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# A VELOCITY COMMAND STEPPER MOTOR FOR CSI APPLICATION

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The application of linear force actuators for vibration suppression of flexible structures has received much attention in recent years. A linear force actuator consists of a movable mass that is restrained such that its motion is linear. By application of a force to the mass, an equal and opposite reaction force can be applied to a structure. In this presentation, the use of a linear stepper motor as a reaction mass actuator is described. The outline of this presentation includes the objective of this work, description of the hardware utilized, analytical application of this device, test beam and Mini-Mast experimental results, future applications, and concluding remarks.

# OUTLINE

- OBJECTIVES
- HARDWARE OVERVIEW
- COMMAND MODE ANALYSIS
- EXPERIMENTAL RESULTS
- FUTURE APPLICATION
- CONCLUSIONS

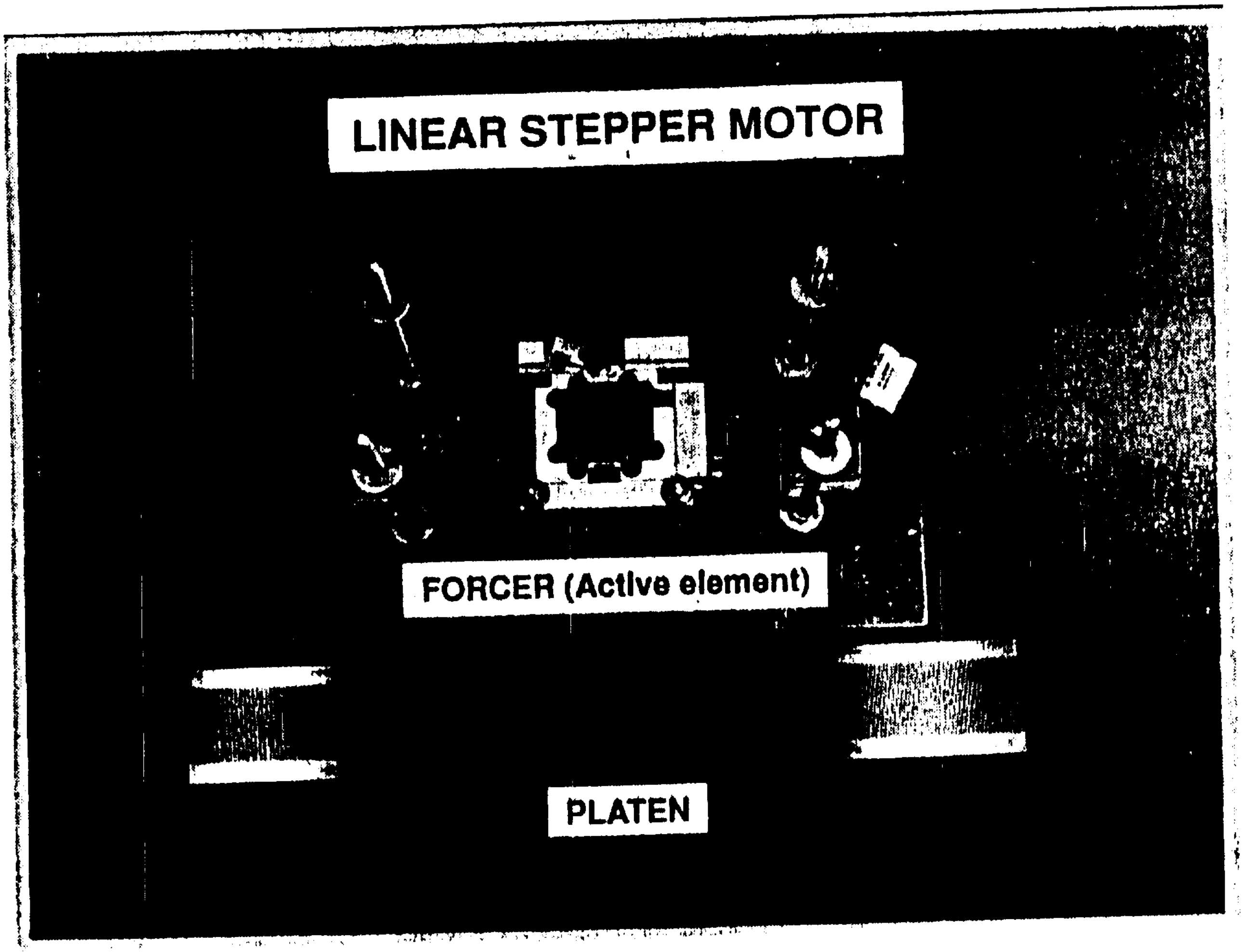
The development of reaction mass actuators is not a trivial undertaking, with much design and analysis effort (and cost) required in the development of prototype reaction mass actuators. The first objective of this work is to demonstrate the ability of an "off the shelf" industrial linear stepper motor system to operate as a reaction mass actuator for CSI applications. The second objective is to utilize the relative velocity command capability of this reaction mass actuator using various output feedback schemes to provide damping augmentation of a flexible structure. This is demonstrated on a simple test beam and the NASA Mini-Mast.

# OBJECTIVES

- **Demonstrate use of an industrial "off the shelf" linear stepper motor system as a reaction mass actuator.**

- **Demonstrate use of the actuator velocity command mode in flexible structure vibration suppression.**

A linear stepper motor is conceptually a very simple device that consists of two elements. The linear motor used is a Compumotor L5A manufactured by the Parker-Hannifin Corporation. In this application as a reaction mass actuator, the stationary part is the forcer and the moving part is the platen (the reaction mass). The forcer consists of two electromagnets and a permanent magnet. The platen is a passive element with teeth cut into its surface (100 per inch) to form pole faces which concentrate the magnetic flux lines generated by the forcer. The platen rides on the forcer supported by ball bearings that maintain the required air gap. By selectively applying current to the two winding of the forcer, magnetic force can be concentrated at the poles faces to cause relative motion between the two motor elements. The motor is classified as a two-phase permanent magnet hybrid linear motor.



