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DISTRIBUTED CONTROL FOR COFS I

R. C. Montgomery
NASA Langley Research Center

Jeff Sulla
PRC Kentron

D. K. Lindner
VPI & SU

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PRESENTATION OUTLINE

This paper presents an overview of the work being done at NASA LaRC on developing the COFS-I Flight Experiment Baseline Control Law. This control law is currently evolving to a generic control system software package designed to support many, but not all, guest investigators. A system simulator is also described. It is currently being developed for COFS-I and will be used to develop the Baseline Control Law and to evaluate guest investigator control schemes. It will be available for use whether or not control schemes fall into the category of the Baseline Control Law.

First, the hardware configuration for control experiments will be described. This is followed by a description of the simulation software. Open-loop sinusoidal excitation time histories are next presented both with and without a local controller for the Linear DC Motor (LDCM) actuators currently planned for the flight. The generic control law follows and algorithm processing requirements are cited for a nominal case of interest. Finally, a closed-loop simulation study is presented, and the state of the work is summarized in the concluding remarks.

INTRODUCTION

HARDWARE CONFIGURATION FOR CONTROL

COFS I REAL-TIME SIMULATOR

OPEN-LOOP EXCITATION OF MAST USING THE TIP ACTUATORS WITH/WITHOUT LOCAL CONTROLLER

GENERIC LINEAR CONTROL ALGORITHM

ALGORITHM PROCESSING REQUIREMENTS

CLOSED-LOOP SIMULATION STUDIES WITH COLLOCATED RATE FEEDBACK

CONCLUDING REMARKS

Figure 1

COFS I REFERENCE LOCATIONS

For control experiment purposes, the COFS-I hardware consists of the space shuttle, a 60-meter statically determinant truss beam, and a tip assembly. The configuration of the experiment is shown in figure 2. Only the hardware of interest in a control system experiment is listed. The truss beam, called the MAST, has 54 sections called bays. The bays are numbered outward from the shuttle, bay 1 being nearest.

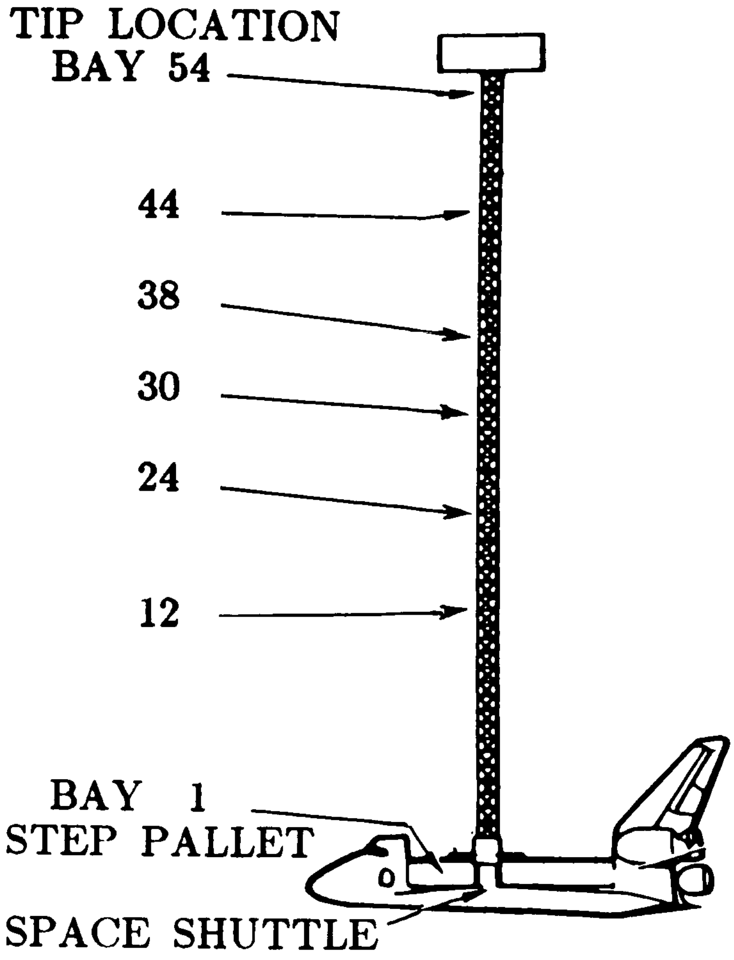

Figure 2

CONTROL SYSTEM COMPONENTS

Control law processing will be done with a digital computer located on the STEP pallet. Sensors are provided at the tip, at the STEP pallet and at five interior MAST stations - bays 12, 24, 30, 38, and 44. The types of sensor equipment provided are rate gyros and linear and angular accelerometers. The only type of actuator provided is the LDCM actuator. LDCM's are located at the tip and at three interior MAST stations. The LDCM's at the interior stations are smaller than the ones at the tip but are of the same type.

