Journal of Sound and Vibration (2000) **235**(2), 261–280
doi:10.1006/jsvi.2000.2921, available online at http://www.idealibrary.com on IDEAL®

VIBRATION SUPPRESSION USING A LASER VIBROMETER AND PIEZOCERAMIC PATCHES

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(*Received* 26 *May* 1999, *and in final form* 7 *January* 2000)

A new vibration suppression technique is investigated that uses a scanning laser Doppler vibrometer to measure structural velocities for feedback in a control system. Piezoceramic patches are used for control actuators and to measure strains for feedback in the control system. Simulations using a finite-element model of a cantilever beam and laser sensing showed that if the laser can be scanned faster than the highest natural frequency of the beam, and all the velocity states are measured, the performance of classical linear optimal control can be approached. To further verify the technique, an experiment using a cantilever beam structure was built and the laser sensor was tested along with other types of sensors. In the experiments, only the first vibration mode of the cantilever beam was controlled because of a limitation in the speed of the scanning mirror used. The testing showed that a hybrid-sensing technique in which the laser and a piezoceramic patch are used simultaneously for sensing, and separate piezoceramic patches are used for actuation, was a very effective approach for vibration suppression. Although laser sensing requires expensive components, the technique proposed can be used for the control of structures that are large, inaccessible, require non-contact sensors, or where a large number of coordinates must be measured.

1. INTRODUCTION

Active vibration suppression can improve the reliability and safety of structures by reducing fatigue cracking and damage. Also, flight and space vehicles designed with an integrated vibration suppression system can be built lighter to improve performance and reduce overall operating and maintenance costs. In this paper, a new smart structures concept is investigated for vibration suppression of flexible structures. The approach combines use of a scanning laser Doppler vibrometer (SLDV) and piezoceramic lead zirconate titanate (PZT) patches. The laser vibrometer measures the velocity of the structure in the direction of the scanning laser beam for use as a feedback control signal. The PZT patches measure strains used for control signals or apply actuation forces to counteract structural vibration. Laser velocity sensing and PZT strain sensing can also be used simultaneously. This hybrid approach is advantageous because the structural velocity is maximum and the strain is zero

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when the structural vibration mode passes through equilibrium, and the structural strain is maximum and the velocity is zero when the vibration mode is at its peak amplitude. These complementary control signals provide a more effective control action because two states are measured instead of one, and when one sensor output is zero the other is at a maximum. In addition, if a single sensor were used, differentiation or integration would be required to obtain the second state. This introduces time delay and noise into the control loop. The single sensor also cannot physically be at two locations, one where velocities are large and a different location where strains are large. In general, velocities and strains will not be the maximum at the same location on complex structures. A simply supported structure is a counterexample where they could be the maximum at the same point. In the control technique proposed, strains should be measured close to the actuators because collocation provides stability [1] for the part of the control loop with strain sensing and actuation. The general control technique proposed has possible applications for structures that require non-contact sensors or where a large number of coordinates must be measured. The applications may include structures that are large or inaccessible (buildings, bridges, space structures, circuit boards), where embedding a large number of sensors is impractical (composite materials, inflatable structures), structures whose surfaces are at high temperature (high-speed aircraft, space structures, engine components), components operating in an abrasive environment (rotating bladed systems), for structures that have a high surface loading (friction surfaces), when the structural surface is underwater (a submarine propeller), when the excitation is impulsive and the feedback signal is at high frequency (gun firing), or for materials that cannot incorporate sensors due to wave transmission properties (radomes, mirrors).

There are very few control laws available in the literature for use with a movable velocity sensor such as a scanning laser vibrometer. Thus, two possible control approaches are considered in this paper based on extending classical techniques of static feedback control. Computer simulation of the two active damping control algorithms is performed to suppress transient and random vibration using low control forces. Different sensor configurations are then experimentally investigated to compare performance of the control system and ease of use of the sensor. These sensors are: (1) an integrated accelerometer output, (2) a differentiated output from a PZT patch, (3) direct velocity feedback from a fixed laser Doppler vibrometer, (4) direct velocity feedback from a SLDV, and (5) using simultaneous strain and velocity measurements for the feedback signal.

This research may be the first time a scanning laser sensor and PZT patches have been combined for vibration suppression use. The hybrid sensor approach, in particular, may lead to improvements in vibration suppression because the two sensor types are complementary. The laser can scan the structure in regions where velocities are large (and strains are low), and a PZT patch can measure strains at locations where they are large (and velocities are low). The following sections present the simulations and experiments performed to investigate the potential of laser sensing with PZT sensing and actuation.

2. CONTROL LAW DESIGN FOR A SCANNING LASER SENSOR

A laser vibrometer is useful as a velocity sensor because no integration or differentiation of the control signal is required, the vibration normal to the surface of the structure is measured, no wires are needed, the sensor is non-contact, and the sensor can be moved over the surface of the structure. The scanning laser can also measure many coordinates to improve control performance as compared to a fixed laser measurement. However, new control laws are needed for use with the laser sensor. Extension of two classical control techniques is considered here for use with the scanning laser. The equations of motion for a feedback control system are presented first, and then the two control schemes are investigated.

2.1. STABILITY THEORY

The linear equations of motion for the closed-loop system with velocity feedback are

$$M\ddot{x} + C\ddot{x} + Kx = f(t) + Du, \tag{1}$$

where M, C and K are the mass, damping and stiffness matrices, x the displacement vector, f the external force, t the time, and the control force is

$$Du = -DG_v C_v \dot{x}. \tag{2}$$

Here, D is the actuator location matrix, G_v is the gain matrix for velocity feedback, and C_v is the sensor location matrix. Combining equations (1) and (2) gives

$$M\ddot{x} + (C + DG_v C_v)\dot{x} + Kx = f(t). \tag{3}$$

Assuming M, C, K are positive-definite and symmetric, then based on Lyapunov theory [1] equation (3) will be asymptotically stable if $(C + DG_v C_v) > 0$. For the case of a rotating system, the structural matrices would be non-symmetric or skew symmetric.

If PZT actuators (for strain excitation) and a laser sensor (to measure normal velocity) are used, the actuators and sensors are not collocated. Thus stability is not guaranteed. Also, if the laser is scanned, $C_v = C_v(t)$ and it is difficult to determine stability because the output location is time varying. Stability will be investigated here by performing simulations. An approach that can be used to maintain stability in experiments is to filter the sensor feedback signal to contain only the frequency components in the desired control bandwidth. In this case the control is only applied within the desired frequency range.

2.2. GAIN SWITCHING CONTROL

One technique to design the controller for the scanning laser is to use gain switching or scheduling. The approach is to determine the optimal gain for each coordinate assuming a fixed sensor, and then use gain lookup in the control law based on the sensor location when scanning. Determination of the stable gain space for each coordinate can be done by trial and error optimization when the number of degrees of freedom (d.o.f.) of the system and the number of design variables is small.

2.3. LQR CONTROL WITH TIME DELAY

Another approach to design the controller is to use a linear-quadratic regulator (LQR) control law [1–9] and update the state vector based on the scanning speed. In this case, MATLAB [10] can be used to find the optimal gain matrix G. The controlled system is written in first order form as

$$\dot{x} = Ax + Bu. \tag{4}$$

where A is the state matrix and B is the actuator location matrix in first order form given as

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} 0 \\ -M^{-1}D \end{bmatrix}.$$

The full state-feedback control law is

$$u = -Gx, \tag{5}$$

where u is the control force vector, and G is the gain matrix that includes velocity and position feedback gains. This control law minimizes the cost function

$$J = \int_{t_0}^{\infty} (x^{\mathrm{T}}Qx + u^{\mathrm{T}}Ru)\,\mathrm{d}t \tag{6}$$

subject to the constraint that the state dynamic equation (4) must be satisfied. Here Q and R are positive-semi-definite and positive-definite weighting matrices, respectively. The gain matrix $G = R^{-1}B^{\mathrm{T}}S$ is determined by solving the Riccati equation

$$SA + A^{\mathrm{T}}S - (SB)R^{-1}(B^{\mathrm{T}}S) + Q = 0, \tag{7}$$

where S is the solution to the Riccati equation. The control law given in equation (5) is used in this simulation study by updating the state feedback vector at the scanning speed of the laser, without any compensation for time delay. The position feedback part of the gains in the G matrix is also set to zero because velocities are measured by the laser, and integration to obtain position feedback would add delay and some computation error to the control loop. Optimizing the control law to compensate for time delay is recommended for future work based on the methods in references [2, p. 69], or [3].