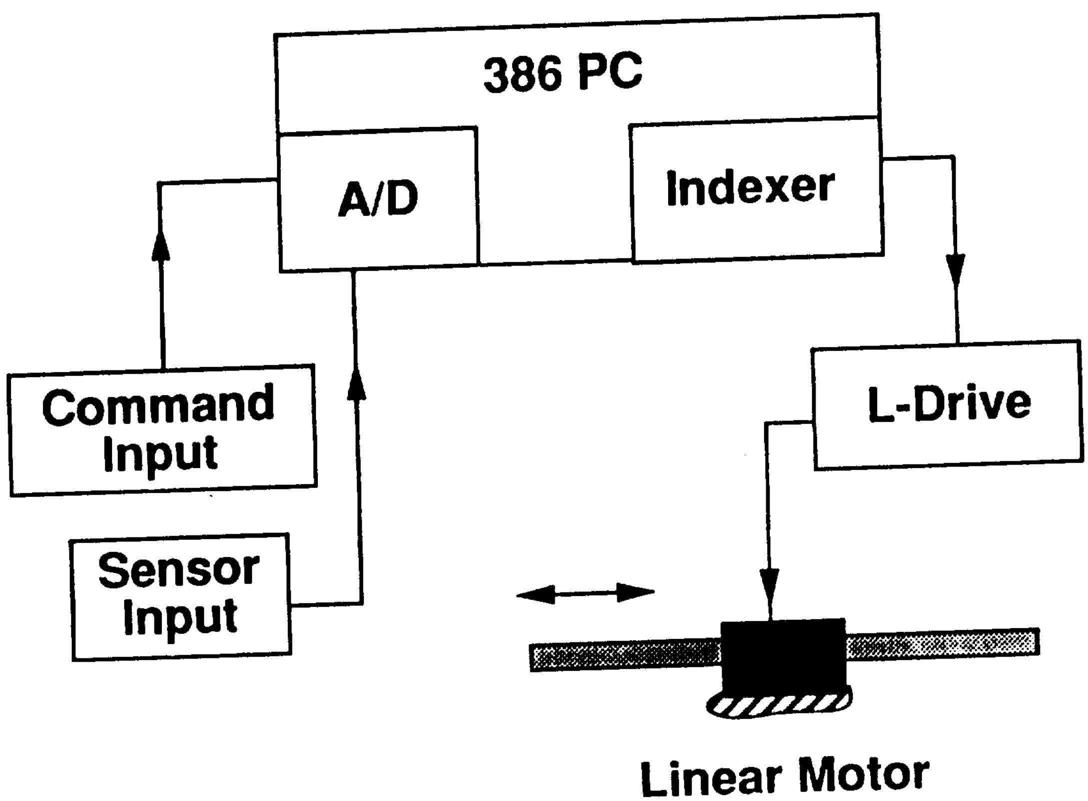
The motor step resolution obtained by the tooth spacing on the platen is increased by the motor control system digitally proportioning the motor current to the winding, resulting in an effective step resolution of 12500 steps per inch. This greatly improves the smoothness of motor operation. The control system also allows the user to command the velocity of the motor with a resolution of approximately 15 steps/sec. The weight breakdown of the linear motor system in its current reaction mass actuator application is 3.5 lbs for the reaction mass, 0.8 lbs for the forcer, and 1.95 lbs for mounting/adapter plates required to interface to the test articles, for a total weight of 6.25 lbs. Each actuator with its associated drive electronics cost about $3000.

# ACTUATOR CHARACTERISTICS

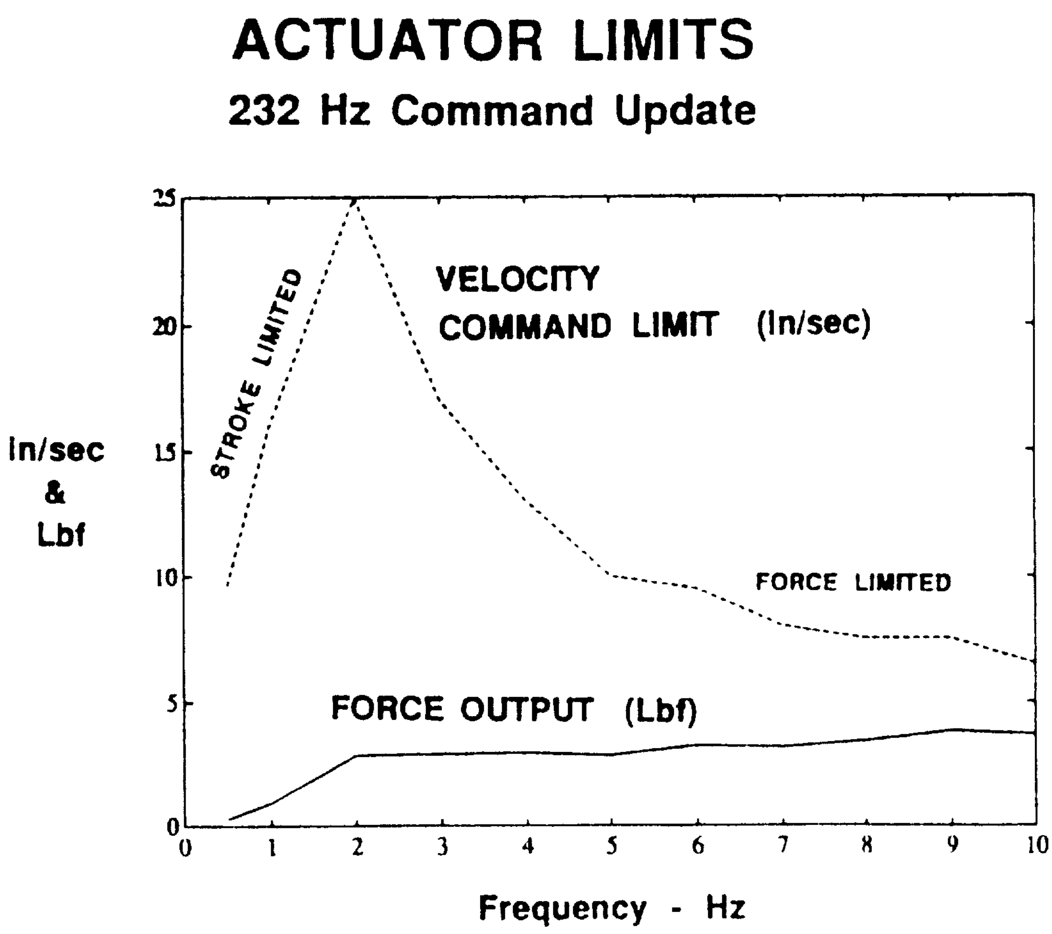
- **12500 steps per inch**
- **Velocity command capability**
- **Total Weight 6.25 Lbs**
  - **3.5 Lbs reaction mass**
  - **0.8 Lbs stationary element**
  - **1.95 Lbs mounting/adaptor plates**
- **Cost - approx. $3000 each**

