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PIEZOELECTRIC DEVICES FOR VIBRATION SUPPRESSION: MODELING AND APPLICATION TO A TRUSS STRUCTURE

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ABSTRACT

For a space structure assembled from truss members, an effective way to control the structure may be to replace the regular truss elements by active members. The active members play the role of load carrying elements as well as actuators. A piezo strut, made of a stack of piezoceramics, may be an ideal active member to be integrated into a truss space structure. An electrically driven piezo strut generates a pair of forces, and is considered as a two-point actuator in contrast to a one-point actuator such as a thruster or a shaker. To achieve good structural vibration control, sensing signals compatible to the control actuators are desirable. A strain gage or a piezo film with proper signal conditioning to measure member strain or strain rate, respectively, are ideal control sensors for use with a piezo actuator. The Phase 0 CSI Evolutionary Model (CEM) at NASA Langley Research Center used cold air thrusters as actuators to control both rigid body motions and flexible body vibrations. For the Phase 1 and 2 CEM, it is proposed to use piezo struts to control the flexible modes and thrusters to control the rigid body modes. A tenbay truss structure with active piezo struts is built to study the modeling, controller designs, and experimental issues. In this paper, the tenbay structure with piezo active members is modelled using an energy method approach. Decentralized and centralized control schemes are designed and implemented, and preliminary analytical and experimental results are presented.

OUTLINE

The use of piezoelectric devices for vibration suppression has received much interest recently [1-5].* The application of the piezoelectric effect to actuation and sensing devices has allowed the investigation of the use of these components in experimental testbeds. The outline of this presentation includes the objectives, a description of the piezo strut and piezo film devices used, and discussion of modeling and implementation issues. A comparison of the analytical model and experimentally measured model for vibration suppression studies is presented.

- **Objectives**
- **Experimental setup description**
- **Modeling and model reduction**
- **Controller designs and experiment**
- **Summary/Future work**

*References 1-16 are cited in text.

OBJECTIVES

The NASA Langley Phase 0 CSI evolutionary model (CEM) used cold gas thrusters as actuation devices for line of sight pointing and vibration suppression testing [6]. Since the use of thrusters for flexible body vibration control may be impractical, alternative actuation devices are considered for the Phase 1 and 2 models of the CEM. Piezoelectric strut actuators show promise in this application. The objective of this work is to obtain experience in the application of these devices to vibration suppression of a truss structure. This includes modeling and control law design and implementation.

- **Demonstrate use of piezoelectric actuators and sensors for vibration suppression of a truss structure**

