E. WOLAVER Dean for Research and Professional Development Air Force Institute of Technology (AFIT) Wright-Patterson AFB, OH 45433		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Experimental Design Control Systems - Regulators Structures- Flexible Structures Control Sequences- Computer Programming Control Test Vehicles		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Experimental demonstration of modern modal control of a flexible clamped-clamped beam in bending was accomplished. Pole placement techniques in conjunction with a Leuenberger observer were used for controller development. Available microcomputer computational capabilities drove the reduced order model to a two mode representation. The controllers, designed with varying degrees of robustness, demonstrated the limitations of reduced order controllers in even the simplest		

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of systems. Sensor and actuator position are demonstrated to be of paramount importance in the modern controller LQ design.

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