The linear motor system hardware is interfaced as follows. A Compumotor PC23 microprocessor-based three axis indexer is installed in a PC-AT compatible card slot. This device provides the step pulses to the motor drive in response to operator commands. A motion control mode defined as velocity streaming is used to provide real-time control of the linear motor velocity. The motor command step pulses are sent to a L series bipolar, micro-stepping drive specifically designed for two-phase permanent magnet hybrid linear motors. The digital proportioning of the motor drive current is done here allowing motor step resolution to be effective increased to 12500 steps per inch. The use of a DT2811 analog to digital converter card in another PC-AT card slot allows the input of various analog signal inputs such as sensors and analog velocity commands to the actuator, depending on the software program used. Software drivers for the stepper motor were converted to C and combined with A/D board software to allow operation of the linear motor in several operating modes. These include indexer based or analog potentiometer relative position measurement, and analog command input with one or two independent linear motors.

# HARDWARE INTERFACE



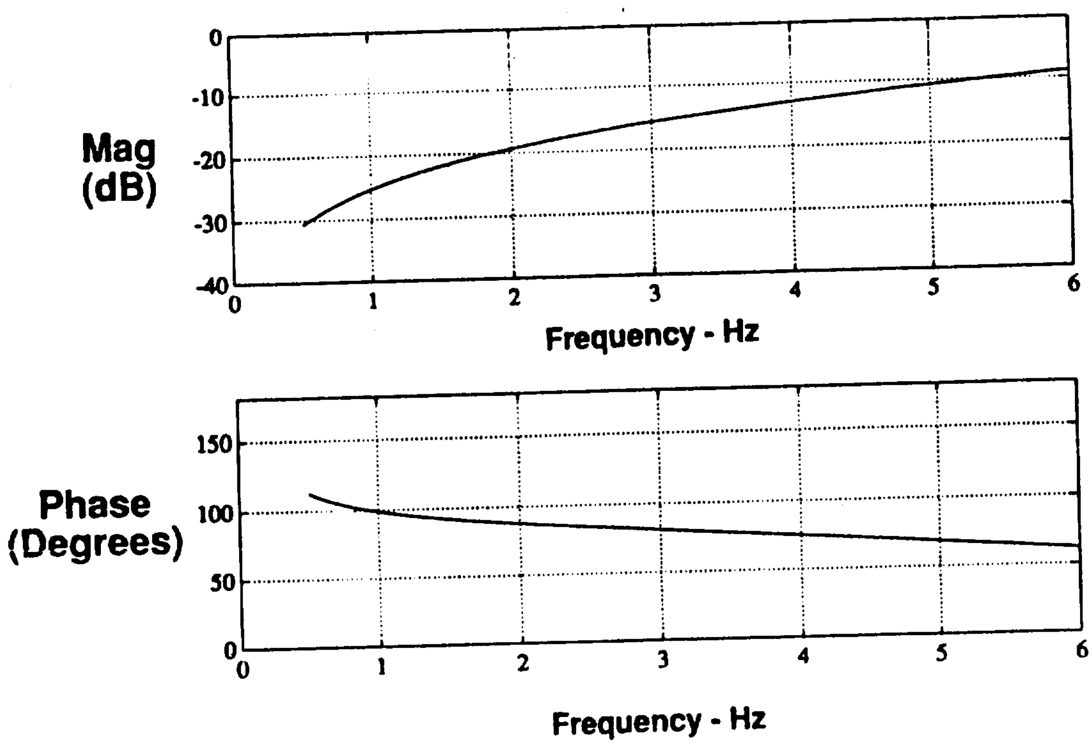
Bench testing of various actuator configurations was performed. The relative smoothness of the linear motors operation was used as a guide to determine the "best" operating mode of the system to use. Since indexer operation was the limiting factor in determining the velocity command update rate (or frame rate), these commands were kept to minimum by using the indexer to only output velocity commands to the motor, instead of also using the indexer to keep track of the reaction mass relative position. By using the analog reaction mass relative position measurement, a velocity command update rate of 232 Hz was obtained. With this configuration, operational limits of the actuator were determined by commanding various velocity command amplitudes at a given frequency. When the linear motor exceeded its stroke limits or began to stall/slip, this velocity command amplitude was used as the maximum velocity command for a given frequency. This procedure was used over the frequency range of 0.5 to 10 Hz. The actuator in this configuration is stroke limited under 2 Hz and force limited over 2 Hz. A calculated actuator force output is shown derived from the sinusoidal frequency and amplitude of the velocity command and the mass of the reaction mass.