- **Derive model of structure system with active devices**

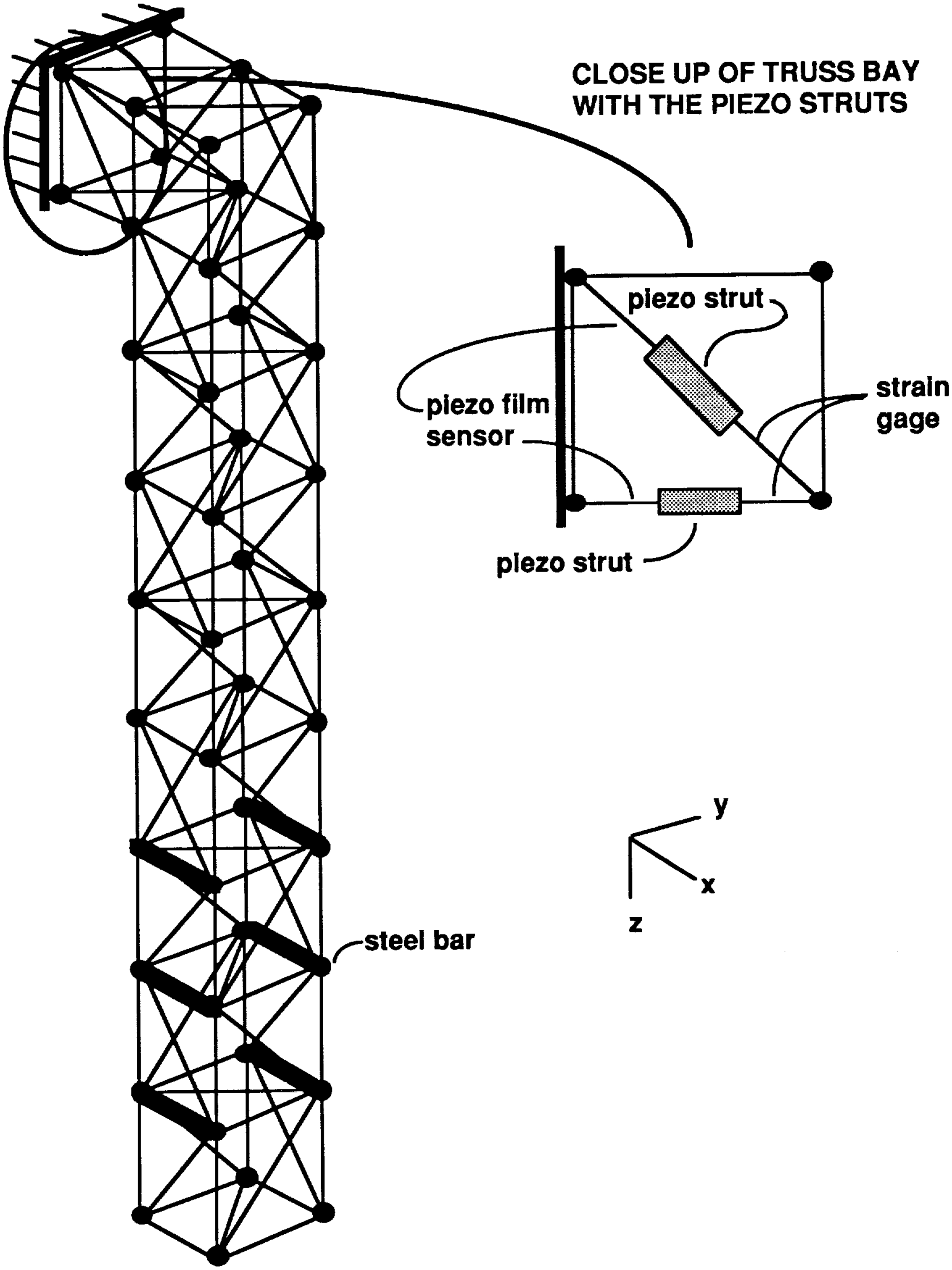
- **Obtain practical "hands on" experience using available piezoelectric actuators and sensors**

TEST SET-UP DESCRIPTION

The following figure is a drawing of the tenbay truss test article, showing the sensor and piezoelectric strut actuator locations. The truss is in an inverted L shape, with a 20 inch section cantilevered horizontally from a base plate and a 90 inch section extending vertically downward. There are a total of ten bays, each bay of the truss is 10 in. x 10 in. x 10 in. in size. The individual struts are made of aluminum, as are the corner ball joints connecting each bay; threaded steel rods are used to secure the struts to the ball joints. In addition, six steel bars of 7 pounds each are mounted on the lower truss battens, 3 each on either side, to reduce the bending frequencies of the structural modes (the first two modes were lowered to below 10 Hz).

Two commercial piezoelectric struts, obtained from Physik Instrumente of Germany, are mounted in the truss bay closest to the support - one as the lower horizontal member (longeron) and one as the adjacent diagonal member. These actuators take the places of the nominal struts, with steel support studs used to connect the piezoelectric struts to the ball joints. The chosen locations correspond to those determined by a finite element model (FEM) of the truss that had the highest strain energy.

Instrumentation consists of a strain gage and a piezo film mounted on opposite ends of each actuator, a tri-axial servo accelerometer set mounted on the free end of the truss and a single axis servo accelerometer mounted midway up the truss. The piezo film is a pre-cut strip of piezoelectric material which senses the relative velocity between its two ends. An additional piezo film sensor and strain gage are placed on the diagonal strut in the truss bay face directly opposite to the face containing the piezoelectric struts. The two piezoelectric strut actuators are driven by a two channel Model 50/750 high voltage power amplifier, from Trek, Inc. of Medina, N.Y., capable of producing DC voltages of up to 1500 V at an average current level of 50 mA. Separate current amplifiers convert the current collected by the piezo films to voltage outputs. This instrumentation is interfaced to a Control and Measurement and Control (CAMAC) rack, which performs the analog to digital (A/D) and the digital to analog (D/A) conversions and the analog filtering of the sensor signals, and a Vax workstation 3200 for real-time control tests. A GenRad 2515 is also used for frequency response measurements.



Schematic of a tenbay active structure

PIEZOELECTRIC SENSOR AND ACTUATOR

The constitutive equations of a piezoelectric material describe the relationships of the six strains, six stresses, three electric displacements, and three electric fields at any time and any point in the piezoelectric material [7-8]. A piezoelectric material is anisotropic, and its constitutive conditions depend on the polarization direction. Due to the piezoelectric effect, a piezoelectric device can transfer mechanical energy to electric energy, or vice versa. In the generator mode, charge and electric field are produced when external forces are applied, and a piezoelectric transducer can be used as a sensor. In the motor mode, dimensional changes occur when electric sources are applied, and it can be used as an actuator.