TIP LOCATION	3 RATE GYROS 3 LINEAR ACCELEROMETERS 4 LARGE LDCM ACTUATORS
BAYS 44, 30, AND 12	2 LINEAR ACCELEROMETERS 1 ANGULAR ACCELERMETER 2 SMALL LDCM ACTUATORS
BAYS 38 AND 24	3 LINEAR ACCELEROMETERS 1 ANGULAR ACCELEROMETER
STEP PALLET	3 LINEAR ACCELEROMETERS 3 RATE GYROS CONTROL SYSTEM COMPUTER 150 HZ UPDATE RATE

Figure 3

FLIGHT COMPUTER SYSTEM

The flight computer is located on the STEP pallet and communicates with it through a serial input/output data channel. The STEP pallet provides power for the MAST flight systems and also data recording. High-speed data transmission is available from the MAST flight system to the STEP pallet. All communications from the STEP pallet to the MAST flight system are through the Modular Distributed Information Subsystem, MDIS, which functions to send commands to and receive data from the Actuator/Sensor network via the MIL-STD 1553B data bus. The MDIS also interfaces with the Excitation and Damping Subsystem, EDS, which processes the control algorithms.

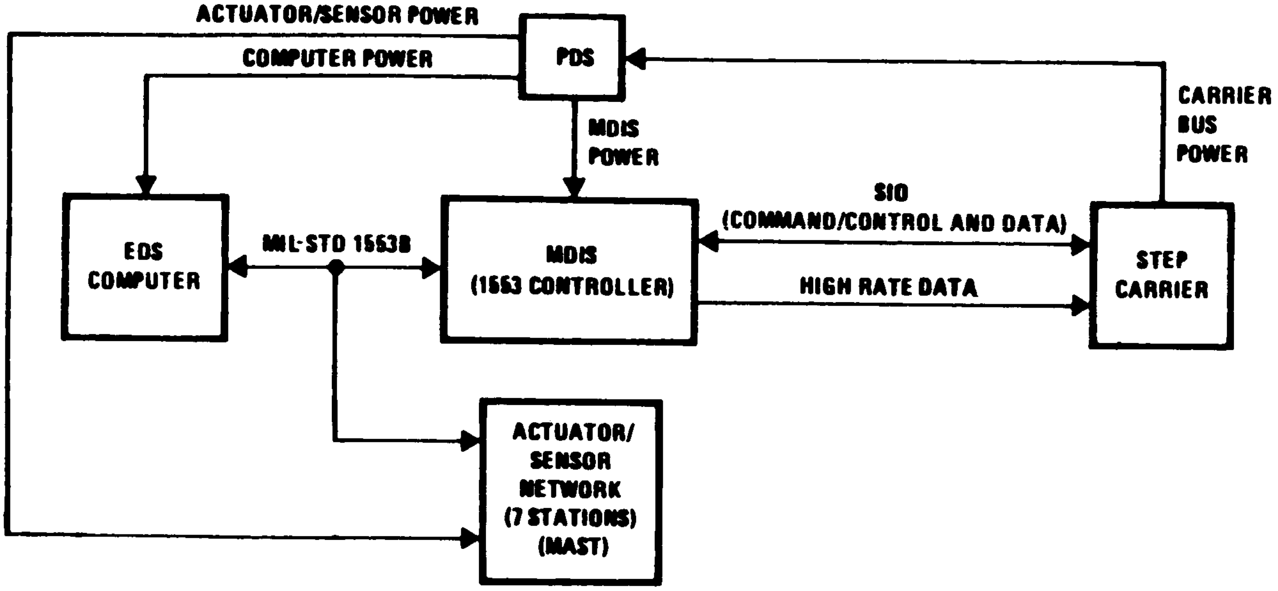

Figure 4

ALGORITHM TIMING REQUIREMENTS

The sample rate of the system is 150 samples/sec. This allows 6667 microseconds between samples. Because of projected system overheads and other necessary functions, only 5033 microseconds can be counted on for algorithm processing.

