CONTROL THEORETICS FOR LARGE STRUCTURAL SYSTEMS

Raymond C. Montgomery
NASA Langley Research Center

Second Annual Technical Review
Large Space Systems Technology Program
NASA Langley Research Center
Hampton, VA 23665

November 18-20, 1980

RESEARCH ISSUES IN STRUCTURAL DYNAMICS AND CONTROL OF LARGE SPACE STRUCTURES

At Langley Research Center, we are addressing the issue of structural dynamics and control with experimentation and theoretical development. Figure 1 lists the areas of research being addressed including modeling identification for both the purposes of analysis and controls, design of structural control systems actuator sensor placement, and distributed sensing and actuation as opposed to co-located sensor and actuators. Also, we will be looking at adaptive/learning processes that could more specifically be refered to as inflight testing procedures where a structure is tested during its deployment or assembly and during its orbital life at specific points where we identify the characteristics of the structure for the purpose of tuning the control system. Another area is redundancy management techniques for structural systems. This is important because of the relaibility issue for managing multiple very large numbers of sensors and actuators. The management approach is indicated on figure 2.

0 MODELING AND IDENTIFICATION PROCEDURES FOR DYNAMIC ANALYSIS AND CONTROL

0 OPTIMUM ACTUATOR AND SENSOR PLACEMENT AND DESIGN

0 DISTRIBUTED SENSING AND ACTUATION VERSUS COLOCATED SENSING AND ACTUATION

0 ADAPTIVE/LEARNING CONTROL SYSTEMS FOR STRUCTURAL SYSTEMS

0 REDUNDANT MANAGEMENT TECHNIQUES FOR STRUCTURAL SYSTEMS

Figure 1

APPROACH - THEORY

Our in-house effort involves research in adaptive/learning by myself; research in basic design of structural control systems actuator placement and sensor placement by Garnett Horner; and research in the application of the coupling theory to structural control by Al Hamer. NASA has a contract to Honeywell, Inc., in Minneapolis, MN, to do studies on closed loop control of the space shuttle orbiter attached to a payload using the RMS arm and to look at measures of parameter identification performance relative to real time identification of structural systems. We have another contract with Vigyan Research Associates to conduct studies on the application of modern control theory, mainly linear quadratic gaussian control techniques, to structural dynamics systems. In research grants, Stanford University is studying the problem of structural dynamics and control design with particular emphasis on the placement of actuators and sensors. MIT has a grant to study reliability issues--the problem of designing the basic control systems considering that the components have a finite reliability and may fail during operation considering large numbers of actuators and sensors. The University of Houston is pursuing the problem of vibrational systems and developing algorithms that are extremely efficient for decoupling of structural models for very large order systems. The City University of New York is conducting research on adaptive/learning control systems. Howard University is dealing with the problem of modeling large structural systems in orbit accounting for the orbital dynamics parameters. North Carolina State A&T University is studying the problem of modeling large structural systems for both analysis and control. The remainder of the talk will concern further detail on the items which have the bullets by them. This is because of my familiarity with those particular subjects. For information regarding the other subjects, one should consult with the principal investigators of those specific grants or contracts.

IN-HOUSE
- • MONTGOMERY - ADAPTIVE/LEARNING
- HORNER - FREE-FREE ACTUATION, PLACEMENT, DESIGN
- HAMER - DECOUPLING THEORY

CONTRACTS
- • HONEYWELL - ACTIVE CLOSED LOOP CONTROL AND PARAMETER ID
- VIGYAN RESEARCH ASSOCIATES, INC. - CONTROLLER DESIGN METHODOLOGY

GRANTS
- • STANFORD - PLACEMENT, DESIGN
- • MIT - RELIABILITY ISSUES
- U. HOUSTON - DECOUPLING STRUCTURAL MODELS
- • CUNY - ADAPTIVE/LEARNING
- VPI&SU - ADAPTIVE, PAR ID, MODELING
- HOWARD UNIVERSITY - MODELING OF ORBITING PLATFORMS
- • NC A&T - MODELING OF LARGE FLEXIBLE STRUCTURES

Figure 2

NONCOLOCATED CONTROL

Langley has just completed a workshop where the specific items which had bullets attached to them in the previous slide were discussed. Now I would like to give you an overview of some of the results which were presented at that workshop. The first item I have chosen to discuss is research which is being undertaken by Prof. Cannon at Stanford University. Prof. Cannon is considering the problem of sensor and actuator placement and, in particular, is investigating the problem of non-colocated feedback. Figure 3 presents a discription of some of that research. On the left of the slide, we have a schematic diagram indicating a feedback from a structural dynamics system which is a series of discs which are connected by a wire that can transmit torsion. Note that the angle θ is measured as the lower disc and is then processed by a compensator which generates a moment applied at another disc. The significant point of this research is that in certain conditions the system becomes a nonminimum phase system which means that in control system jargon, the system will be conditionally stable. That is, it may be stable at one value of feedback gain on the compensator and unstable at another. To assure that you will have a stable system requires precise modeling.