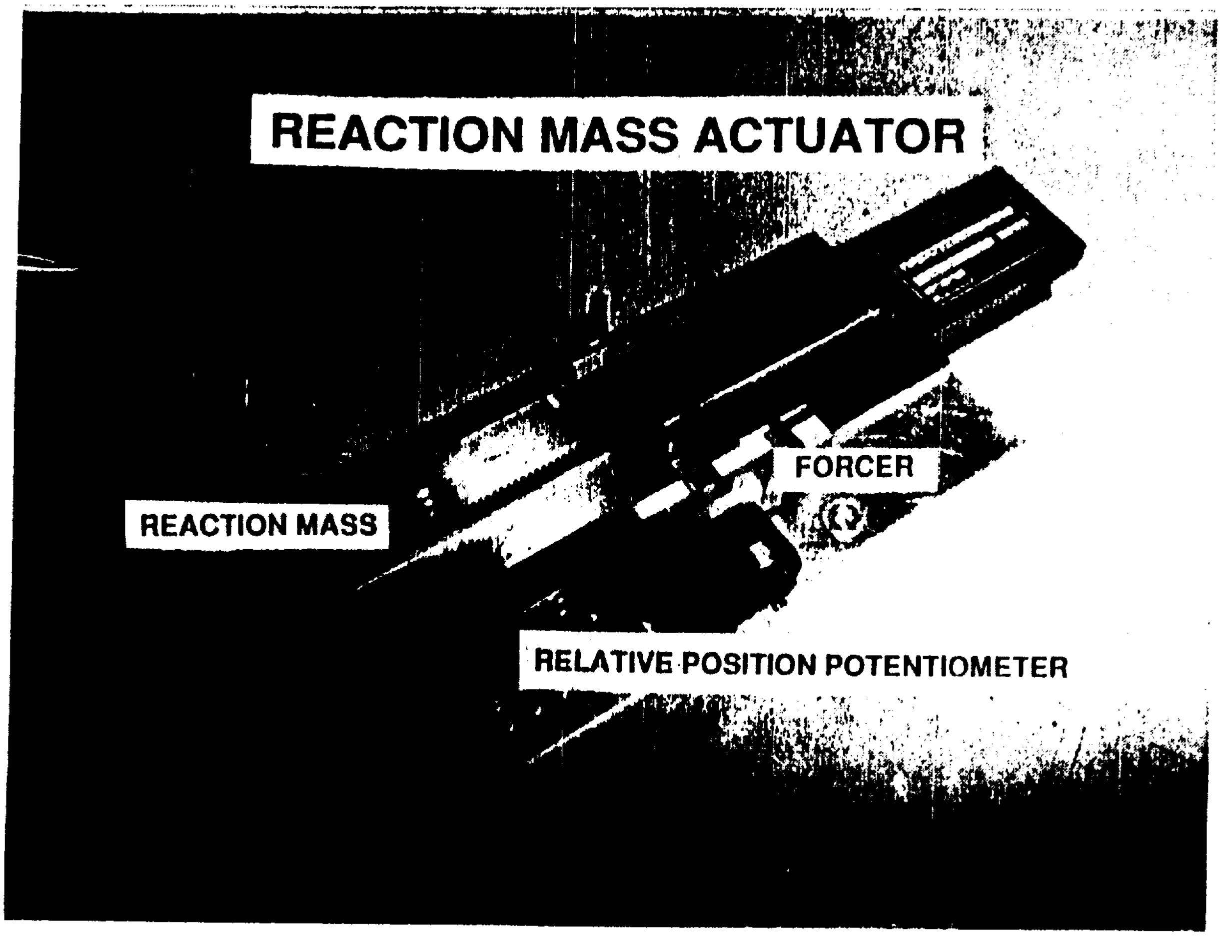
Using two actuators connected to the indexer causes the command update rate to decrease to approximately 106 Hertz. With the analog command input mode used and an accelerometer attached to the reaction mass, a dynamic signal analyzer was used to perform sine sweep tests over a frequency range of 0.5 to 6 Hz. The transfer function shown is actuator force output over velocity command input. This frequency response shows the expected results using a velocity command actuator.

## ACTUATOR FREQUENCY RESPONSE

### Lbf / (in/sec)



This photo shows the current configuration of the actuator assembly. A crude rack and pinion drive is used to provide an analog feedback signal proportional to the relative position of the reaction mass to ensure the reaction mass remains centered at low velocity command frequencies. A steel cable is attached between the reaction mass and base to prevent the reaction mass from exceeding its stroke limits. Total weight as shown here is 6.25 lbs.



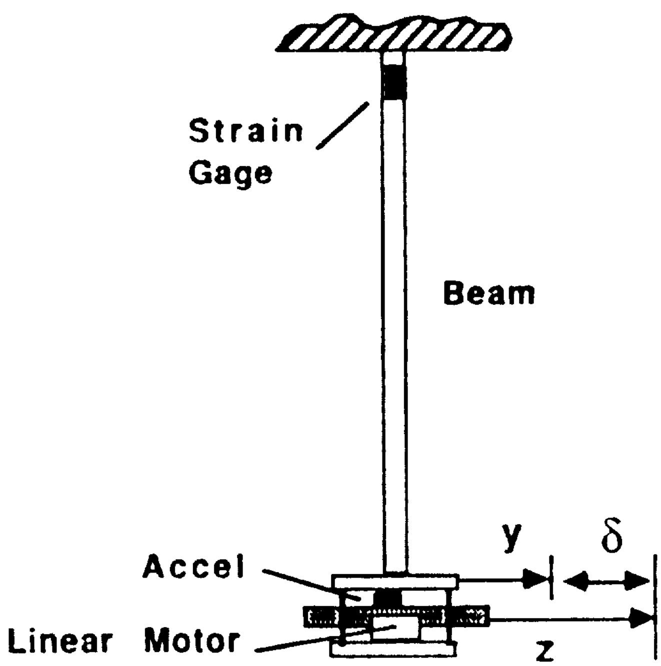
The usual implementation of reaction mass actuators for vibration suppression requires that the actuator be considered a force command or a relative position command device. The use of a velocity command reaction mass actuator allows some simple output feedback schemes to be implemented. Analytically, it can be shown that using direct output feedback, a velocity command device requires displacement or acceleration signals to augment the damping of a flexible structure. This is in contrast to the velocity feedback signal required for a force command actuator to provide additional damping in a flexible structure.