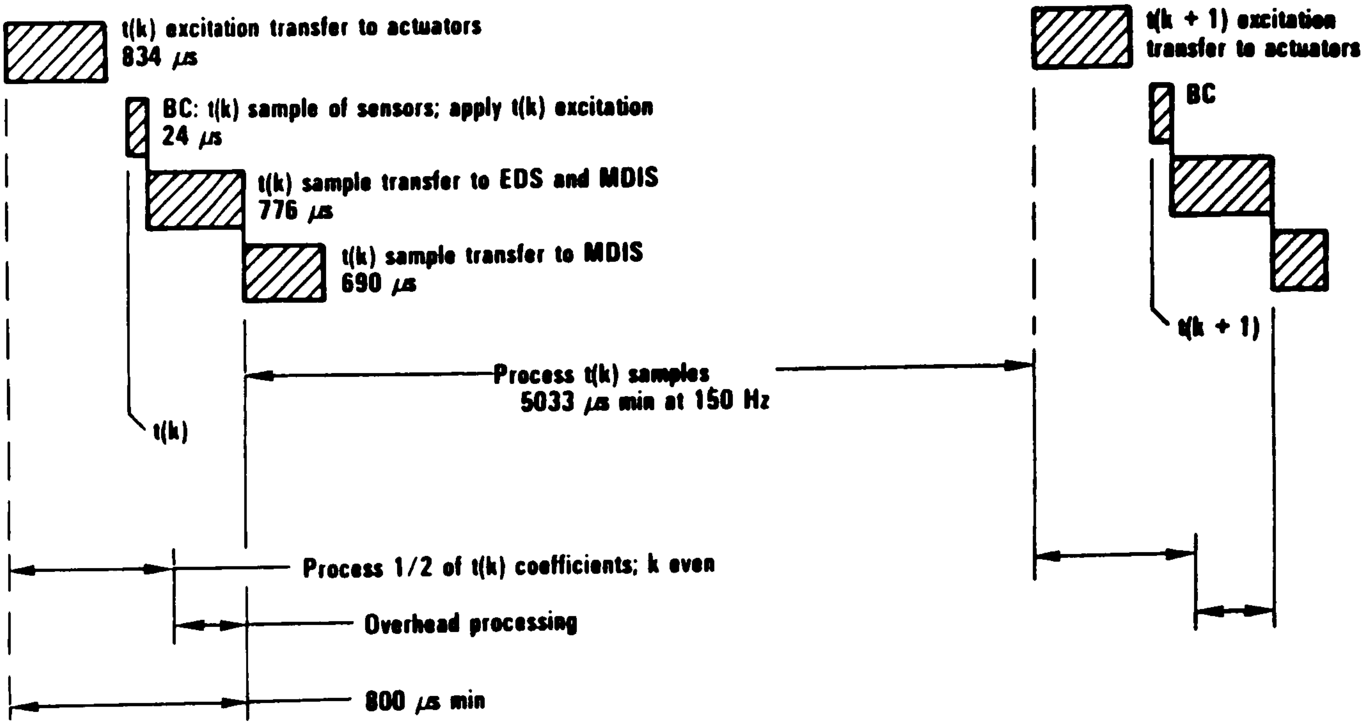

Figure 5

LDCM ACTUATOR

The LDCM actuators are currently being designed, thus, only a shetch is available. The Stator contains electrical wire windings and is hard mounted to the MAST tip. The Moving Mass contains permanent magnets and can traverse finite limits relative to the Stator. Relative force is generated between the Stator and a Moving Mass by passing electrical current through windings of the Stator, thus, moving both the Stator and the Moving Mass.

Because of travel limits, the Moving Mass is not able to store energy as would more conventional devices such as torque wheels or CMG's. Its position must at all times be a foremost consideration of the control algorithm since bi-directional control is lost at extremes. This complication is in addition to saturation which is normally considered by control analysts. At high frequencies, saturation limits the force output, but at low frequencies, force commands must be limited because of travel limits. A local controller can be designed whose frequency response is shaped according to these limits at frequencies of interest. This will somewhat alleviate the problem, but does not allow the control algorithm to ignore position management of the Moving Mass.

