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SIMULATOR EVALUATION OF SYSTEM IDENTIFICATION WITH ON-LINE CONTROL LAW UPDATE FOR THE CONTROLS AND ASTROPHYSICS EXPERIMENT IN SPACE

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SIMULATOR EVALUATION OF SYSTEM IDENTIFICATION WITH ON-LINE CONTROL LAW UPDATE FOR THE CONTROLS AND ASTROPHYSICS EXPERIMENT IN SPACE

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ABSTRACT

This paper presents a procedure for optimizing the performance of large flexible spacecraft that require active vibration suppression to achieve required performance. The procedure is to conduct on-orbit testing and system identification followed by a control system design. It is applied via simulation to a spacecraft configuration currently being considered for flight test by NASA -- the Controls, Astrophysics, and Structures Experiment in Space (CASES). The system simulator is based on a NASTRAN finite-element structural model. A finite number of modes is used to represent the structural dynamics. The system simulator also includes models of the electronics, actuators, sensors (including an optical sensor that can sense deflections at locations along the CASES boom), the digital controller and the internal and external disturbances. Nonlinearities caused by quantization are included in the study to examine tolerance of the procedure to modelling errors. Disturbance and sensor noise is modeled as a gaussian process.

For system identification, the structure is excited using sinusoidal inputs at the resonant frequencies of the structure using each actuator. Mode shapes, frequencies, and damping ratios are identified from the unforced response sensor data after each excitation. Then, the excitation data is used to identify the actuator influence coefficients. The results of the individual parameter identification analyses are assembled into an aggregate system model. The control design is accomplished based only on the identified model using multi-input/output linear quadratic gaussian theory. Its performance is evaluated based on time-to-damp as compared with the uncontrolled structure.

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CASES - Controls, Astrophysics, and Structures Experiment in Space

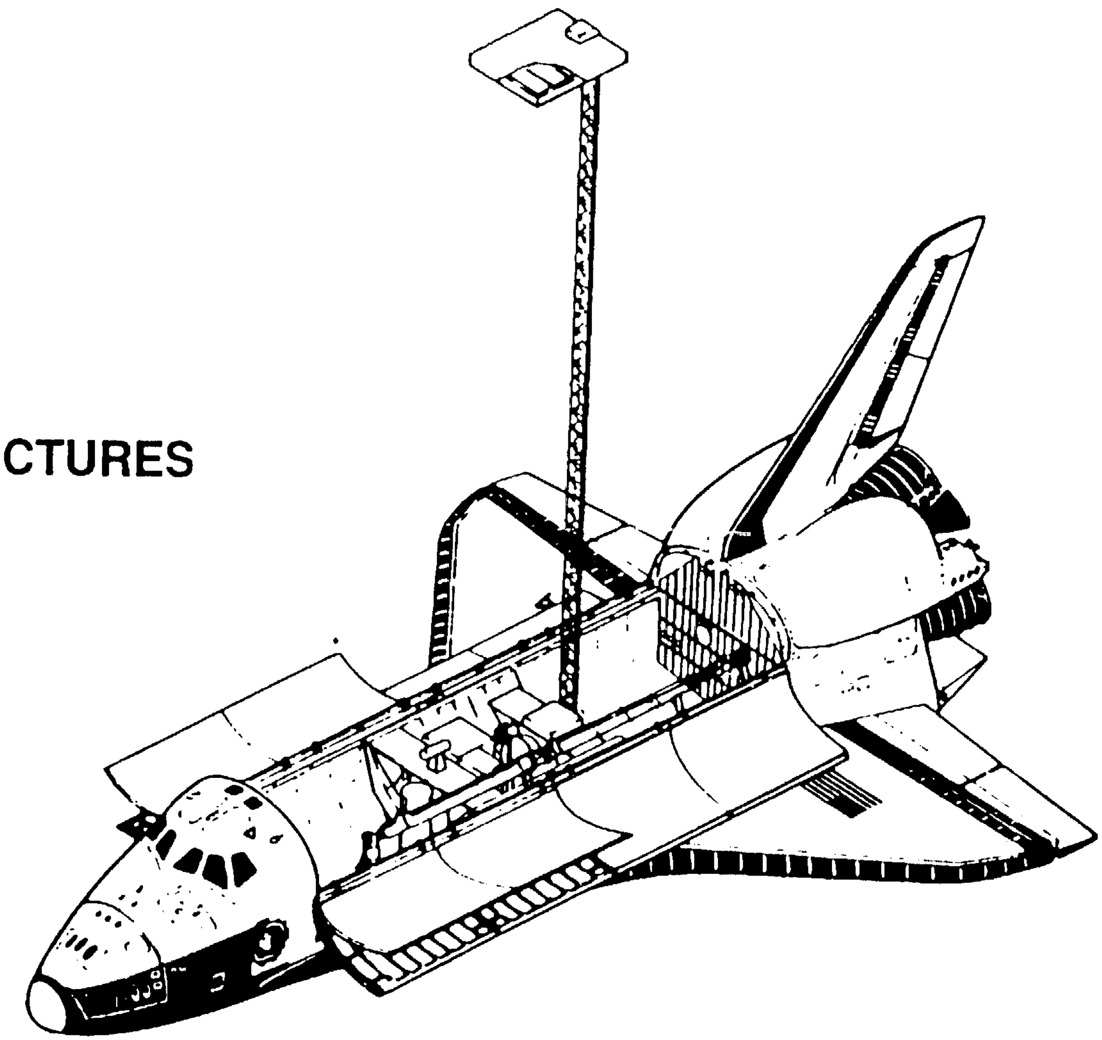
This paper presents a procedure for optimizing the performance of large flexible spacecraft that require active vibration suppression to achieve required performance. The procedure is to conduct on-orbit testing and system identification followed by a control system design. Having applied the procedure successfully to the Mini-Mast ground test article (reference 1), this paper considers application in a spacecraft currently being considered for flight test by NASA -- the Controls, Astrophysics, and Structures Experiment in Space (CASES).

CASES is a very long focal-length camera. The "film" of the camera is in the payload bay of the Space Shuttle and the "lens" is at the opposite end of the 105 ft. boom extending from the payload bay. This accommodates the astrophysics role of CASES. Relative to this role, CASES accommodates an Astrophysics/Solar Physics Hard X-Ray Imaging experiment, thereby addressing two primary science goals. The "lens" is actually a pinholed plate and the "film" is an X-ray photon counter. The goals supported by this configuration are identifying energy sources from the galactic center, and the energy release mechanisms during solar flares. Precision pointing and stability of the optical axis is required when high energy photons are counted so that image reconstruction can be made.