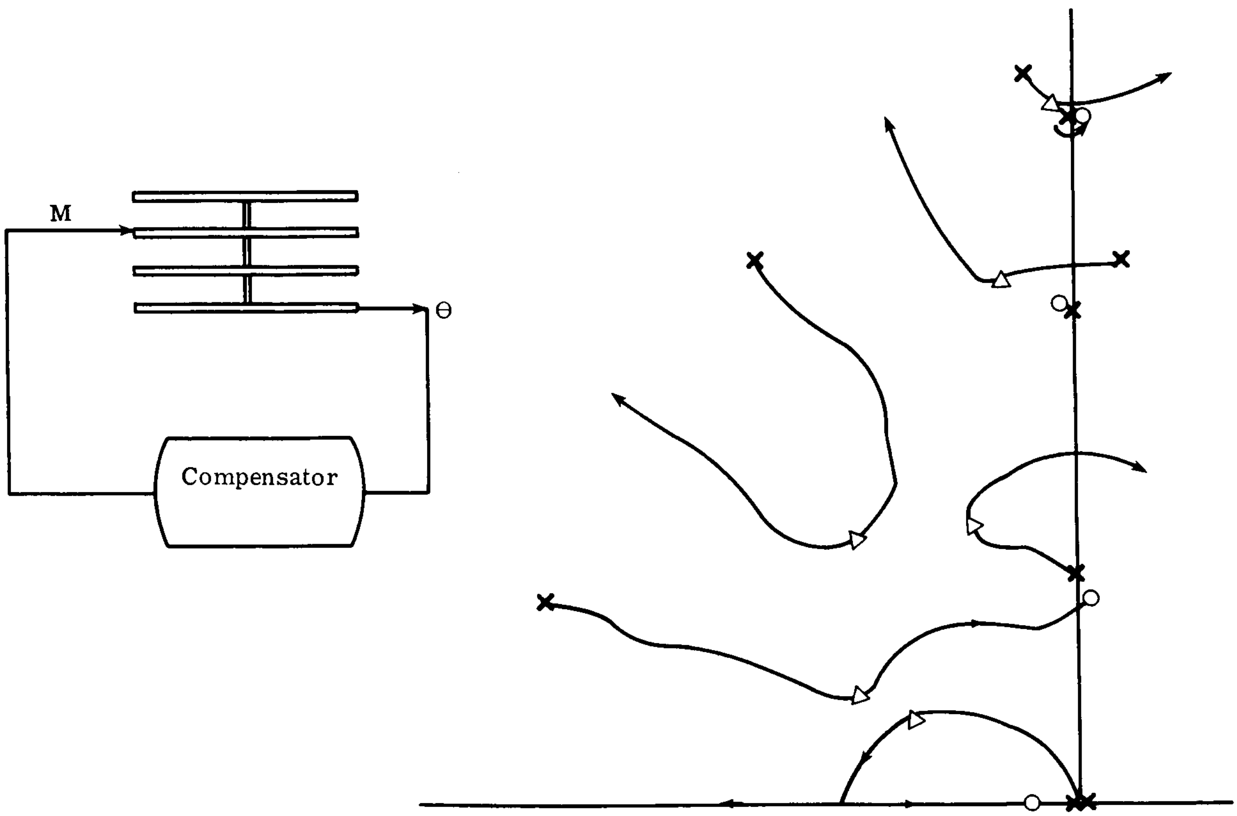

Figure 3

WHY DO WE NEED TO CONSIDER COMPONENT UNRELIABILITY?

The MIT research effort involves reliability issues for large structures. Figure 4 lists reasons that we need to consider component reliability or unreliability as the case may be. Large lightweight structures in space may need active damping because of the tradeoffs in delivering mast orbit versus the cost of providing active control. Also, to effect control of many modes for large platforms being conceived will involve many sensors and actuators, possibly hundreds of them. The next point is that, even if these systems are serviced in orbit, we would like for the service interval to be very long. It is unfortunate that the mean time between failures that can reasonably be anticipated will still dictate some means of automatic system reconfiguration because of the number of components which may fail during one year.

- A LARGE, LIGHTWEIGHT STRUCTURE IN SPACE WILL DISPLAY MANY VIBRATORY MODES WHICH MAY HAVE TO BE ACTIVELY DAMPED TO ASSURE MISSION SUCCESS.
- EFFECTIVE CONTROL OF THESE MANY MODES WILL REQUIRE USE OF A LARGE NUMBER OF SENSORS AND ACTUATORS—POSSIBLY HUNDREDS OF THEM.
- EVEN IF THESE CONTROL SYSTEMS ARE SERVICED IN ORBIT, ONE WOULD LIKE THE SERVICE INTERVAL TO BE LONG—AT LEAST ONE YEAR.
- WITH COMPONENT MEAN TIME BETWEEN FAILURES WHICH CAN REASONABLY BE ANTICIPATED, ONE MUST EXPECT MANY OF THE CONTROL SYSTEM COMPONENTS TO FAIL IN THE COURSE OF A YEAR.

Figure 4

EXPECTED NUMBER OF FAILURES PER YEAR

Figure 5 is a graph of expected number of failures which may occur in one year versus component mean time between failure. The 100,000 hour point on the graph in component mean time between failure corresponds to approximately 12 years. Note that if we have 200 components and for each we expect 12 years mean time between failure, then we can expect to have about 20 failures during the course of one year. This dictates automatic system reconfiguration to account for failures. This implies, however, that the designers of the structure consider the reliability issue and automatic reconfiguration limitations.