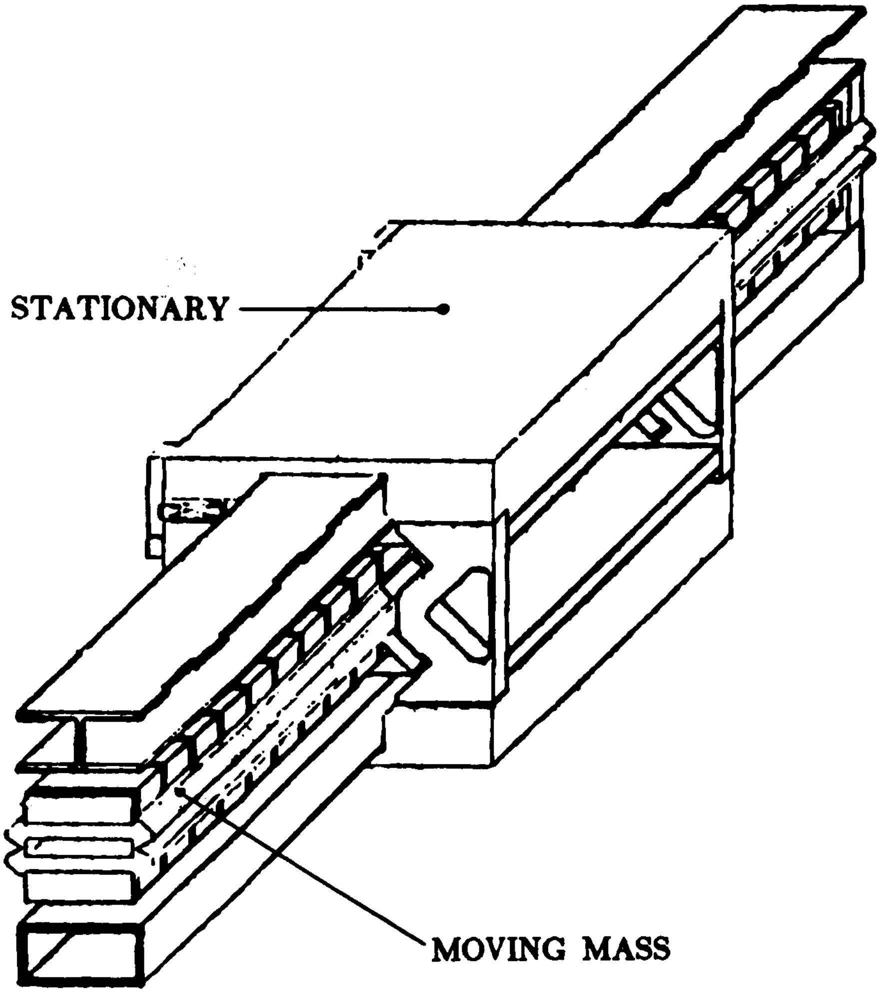

Figure 6

LOCAL CONTROLLER

Because of the problems cited concerning the use of the LDCM's, a local controller is being considered. The control computer sends commands to this controller which, based on sensor inputs from a Stator-mounted accelerometer and a sensor that measures relative position of the Moving Mass to the Stator, generates a current signal for the Stator windings.

The schematic below describes one scheme currently being considered for the local controller. Current command from the local controller is converted into a relative force, F, through a linear gain. Any nonlinearities in the conversion are modelled by f. The relative force is applied to the moving mass and in the opposite direction to the structure through transfer function Q(s). Q(s) includes the dynamics of the space shuttle, MAST, and Stator. The accelerometers mounted to the Stator respond to the MAST motion with transfer function A(s). The accelerometer output with error is twice integrated in the local controller to generate an estimate of the position of the Stator. Each integration is accomplished by transfer function I(s) which is stabilized. The sum of the estimated Stator and relative position signals is an estimate of the inertial position of the moving mass. Thus, the primary feedback of the local controller is the estimated inertial position of the moving mass.