CASES also accommodates research in controls and structural dynamics. The structural dynamics research capability is enhanced by a Parameter Modification System which is designed to alter the mode shapes and frequencies while in orbit. Advanced control law research can be accomplished using a variety of sensors and actuators provided by CASES covered in the next chart.

CASES - CONTROLS, ASTROPHYSICS, AND STRUCTURES EXPERIMENT IN SPACE

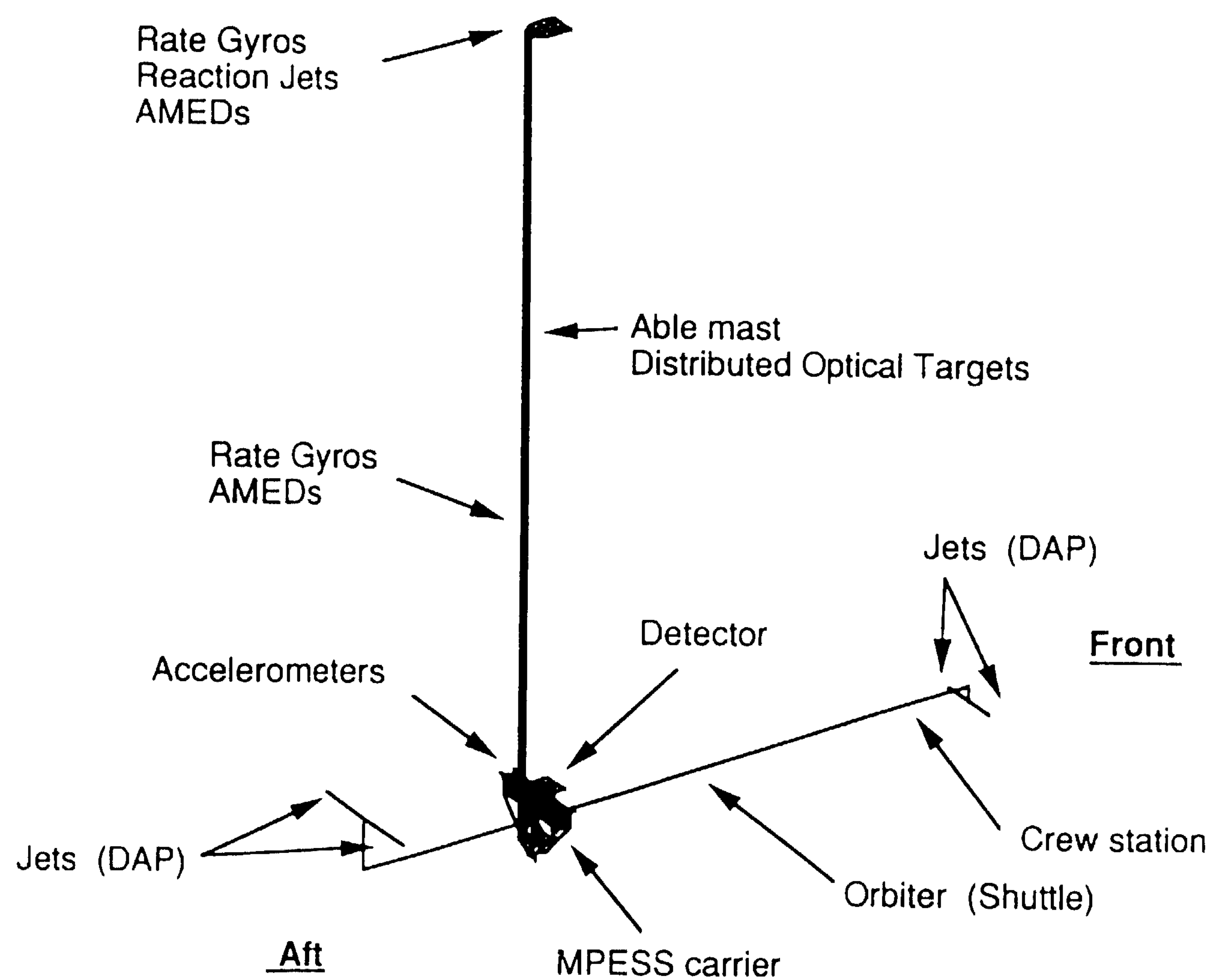
- X-RAY ASTRONOMY
- CONTROLS AND STRUCTURES EXPERIMENTS



CASES INTEGRATED FINITE-ELEMENT MODEL

A finite-element model of the on-orbit CASES configuration has been assembled from 2050 beam elements. This chart is a sketch of the model which also indicates the location and type of sensors and actuators available on CASES. The actuators include small cold gas thrusters and angular momentum exchange devices (AMEDs). AMEDs are electric motors with flywheels attached to the armatures to affect moment control. The sensors include rate gyros, accelerometers, and a novel optical sensor that detects motion of optical targets distributed along the mast.

