The next step in the design process is to determine an open-loop control law. This can be accomplished by minimizing an appropriate cost functional under specified state and control input constraints. A nonlinear programming package (e.g., NPSOL[7]) can be used to generate the optimal time history of the control inputs.

The open-loop control policy, when applied to the actual system, may not produce the desired output because of modeling uncertainties, external disturbances, and a mismatch in the initial conditions. Techniques such as the structured singular value (μ) (Ref. 6) for energy-bounded signals, or ℓ_1 (Ref. 8) for amplitude-bounded persistent signals, can be used to synthesize a robust controller, which will attempt to eliminate these errors.

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Self-Sensing Magnetostrictive Actuator for Vibration Suppression

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Nomenclature

A	= area
B	= flux density
$\hat{d}, \hat{e}$	= piezomagnetic constants
H	= magnetic field
i	= current
L	= inductance
ℓ	= length
n	= number of wire turns
R	= resistance
S, ε	= strain
s	= elastic compliance
T, σ	= stress
v	= voltage
Y	= elastic stiffness
μ	= permeability
Φ	= magnetic flux

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Introduction

THE concept of a self-sensing actuator originated in the control of electromagnetic mechanisms used in ordinary speakers.[1] The technique was proposed as a simple method for adding damping to their resonant modes. By using simple bridge circuitry, a signal could be generated independent of the applied control voltage that is proportional, albeit with some frequency dependence, to the velocity of the coil being driven in the magnetic field.

Recent work has applied the self-sensing concept to the control of smart materials, specifically piezoceramics and magnetostrictives.[2–7] Pratt and Flatau[6] first investigated the concept of a self-sensing magnetostrictive actuator. A self-sensing model was proposed as was an initial investigation into the use of a magnetostrictive actuator for active isolation. The experiments were limited in their success because of the high bandwidth the actuator system was trying to control. Fenn and Gerver[7] also developed models and produced data, which supported the use of magnetostrictive materials in a self-sensing configuration. The success of applying the self-sensing technique to a magnetostrictive active strut as it is presented in this Note is largely due to focusing on the damping of low-frequency modes of a truss structure.

Magnetostriction Overview

Even though magnetostriction, like electrostriction, is inherently a second-order effect, it is common to treat it as a problem in linear elasticity using the approximation of small strain theory.[8,9] Treating the effects in this fashion results in a one-to-one analogy to the constitutive relations defining linear piezoelectricity theory.[9,10] Thus, a practical form of the magnetostrictive constitutive relations is expressed as follows:

$$S_{ij} = s^H_{ijkl} T_{kl} + \hat{d}_{kij} H_k \tag{1}$$

$$B_i = \hat{e}_{ikl} S_{kl} + \mu^S_{ik} H_k \tag{2}$$

This form is more practical because of its ease of use in approximation methods.

Since we are only concerned with a one-dimensional case where the stress, strain, and fields are applied/measured in the same direction and the magnetostrictive material is assumed to be isotropic, these tensor equations can be compressed into the following set:

$$\varepsilon = (\sigma/Y) + \hat{d}H \tag{3}$$

$$B = \hat{e}\varepsilon + \mu H \tag{4}$$

For experimentation, it is helpful to further manipulate Eqs. (3) and (4) to gain some intuition for the problem as well as simplifying the simulation process. Using a priori knowledge of the active magnetostrictive element, i.e., the actuator, some simplifying assumptions can be made. The actuator can be modeled as a simple wire-wound solenoid assuming the wires are thin, the spacing between the wires is small relative to the solenoid's radius, the solenoid is long relative to its diameter, and the magnetostrictive material enclosed has a constant permeability. The field induced by current flow in a simple solenoid is given as

$$H = (n/\ell)i \tag{5}$$

When Eq. (5) is substituted into Eq. (3) the following results:

$$\varepsilon = (\sigma/Y) + \hat{d}(n/\ell)i \tag{6}$$

Equation (6) shows the strain to be clearly a result of two effects, one of an imposed stress and an imposed current through the wire.

Turning now to Eq. (4), we can use fundamental laws of magnetics to derive an equation in terms of voltage and current instead

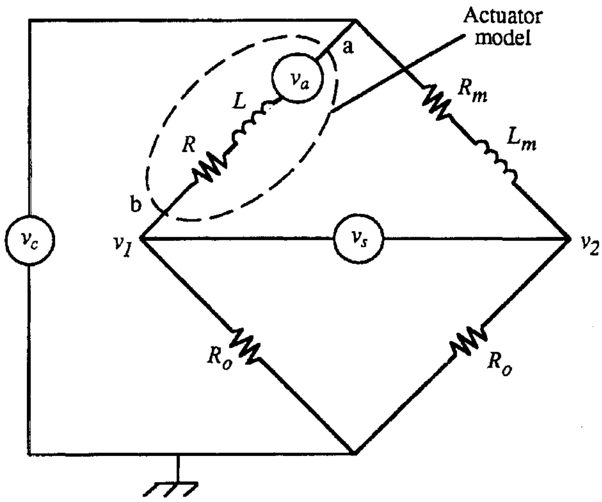

Fig. 1 Self-sensing circuit using a bridge technique.