# COMMAND MODE ANALYSIS

- **Force command actuator requires velocity feedback to augment damping in a flexible structure.**
- **Velocity command actuator requires displacement or acceleration feedback to augment damping in a flexible structure.**

The linear motor was first tested on a simple test beam. The test beam was a vertically cantilevered seven foot aluminum tube (beam) with an actuator mounting plate attached. The mass of the beam was approximately five times that of the reaction mass. The first bending mode of this system was 1.8 Hz. The feedback sensors used were a strain gage at the beam root which provided a signal proportional to beam displacement, and a servo accelerometer which was used to measure beam or reaction mass inertial acceleration.

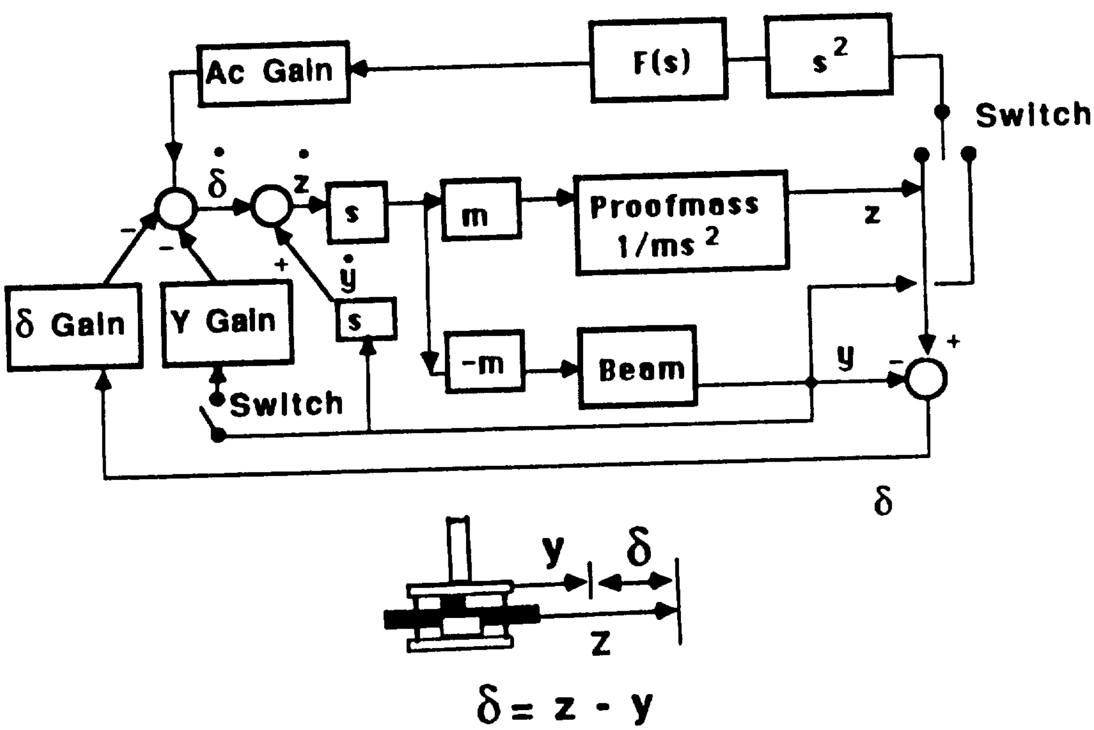
# TEST BEAM




$$\delta = z - y$$

A block diagram of the feedback loops demonstrated on the test beam is shown here. For all tests, reaction mass relative position feedback was used to ensure the reaction mass remained centered. For damping augmentation of the beam, strain gage, beam acceleration, or reaction mass acceleration was used.