- **Constitutive equations: electro-mechanical coupled equations**

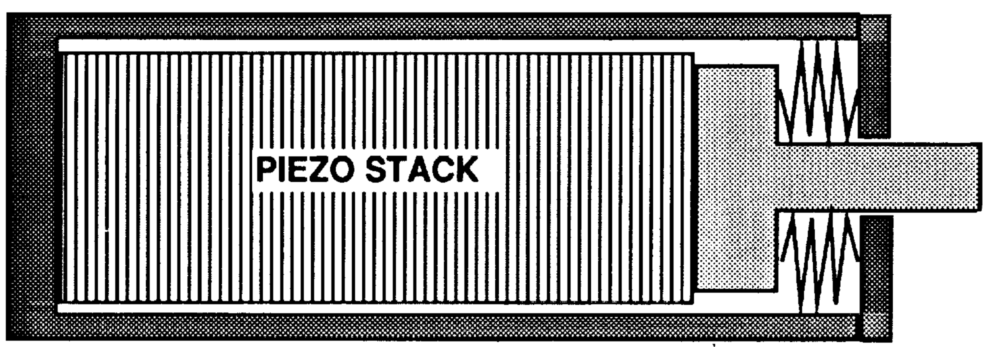
- **Properties of a piezoelectric material**

  - **Direct piezoelectric effect: charge produced when forces are applied**

  - **Indirect piezoelectric effect: dimension changed when electric sources are applied**

PIEZOELECTRIC ACTUATOR

The piezo strut is made of a stack of piezoceramic disks. It has a preload mechanism to prevent the piezoceramics from experiencing tensile forces. To prevent depolarization of the piezoceramic, an electric field is applied in the same direction as the DC electric field that polarized the piezoceramic. Normally, the housing of a piezo strut is grounded, and a negative voltage is applied to the piezoceramics inside the housing. For a dynamic application, a piezo strut is biased by a negative DC voltage with an AC dynamic signal superimposed.

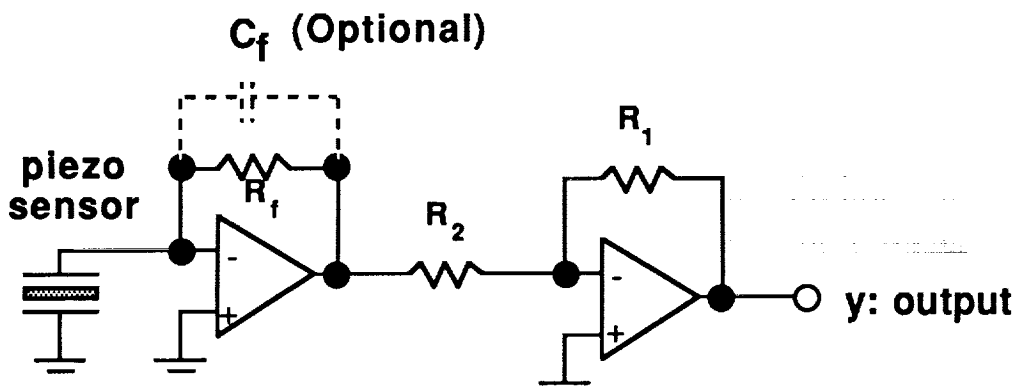


Commercial Piezoelectric Strut Data [14]

Strut Parameter	Longeron Strut	Diagonal Strut
Model No.	P243.30	P243.40
Expansion at -1000 volts	40 microns	60 microns
Expansion at -1500 volts	60 microns	90 microns
Stiffness (lb/in)	1.1992×10^6	0.7995×10^6
Total length (in)	4.58	5.67
Weight (lb)	2.75	3.25
Resonant frequency (Hz)	4500	2200