The laser scanning approach attempts to obtain full state feedback to improve control performance. Another approach to obtain full state feedback is to build an observer to estimate the states that are not measured. Luenberger [5] showed that a state observer of order *n-m* can be constructed having arbitrary eigenvalues for any *n*th order completely controllable linear time-invariant system having *m* linearly independent outputs. Various approaches [6–9] have been developed for constructing reduced-order identity observers, including the matrix second order observer [7]. Design in the second order system is important because it is shown [8] that an error in the estimated velocity states occurs if an observer for a second order system is designed in a controllable and observable first order state-space framework. Also, when designing the observer, the system model must be known exactly and there must be no noise in the outputs. Otherwise, the control performance can deteriorate or the controlled system can become unstable. The linear quadratic Gaussian or Kalman filter methods can be used to design a controller and estimator for a stochastic system.

An observer requires extra computations in the processor and introduces time delay into the control system. If a reduced-order model of the system is used, the sensor output can be contaminated by the residue modes, and the control can excite the residue modes [2]. These spillover effects can occur when using the laser sensor or the observer. The value of the laser sensor is that it tries to eliminate the need for an observer and also reduce spillover effects. It is also possible that an efficient control system can be designed using a laser sensor and a second order observer. The laser can be used to measure more states than with conventional sensors, and the observer can be used to estimate the unmeasured states. This will minimize spillover effects. Simpler non-observer-based controllers using output feedback could also be developed using laser scanning.

3. CONTROL SIMULATION

The control simulation is performed for two different types of control laws; gain switching and LQR control. A uniform cantilever beam that is 0·838 m long, 4·45 cm wide, and 3·175mm thick with PZT patches near the root is modelled for the numerical simulation. The beam material is aluminum with an elastic modulus of 7×10^{10} N/m^2 and a mass density of $2{\cdot}7 \times 10^3$ kg/m^3. A Finite element model (FEM) of the beam [11] using three planar elements (six degrees of freedom) is built as shown in Figure. 1. The simple beam model has three nodes and six d.o.f. The highest frequency of the modes is at 587 Hz. The PZT actuator patch located at the fixed end of the beam is used to apply a moment at coordinate $x2$, but the mass and stiffness of patch are not modelled. The disturbance force $f(t)$ is a 50 Hz sine input acting perpendicular to the beam as shown in Figure 1.

3.1. SIMULATION USING GAIN SWITCHING CONTROL

Direct velocity feedback with constant gain for each node is used. Initial condition, impulse, and sine inputs were examined. The scan rate of the laser and the gains for each node in the controller are input to the code. The simulation is run for different conditions of fixed and scanning sensors. The time step for all simulation cases is $dt = 2\text{e-}6$ s. Results for a sine excitation at 50 Hz are presented here. Figure 2(a) shows the beam response with the fixed laser measuring the vibration at the free end of the beam. In this case, there is no scanning and the root mean-square (r.m.s.) displacement of the three translational d.o.f. $(x, x3, x5)$ is 5·54 mm. The response with fast scanning and gain switching is shown in Figure 2(b). In this case, the scanning update time is $ts = 2\text{e-}6$ s and the RMS displacement of the three translational d.o.f. is 4·7 mm.

These results show that the scanning laser using gain switching gave only a small performance improvement compared to using the fixed laser. This is because at each time point in the solution the control force is based on feedback from only one measurement coordinate (from the FEM grid point closest to the position of the scanning laser), and information on past measurements is not used.

3.2. SIMULATION USING LQR CONTROL WITH TIME DELAY

All velocity states (translation and rotation) are assumed to be able to be measured or calculated from measurements and are used for state feedback. In addition, the position

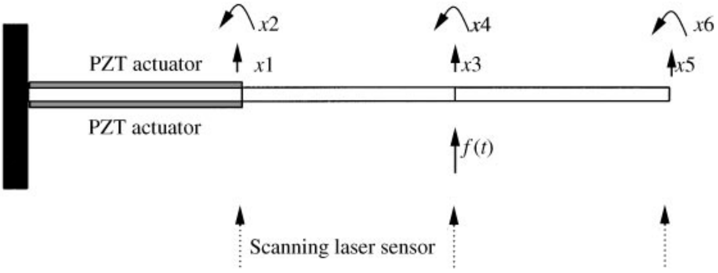

Figure 1. Finite element model of a cantilever beam for the control simulation.

gains are set to zero so that only velocity feedback is used in the control. A sine force at 50 Hz is used to excite the cantilever beam. The scan rate for the laser and the LQR gains are input to the code.

The response of the cantilever beam is first computed using a relatively slow time to scan of $ts = 2\text{e-}3$ s, that is, a delay of ts between updates of the full velocity state vector. This delay is equivalent to sampling the state vector at $1/ts = 500$ Hz. The response of the three translational d.o.f. is shown in Figure 3(a). In this case, the response goes unstable because the sampling time is slower than the sixth mode frequency of 587 Hz. The r.m.s. displacement of the three d.o.f. for this case is 0·71 mm.

This simulation is re-run with a smaller sampling time of $ts = 1\text{e-}4$ s for the full state vector. In this case, the vibration response is suppressed very quickly, and the r.m.s. displacement of the three translational d.o.f. is 0·32 mm. This response is shown in Figure 3(b). This simulation shows that if scanning can be done fast, the full performance of the LQR method can be approached. With a slower scan rate, performance degrades to instability when there is no compensation for the time delay in scanning.

The natural frequencies and damping ratios for the FEM model beam for the uncontrolled, controlled with the fixed laser, and controlled with the LQR fast scanning laser are given in Table 1. These results show that the natural frequencies are changed only

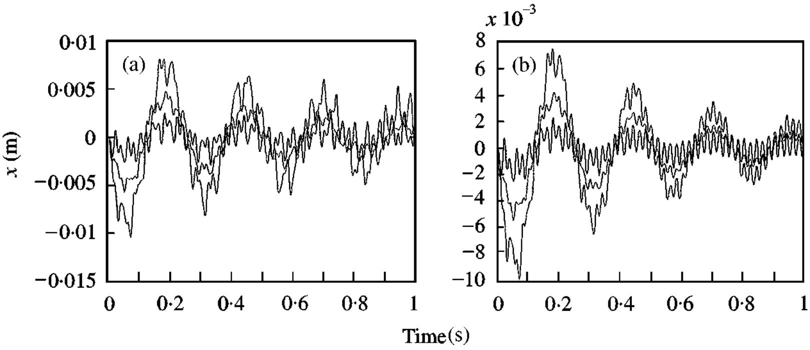

Figure 2. Simulation of the cantilever beam translational displacements ($x1$, $x3$, $x5$) in meters for the cases of (a) no scanning (r.m.s. displacement is 5·53 mm), and (b) with laser scanning and gain switching (r.m.s. displacement is 4·7 mm).