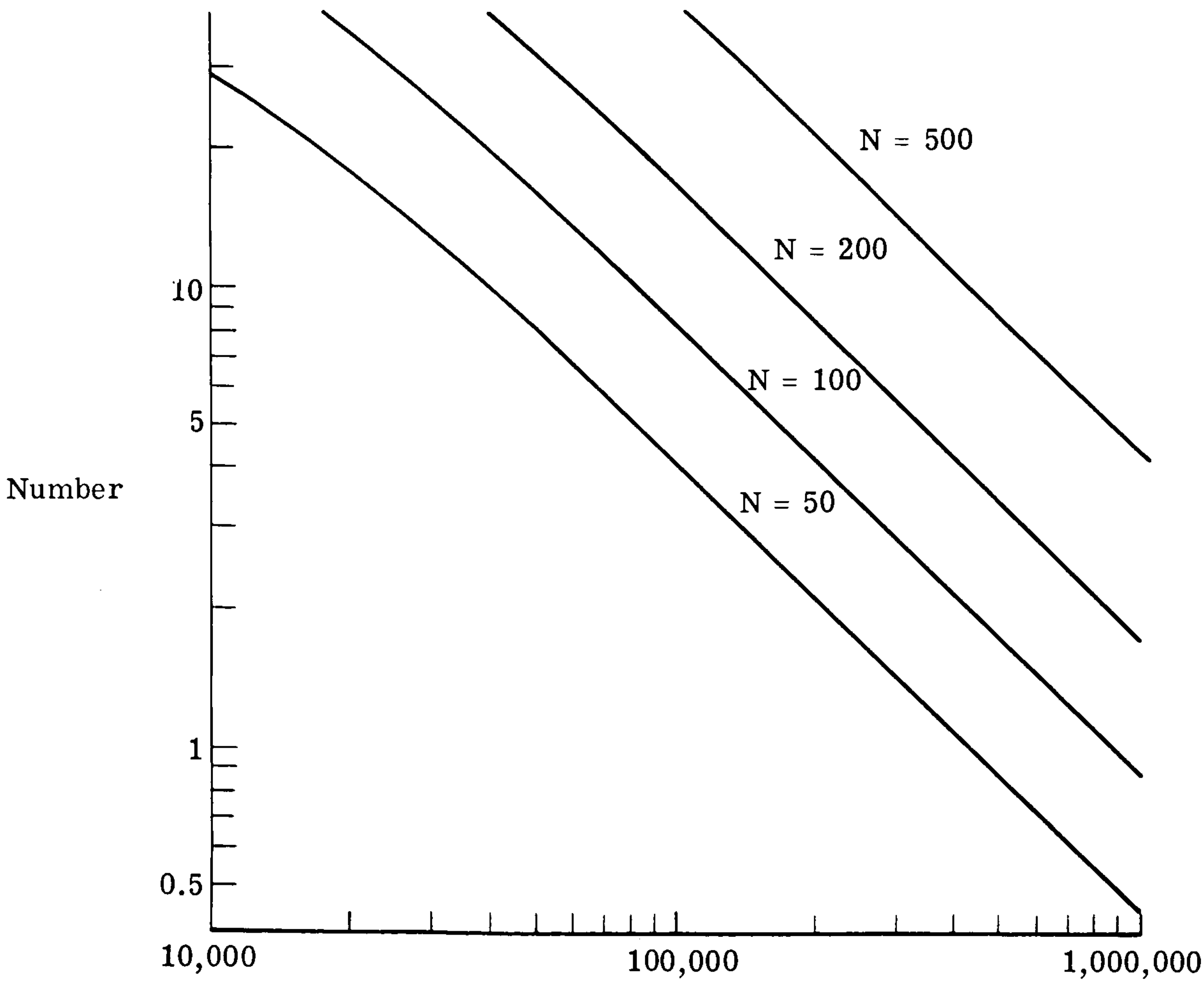

Figure 5

DETECTION FILTER

One mechanism for detecting failures has been developed at MIT which is called the failure detection filter. This filter is shown in figure 6 and is quite similar to the Kalman filter except that the system matrices are selected in order that failures be amplified. If a failure does occur, the output error on the slide readily indicates the type of failure that has occured.

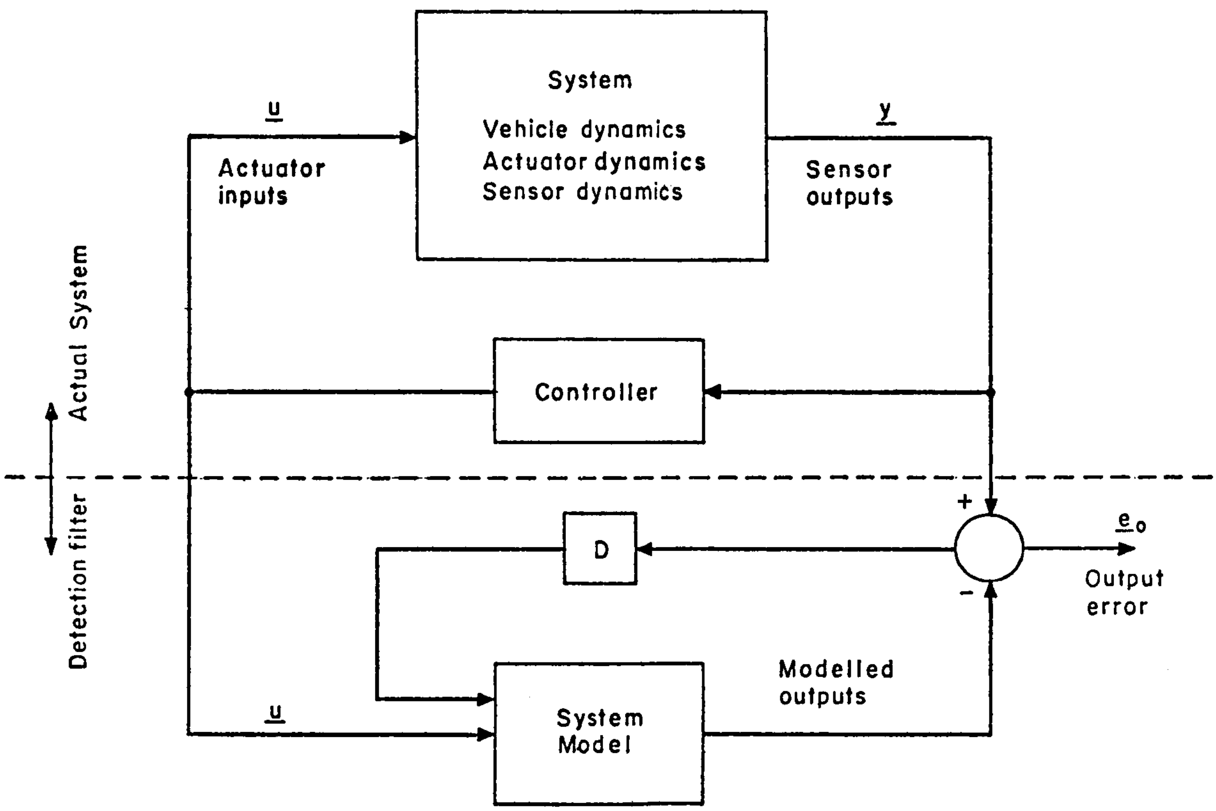

Figure 6

MLE

The Honeywell research involves determining performance measures of models for distributed parameter systems. Figure 7 summarizes the research involved. The equation which is at the top of the slide indicates the form of a model which is being considered where parameters A, B, L and C would have to be identified in real time. The model from which measurements Z were generated is called the truth model and the parameters A, B, etc., take on values which have a star on them. The model which is used in the control process, however, may use values of A, B, and C which are subscripted with an alpha. The truth model is really not known to the onboard control system and must be identified. For finite dimensional systems the truth model can be in the same class as the model stored on the computer but for distributed systems or structural dynamics systems the truth model cannot be represented by model of finite dimension. Therefore, one cannot compare, in an elementary context, the model which is used for onboard computation with the actual distributed parameter model. One breakthrough in this research allows one to obtain a measure of distance from the computational model, represented by M_α, and the truth model which is represented by M_* has been accomplished at MIT by Yoram Baram and later extended by Yared allowing one to obtain measures of modeling performance of this type of problem. The Honeywell will test these measures to determine their suitability on realistic problems involving the space shuttle coupled to a payload using the RMS arm.

$$x(k+1) = A_* x(T) + B_* u(T) + L_* \zeta(T)$$
$$Z(T) = C_* x(T) + \Theta(T)$$

TRUTH: $M_* = \{A_*, B_*, C_*, L_*, \Xi_*, \Theta_*\}$

MODEL: $M_\alpha = \{A_\alpha, B_\alpha, C_\alpha, L_\alpha, \Xi_\alpha, \Theta_\alpha\}$

GOAL: FIND MODEL M_α "CLOSEST" TO M_*.

CLOSEST = MINIMIZE THE NEGATIVE LOG LIKELIHOOD FUNCTION (COMPUTED FROM KBF FOR M_α)

Figure 7

DISTANCE MEASURE

Figure 8 is a graph of this measure of performance of a structural dynamics model versus one of the model's parameters. In this case, the true value of the parameter produces a minimum value of the measure for which one would hope. However, for using a computational algorithm to solve for the minimum value of the measure, and if we use a gradient-type algorithm, one can see that if our initial guess of estimate of parameter W_1 is two, then we will diverge from the true value of the model. This slide indicates that research is needed both in obtaining the distance measure and in obtaining the optimal estimates of the onboard computational or parameter identification process.