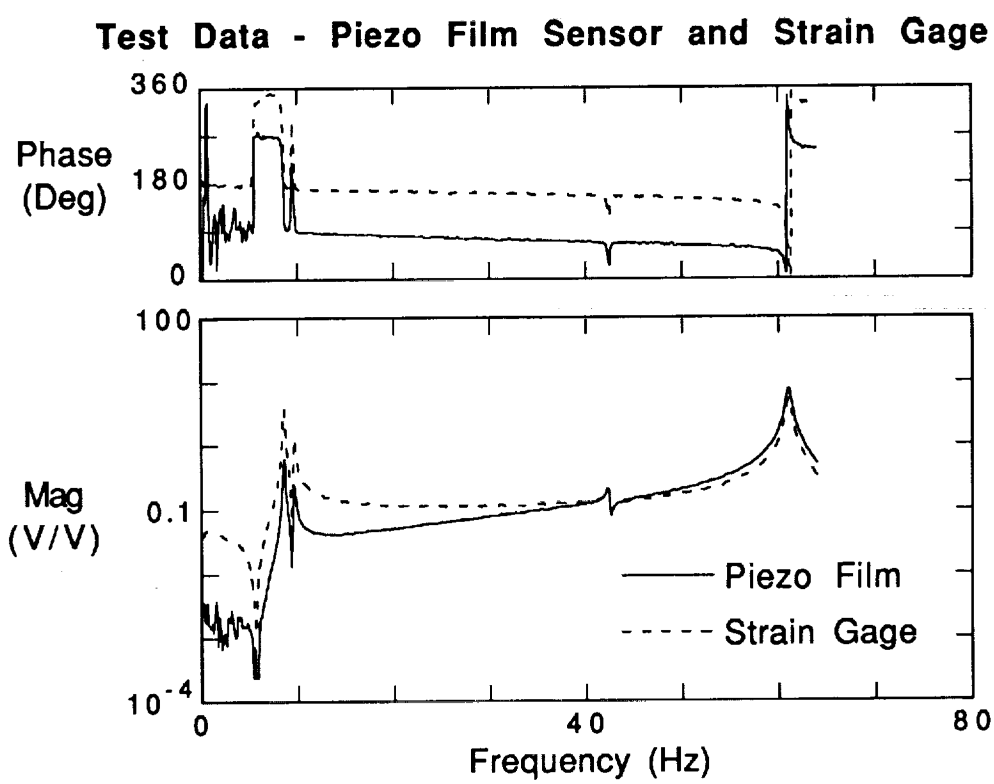
PIEZOELECTRIC SENSOR AND CURRENT AMPLIFIER

A piezo film sensor is a self-generating transducer, and does not require an external power supply. However, a signal conditioner is needed to convert the charges collected on the electrodes of the piezo film. A current amplifier converts the current drawn from the piezo film to a voltage output. The circuit diagram of a current amplifier is illustrated below.



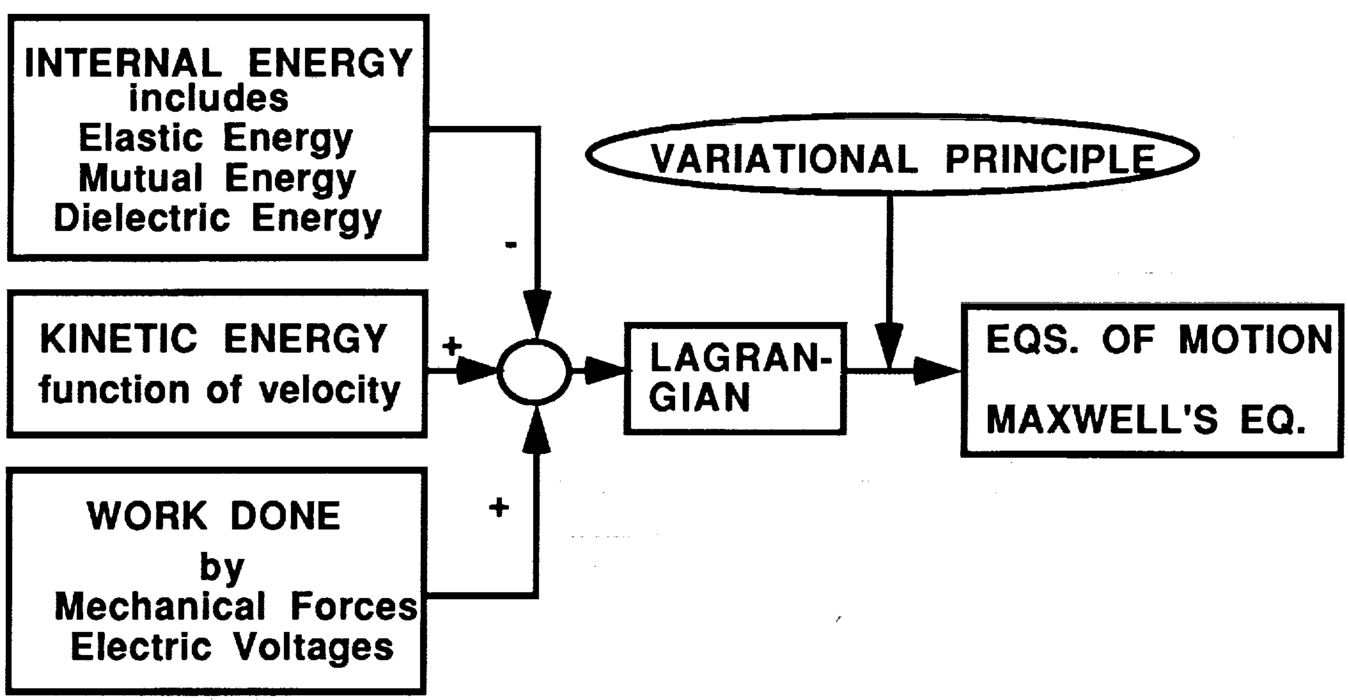
STRAIN AND RELATIVE VELOCITY MEASUREMENTS