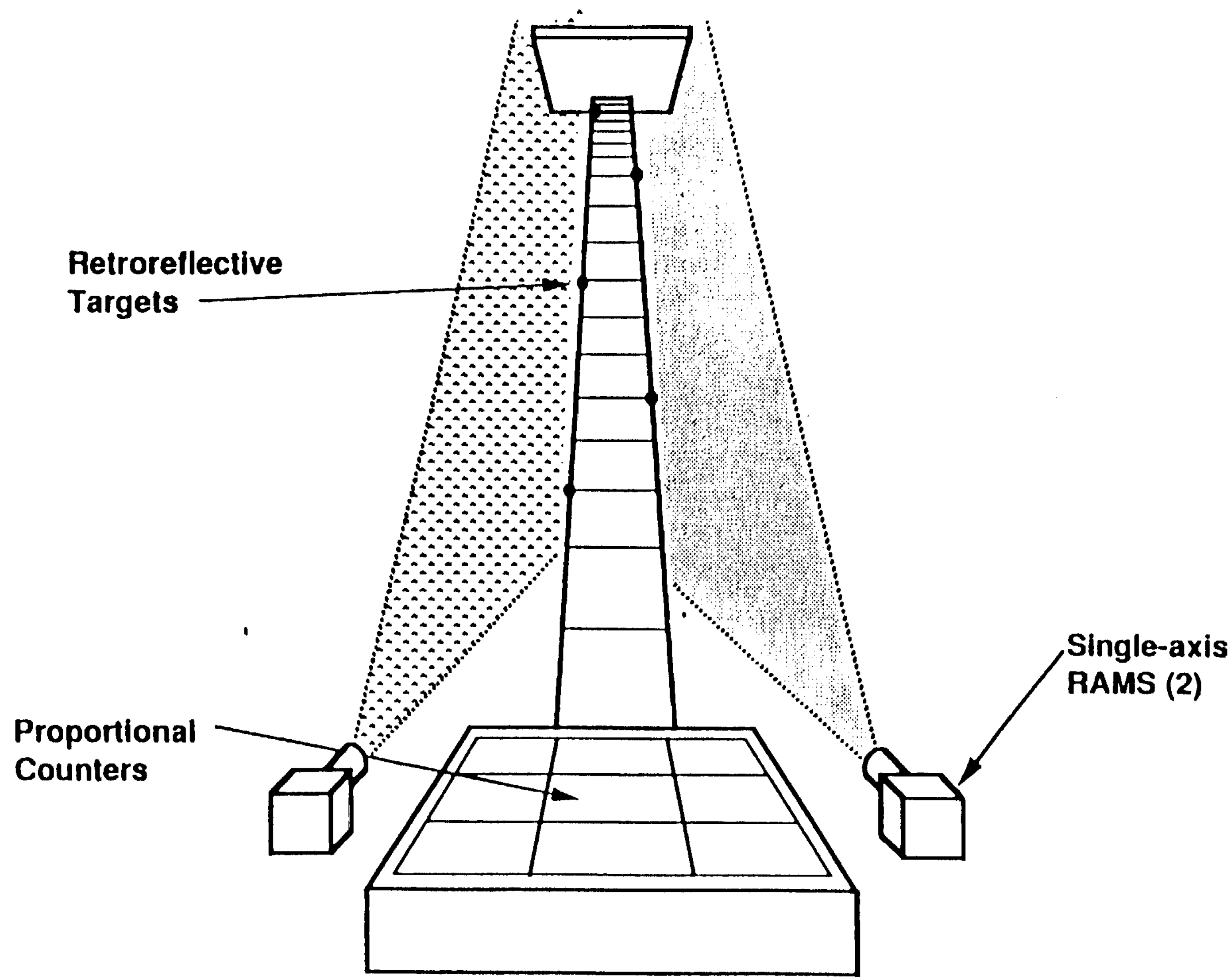
CASES INTEGRATED FINITE-ELEMENT MODEL



CONFIGURATION FOR BOOM MOTION TRACKER USING RAMS

The remote attitude measurement system (RAMS) employs a laser to illuminate retroreflective targets. The return from the laser targets is focused onto a linear CCD (charge-coupled device) array. The output of the array is processed to indicate the movement of the targets. RAMS is capable of optically sensing the motions of the boom at multiple target locations. Twenty-four targets distributed along the 102-foot boom are optically detected by the RAMS system to monitor boom motion and the tip displacement. Additionally, targets are placed on the tip-plate that allow determining the rigid-body rotation and translation of the plate. Two single-axis sensor heads on orthogonal axes at the base of the experiment platform are used to detect target motion. The discrete projections of the target images as perceived from the sensor heads are used in the control system.

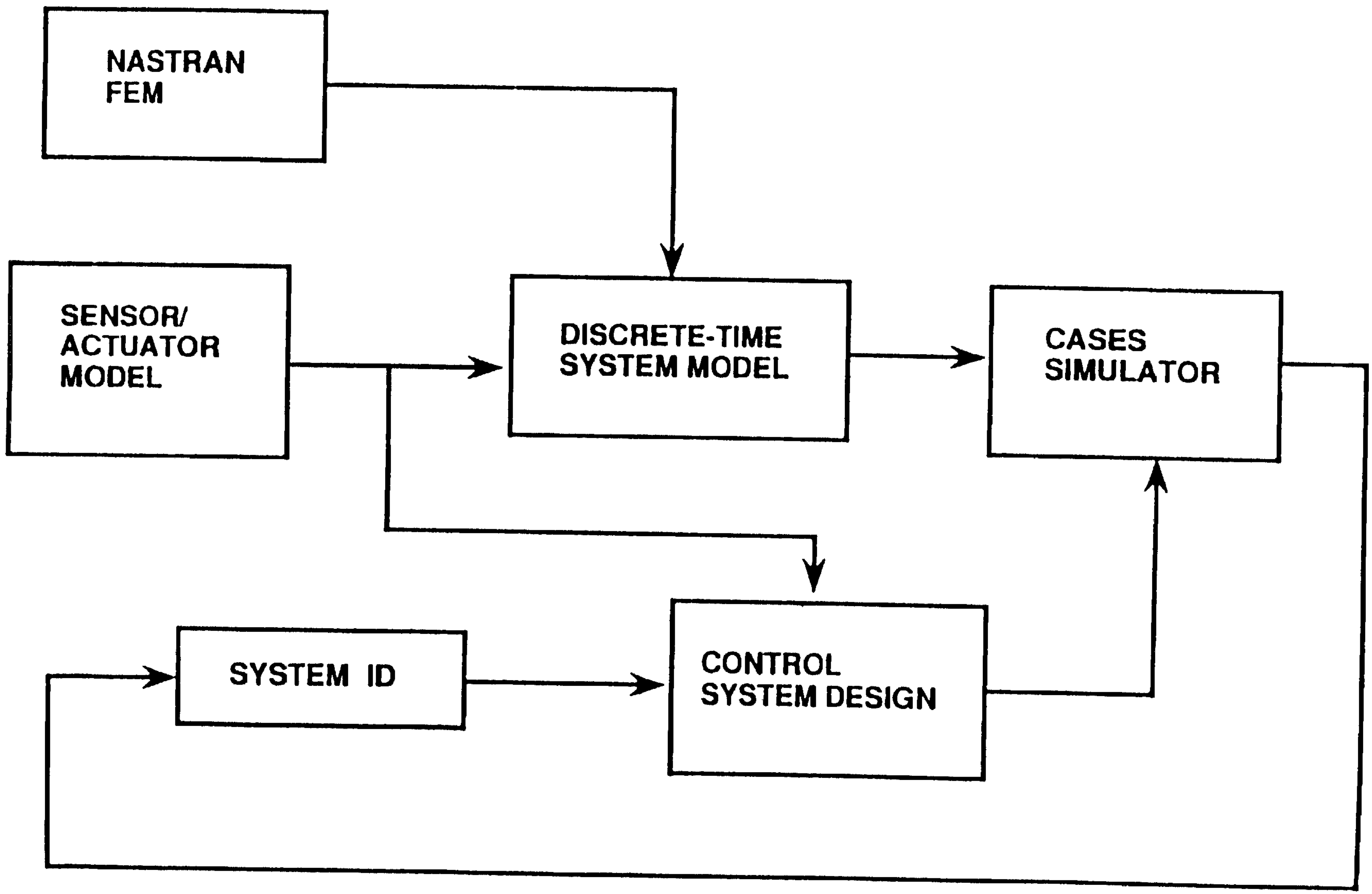
CONFIGURATION FOR BOOM MOTION (Eigenvector) TRACKER USING RAMS