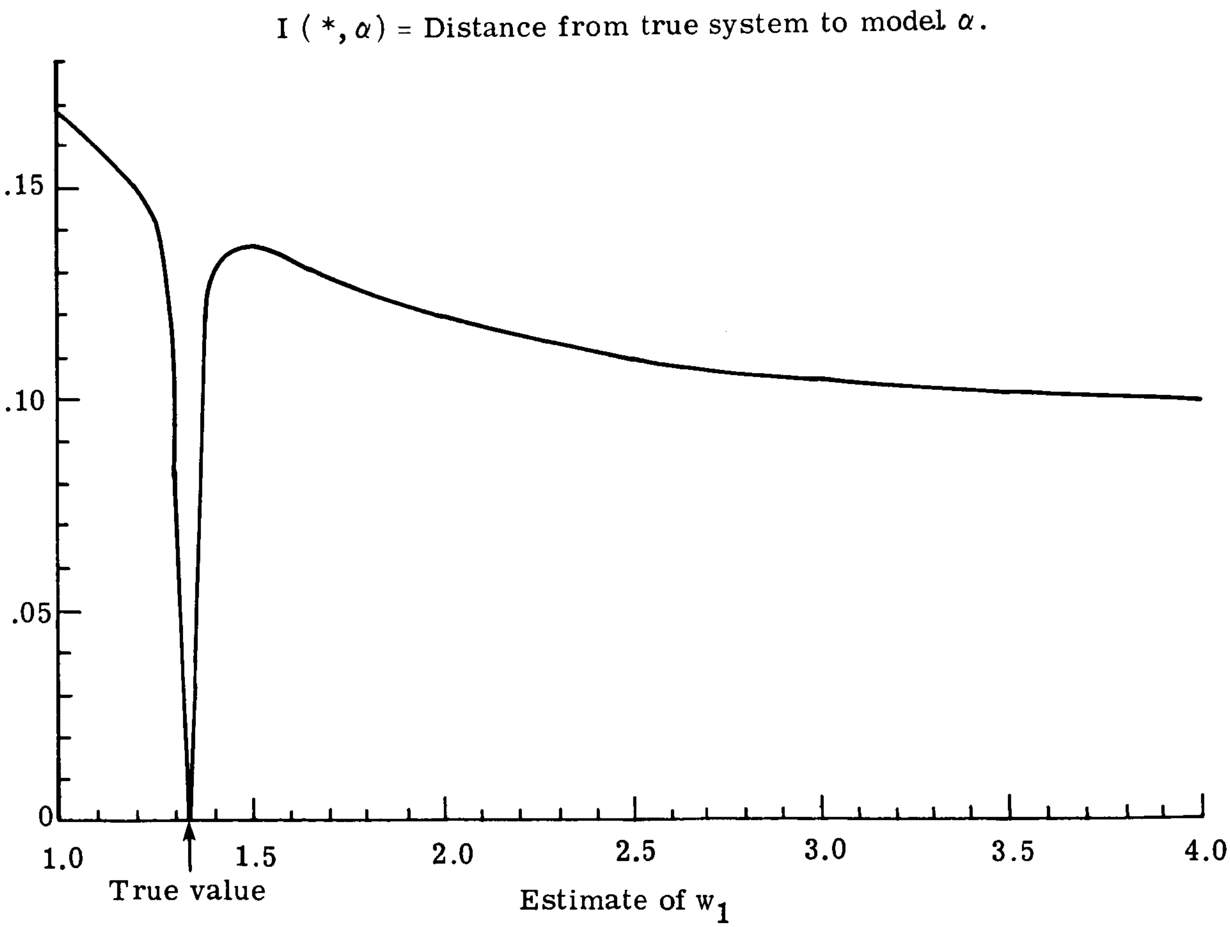

Figure 8

SEP MODELING

The next several figures will concern an area of research which is being undertaken in-house at Langley Research Center--adaptive/learning control. This effort is also being undertaken at CUNY with Prof. Frederick Thau as the principal investigator. Figure 9 shows a physical model of the solar electric propulsion array which has been modeled analytically at LaRC and NC A&T by Prof. Elias Abu-Saba using the SPAR computer program which was generated by Lockheed. The model is a full six-degree-of-freedom model which involves bending elements and axial force elements of the astromast. The SEP array will be deployed from the space shuttle orbiter from its payload bay in orbit.

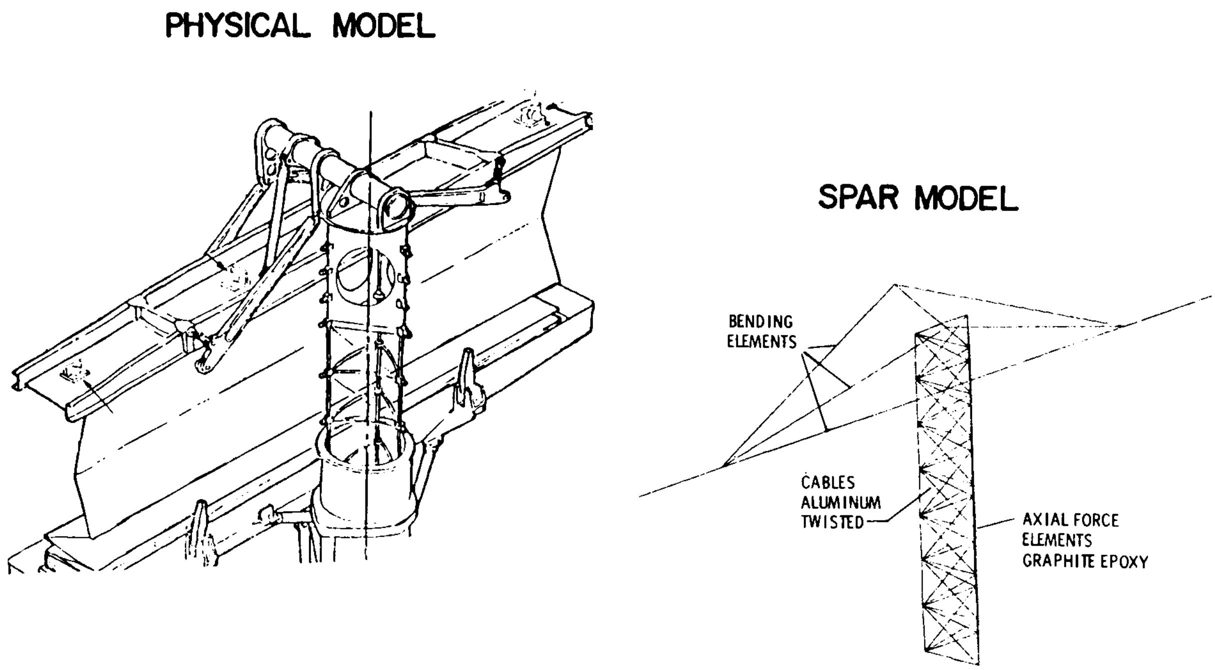

Figure 9

SEP REMOTE SENSING CONCEPT

Figure 10 shows a view of the space shuttle orbiter with the SEP array deployed. It also indicates a sensing concept which has been used in the simulation of the motion of the SEP as attached to the shuttle orbiter. The sensing concept involves targets which can be viewed by cameras mounted at the four corners of the shuttle payload bay (left side of the figure). The sensor targets are perceived by each camera and are registered in the digital computer and by triangulation, the motion of each of the sensor targets is determined.