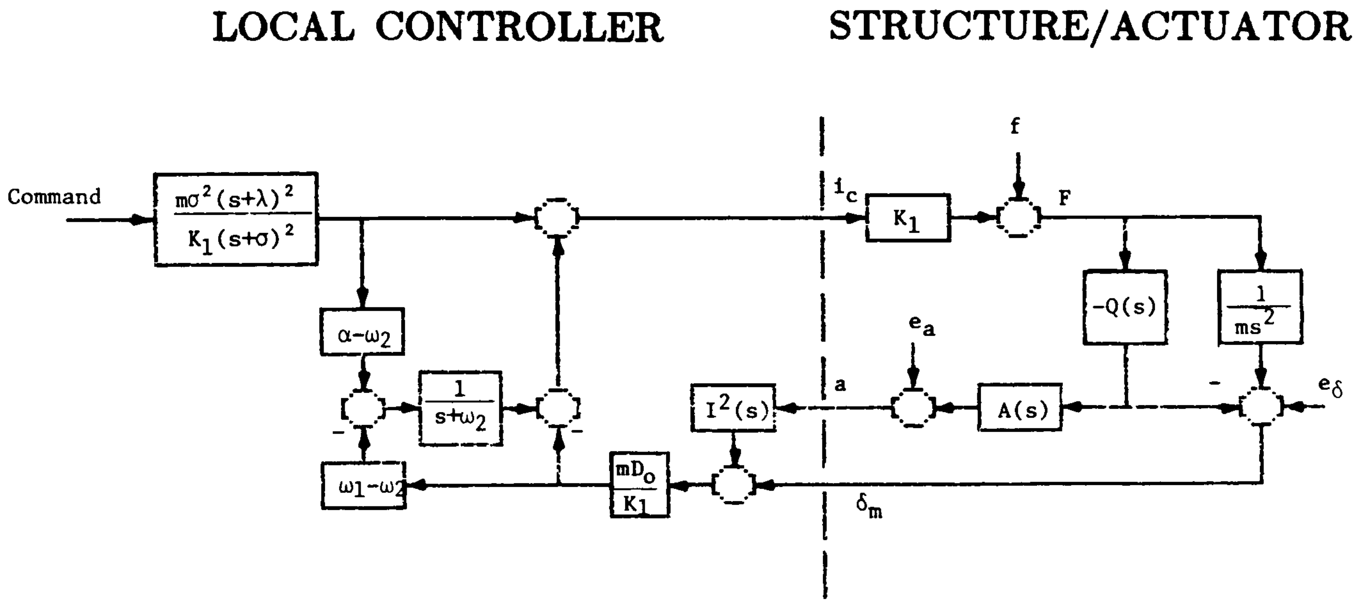

Figure 7

MODEL AND SIMULATOR

Ground tests for COFS will involve the MAST flight system, a 20-meter truss beam of similar construction called MINI-MAST, and a pendulum suspended shuttle, truss beam, and antenna apparatus called SCOLE (in support of COFS II). The ground test activities are expected to play an important role in evaluation of the guest investigator control laws for flight. A simulator has been developed for the MAST flight system and is under development for the MINI-MAST and ground test systems. For the flight system, the physical apparatus — the space shuttle, the MAST, sensor and actuators were modelled using finite element analysis techniques. The output of the finite element analysis is a set of mode shapes and frequencies that are used by the system real-time simulator resident on the LaRC CYBER 175 simulation system. The control computer is functionally simulated assuming an update rate of 150 Hz. The detailed bit manipulation, computation, and communications required by the flight system are not simulated. The number of modes used in a simulation is a variable and is typically 15 (including the 6 rigid-body modes of the system).