The use of the piezo film as a relative velocity sensor can be seen in the following figures. The top figure shows the respective phase plots for a strain gage and a piezo film strip collocated on the tenbay truss; the bottom figure shows the magnitude plots of the two sensors. The two measurements are not independent, but differ only by a scalar factor of $j\omega$, implying a phase lag of $\pi/2$ and a magnitude ratio of ω.



SYSTEM MODELING

System governing equations are derived here based on an energy method developed in Ref. [13]. Lagrangian is defined as a function of internal energy, kinetic energy, and work done by the external forces and voltages. The internal energy consists of elastic energy, mutual energy, and dielectric energy, and is a function of mechanical and electric displacements. The kinetic energy is a function of velocity. The work is done by the surface tractions applied on the surface of the piezoelectric medium less the flux of electric energy flowing outward across the surface [9]. The variational principle yields the displacement equations of motion and Maxwell's second equation, and they are coupled through the piezoelectric effect. The equations of motion describe the force equilibrium conditions, and Maxwell's second equation states that the curl of electric fields is zero in the electrostatic case. The applied mechanical forces appeared in the equations of motion as driving forces, and the external electric voltages in Maxwell's second equation.



Since only a quasi-static electric field is considered, Maxwell's second equation is algebraic in the electric displacement. One can solve Maxwell's second equation for electric displacement in terms of mechanical displacements, and back substitute into the equations of motion to decouple the mechanical and electric displacements in the equations of motion. By doing this, the external electric voltage is converted to a pair of piezoelectric axial forces asserted on the nodal point of the piezo strut. The piezoelectric axial forces have the same magnitude but opposite sign.

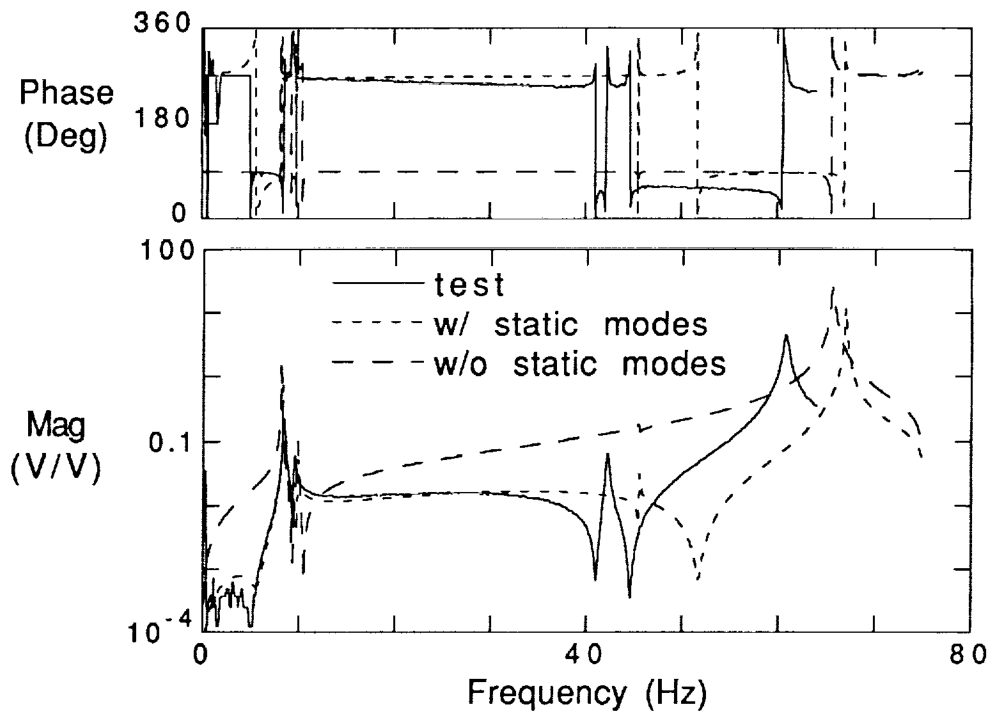
A polyvinylidene fluoride film (PVDF) can be used as a piezo sensor. A current amplifier is used to convert the current generated from the piezo film to electric voltage. The input terminals of the current amplifier are virtually grounded, therefore the system governing equations described above are good for a piezo medium used as either a sensor or actuator. The piezo film incorporated with a current amplifier generates a signal proportional to the relative velocity of the ends of the piezo film [3,10-11].