SYSTEM SIMULATION

The design procedure presented in the paper is applied to the CASES configuration. This is done by developing a system simulator capable of accurately representing the on-orbit environment. NASTRAN model data is passed to a preprocessor that generates a discrete-time model of the CASES dynamics suitable for digital control. Actuator and sensor data is also input to this module. This data is also used in the control system design module along with output from the system identification conducted using simulated open-loop, on-orbit data. The discrete-time model as well as the control system design are passed on to the simulator for the closed-loop control system performance evaluation. Thus, the control system design is based only on results of the system identification and prior knowledge of the sensors and actuators (assumed obtained from bench tests and geometrical mounting data for locations of the components).

SYSTEM SIMULATION



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SIMULATOR FEATURES

The finite-element model of the CASES configuration includes 663 grid points, 2050 beam elements, and lumped masses representing the actuator and sensor components at the tip and mid boom assemblies. NASTRAN was asked for the modes with frequencies less that 10 Hz. Open-loop eigensolution analysis provided the necessary mode shapes and frequencies to build the system simulator. Based on the 40 Hz sample frequency fourteen modes were used in the simulator. The table below lists the frequencies and description of these modes (0.5 percent structural damping was assumed for each mode). In addition to the structural model, the system simulator also includes detailed models of the electronics, actuators, sensors (including RAMS) and the digital controller. Sensor noise and disturbances are modelled as Gaussian random noise. The procedure for modelling the in-situ noise characteristics of the sensors caused by uncertainty in modelling, mounting, and quantization is covered later.

TABLE - List of frequencies obtained from the FEM and used in the simulations.

Mode no.	Description	Frequency (Hertz)
1-6	Rigid Body	0
7	1st Bending Y	0.033
8	1st Bending X	0.034
9	1st Torsion Z	0.165
10	2nd Bending Y	0.431
11	2nd Bending X	0.441
12	3rd Bending Y	1.412
13	3rd Bending X	1.543
14	4th Bending Y	2.744