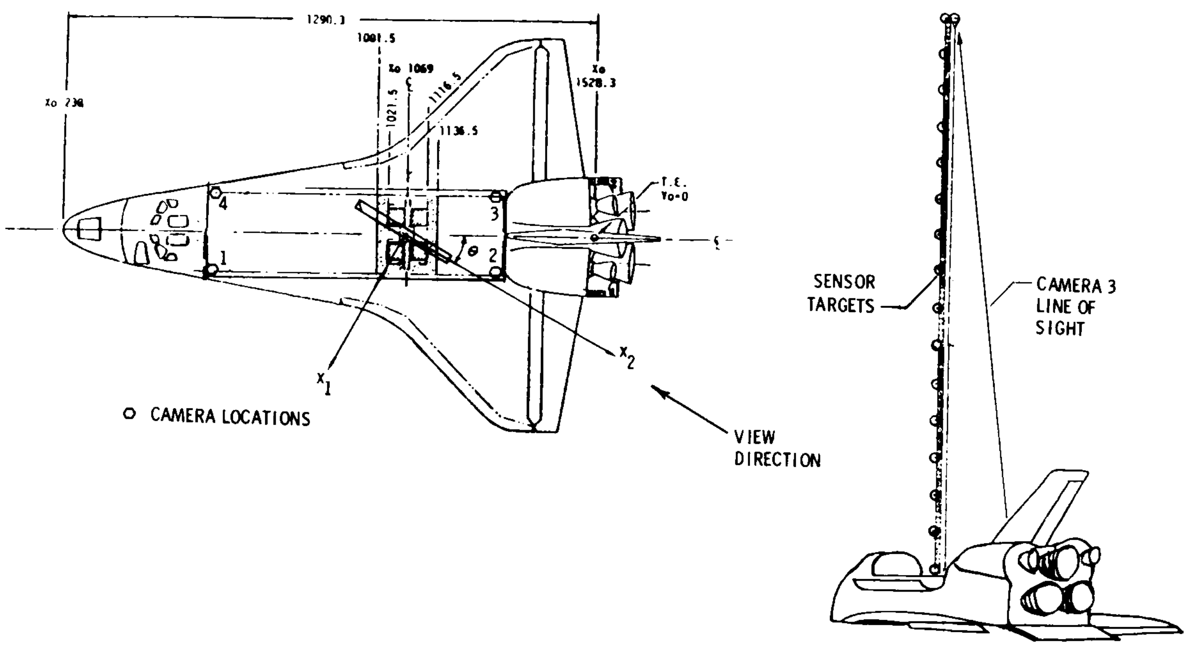

Figure 10

MEASUREMENT TIME HISTORIES

Figure 11 indicates the raster components of the motions of one of the targets located mid-way up the mast as perceived by Cameras 1 and 2. This is a 10 second batch simulation using the CYBER 175 computer system. At each instant in time, this measurement data is processed by first fitting the measurements to a set of approximation functions stored in an onboard digital flight computer. This produces a set of modal amplitudes which are then processed in parallel to identify frequency and control characteristics of modal amplitudes in real time. Thus, a bank of parallel second order identification processors, amenable to microcomputer implementation, is the main element in the system identification logic.

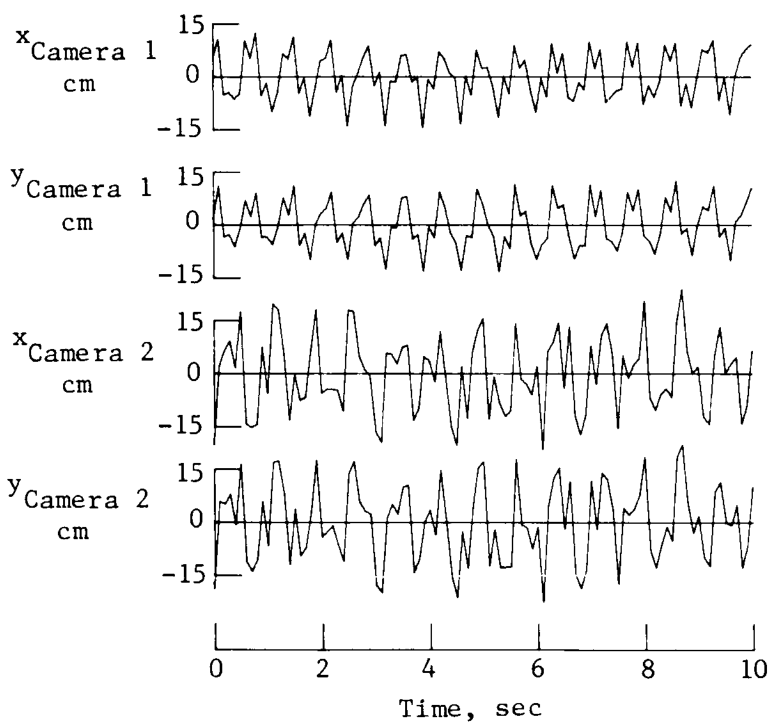

Figure 11

MODE 2 ESTIMATION AND INDENTIFICATION RESULTS

Figure 12 is the output of one element of the bank of processors for Mode 2. The top graph is the estimate of the modal amplitude of the second approximation function. The next two lower graphs on this slide are two parameters which indicate the frequency and damping of Mode 2. It is seen from the graph that convergence of the two parameters occurs in approximately one quarter of the cycle of Mode 2. The next figure will amplify on this characteristic for Mode 10.