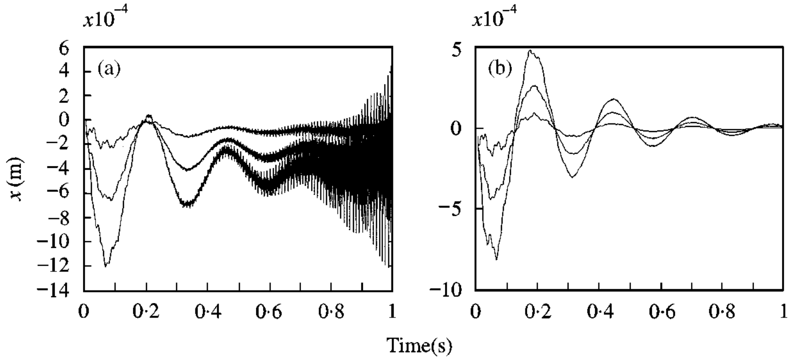

Figure 3. Simulation of the cantilever beam translational displacements ($x1$, $x3$, $x5$) in meters versus time using laser scanning with LQR velocity feedback control for the cases of (a) the scanning update time is $ts = 2\text{e-}3$ s and (b) scanning update time is $ts = 1\text{e-}4$ s.

TABLE 1

Beam FEM natural frequencies and damping ratios for the uncontrolled and controlled cases

	Natural frequencies (Hz)			Damping ratios (ζ)		
Vibration mode no.	No control	Fixed laser sensor	LQR with fast scan	No control	Fixed laser sensor	LQR with fast scan
1	3·9131	3·9130	3·9229	0·0286	0·0415	0·1521
2	24·601	24·601	24·595	0·0053	0·0012	0·0511
3	69·513	69·513	69·537	0·0038	0·0024	0·0197
4	156·54	156·54	156·78	0·0056	0·0097	0·0485
5	294·61	294·61	293·73	0·0096	0·0058	0·0545
6	587·34	587·3	586·69	0·0186	0·0203	0·0304

a very small amount due to the control, and that the LQR control has a large increase in the damping ratios for all modes. The fixed laser control adds moderate damping to only the first mode. Thus, there is a strong motivation to obtain full state feedback by using the fast scanning laser. Other control laws would give a somewhat different comparison; however, the LQR method is the optimal control for a linear system given a set of pre-selected weighting matrices, and is the best that can be achieved in terms of performance.

As shown in Table 1, the switching control simulation did not give as good a performance as the LQR control. This is because in the switching control only one spatial measurement point at a time is considered, while the LQR method considers all d.o.f. to be measured. If the time delay in updating the measurements can be incorporated into an LQR control law, this approach is expected to provide better performance than the switching control. If the laser is scanned fast to obtain full state feedback and minimize delay, optimal performance can be achieved.

4. EXPERIMENTATION USING DIFFERENT SENSOR TYPES

Vibration control is critical to the aerospace field because flexible structures can undergo damaging high-amplitude oscillations near their lower natural frequencies. In many applications, active damping using velocity feedback can suppress vibrations using low control forces. In reference [12], rate feedback or active damping was shown to be an efficient method of suppressing vibration for the case of a random vibration input to a flexible structure. In this section, velocity feedback and a PZT actuator are used to suppress vibration of a flexible cantilever beam. Different types of vibration sensors are used to obtain the velocity feedback, and the control system performance for the different sensors is compared for effectiveness and practically.

The type of sensor used to obtain rate feedback is an important part of the vibration control system. Conventional accelerometer output signals can be integrated to obtain rate feedback, but the integration introduces time delay in the control system. The PZT patch sensor measures strain, and this signal can be differentiated to obtain strain rate, but the differentiation puts time delay in the control system and amplifies noise. Filtering is then necessary to remove the high-frequency components of the control signal. A third type of sensor, the fixed laser Doppler vibrometer, measures velocity directly, but filtering is necessary to remove high-frequency noise due to speckle pattern motion. These three types of sensors are compared for effectiveness using the controlled beam structure.

4.1. TEST SET-UP

A cantilever beam structure was built for testing the sensor types. The test apparatus consists of the aluminum cantilever beam with the same dimensions and properties as used in the FEM model in section 3, an alpha DEC high-speed processor [13], and a fixed laser vibrometer [14]. The experimental set-up is shown in Figure 4. The laser Doppler vibrometer is used to measure the normal velocity of the vibrating cantilever beam. The laser beam or object beam reflecting from the structure is interfered with a reference beam in the laser head and the Doppler shift of the object beam causes an intensity variation that is proportional to the velocity of the vibrating structure. The laser is very accurate and has a wide bandwidth for measuring vibrations. A PZT patch [15] nominally $5{\cdot}08\,\text{cm} \times 3{\cdot}81\,\text{cm} \times 0{\cdot}254\,\text{mm}$ is mounted on each side at the root of the beam. This positioning was chosen to take advantage of the theoretically guaranteed stability provided by using collocated actuators and sensors, and because the greatest strains occur at the fixed end of the beam. The data acquisition system or controller [13] accepts the input sensor signal, and computes the feedback signal. Figure 4 also shows the block diagram of control circuit. The modelling was done using MATLAB SIMULINK and the block diagram was downloaded to the controller for real-time hardware-in-the-loop control design.

The control method used is rate feedback, which essentially entails changing the sign and amplitude of the feedback signal from the sensor and applying it to the actuator mounted to the structure. Rate feedback is often a reliable method of control because it reduces the computational complexity of the control law. However, processing time can still be a problem with some data acquisition systems if the PC processor is used to perform some of the computations. The phase lag between the sensor input signal and the control output signal could be large enough that the system has changed before an output can be applied. The data acquisition system used in this experiment uses its own processors to compute the feedback signal with a minimum delay. The effectiveness of the vibration suppression

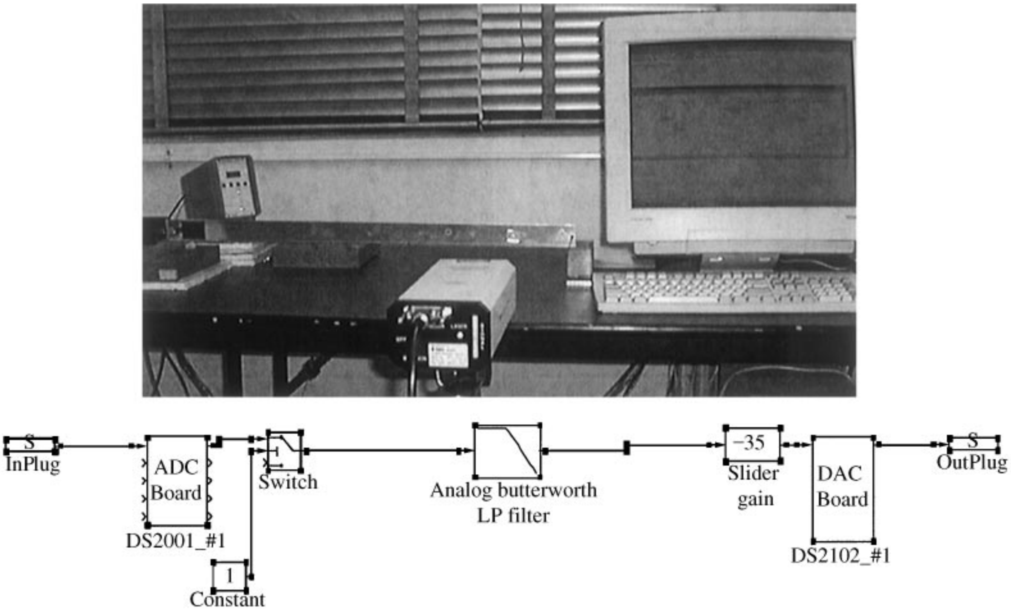

Figure 4. Experimental set-up for testing different sensor types of vibration suppression and SIMULINK block diagram of the control circuit for direct velocity feedback.

system using individually PZT patches, accelerometers, and a laser vibrometer as sensors is discussed below.