SIMULATOR FEATURES

FINITE ELEMENT MODEL -- 2050 ELEMENTS, MODES < 10 Hz

MODAL SIMULATION -- 6 RIGID BODY, 8 FLEX MODES

DETAILED MODEL OF OPTICAL SENSOR

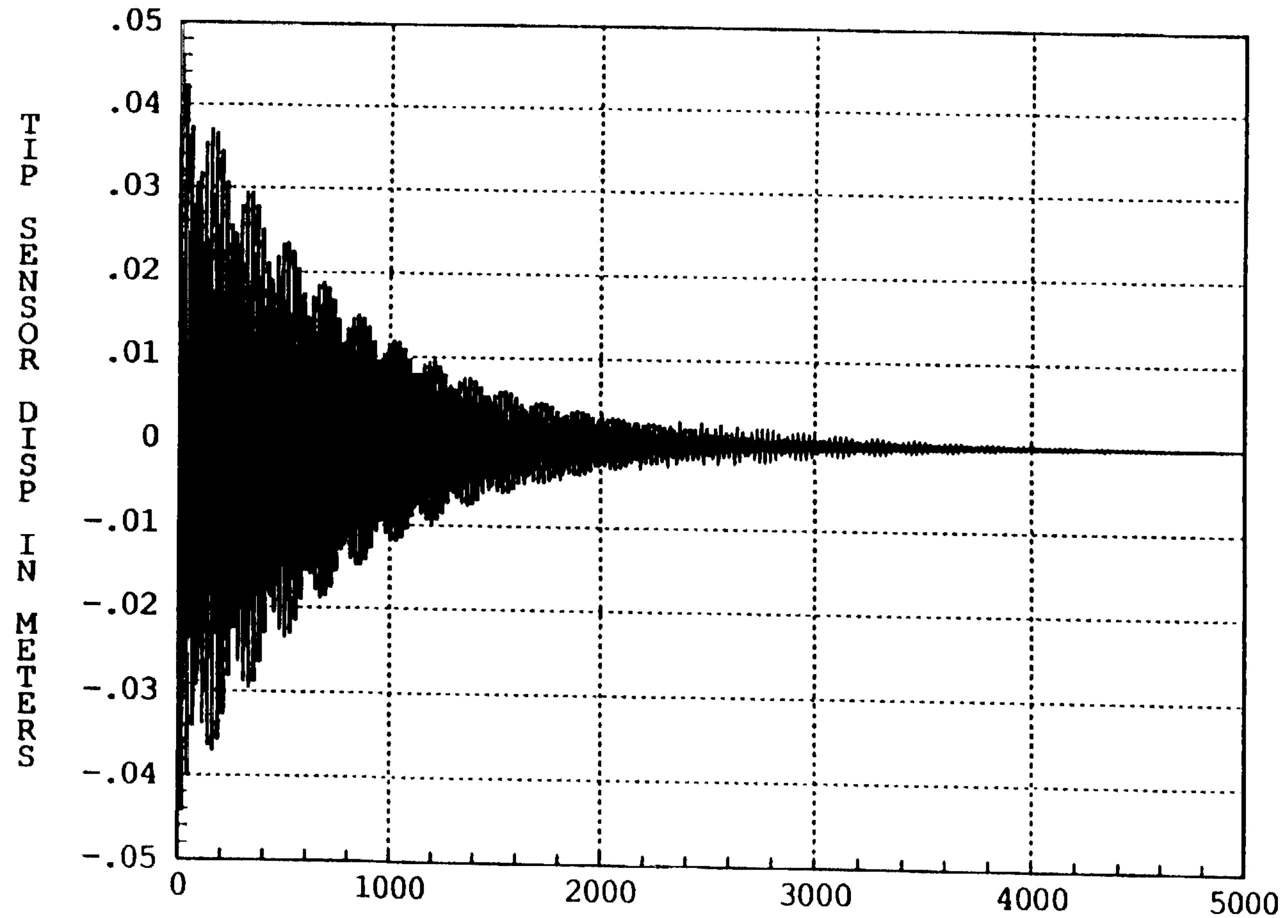
DIGITAL CONTROL AT 40 HZ SAMPLE RATES

QUANTIZATION FROM DIGITAL CONVERSION

OPEN-LOOP RESPONSE TO AN IMPULSE
1 N-SEC

The response of the system to an impulse of 1 N-sec is shown in the figure. The important characteristic is that the system does not damp to an undetectable motion for 4,000 sec and does not fall below 1 cm for over 1,000 sec.

OPEN-LOOP RESPONSE TO AN IMPULSE
1 N-SEC



TIP IMPULSE INPUT (FREE DECAY- 0.5% DAMPING)

SENSOR RANGES AND NOISE LEVELS AND ACTUATOR LIMITS

The sensor range and noise levels used in the system simulator are shown in the chart. The expected range of the sensors is determined during the excitation period of the system identification tests. Therefore, prior to assigning values for the sensor noise a complete simulation was performed to determine the peak response of the sensors to each of the SID excitation tests. To prevent sensor saturation, the expected range is defined as six times the peak of the actual response of the SID tests. Thus, the data were carefully inspected, peak displacements were identified, noise levels were determined and added to the data prior to performing system identification on the data. The three-sigma noise range levels correspond to one percent of the expected range for the inertial sensors. The optical sensor noise levels correspond to 0.1 of one percent of the expected range. The open loop excitation tests indicated the peak displacements are high near the tip of the boom. Thus, the noise levels added to the optical sensor increase near the tip of the boom.

The actuator limits were determined based on the maximum output of the components in the CASES flight experiment design. In the case of the bilinear thrusters (BLTs), their maximum force is almost equal to the static buckling limit of the boom. Here an industry standart safety factor of 2.5 was applied to the maximum commanded value of the thrust resulting in a .43 lbf limit.

SENSOR RANGES AND NOISE LEVELS

RANGE --

- ACCELEROMETERS - .012 M/S/S
- RATE GYROS - .06 1/S
- OPTICAL - .04 TO 1 M, DEPENDS ON TARGET LOCATION

NOISE LEVELS --

- ACCELEROMETERS - 3 SIGMA = 1% OF RANGE
- RATE GYROS - 3 SIGMA = 1% OF RANGE
- OPTICAL - 3 SIGMA = 0.15% OF RANGE

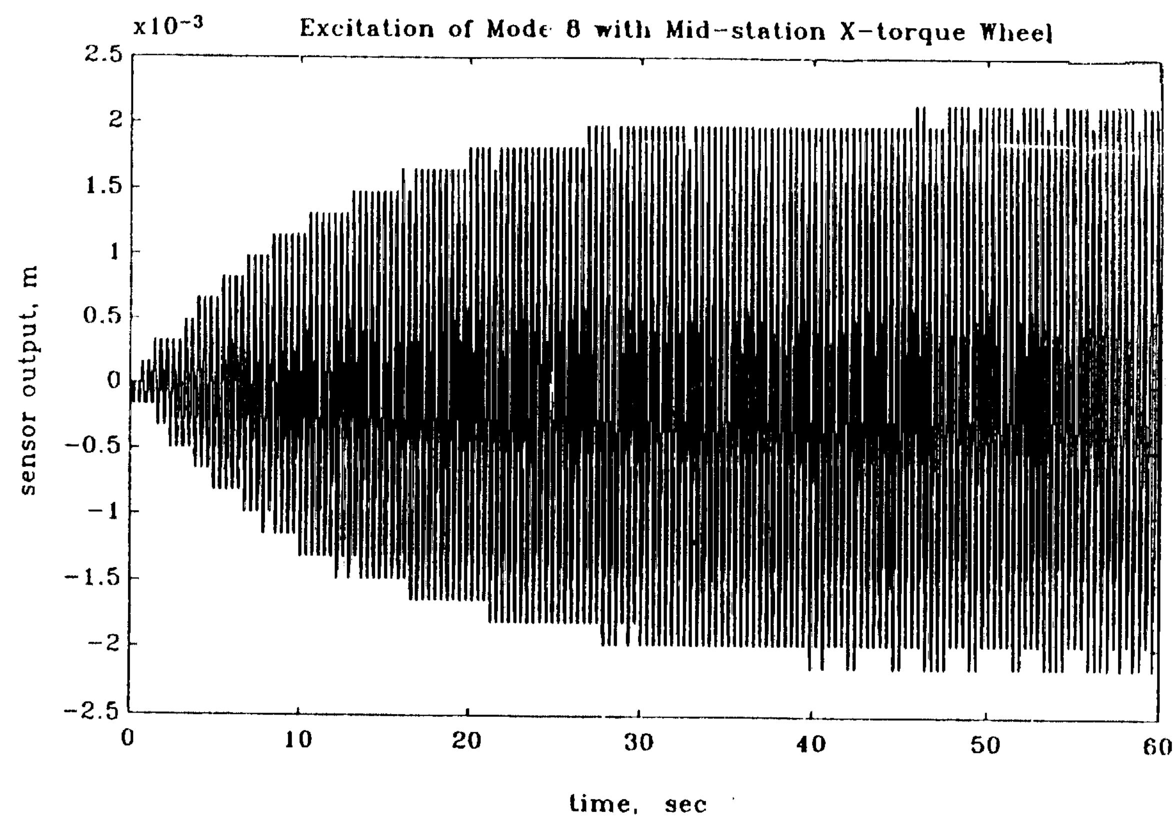
ACTUATOR LIMITS --

- AMEDS - 141.2 OZ-IN (1 N-M)
- BLTS - 1.5 LBF - SAFETY LIMIT AT .43 LBF (2 N)
  SAFETY FACTOR OF 2.5 OVER STATIC BUCKLING LOAD

EFFECTS OF QUANTIZATION
MID-BOOM DEFLECTION

This chart shows the character of the signals that resulted from application of the actuator command limits of the previous chart. Here the boom is excited with the mid-station torque wheel at the mode 8 resonant frequency. The effect of quantization in the signal is apparent by the step-like nature of the sensor output. The maximum amplitude of the signal is approximately 4 mm peak-to-peak and the quantization is approximately in .2 mm increments.