A reduced model was derived from a finite element model by considering the piezo strut and the supporting studs as a single element. Transfer functions calculated from the model were compared with the test data. Although the model predicted the global responses accurately, large errors were observed for the sensors situated in the same and the adjacent truss elements of piezo struts. It indicated strong local stress concentration is introduced from the forces asserted by the piezo strut. Static mode shapes were used together with vibrational mode shapes in the model reduction to alleviate the modeling error due to the local effect [12-13].

- **Internal forces are produced from the piezoelectric strut due to the piezoelectric effect**
- **Local strain concentration is introduced from the forces applied by the piezoelectric strut**
- **Static mode shapes are used together with vibrational mode shapes in the model reduction to alleviate modeling error due to the local effect**

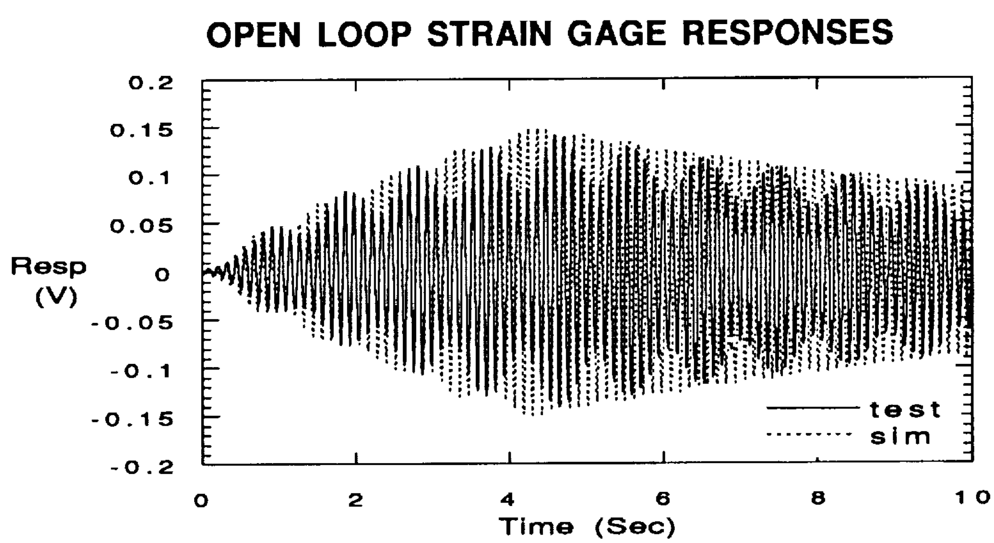
MODELING ISSUES

The improvement to the analytical model of the tenbay truss brought on by including the static modes can be seen in the following figures. The bottom figure shows the magnitude plots for the respective transfer functions between a piezo strut and a sensor located in an adjacent strut, as directly measured on the GenRad, as computed from a finite element model (FEM) with vibrational modes only, and as computed from a model which included both vibrational and static modes. The top figure shows the phase plots for the three respective transfer functions. As both figures show, the model with the static modes better represents the dynamics of the tenbay truss, particularly in the region around the first two modes.