4.2. EXPERIMENTAL RESULTS

The experiment is conducted using one or two PZT patches as actuators and individually the accelerometer at the end of the beam, the PZT patch at the root, and the laser near the tip of the beam as sensors. The cantilever beam is displaced and released from the same position each time and the control effectiveness is judged based on how fast the transient vibration can be suppressed. The gains are adjusted for each sensor type to optimize the control performance. Direct velocity feedback is used with the optimized constant gain value, but no correction was made for phase lag for any of the circuits. The uncontrolled vibration response of the beam is shown in Figure 5(a). The first vibration frequency of the uncontrolled beam is about 4 Hz.

The controlled responses for different cases are measured using the accelerometer, PZT patch, and the laser as the sensors, and one or two PZT patches as the actuator. Retro-reflective tape was used on the cantilever beam to increase the intensity of the reflected laser signal. The damping ratios for each case were computed [11] using the equation

$$\zeta = \delta/\sqrt{4\pi^2 + \delta^2}, \tag{8}$$

where $\delta = (1/n)\ln(x_0/x_n)$, and x_0 and x_n are the vibration amplitudes at an initial point and n cycles later.

Figure 5(b) shows the response with the accelerometer sensor and one PZT patch actuator. Different time scales are used on the plots to show the details of the response. The least improvement in the damping ratio occurred for the accelerometer and one patch case. This is partly due to the difficulty in optimizing the gain due to time delay from integrating and filtering the accelerometer signal. The filter could have been optimized further to increase performance in this case. Figure 5(c) shows the response with one patch as a sensor and one patch as an actuator. For the PZT sensor, the differentiation of the signal introduced time delay in the output, but an increase in the damping ratio was achieved. Figure 5(d) shows the controlled vibration response of the cantilever beam with a laser sensor at the free end and one PZT patch actuator near the fixed end. Figure 5(e) shows the response for the accelerometer sensor and two PZT patch actuators. The second actuator significantly improved the control action. Figure 5(f) shows the controlled vibration response of the cantilever beam with a laser sensor at the free end and two PZT patches near the fixed end. The largest damping ratio was obtained using the laser sensor because there was no integration or differentiation of the control signal, only filtering to remove the high-frequency components that could destabilize the control system.

The resulting damping ratios for all cases are listed in Table 2. There is some variation in computing the damping ratios depending on how many cycles and which part of the response is used. Based on the calculated damping ratios, the laser and PZT sensors both perform well and somewhat better than the accelerometer. When using the PZT sensors, they act as a capacitor. The resistance of the load in series with the PZT creates an R-C circuit. This circuit acts as a highpass filter [16] and causes some phase lag in the sensor signal at low frequencies. The cases using the PZT sensor may have been optimized further by correcting the phase lag. The experiment using both of the PZT patches as actuators and the laser sensor provided a large increase in damping ratio compared to the undamped

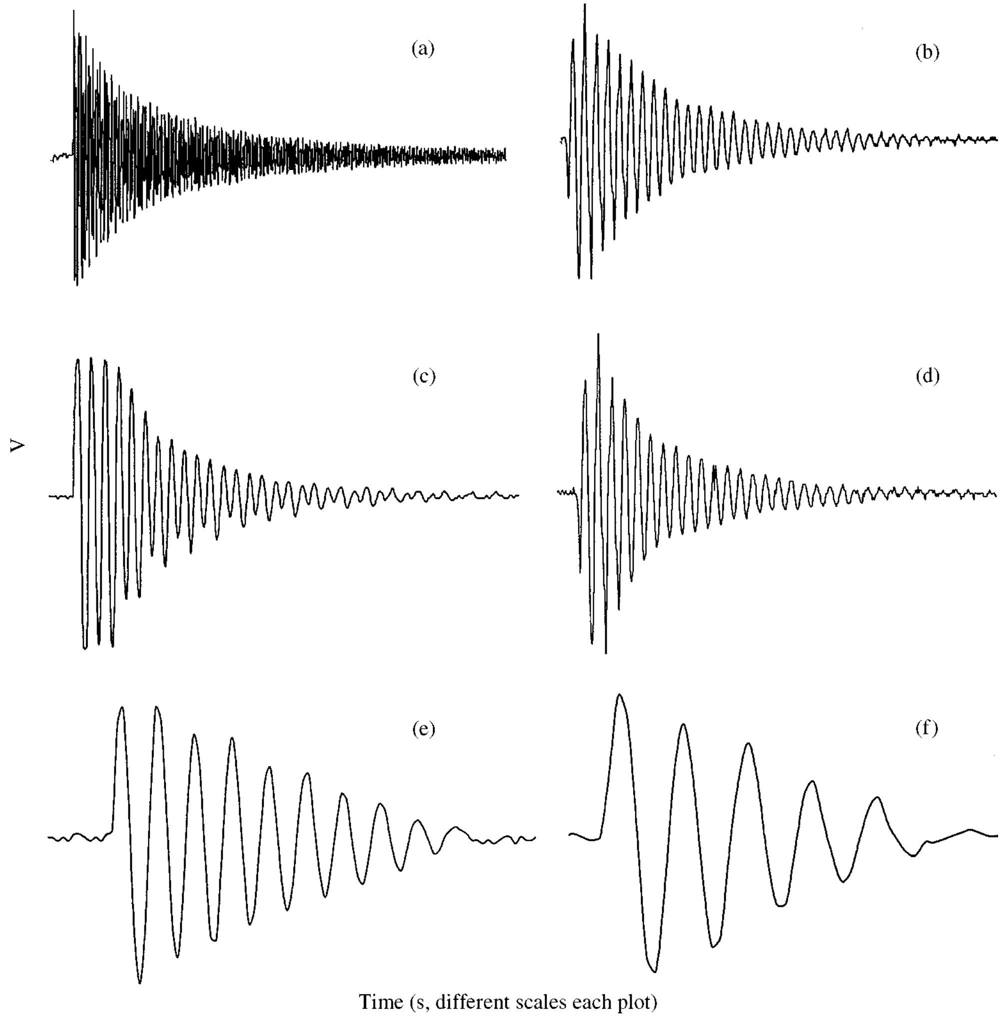

Figure 5. The measured vibration response of the cantilever beam (voltage versus time plots use different scales): (a) no control, (b) control with an accelerometer sensor at the free end and one actuator patch at the fixed end, (c) control with one sensor patch and one actuator patch collocated near the fixed end, (d) control with a laser sensor at the free end and one actuator patch near the fixed end, (e) control with an accelerometer sensor at the free end and two actuator patches near the fixed end, and (f) control with a laser sensor at the free end and two actuator patches near the fixed end.

beam, and the PZTs added very little mass to the beam. The combination of the Alpha Dec high-speed controller, the PZT patch actuator with wide bandwidth, and the direct velocity feedback from the laser provided a control system with a fast response. However, the practicality of using the laser in cases where the line of sight to the structure is obscured, or at small incident angles is a limitation. The laser sensor [14] is also very expensive compared to a simple PZT patch or a coupler and accelerometer. An advantage of the PZT patch is that signal conditioning is not necessary as when using the accelerometer.

This section examined the feasibility of using a smart material actuator, rate feedback, and different sensor types for vibration suppression of flexible structures. It was shown that rate feedback could be used with PZT actuators to provide substantial increases in the structural-damping ratio using small control forces. The use of the laser for velocity

TABLE 2

Experimental damping ratios for different sensor types using constant gain feedback

Control case	Damping ratio ζ and (transient response)	Figure no.
Uncontrolled	0·01 (∼ 40 s transient)	5(a)
Accelerometer sensor, 1 PZT patch actuator	0·02 (∼ 7 s transient)	5(b)
1 PZT patch sensor, 1 PZT patch actuator	0·029 (∼ 5 s transient)	5(c)
Fixed laser vibrometer sensor, 1 PZT patch actuator	0·029 (∼ 5 s transient)	5(d)
Accelerometer sensor, 2 PZT patch actuators	0·031 (∼ 3 s transient)	5(e)
Fixed laser vibrometer sensor, 2 PZT patch actuators	0·069 (∼ 1·5 s transient)	5(f)

measurements in a control system is a new approach that potentially offers improved performance, but the practicality of laser sensing has to be established. The control technique presented in this section was shown to efficiently suppress vibration of a simple structure. The technique can potentially be extended to large complex structures where the advantages of laser sensing are the capability to provide centralized control, reduced communication difficulties, and the ability to measure the response at many points on the structure by scanning the laser. Control by scanning the laser is investigated in the next section.