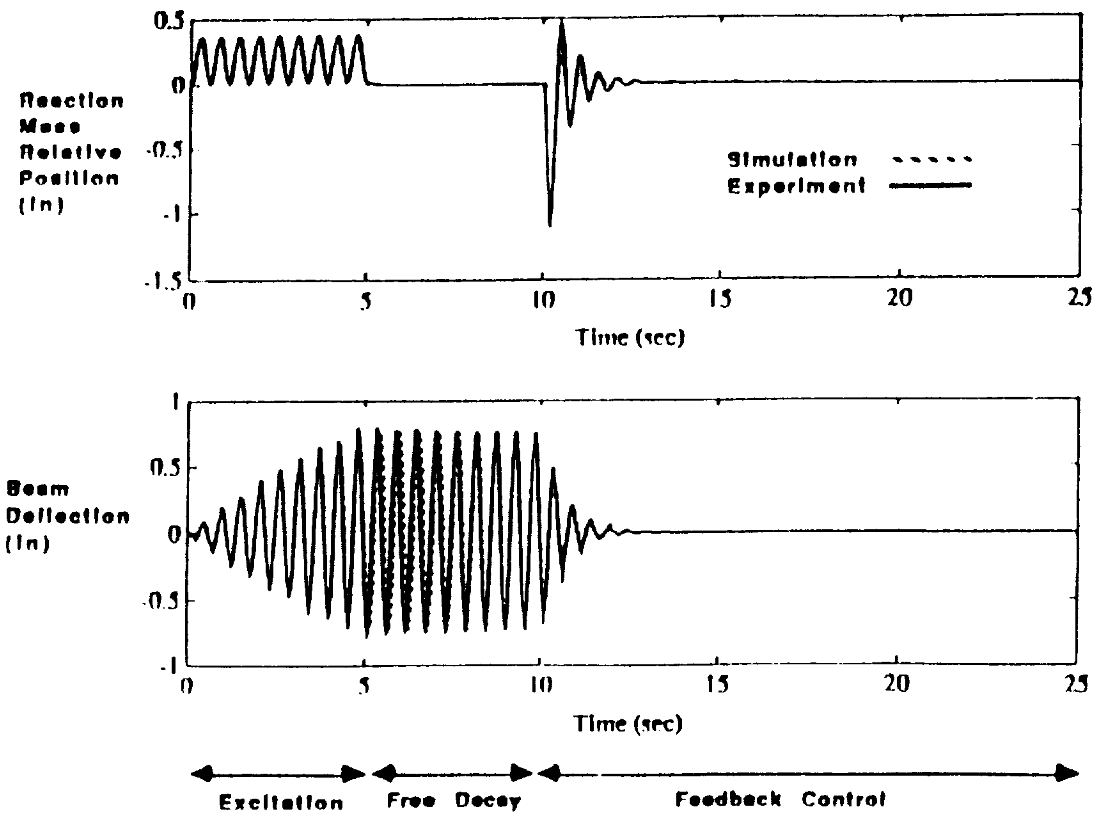
# CLOSED LOOP SYSTEM BLOCK DIAGRAM



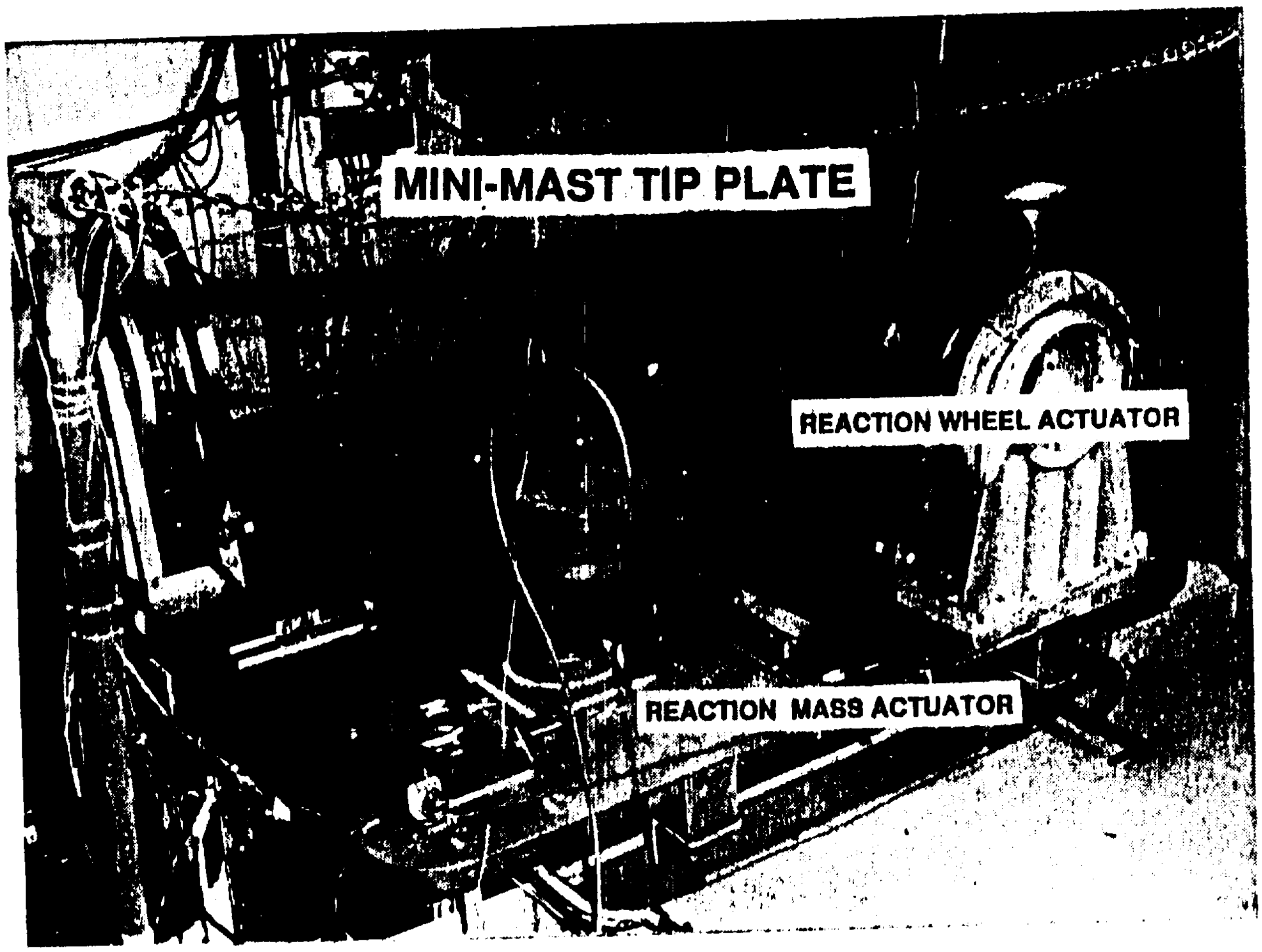
The beam was excited at its first mode frequency for five seconds, with no feedback loops closed. From five to ten seconds, the reaction mass relative position feedback loop was closed. At ten seconds, the damping augmentation feedback loop was closed, with a total test time to twenty-five seconds. A command update rate of 55 Hz was used. The following figure shows a comparison of simulated and experimental results for the case using strain gage and reaction mass relative position feedback. In this case, a closed loop damping of 14.5% is achieved. Similar results were obtained for the acceleration feedback cases.