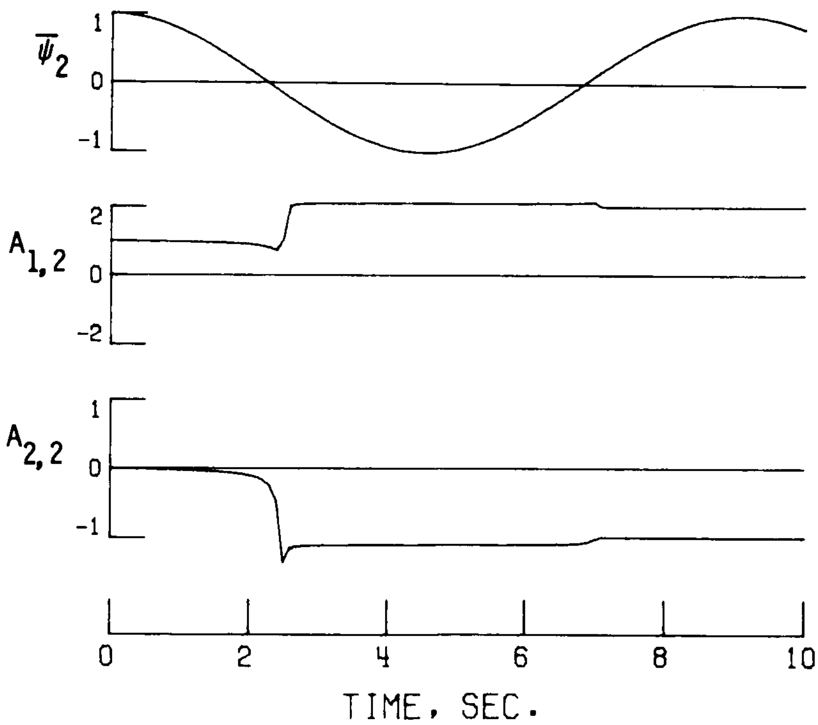

Figure 12

MODE 10 ESTIMATION AND INDENTIFICATION RESULTS

Figure 13 shows results from the processing of one processor of the parallel banks of identification processes in simulated real time. This is for the 10th mode and the upper graph shows the estimate of the modal amplitude of the 10 mode as perceived by the measurement system. The next curve is the error in the 10th mode and you can see that there is some correlated error in time for the estimate of that mode. The next lower graphs are parameters which indicate the frequency of mode 10. Convergence of the parameters A_1 and A_2 for mode 10, in the real time identification process, is seen to occur in approximately one quarter of the cycle of the amplitude of mode 10 at the top of the graph. This, however, is a perceived oscillation since the simulated flight computer is digital and samples the motion at intervals taken at 1/32 of a second. In fact, mode 10 is a very high frequency oscillation but the perceived frequency, readily apparent from the graph at the top of the page, is much lower. One of the significant outputs of the research is that the time required to identify a mode is about 1/4 the period of the perceived frequency, not the actual model frequency.

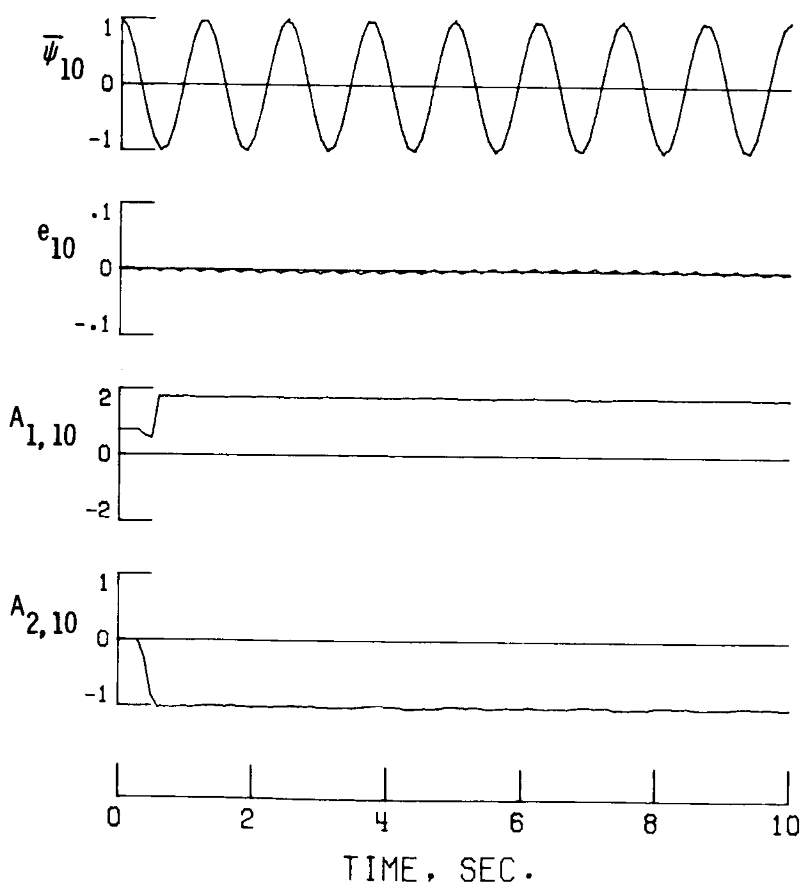

Figure 13

BEAM EXPERIMENTAL APPARATUS

The theoretical concepts which have been discussed, in addition to others, will be tested using an experimental apparatus described earlier by Dr. Horner which I will now describe in a little more detail. The experimental facility consists of a beam as shown in figure 14 where noncontacting sensors measure the deflection of the beam and piezotrons, attached to the actuator arms measure the load input to the beam. Signals from the sensors and the piezotrons are transmitted using the signal distribution system to the Cyber 175 real time digital computer system at Langley.