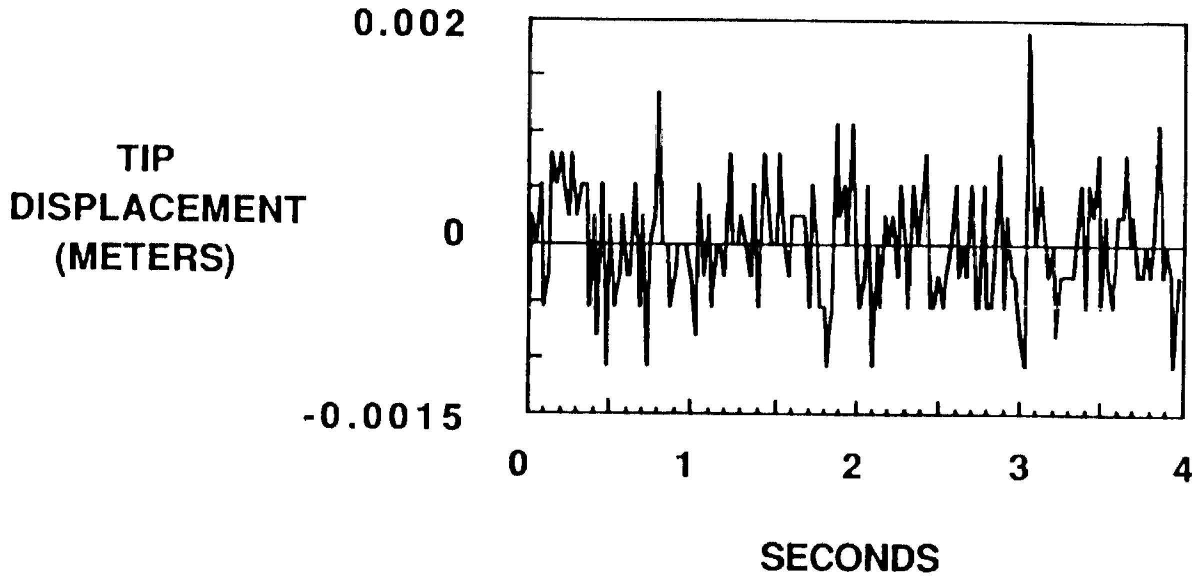
EFFECTS OF QUANTIZATION
MID-BOOM DEFLECTION



EXCITATION RESPONSE
(8th MODE)

This chart shows the first 4 seconds of the previous chart with the scale of the ordinate expanded.

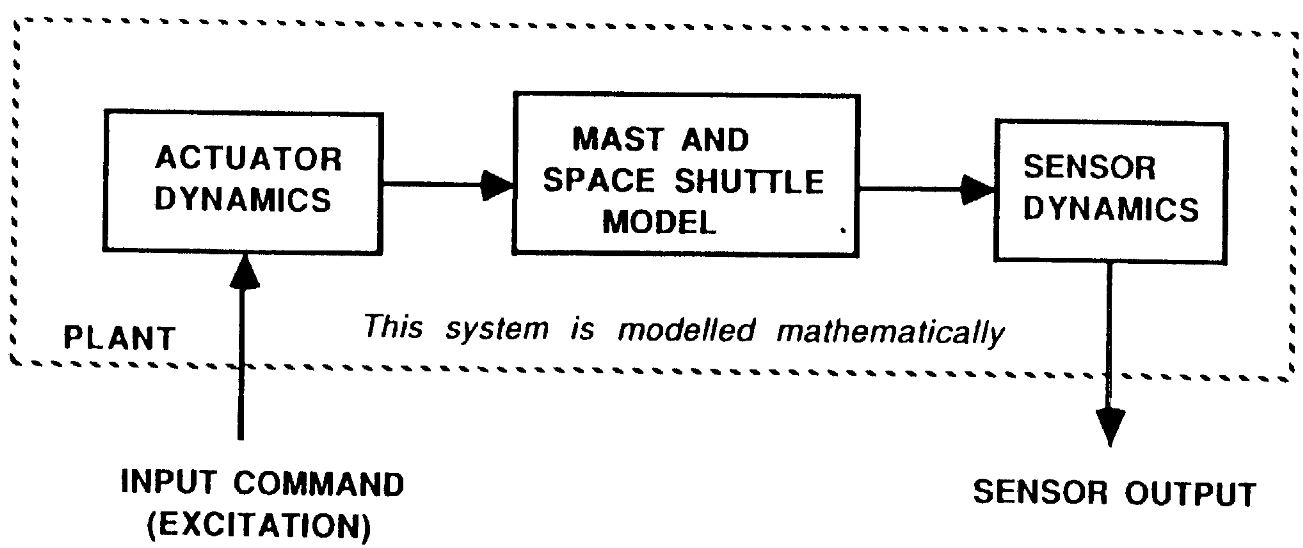
EXCITATION RESPONSE
(8^{TH} MODE)



SYSTEM IDENTIFICATION

System identification was carried out using the simulator to generate data sets as they would be generated in a flight experiment. The flight computer generated an excitation signal that is implemented by the actuators on CASES. This generates a response of the structure which gives rise signals from the CASES sensors simulated.

SYSTEM IDENTIFICATION



SYSTEM IDENTIFICATION APPROACH

An unsuccessful attempt was made to identify the mode shapes using the sine-sweep and random excitation tests. Because of actuator input limitations dictated by flight safety requirements, sine-sweep and random excitation techniques do not excite the structure sufficiently to identify mode shapes and actuator influence coefficients. However, the modal frequencies can be identified. First, ERA (reference 2) was used to determine the frequencies from a sine-sweep test. It was used again to identify the mode shapes, frequencies, and damping ratios from 28 sine-dwell tests. These tests were determined from the finite-element predictions to eliminate unnecessary data processing. In an actual flight the complete matrix of tests (number of modes by the number of actuators) would be used. The least squares method (reference 3) and a closed form solution method (the b-coefficient method, explained herein) were used on the data to determine the actuator influence coefficients. The results of the individual parameter identification analyses are then assembled into an aggregate system model for use in the control system design phase.