of magnetic flux density and field. First substitute in Eq. (5) and multiply through by the cross-sectional area A:

$$\Phi = \hat{e}A\varepsilon + (nA\mu/\ell)i \tag{7}$$

Now applying Faraday's law of induction for a solenoid, which states that the induced emf in a solenoid is equal to the negative time rate of change of the magnetic flux times the number of turns in the coil, Eq. (7) becomes

$$v = -n\hat{e}A\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} - L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{8}$$

In comparing Eqs. (6) and (8) notice that when an actuation current is applied to the strut a strain results; however, the sensing voltage is proportional to the time rate of strain. It is this strain rate signal that will be extracted as our self-sensing signal.

Self-Sensing Overview

The implementation of self-sensing is straightforward for magnetostrictive materials (see Fig. 1); the magnetostrictive actuator, modeled as a voltage source, resistor, and inductor in series, is inserted in one leg of a simple Wheatstone bridge at connection points a and b. If R_m and L_m are matched with R and L, respectively, the resulting signal voltage $v_s = v_1 - v_2$ will be free from the control voltage v_c and only proportional to v_a, the voltage generated because of the magnetostrictive sensing effect. The self-sensing signal v_s now can be used as the source for any of a variety of control techniques for feedback to v_c.

Testbed

The truss and active magnetostrictive strut were developed for proof of concept of the self-sensing as applied to magnetostrictive materials. It is composed of aluminum node and strut elements manufactured by Mero Structures, Inc. Each truss element has a 22-mm o.d. and a thickness of 1 mm. Each node weighs 78.2 g, with additional weight added nodally by the beam fasteners, which weigh 77.8 g each. Its dimensions are 2.5 × 0.5 × 0.36 m. The truss was cantilevered horizontally and attached to a large monolithic steel structure. The truss was constructed such that the actuator could be placed in locations resulting in structural symmetry if only lateral bending modes (those modes parallel to the floor) are to be controlled.

The magnetostrictive strut was adapted from the research actuator RA101 developed by the ETREMA Division of Edge Technologies, Inc. The components of the actuator are simple; a rod of the giant magnetostrictor Terfenol-D® is surrounded by a solenoid, all of which is encased in a prestressed housing to enhance strain per field performance. Additionally, this research actuator consists of a permanent magnet to provide dc strain biasing allowing the strut to be driven in a bidirectional manner.

Preliminary Analysis

Before designing the simulation and experiment for this project the objectives had to be clearly defined. Since the overall goal was simply to prove the viability of employing a magnetostrictive actuator in a self-sensing configuration, the authors chose to attempt an increase in damping of the first lateral bending mode of the truss.

The control methodology used in this project is known as positive position feedback (PPF) control and was first presented by Goh and Caughey.[11] This technique has been used by several researchers to suppress vibrations in flexible structural systems. Vibration suppression is realized by electromechanically coupling the lightly damped dynamics of a flexible structure to a highly damped electrical filter. The position output of this second-order filter is fed back positively to the structure. The net closed-loop effect is a tradeoff in the damping of the filter for increased damping in the structure.

Using a priori knowledge of the structure, namely, its first mode properties, a root locus analysis was carried out on the feedback system. Using a filter natural frequency 1.1 times greater than that of the truss and a filter damping ratio of 30%, the root locus diagram was generated. The optimum gain value was then selected from this diagram resulting in closed-loop damping ratios of the structure and filter of 12 and 20%, respectively.

Experimental Results

First, open-loop transfer function data of the truss was acquired. The first mode had a damped natural frequency of 22 Hz with a damping ratio of 0.6%. The second mode's damped natural frequency and damping ratio were 112 Hz and 0.9%, respectively.

The goal of this project was to increase damping in the first mode of the truss. One modal PPF filter was used with a natural frequency of 24 Hz and a damping ratio of 30%. The gain was increased by small increments until maximum damping was achieved. The results can be seen in Fig. 2. The damping in the first mode was increased from 0.6 to 2.2%. By tweeking filter parameters and increasing the gain, a second type of response resulted. This response can be seen in Fig. 3. This time response was characterized by a large absorption of energy initially followed by an apparent decrease in damping leaving a residual lightly damped vibration with limit cycle behavior. Its initial damping ratio was 11.6% (which compares closely with predicted results) with the limit cycle damping out at a ratio of only 0.4%.