# TEST BEAM EXPERIMENTAL RESULTS

**(Strain Gage and Relative Position Feedback)**

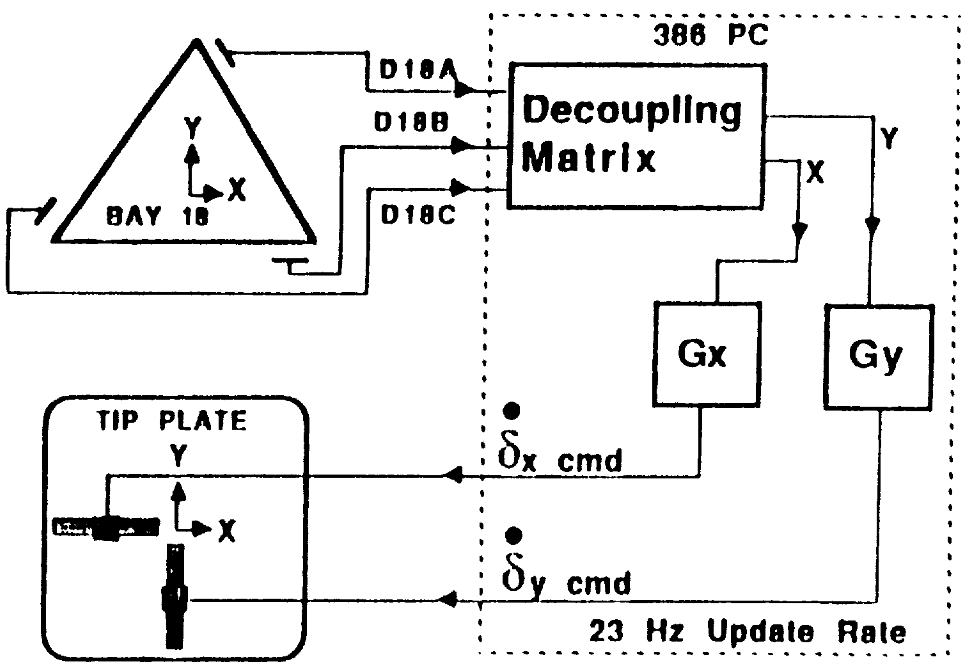


The second test article used was the NASA Mini-Mast, which is a 20 meter vertically cantilevered near-flight quality truss beam. For these tests two linear motors were used to provide two axis control. The linear motors were mounted on the tip plate to provide control forces along the Mini-Mast global X and Y bending axis (see next chart). The first five modes of the Mini-Mast are as follows: 1st X & Y bending (0.85 Hz), 1st Torsion (4.2 Hz), and 2nd X & Y bending (6.2 Hz). A interesting comparison between the two types of actuators shown (reaction wheel vs. reaction mass) can be made. Given the 50 ft-lbf torque output of the reaction wheels and the 0.7 lbf force output of the linear step motor, the torque available for application to the structure is equivalent, but the weight of the reaction wheels is 13 times that of the reaction mass actuator.



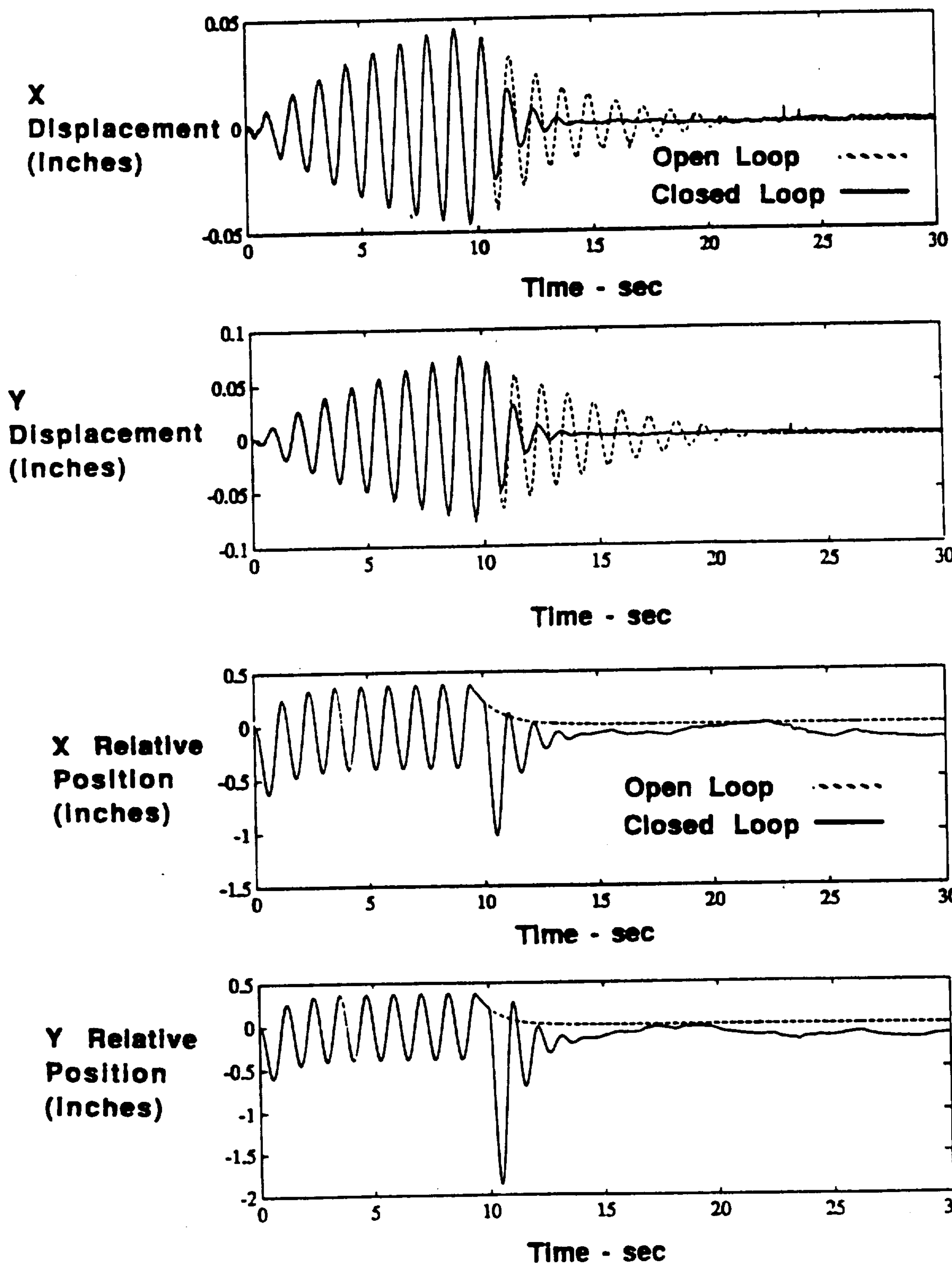
The Mini-Mast tip displacement feedback loop implemented is shown below. Mini-Mast tip deflection detected by three non-contacting displacement probes are input to the 80386 PC system. The displacement inputs are multiplied by a geometric de-coupling matrix to obtain X and Y displacement of the Mini-Mast tip plate with respect to the global bending axis. These global X and Y displacements are multiplied by their respective gains to generate the corresponding reaction mass actuator relative velocity command. The frame cycle for this process was only 23 Hz, since the indexer was used for relative position measurement. The reaction mass relative position feedback loops are not shown for clarity.