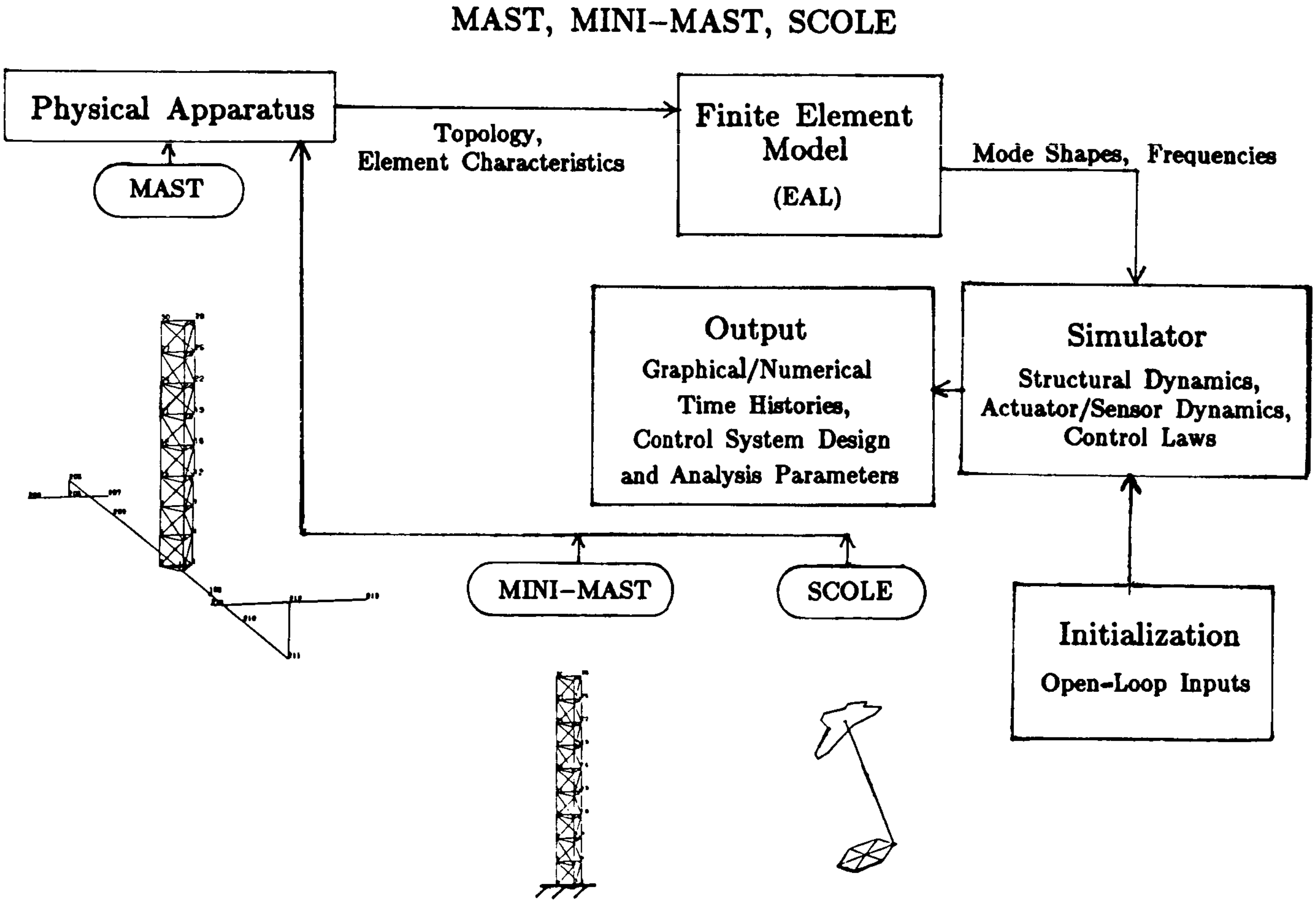

Figure 8

EFFECTS OF LOCAL CONTROLLER FIRST BENDING FREQUENCY

Figure 9 is time histories of the MAST flight system in response to sinusoidal input commands to the LDCM's to excite the first bending mode of the MAST in the direction normal to the plane of symmetry of the space shuttle. On the left are the responses using direct current command to the LDCM's. This set illustrates one fundamental problem — that the relative position of the Moving Mass continually drifts to one side. When the same simulation is conducted with the local controller engaged, the result is shown on the right. Here, the local controller corrects the drift and produces a zero steady-state response.

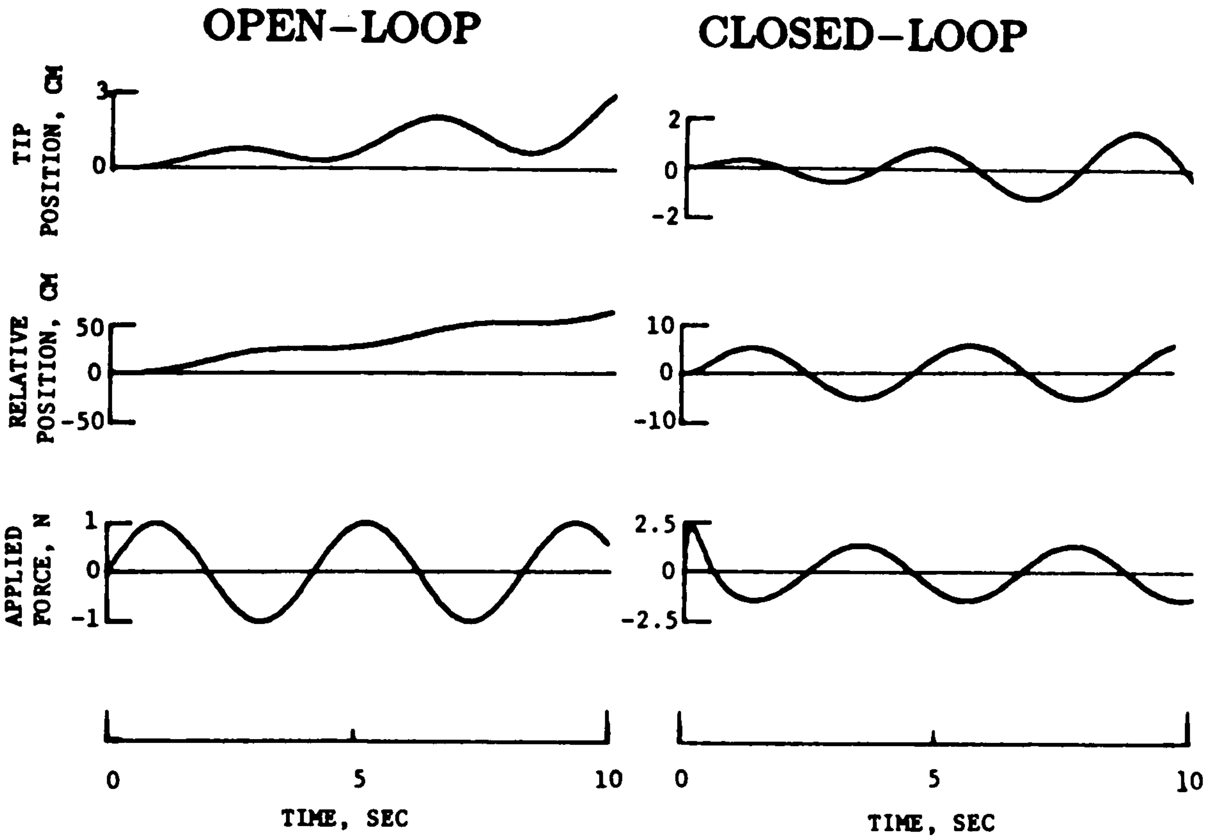

Figure 9

CONTROL EXPERIMENT SOFTWARE

The Baseline Control Law software package is envisioned to contain three subsystems. One provides excitation and disturbances, one is the control algorithm, and the last is performance evaluation.

EXCITATION AND DISTURBANCE INJECTION SUBSYSTEM

CONTROL ALGORITHM SUBSYSTEM

PERFORMANCE EVALUATION SUBSYSTEM

Figure 10

EXCITATION AND DISTURBANCE INJECTION SUBSYSTEM

The excitation and disturbance injection subsystem will be able to generate sinusoidal inputs at a single frequency or inputs that are a finite sum of several weighted sinusoidal signals (multi-mode sinusoidal). Other input types include amplitude-limited random signals. These inputs may be used for excitation in an open-loop manner or may be used during a control law test to provide disturbances.