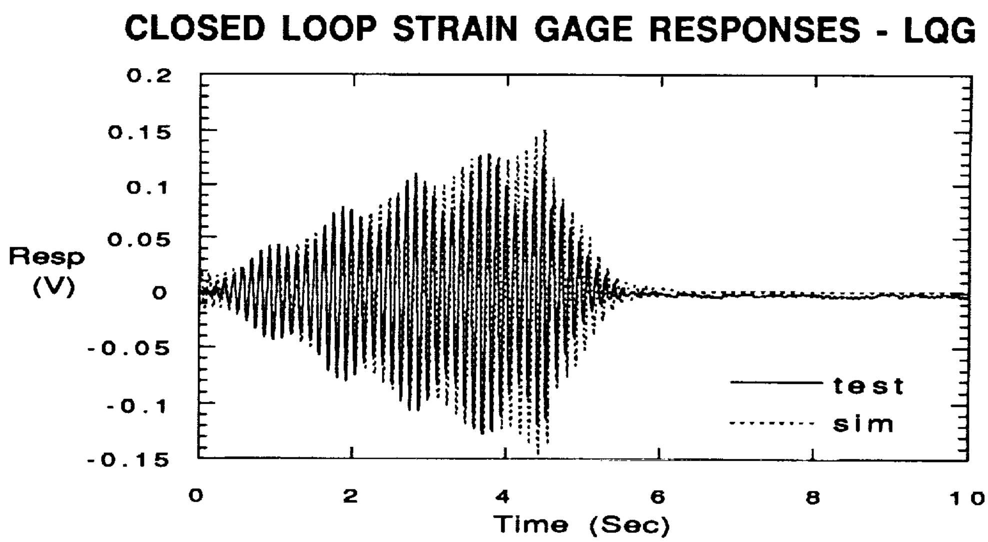
EXPERIMENTAL PROCEDURE

Each controller was tested on the truss structure by commanding the two piezo struts at 8. 4 Hz and 9.5 Hz respectively for 4.5 seconds to excite the first two bending modes of the structure. For the open loop case, the structure was allowed to free decay for the remainder of the 5.5 second test duration. For the closed loop tests, the controller was switched on at 4.5 seconds to actively damp the truss. The open loop response is shown below overlaid with simulated results from the finite element model. The "beating" effect was not observed in the simulated results due to modal frequencies being slightly different from the actual system.



CONTROLLER DESIGNS - LQG

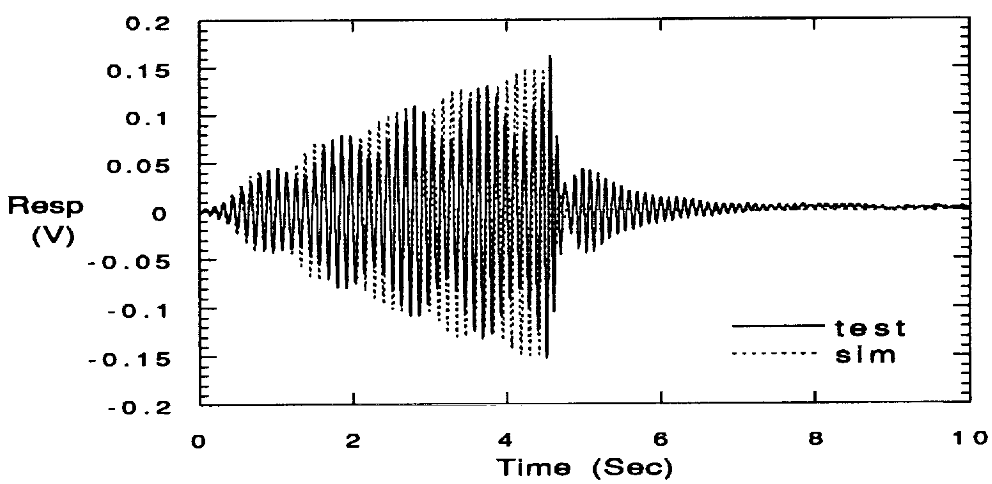
Linear quadratic gaussian (LQG) controller design is a model based technique. For this application, a system identification approach was taken. Three 30 second data sets were obtained, using a 15 Hz bandwidth random signal as input to the piezo struts, collocated strains as the output, and a 250 Hz sample rate. Using the Observer/Kalman Filter Identification (OKID) technique in the System/Observer/ Controller Identification Toolbox (SOCIT) for MATLAB [15], a discrete 40 state, 2 input, 2 output model was obtained. A balanced model reduction was performed on this model to obtain a 10 state LQR design model. Using diagonal state weight (Wx=10) and control weight (Wu=0.01) matrices, LQR gains were obtained and coupled with the identified observer to form the LQG compensator. This controller was tested on the truss structure, with the damping of the first two modes increased to 7.25% and 6.7% respectively.