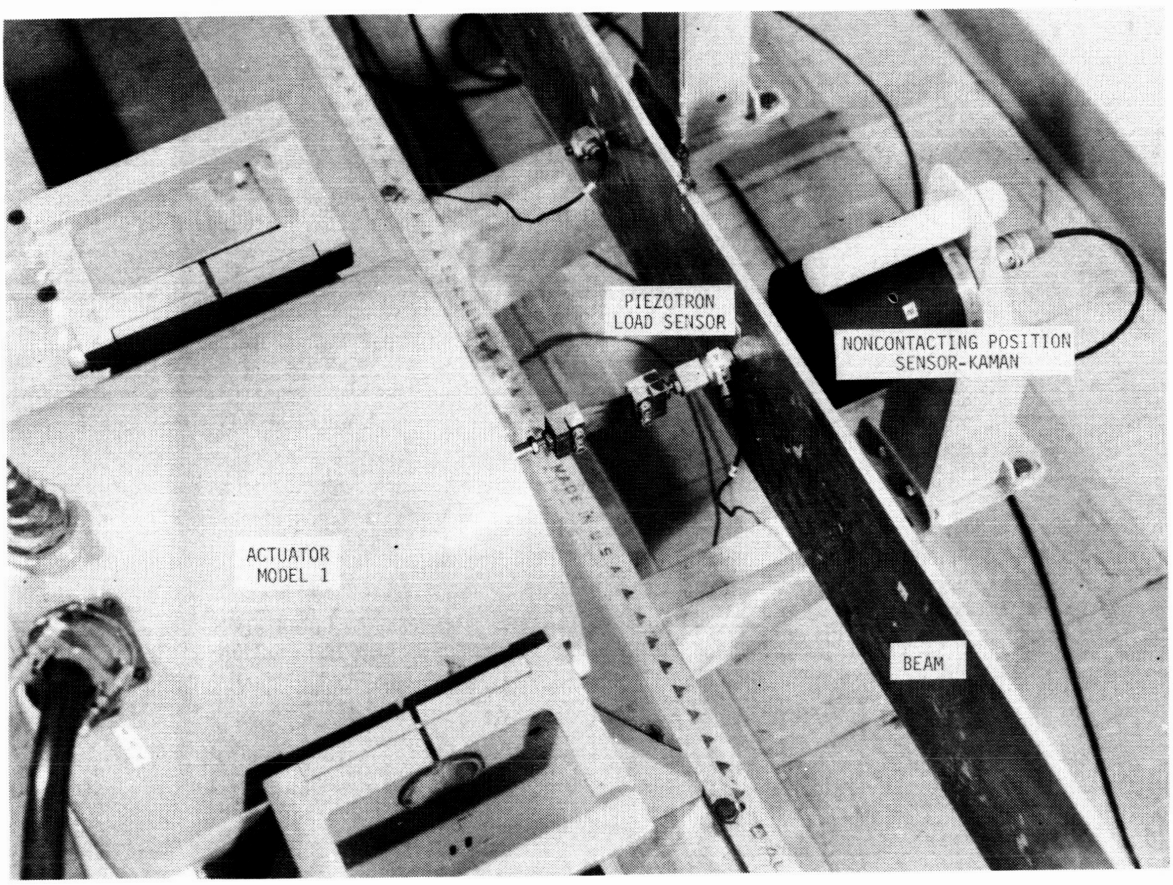

Figure 14

The real time signal distribution system is schematically indicated in figure 15. The beam experimental apparatus is located in Building 1232 and is interfaced through an EAI 690 Hybrid computer system to the main signal distribution system of this Center. The signals are then sent to DASS 1 or DASS 2 which are the digital real time interfaces for the Cyber 175 which are to be used to control the beam.

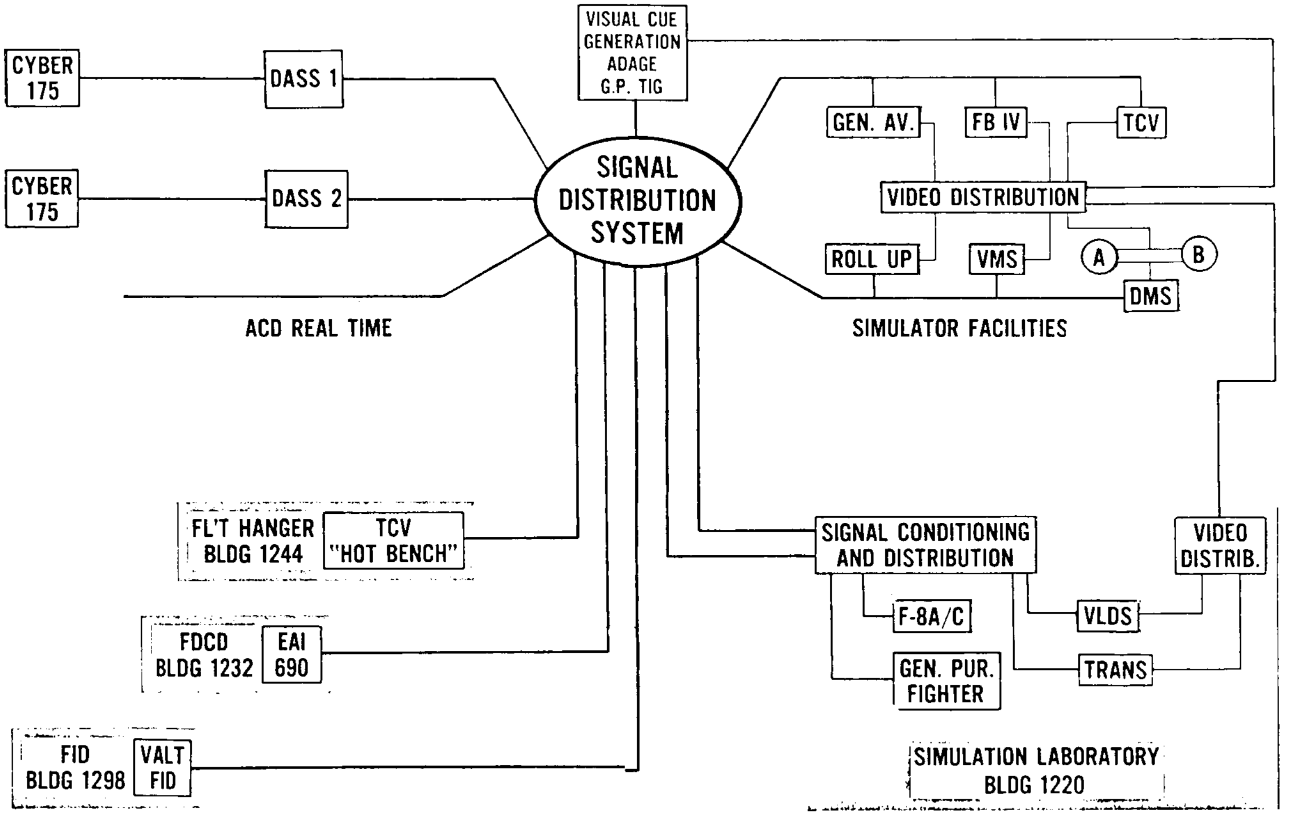

Figure 15

SIGNAL AND POWER DISTRIBUTION OVERVIEW

Figure 16 shows a diagram of the signal distribution of the experimental apparatus. The sensor outputs of the Kaman probes (noncontacting sensors) are sent through the signal buffer to the Cyber RTS interface. The Cyber computer processes the signals and determines commands to the actuators which were shown in Slide 10-L. The Pacer Hybrid interface is used for analog processing of these signals and for processing of an optical scanning sensor which will be included in the apparatus at a later time.