5. EXPERIMENTATION USING A SCANNING LASER SENSOR

Control experiments were performed using an alpha DEC high-speed processor, a fixed laser vibrometer, a mirror scanner developed at NCA&TSU, one piezoceramic sensor patch to drive the scanning mirror and for use as a feedback control signal, and two piezoceramic patches for actuation of the cantilever beam structure. The same cantilever beam is used as modelled in the FEM simulation in section 3 and in the sensor study in section 4. A SIMULINK control diagram with filters and gains was downloaded to the controller for real-time hardware in the loop simulation.

A schematic of the control system is shown in Figure 6. The actual hardware is shown in Figure 7(a). The mirror scanner developed at NCA&T is shown in Figure 7(b). In the mirror scanner, a bimorph PZT patch is used to oscillate the mirror. The PZT actuators on the cantilever beam are nominally 5·08 cm × 3·81 cm × 0·254 mm and are encapsulated and electrically insulated from the structure. The two patches were driven from two separate channels of an amplifier where the control signal to the amplifier was input to both channels. This reduces the capacitive load on the amplifier and gives the control system the highest bandwidth. A PZT sensor patch is used to synchronize the mirror with the beam vibration and is nominally 5·08 cm × 2·54 cm × 0·254 mm in size. A polyvinylindene fluoride (PVDF) [16] film 5·08 cm × 5·08 cm × 0·050 mm bonded directly to the aluminum beam was initially used as the sensor. The PVDF has an advantage that a large sensor can be used

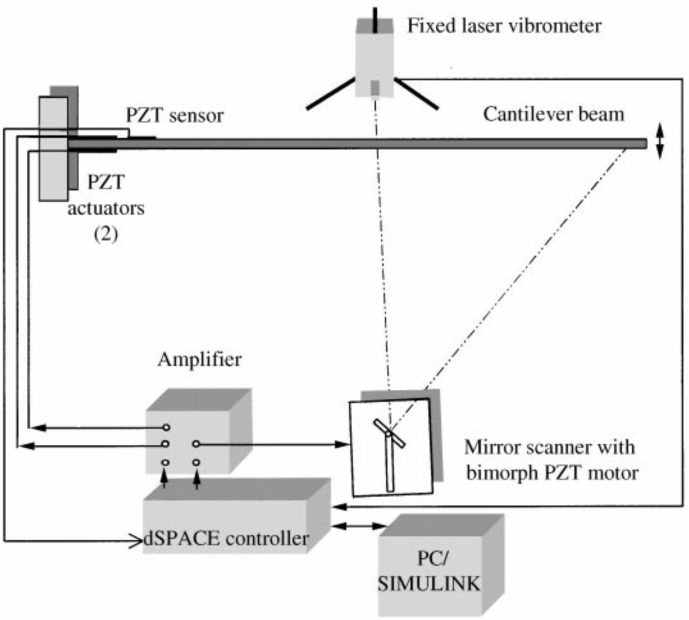

Figure 6. Schematic of the vibration suppression control system using a scanning laser and PZT patches.

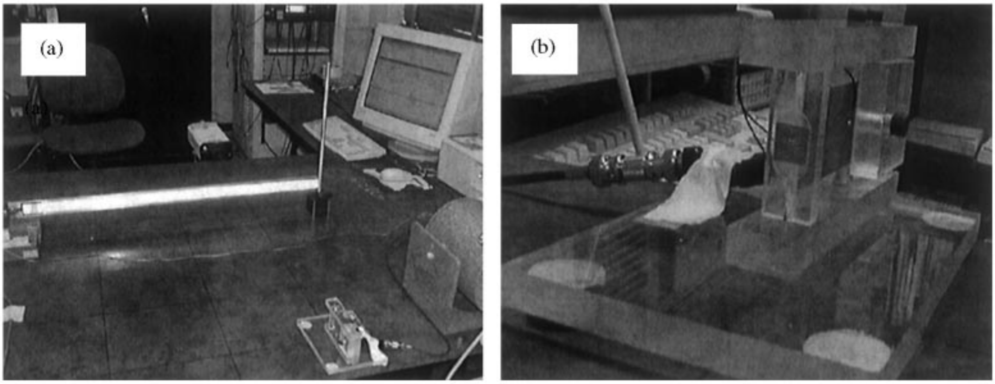

Figure 7. The vibration suppression set-up: (a) the laser, scanning mirror, and beam with PZT patches, and (b) the scanning mirror using a PZT bimorph motor.

to spatially filter the response. However, in this experiment the voltage output of the PVDF film was small and contained 60 Hz noise. Thus, it was decided to use an encapsulated PZT patch for the sensor that was electrically insulated from the structure. The voltage output from the PZT patch for the first mode of vibration was about 100 times greater than from the PVDF film.

At high scanning speeds, laser speckle noise (laser drop out when passing dark speckle lines) and optical path length change are problems that occur when using a laser sensor. Reflective tape is used to reduce speckle noise. The PZT bimorph scanner with the laser aligned on the pivot shaft minimizes the optical path length change. In testing, it was found that the maximum speed of the mirror scanner built is relatively slow (15–30 Hz) due to chatter in the pivot. This limits the control performance to low frequencies. Therefore, the simulation was conducted by controlling the free vibration of the beam due to an initial displacement at the tip of the beam. The same displacement is repeated for each test by displacing the tip of the beam to touch a stop and releasing the beam which then vibrates mainly in the first mode. Since the control was limited to the first mode, Butterworth filters are used to filter out high frequencies in the sensor signals, and then a simple constant gain feedback is used. The scanning mirror was driven by the absolute value of the sensor PZT patch which synchronized the mirror scanning to the first vibration mode of the beam. This control technique does not need a model of the structure, and it is simpler that the LQR method used in the simulations. When a faster scanning mirror is developed, the LQR control method can be implemented in the experiment. With this, the control performance is expected to improve and the controller will be able to operate over a wider bandwidth.

In the following experiments, to given an equal basis for the control comparison, the peak voltage of the actuator control signal from the DAC is kept at 1·6 V for all cases. This voltage is amplified 10 times by the controller and then 10 times in the amplifier. This gives a peak voltage to the patches of 160 V. In the experiments, the Butterworth filter for the laser has a low-pass range of 0–10 Hz, and the filter for the PZT sensor feedback has a range of 0–5 Hz. Thus, only the first mode of the beam is controlled. This was necessary because the mirror scanner chattered at frequencies above 15 Hz. The mirror must be redesigned to have a higher bandwidth to improve performance of the existing system. Five experiments were performed to determine the response of the uncontrolled beam and to investigate different control configurations. These experiments are described below.

5.1. RESPONSE OF THE UNCONTROLLED BEAM

The response of the cantilever beam with no control is measured here as a baseline case to compare the control performance. The system response (PZT and laser sensor voltages versus time) showed that the uncontrolled system has very small damping. The damping ratio for the uncontrolled case is $\zeta = 0{\cdot}008$.

5.2. CONTROL USING PZT SENSOR FEEDBACK

The SIMULINK block diagram for control using only the PZT sensor feedback is shown in Figure 8. The system response is also shown in Figure 8. The damping ratio is increased to $\zeta = 0{\cdot}038$.