CONTROLLER DESIGNS - SECOND ORDER DECENTRALIZED

A second order decentralized controller which digitally simulates a second order spring-mass-damper system at the piezoelectric strut/strain gage location was designed. With collocated actuators and sensors, this provides the necessary temporal phase shift to effect damping using strain measurements. The controllers were designed as SISO for each mode at each actuator/sensor pair. Test results are shown below.

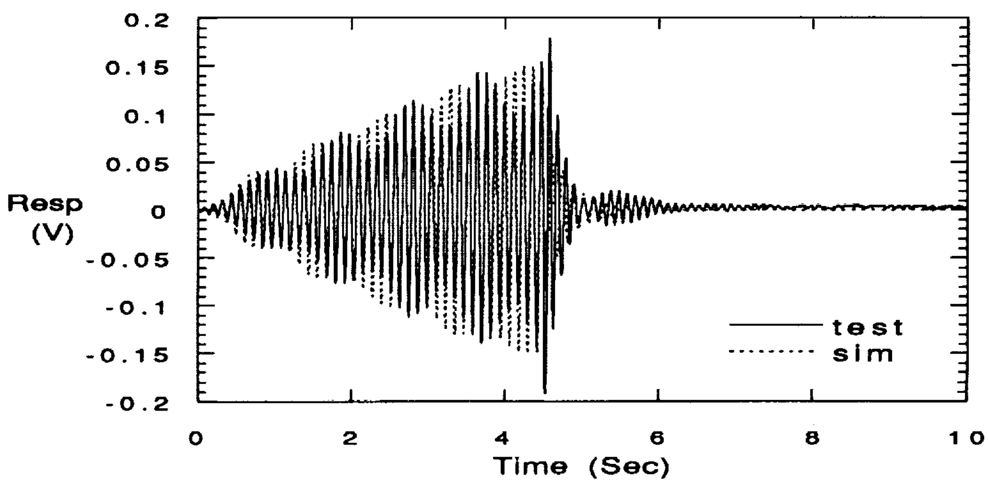
CLOSED LOOP STRAIN GAGE RESPONSES - 2ND ORDER DECENTRALIZED



CONTROLLER DESIGNS - DIRECT RATE FEEDBACK

Collocation of actuator and sensor pair implies that the output influence matrix is the transpose of the input influence matrix. A piezo film sensor is compatible with a piezo strut, and measures relative velocity if a current amplifier is used as a signal conditioner. Therefore, a piezo film/piezo actuator pair closes a direct rate feedback loop. The constant gain matrix, a positive definite diagonal matrix, results in a decentralized controller. When the damping matrix of the closed loop system is positive definite, the closed loop system is guaranteed to be stable [16]. The analytical and test results are shown below.

CLOSED LOOP STRAIN GAGE RESPONSES - DIRECT RATE FEEDBACK



SUMMARY

In this paper, an active truss structure using piezoelectric sensors and struts was modelled and tested. By comparing with the test data, the truncated finite element model obtained based on the modal mode model reduction scheme cannot predict the local stress concentration introduced by the forces applied by the piezo struts. Numerical results indicated that increasing either vibrational modes or nodal points on the active member did not improve the ability of the truncated model to predict the local effect. Combining static mode shapes with the dynamic modes adequately represents the deformations induced by the piezo struts. Closed loop tests using centralized and decentralized controllers demonstrated the ability to perform vibration suppression with piezoelectric devices on a truss structure.

- **Obtained practical experience in use of piezoelectric sensors and actuators**
- **Derived model of an active structure with piezoelectric devices**
- **Local stress concentration is observed due to the forces applied by the piezo strut**
- **Static mode shapes are used together with the vibrational mode shapes in the model reduction to emphasize the local effect**
- **Demonstrated ability to perform vibration suppression with these devices on a truss structure**

FUTURE WORK

With the experience obtained in this application of piezoelectric devices, several areas of future work are identified. In order to ensure sensor/actuator collocation, a piezoelectric strut with an integral strain gage sensor and/or piezoelectric film sensor will be built. On a large structure such as the Phase 2 CEM, it must be determined how many active struts are required to meet a performance objective, and what locations are best. This optimization process is currently underway. After piezo struts are installed in the Phase 2 structure, open and closed loop testing will be required to validate design methodologies. A final goal is creation of a "smart" structure, in which the structure, sensors, actuators, and controllers are integrated to form a total system.

- **Piezoelectric strut with built in piezoelectric sensor or strain gage to ensure sensor/actuator collocation**
- **Optimization of locations for sensors and actuators**
- **Open and closed loop testing on the more realistic testbeds**
- **Integration of structure/sensors/actuators/controller**

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