A necessary feature of the system is command limiting. This will be done to avoid exceeding load and deflection limits on the MAST and relative position limits on the LDCM's.

SINGLE & MULTI–MODE SINUSOIDAL

AMPLITUDE-LIMITED RANDOM

COMMAND LIMITING ––
DEFLECTION AND LOAD MONITORING

Figure 11

C-6

CONTROL ALGORITHM SUBSYSTEM

The control algorithm will include variable order sensor prefilters that are of the ARMA form wherein the user provides the filter constants. These are scalar digital filters for each sensor signal used. A modest form of fault detection will be used to insure that the data passed along in the control algorithm are valid. This will include reasonability tests based on past sensor data. The primary control algorithm is linear. It is based on a state estimator followed by a control command calculation. Efficient software will be developed to take advantage of sparse matrices. The matrices in this subsystem are user supplied. The output from the control algorithm subsection is passed to scalar compensators. The compensators are also of variable order ARMA form with the coefficients user supplied. The output of the compensators is command limited prior to being sent to the MDIS.

SENSOR PREFILTERS

- SCALE FACTOR & BIAS CORRECTIONS
- ARMA FILTER FORM
- FAULT DETECTION

LINEAR ESTIMATION & CONTROL ALGORITHM

ESTIMATOR: $x_{k+1} = Ax_k+B_k+Cy_k$

CONTROLLER: $u_{k+1} = Dx_k+E_k+Fy_k$

ACTUATOR COMPENSATORS

- SCALE FACTOR & BIAS CORRECTIONS
- ARMA COMPENSATOR FORM
- COMMAND LIMITING

Figure 12

PERFORMANCE EVALUATION SUBSYSTEM

Measures of control law performance will be time histories of the sensor outputs (raw and filtered), state estimates, control commands (raw and compensated), and commands transmitted to the MDIS. This will be augmented by RMS calculations and on-line estimates of frequency and damping of selected scalar signals.

RECORDS & RMS OF

- SENSOR OUTPUTS
- ESTIMATED VARIABLES
- CONTROL COMMANDS

ON-LINE ESTIMATES OF
FREQUENCY & DAMPING FOR
SELECTED SCALAR SIGNALS

Figure 13

ALGORITHM PROCESSING REQUIREMENTS

To get a measure of the demands the control algorithm makes on the EDS computer, calculation of the number of floation-point multiply and add operations required for a specific case has been made. The assumptions of the algorithm are that all data are processed 150 times per second. This may not be required. For example, in a modal controller, the lower frequency mode calculations may not require complete updating at 150 times/sec. The sensor outputs are assumed to be filtered by a 6th order ARMA filter. Twelve sensors are assumed. The six rigid-body and eight of the flexible modes are included in the control algorithm. This produces fully populated matrices with a state dimension of 28. Each scalar output of the linear control algorithm is passed to a 4th-order, ARMA form compensator. The time frame used in the calculation taken from a previous chart is 5033 microseconds and 20 percent overhead is used to represent operating system and logic required to process the control law. To process this algorithm under the assumptions discussed, the EDS processor must be capable of performing a multiply and add operation in 1.2 microseconds. If only the eight flexible modes are used, the processing time requirement reduces to 2 microseconds.

ALGORITHM ASSUMPTIONS:

150 SAMPLES/SECOND
12 SENSORS -- 6th-ORDER FILTERS
6 RIGID-BODY & 8 FLEXIBLE MODES
9 ACTUATORS -- 4th-ORDER COMPENSATORS

SYSTEM ASSUMPTIONS:

TIME FRAME -- 5033 μSEC
20% OVERHEAD -- LOGIC & SYSTEM

SPEED REQUIREMENT -- μSEC/MAD:
(MAD == MULTIPLY & ADD OPERATION)

1.2 μSEC/MAD

2.0 μSEC/MAD FLEXIBLE MODES ONLY

Figure 14

COLLOCATED RATE FEEDBACK
CLOSED-LOOP

One obvious control law to process with the algorithm is collocated rate feedback using estimated velocity of the Stator. Figure 15 shows a simulation run sending direct current commands to the LDCM's, i.e., no local controller. The left set of charts is the excitation phase of the simulation and the right is the controlled phase. The applied force was generated by open-loop sinusoidal force commands at the frequency of the first flexible mode. The excitation phase lasted 10 seconds. No attempt was made to limit or monitor motion of the Moving Mass. This would be required for the flight software. At the end of the 10-second excitation phase, a collocated rate feedback control law assuming perfect estimation was engaged. The collocated rate feedback gains were precalculated to produce 5 percent damping in the mode excited. The 15 lowest frequency modes of the MAST flight system were included in the simulation. The design damping was indeed obtained; however, during the experiment approximately 1.2 meters of relative motion of the LDCM's was observed. It is indeed unfortunate that their travel is projected to be only 20 CM. A study using the local controller is in the process of being made but is not available at this time. Hopefully, the local controller will produce similar results and not exceed the travel limits of the LDCM's.