The actuator influence coefficients were identified using least squares estimation and a closed form solution method. Both techniques analyze single-input, single-output data. The sensor with the highest output to noise ratio was selected for determining the actuator influence coefficient for the corresponding mode-actuator combination. For the higher frequency modes, quantization effects and low levels of excitation prohibited least squares estimation from converging. For these modes the b coefficient method was used. This method is based on fitting the the envelope of the forced response curve. The equation governing the envelope for this method is

$$y(t) = \frac{b\,[1 - e^{-\zeta\omega_n t}]}{\omega_n(2\zeta\omega_n)}$$

which assumes zero initial conditions, small damping, and the presence of a single mode. The unknown b coefficient is determined from the knowledge of a sensor output y at time t. The damping coefficient ζ and the natural frequency ω_n were previously determined using ERA.

The closed form method accurately predicts the magnitude of the coefficient. However, it does not predict the sign of the coefficient. The sign is determined by examining the phase relationship of the sensor output to the excitation input. If the output lags the input by 90°, the influence coefficient is positive. If the output leads the input, the coefficient is negative.

SYSTEM IDENTIFICATION APPROACH

ACTUATOR INFLUENCE COEFFICIENTS

- SINUSOIDAL EXCITATION AT PREDICTED RESONANTES
- ALGORITHMS -- LEAST SQUARES, LOG DECREMENT, B COEF

FREQUENCY, DAMPING, AND MODE SHAPES

- FREE-DECAY FOLLOWING SINUSOIDAL EXCITATION
- ALGORITHMS -- ERA

ACTUATOR INFLUENCE COEFFICIENTS

This chart shows the actuator influence coefficients that were generated in the finite-element analysis and which were simulated (BFEM). It also shows the results of the system identification of the same parameters. The elements blocked are the best and worst case system identifcation results.

ACTUATOR INFLUENCE COEFFICIENTS

BFEM =

-0.0002	0.0000	-0.0003	0.0000	0.0000	0.0000	0.0066
0.0000	-0.0002	0.0000	-0.0003	0.0002	-0.0061	0.0000
0.0000	0.0002	0.0000	0.0002	0.0240	0.0065	0.0000
-0.0019	0.0000	0.0032	0.0000	0.0000	0.0000	-0.0022
0.0000	-0.0020	0.0000	0.0033	0.0018	0.0027	0.0000
-0.0046	0.0000	0.0170	0.0000	0.0000	0.0000	-0.0018
0.0000	0.0066	0.0000	-0.0180	-0.0021	-0.0035	0.0000
-0.0063	0.0000	-0.0164	0.0000	0.0000	0.0000	-0.0011

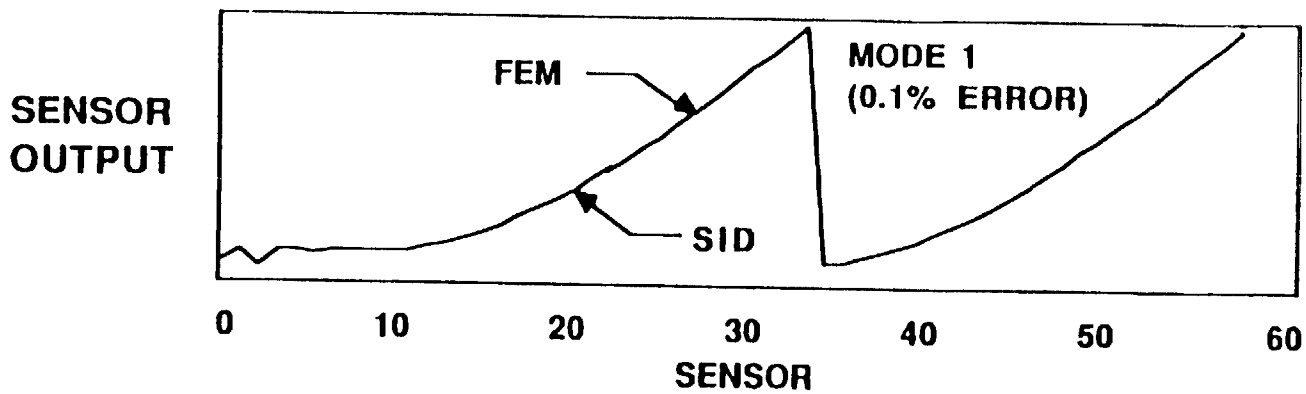
BID =

-0.0002	0.0000	-0.0003	0.0000	0.0000	0.0000	0.0072
0.0000	-0.0002	0.0000	-0.0003	0.0002	-0.0060	0.0000
0.0000	0.0002	0.0000	0.0003	0.0250	0.0067	0.0000
-0.0019	0.0000	0.0032	0.0000	0.0000	0.0000	-0.0022
0.0000	-0.0019	0.0000	0.0028	0.0016	0.0025	0.0000
-0.0045	0.0000	0.0170	0.0000	0.0000	0.0000	-0.0019
0.0000	0.0065	0.0000	-0.0174	-0.0020	-0.0034	0.0000
-0.0071	0.0000	-0.0204	0.0000	0.0000	0.0000	-0.0019

SYSTEM IDENTIFICATION RESULTS

Using ERA the mode shapes, frequency, and damping coefficients of the 8 lowest frequency flexible modes were identified. This chart tabulates results of the ERA analysis and shows a line graph of the mode 1 sensor influence coefficients plotted against sensor number. For the line graph, the first 4 sensors are rate gyros. The next 24 are laser retroreflective targets using one of the detectors and the last 24 are the retroreflective targets for the other detector. Also plotted is the finite-element simulated value of the parameter. It cannot be destinguished from the parameter identification value on this chart.