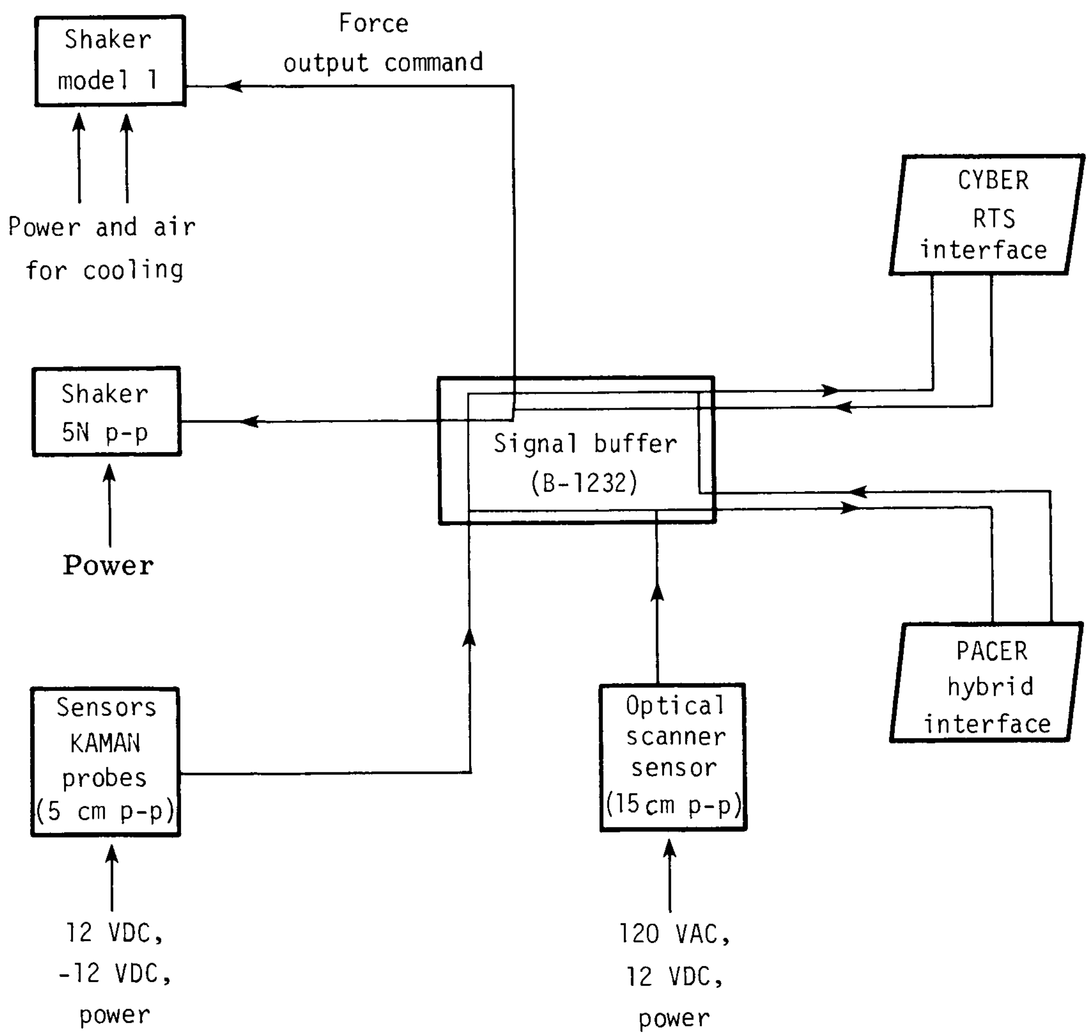

Figure 16

Figure 17 is a batch simulation of the motion of the beam. Each of the graphs is a plot of the horizontal deflection of the beam versus the beam longitudinal axis coordinate x-3. Along the abscissa of each graph is a series of arrows which indicate the locations of the actuators used in the beam apparatus. The triangles which appear on the graphs are the locations and the outputs of the Kaman probes. This particular set of graphs is the free response characteristics of the beam with an initial condition as shown at t=0. In five seconds using a 10 Mode simulation obtained from the SPAR computer program, the motion evolves as is shown in the second graph. This is continued to 10 seconds on the third and final graph. The same program which was used to generate the system identification used for the SEP array has also been used for the beam. The performance of the parallel bank of system identification modules for the beam simulation is similar to that for the SEP array. This same algorithm will be tested using the experimental apparatus when it becomes operational. The experimental apparatus will also provide the capability of studying the effects of failures in actuators and sensors. It will be used to develop and test algorithms for automatic system reconfiguration in real time parameter identification and control of structural systems. Current plans call for another structure more representative of the problems of large structural systems in space to be substituted for the beam at a later date.

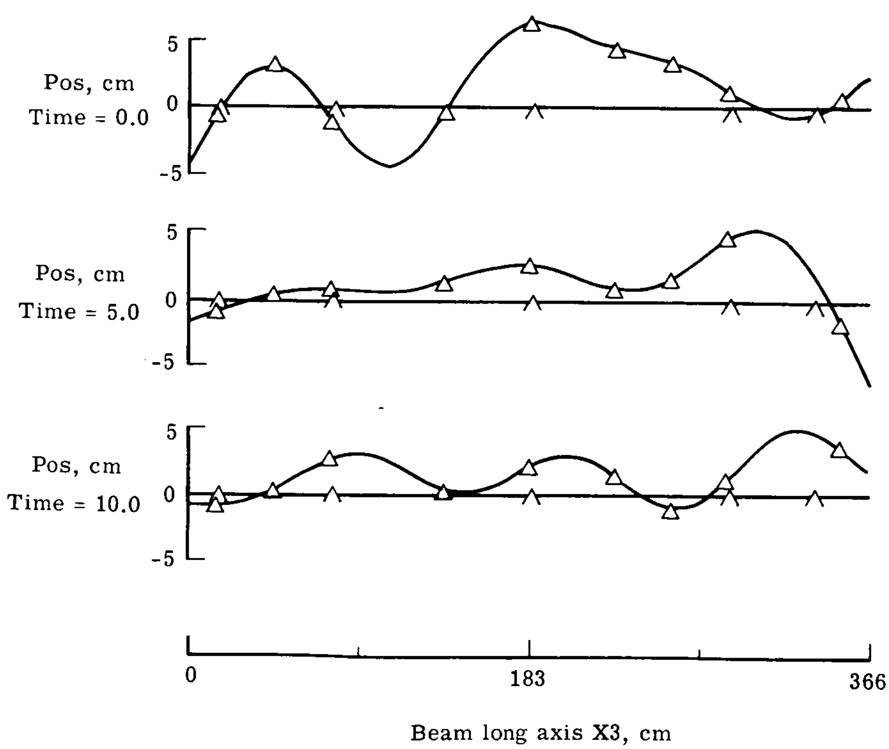

Figure 17