# MINI-MAST FEEDBACK LOOPS



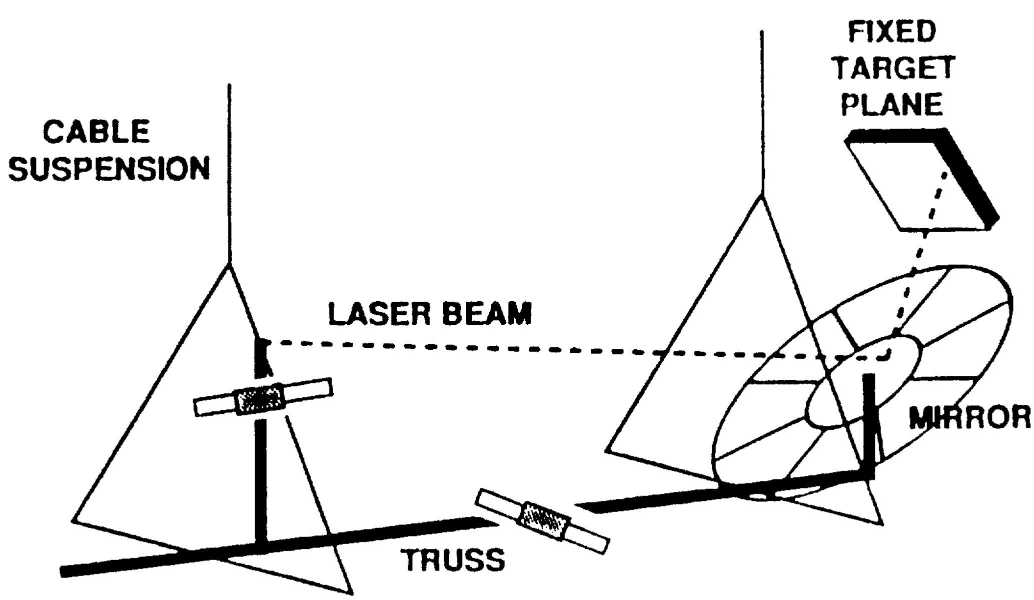
The Mini-Mast was excited for 9.8 seconds at the 1st bending mode frequency (.85 Hz) with both reaction mass actuators, followed by the feedback control at 10 seconds. The structural damping was increased from the 4.5 % free decay damping to approximately 15 % with displacement feedback.

# MINI-MAST TEST RESULTS



Plans are currently underway to use these linear stepper motor actuators on the CSI Evolutionary Model at NASA Langley Research Center. Initially, they will be used as inertial disturbance sources. Later, closed loop control of the 1.4 to 1.7 Hz flexible modes will be conducted.

# CSI EVOLUTIONARY MODEL TESTS



In conclusion, this presentation has shown that an industrial linear stepper motor system can be utilized as a reaction mass actuator for CSI applications. The use of a velocity command reaction mass actuator allows simpler output feedback implementation for vibration suppression since common sensor outputs are used. The performance of these actuators was demonstrated by closed loop tests on a simple test beam and the NASA Mini-Mast.

# CONCLUSIONS

- **Industrial linear stepper motor system can be used as a reaction mass actuator.**
- **Velocity command actuator allows use of displacement or acceleration measurements for direct output feedback to augment damping for vibration suppression of flexible structures.**
- **Actuator vibration suppression capability demonstrated on a test beam and the NASA Mini-Mast.**

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15. Supplementary Notes

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16. Abstract

The application of linear force actuators for vibration suppression of flexible structures has received much attention in recent years. A linear force actuator consists of a movable mass that is restrained such that its motion is linear. By application of a force to the mass, an equal and opposite reaction force can be applied to a structure. In this presentation, the use of an industrial linear stepper motor as a reaction mass actuator is described. With the linear stepper motor mounted on a simple test bean and the NASA Mini-Mast, output feedback of acceleration or displacement are used to augment the structural damping of the test articles. Significant increases in damping were obtained for both the test beam and the Mini-Mast.

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