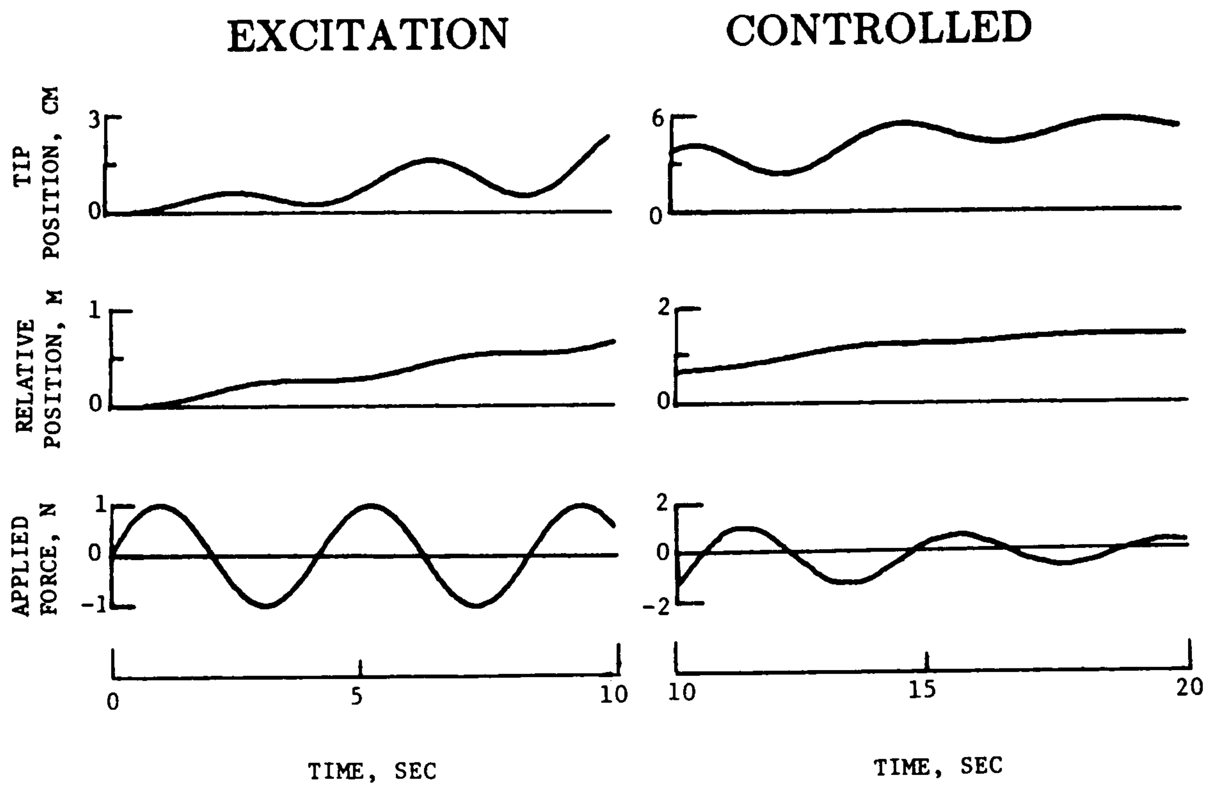

Figure 15

CONCLUDING REMARKS

This paper has proposed a Baseline Control Law software package that will, hopefully, support the research of many guest investigators. Elements of the package are an Excitation and Disturbance Injection Subsystem, a Linear Control Algorithm Sybsystem, and a Performance Evaluation Subsystem. Definition and evaluation of the Baseline is in progress, but it must be preceeded by a precise definition of the LDCM controllers. A real-time simulation of the MAST flight system is currently available at LaRC and will be used with hardware in the loop to evaluate the Baseline and software for potential guest investigators. The hardware to be used in the simulation are actuators similar to LDCM's save that they use conventional rotary DC motors to accelerate the Moving Mass. These are being developed in-house at LaRC and are expected to be available for use between January and March of 1987.

CONTROL EXPERIMENTS SOFTWARE
PROPOSED FOR COFS I

EXCITATION
GENERIC LINEAR CONTROL ALGORITHM
PERFORMANCE EVALUATION

DEFINITION AND EVALUATION IN-PROGRESS

DEPENDS ON DEFINITION OF
ACTUATOR WITH LOCAL CONTROLLER
REAL-TIME SIMULATION READY
TO EVALUATE VARIOUS LINEAR
CONTROL SCHEMES
HARDWARE IN LOOP SCHEDULED
1st QTR 1987

Figure 16