Further increases in gain for both responses resulted in instability. The authors believe this was because of the control voltage bleeding into the self-sensing signal because of nonlinearities in the Terfenol-D. Large hysteretic effects in magnetostrictive materials are well documented. Other nonlinearities can be seen as hysteretic variations of the actuation material's permeability. This effect is also common in most magnetic materials and leads to impedance mismatching in the self-sensing implementation. Since the success of

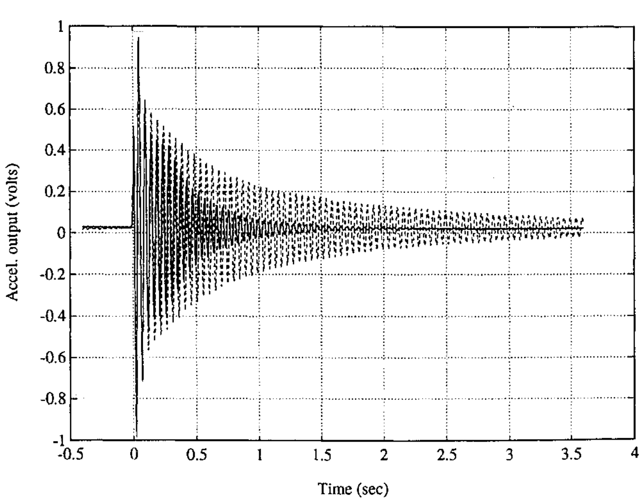

Fig. 2 Closed-loop first mode impulse response (solid line) compared to open loop (dashed line).

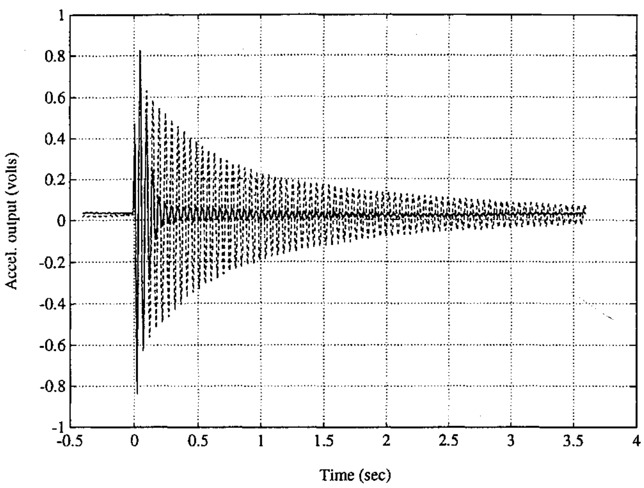

Fig. 3 Closed-loop response displaying residual vibration (solid line) compared to open loop (dashed line).

the self-sensing methods depends on proper impedance matching of elements to cancel out the control voltage, this nonlinearity is of crucial importance.

The limit cycle behavior of Fig. 3 can also be explained by nonlinearities of the system. Hysteresis, control voltage bleed through, and noise are the three most prevalent causes of suboptimum closed-loop performance for this project. The latter two phenomena were ruled out as causes of the limit cycle behavior after performing numerous simulations. Hysteresis is difficult to simulate but is known to cause limit cycle behavior in control systems.[12] Recall that not only does the actuator exhibit hysteresis, but the self-sensing signal does as well.

Conclusions

Implementation of the self-sensing control technique using a magnetostrictive actuator is viable. Results of this Note show that significant damping can be added to a structure. However, the effects of nonlinearities inherent in Terfenol-D make the implementation process nontrivial. A good system estimator would have to be used to implement a proper self-sensing control law. Although seemingly complex, additional self-sensing circuitry would eliminate the need for independent, and potentially noncollocated, sensors. Thus, this proof of concept may motivate actuator designers to consider the potential benefits of self-sensing actuation.

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Precise Trajectory Tracking Control of Elastic Joint Manipulator

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I. Introduction

IN the design of high-performance motion systems, the flexibility of the drives and structures, particularly at manipulator arms, presents an obstacle. Some techniques and strategies related to the subject are extensively discussed in Ref. 1.

Similar to the compliance and control of the manipulator arms, a good example of the flexible system is flexible spacecraft, because the location of points at their extremities must be controlled, sometimes to very high precision, by torquing some other point that is separated from the first by sections of flexible structures.[2] In Ref. 3 a survey on the active control technology for large space structures focuses on the development of systematic modeling and design tools for the control of large space structures that has occurred over the past decade.

The objective of this Note is to obtain a transfer function of the servomotor-driven flexible shaft system that includes the natural frequency and damping ratio of the shaft and to propose a trajectory function with which precise trajectory tracking is possible.

The flexible system consists of dc servomotor, harmonic drive, flexible shaft, and manipulator arm. A transfer function relating the actual angular position to the desired angular position of the arm is obtained, including proportional-integral-derivative (PID) type control gains, inductance, flexible system natural frequency, subsystem natural frequency, and the material damping. Transfer function zeros and poles are analyzed in the Laplace domain, and system response to cycloidal input motion is discussed. The close relation between the settling time of the system and the rise time of the trajectory function is presented, and the possibility of the precise tracking of the cycloidal trajectory for the flexible system is shown.

II. Formulation

The flexible system considered here consists of a dc servomotor, harmonic drive, flexible shaft, and a manipulator arm. A sketch of the system is shown in Fig. 1a. Also the equivalent system, at which the motor inertia is reflected to the manipulator arm axis, is shown in Fig. 1b. Here, T indicates torque applied by the dc servomotor, J_m is the motor inertia, θ_m is the motor angular displacement, k and c

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