SYSTEM IDENTIFICATION RESULTS



	SYSTEM		SYSTEM IDENTIFICATION	
FLEXIBLE MODE	FREQUENCY (HZ)	DAMPING (%)	FREQUENCY (HZ)	DAMPING (%)
1	0.033	0.5	0.033	1.674
2	0.034	0.5	0.034	1.013
3	0.165	0.5	0.165	0.667
4	0.431	0.5	0.431	0.463
5	0.441	0.5	0.441	0.297
6	1.412	0.5	1.412	0.501
7	1.543	0.5	1.543	0.482
8	2.744	0.5	2.743	0.540

CONTROL DESIGN PROCESS

The vibration suppression control law is developed using the linear quadratic gaussian analytic design method (reference 4). This procedure uses a linear steady-state minimum-variance estimator to obtain the states for use in a linear fixed gain regulator. The control law chosen minimizes the time integral of weighted squared disturbance and applied control signals. The weighting matrix for the disturbance is the identity matrix divided by the frequency squared. The weighting matrix for the control input is the identity matrix.

CONTROL DESIGN PROCESS

SENSORS ⟶ ESTIMATOR ⟶ CONTROL LAW ⟶ ACTUATOR COMMAND

CRITERIA : ESTIMATION - MINIMUM VARIANCE

CONTROL LAW - MINIMIZE THE TIME INTEGRAL OF WEIGHTED SQUARED DISTURBANCE AND APPLIED CONTROL SIGNALS.

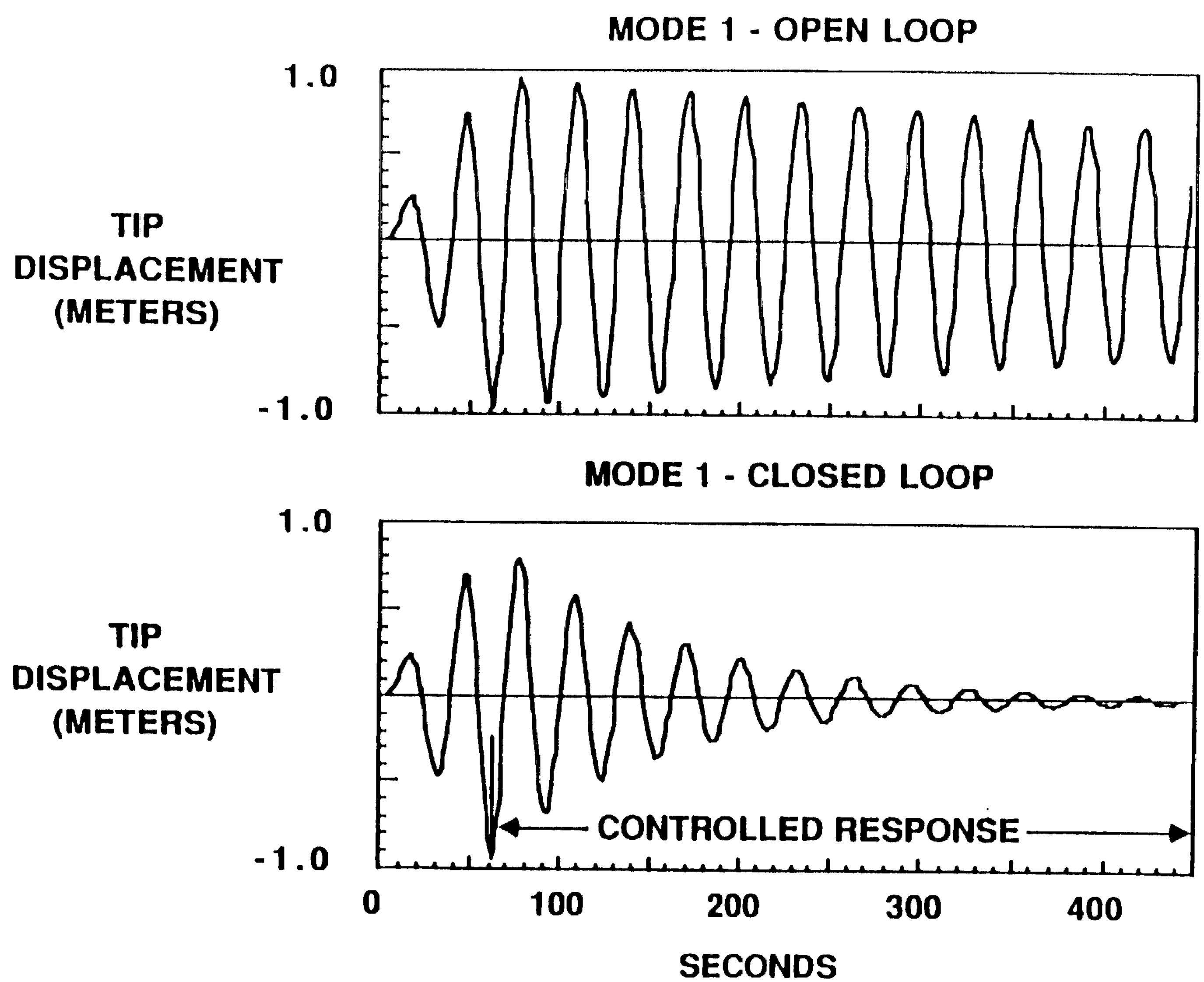
DESIGN USES

- 8 LOWEST FREQUENCY VIBRATION MODES
- 2 JETS (1 NEWTON)
  5 TORQUE WHEELS (1 N-M)
- 24 LASER TARGETS
  5 RATE GYROS
  3 ACCELEROMETERS

CLOSED-LOOP PERFORMANCE

The closed loop performance of CASES was evaluated with the results of the system identification information. An updated regulator and state estimator based on the SID results was obtained. This chart shows the tip displacement (in meters) of the CASES mast due to sinusoidal excitation (using the tip thruster) at the first resonant frequency of the structure. The upper graph shows the forced response for the first 60 seconds and free decay response after 60 seconds. The lower graph shows the forced response to the same input disturbance with the controlled response after 60 seconds. The open-loop system (0.5 percent damping) takes approximately 10 times longer to achieve the same level of damped response as the closed-loop system (5 percent damping).

CLOSED LOOP PERFORMANCE



CONCLUDING REMARKS

A procedure has been presented for the on-orbit design of a control system for flexible space structures. This procedure has been successfully implemented in a CASES flight experiment simulation. Results indicate that system identification will be difficult but can be done. The actuator influence coefficients are difficult to obtain with the levels of actuator force allowed. With current actuator force levels, 5 percent damping can be added to the system.

CONCLUDING REMARKS

- SYSTEM IDENTIFICATION WILL BE DIFFICULT BUT CAN BE DONE
- 5% DAMPING CAN BE ACHIEVED WITH CURRENT ACTUATOR FORCE LEVELS

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