5.3. CONTROL USING FIXED LASER FEEDBACK

The non-scanning laser is used for feedback and the cantilever beam is controlled by the two PZT patches near the root of the beam. The SIMULINK control circuit is shown in Figure 9. The free vibration response of the sensor patch on the beam and the control signal to the actuator patches are also shown in Figure 9. The response of the beam is damped quickly for a small initial displacement at the end of the beam. The damping ratio for this case is $\zeta = 0{\cdot}072$. For larger initial displacements, saturation of the amplifier at 200 V output occurs at the beginning of the response indicating that larger PZT patches could damp the vibration quicker. The voltage limit of the PZT patch is ±200 V.

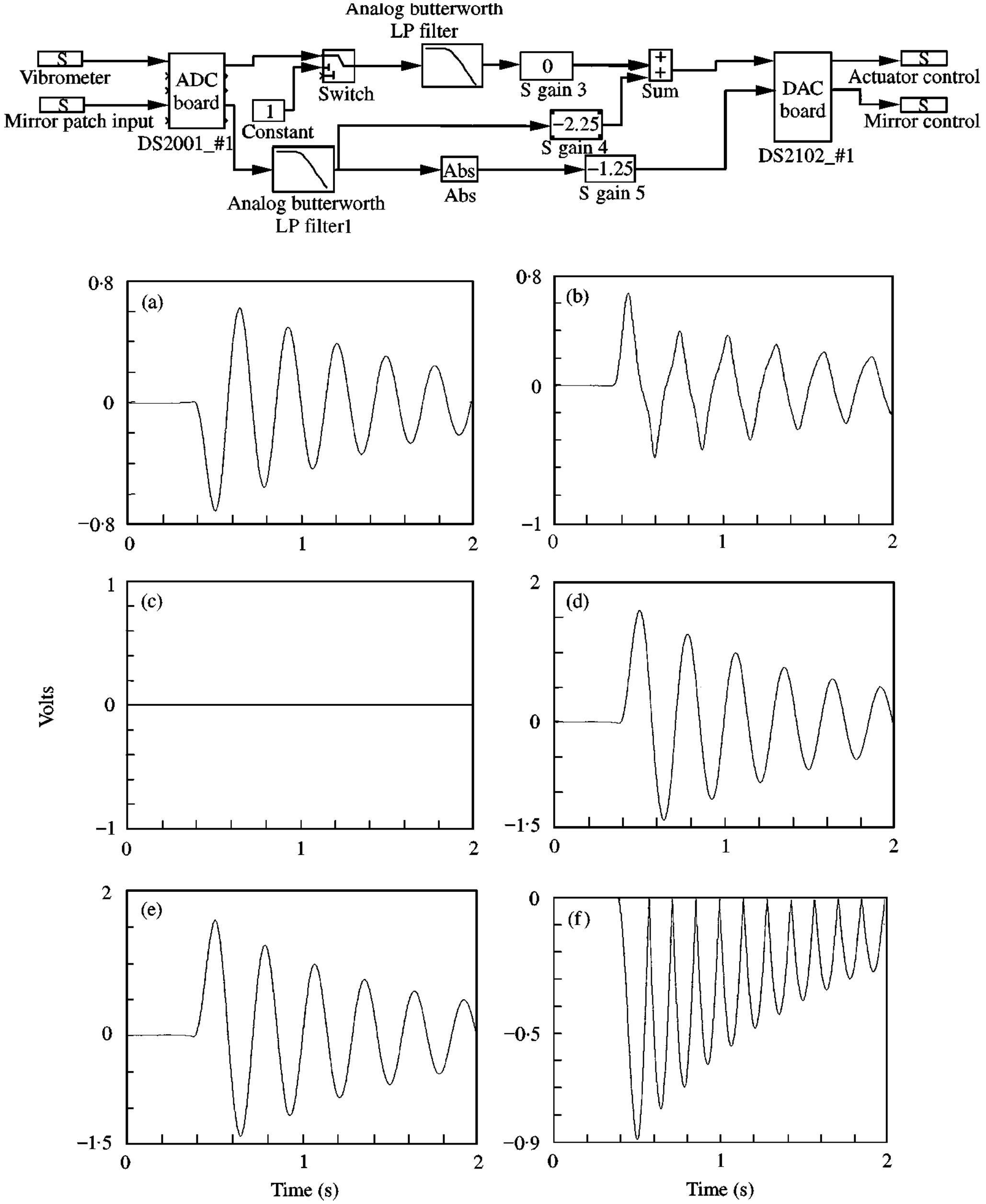

Figure 8. The SIMULINK block diagram and the system response using the PZT sensor feedback only: (a) the PZT sensor signal after filtering, (b) the vibrometer signal after filtering, (c) the laser feedback control signal, sgain3, (d) the PZT feedback control signal sgain4, (e) the control signal from the DAC to the actuators, and (f) the control signal from the DAC to the mirror. The laser control gain is 0 and the PZT sensor control gain is −2·25.

5.4. CONTROL USING SCANNING LASER FEEDBACK

The laser is now scanned over half of the beam near the free end to obtain the feedback signal. The mirror is controlled by the sensor PZT patch near the actuator patches. The two large actuator patches are used for control. The SIMULINK control circuit is shown in

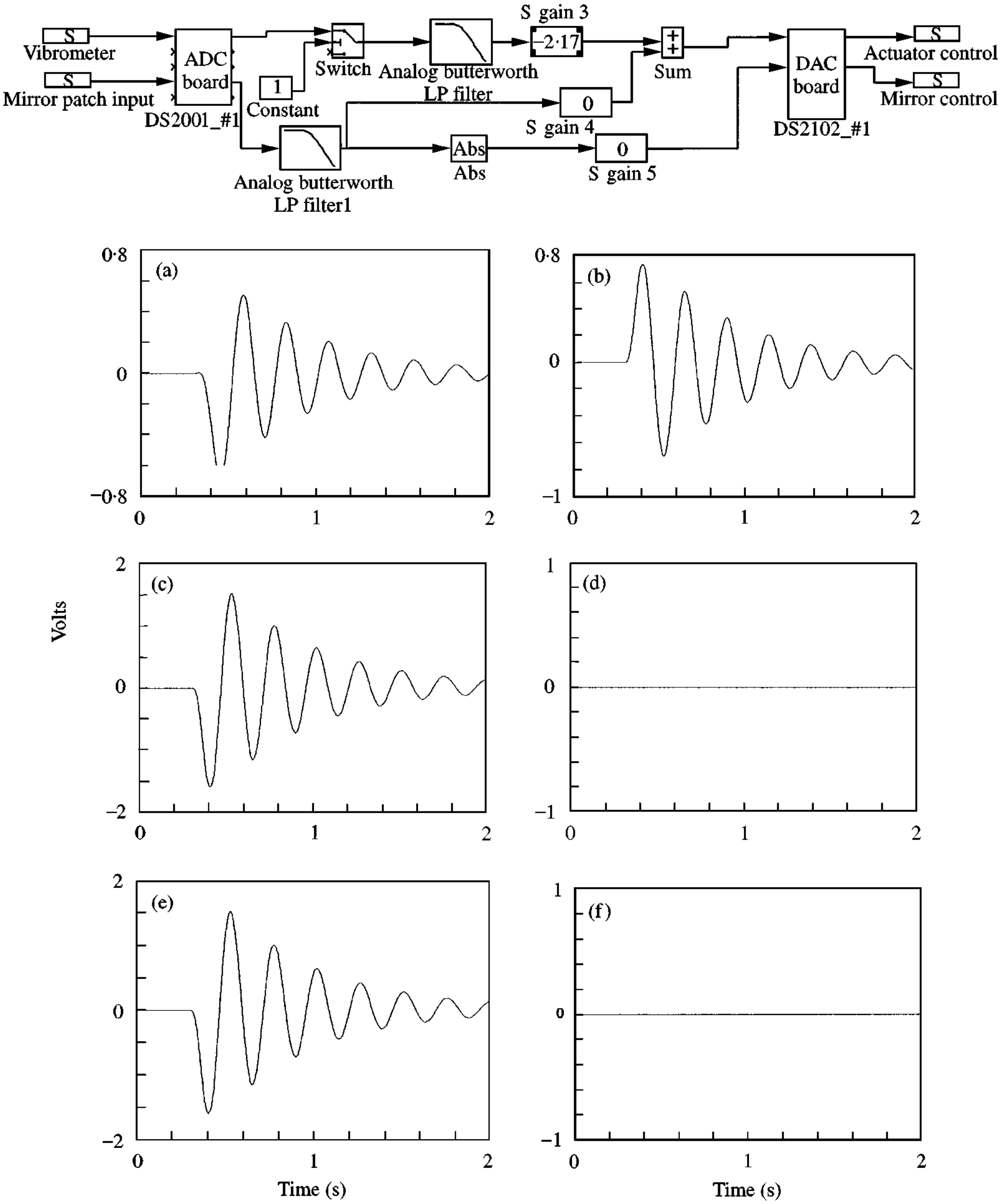

Figure 9. The SIMULINK block diagram and system variables using the fixed laser feedback: (a) the PZT sensor signal after filtering, (b) the vibrometer signal after filtering, (c) the laser feedback control signal sgain3, (d) the PZT feedback control signal sgain4, (e) the control signal from the DAC to the actuators, and (f) the control signal from the DAC to the mirror. The laser control gain is $-2{\cdot}17$ and the PZT sensor control gain is 0.

Figure 10. The response of this system is also shown in Figure 10. The damping ratio for this case is $\zeta = 0{\cdot}035$.

5.5. HYBRID CONTROL USING A SCANNING LASER AND PZT FEEDBACK

In this experiment, the scanning laser is used for feedback and the mirror to scan the laser is controlled by a sensor PZT patch near the root of the beam. The signal from the sensor

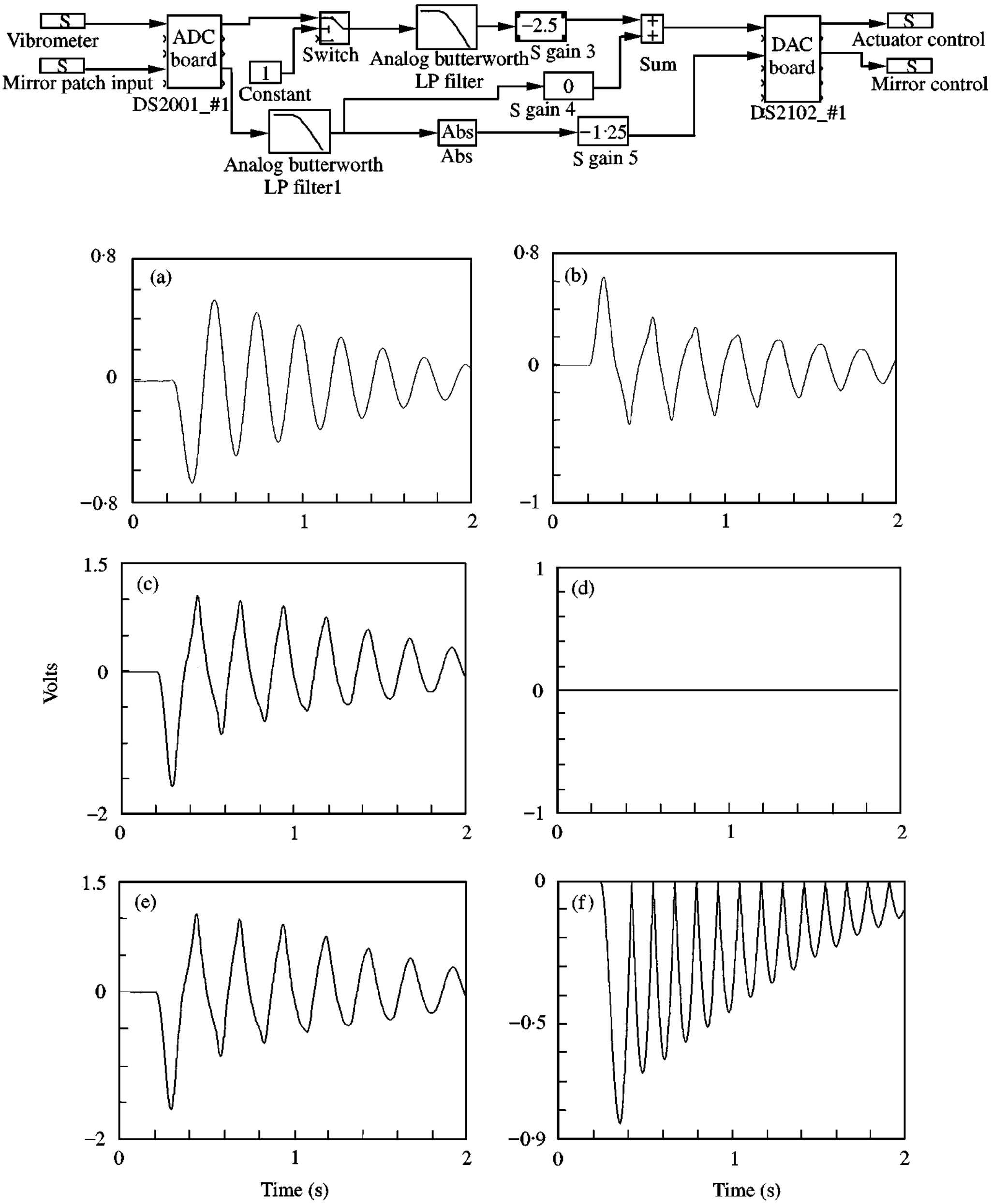

Figure 10. The SIMULINK diagram and system variables using scanning laser feedback: (a) the PZT sensor signal after filtering, (b) the vibrometer signal after filtering, (c) the laser feedback control signal sgain3, (d) the PZT feedback control signal sgain4, (e) the control signal from the DAC to the actuators and (f) the control signal from the DAC to the mirror. The laser control gain is −2·5 and the PZT sensor control gain is 0.

PZT is also used for feedback in the control circuit. The SIMULINK control circuit is shown in Figure 11. The PZT sensor is approximately collocated with the two PZT patch actuators. Thus, this part of the circuit is guaranteed stable in the presence of variations in the system parameters, neglecting the effect of imperfect collocation and noise in the sensor signals. The circuit using the scanning laser, PZT sensor, and two PZT actuators is not

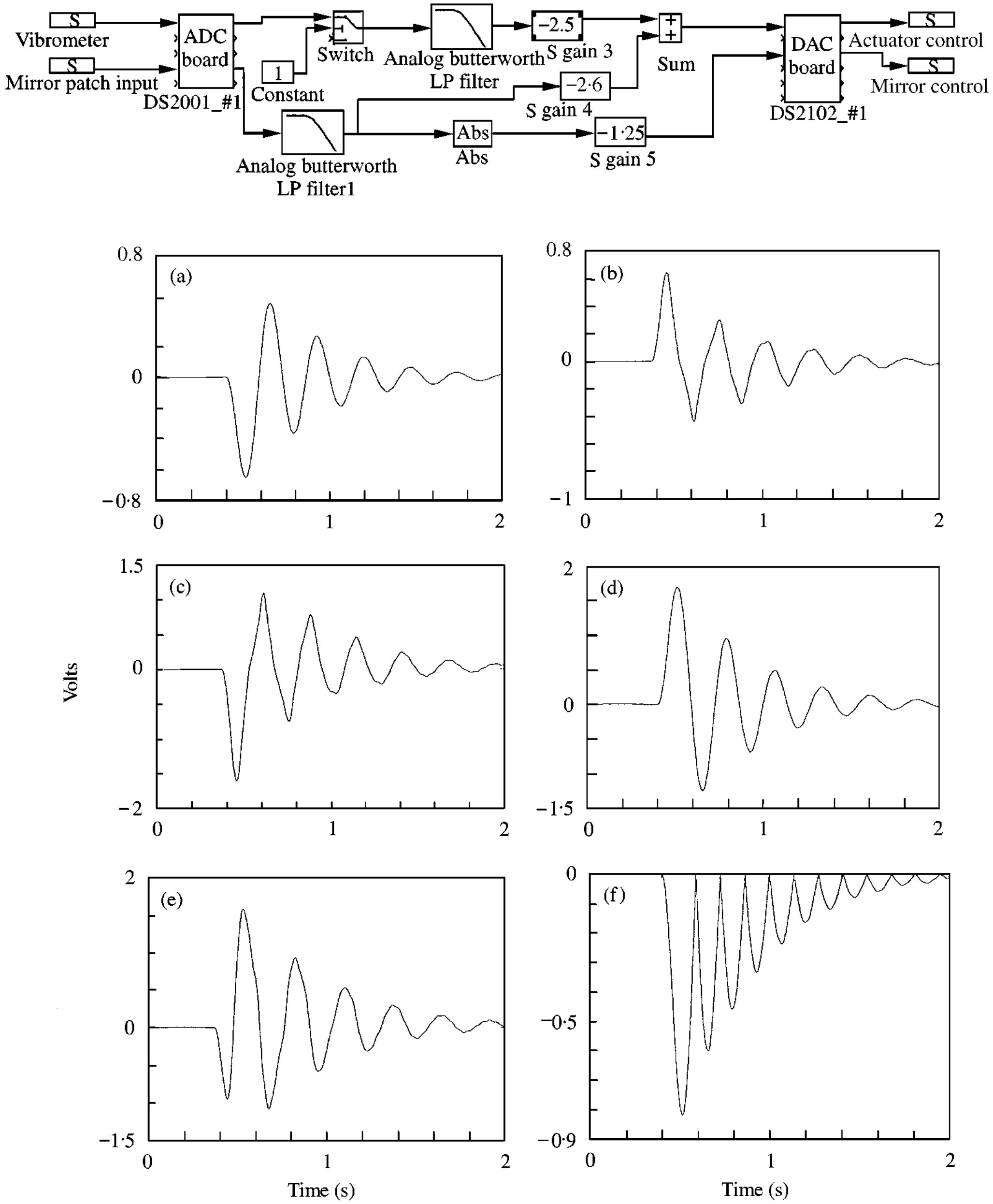

Figure 11. The SIMULINK diagram and system variables using hybrid control: (a) the PZT sensor signal after filtering, (b) the vibrometer signal after filtering, (c) the laser feedback control signal sgain3, (d) the PZT feedback control signal sgain4, (e) the control signal from the DAC to the actuators, and (f) the control signal from the DAC to the mirror. The laser control gain is −2·5, the sensor PZT patch gain for the actuator control is −2·6, and the mirror control gain is −1·25.

guaranteed stable. However, the guaranteed stable part of the control adds confidence that the overall control system is stable for variations in the parameters of the control system. The gains for the hybrid control case were determined by sequential optimization. Since two control loops were involved, the gain interactions were out of phase and complicated. This is shown in Figure 11 where (e) is the sum of (c) and (d). Non-optimal gain solutions could be found in which the peak voltage limit to the actuators was reached. The trial and error procedure of sequentially adjusting the gains finally produced the optimal design of the two gains.

The response of the beam with the hybrid control was better than the response using the laser only without the sensor patch feedback to the actuators. Using velocity feedback from the laser and position feedback from the PZT patch improved performance and robustness of the control system. The damping ratio for this case is $\zeta = 0{\cdot}103$. The damping ratios for all the control cases using the same peak control force limit are given in Table 3. These experiments show that the hybrid control approach performs the best, and indicates that the laser scanning should be done faster to improve the control performance. Also, a LQR or other control law that correlates the position of the laser with the velocity measured would improve performance compared to the single gain used.

In the experiment, the bandwidth of the scanning mirror limited control to the first mode of the cantilever beam. In all cases, the actuation force was limited by the force capability of the piezoceramic patches. A higher voltage or larger patch would improve control performance. The constant gain is adjusted as large as possible and is limited by the voltage or force limit (saturation) of the actuator patch (160 V in this case) during the peak of the response. This means that the controller is providing maximum force to suppress the vibration only during the first peak of the response, for the case of the free vibration response. Thus, the controller is operating at maximum power only for a brief time at the start of the response. If the controller could apply maximum power during the full response, the vibration could be suppressed more quickly. Thus, future work could consider development of a control law to deliver maximum power during most of the response. Combining fast laser scanning and a maximum power control law could improve the performance of the control technique presented here.

6. SUMMARY OF RESULTS

In the simulation study using the FEM in section 3, the switching control did not give as good of performance as the LQR control because in the switching control only one spatial measurement point at time is considered. The LQR method assumes that all d.o.f. are measured. If the time delay in updating the measurements can be incorporated into the LQR control law, this approach is expected to provide stability and better performance than the switching control. In theory, if the laser is scanned fast and full state feedback can be measured, the optimal LQR performance for a linear system can be achieved.

A qualitative experiment was performed in Section 4 in which an accelerometer, a PZT patch, and a fixed laser vibrometer sensor were compared to obtain velocity feedback to

TABLE 3

Summary of damping ratios for different feedback cases

Control configuration	Damping ratio (ζ)
Uncontrolled	0·008
Scanning laser feedback only	0·035
PZT patch feedback only	0·038
Fixed laser feedback only	0·072
Hybrid control (scanning laser and PZT feedback)	0·103

control the free vibration of a cantilever beam. The PZT patches add some mass and stiffness and were attached to the root of the beam for all experiments. The accelerometer adds a small mass to the free end of the beam, and the accelerometer cable had to run along the length of the beam. In the experiment, the effect of the mass and stiffness of the sensors on the control performance was not quantified. Also, no compensation for time delay was used in these experiments. The results showed that the control system performance using the PZT and laser sensors was similar, and somewhat better than when using the accelerometer sensor. An advantage of using the PZT sensor is that the actuator and sensor are collocated which can provide stability for higher modes. However, strain feedback must be differentiated to obtain strain rate, which makes the control system more complicated. An advantage of the laser sensor is that non-contact direct velocity feedback is obtained which simplifies the control system. A disadvantage is that measurement noise occurs due to speckle pattern motion and the cost of the instrument is high. With the accelerometer, the feedback signal must be integrated to obtain velocity feedback and a coupler must be used to amplify the signal.

Feedback using the scanning laser was investigated in section 5. Because the scanning speed of the laser mirror was limited, a simple control algorithm was used in place of the LQR method. Various combinations of PZT and laser feedback were investigated and a hybrid control approach that uses both the laser and PZT patch for feedback provided the best performance.

7. CONCLUSIONS

A simulation performed to control a cantilever beam using a scanning laser velocity sensor showed that if the laser can be scanned fast, the performance of classical linear optimal control can be achieved. Practically, some time delay compensation may be needed to control higher modes. An experiment with a cantilever beam compared different sensor types. This showed that the laser sensor is the simplest approach to obtain velocity feedback, while the PZT sensor has the advantage of being able to be collocated with a PZT actuator. The laser-velocity-sensing control technique was further experimentally demonstrated to effectively suppress vibration of the cantilever beam structure. A hybrid control system was then shown to have advantages of improved performance and stability. This approach simultaneously uses a PZT strain sensor at the root of the beam where the strain is the largest, and a scanning laser velocity sensor over the part of the beam where the velocities are the largest. The PZT sensors and actuators are collocated to add stability to the control system. The technique presented can potentially be extended to large complex structures where the advantages of laser sensing are the capability to provide centralized control, simplified sensing and communication, and the ability to improve control performance by measuring the response at many points on the structure by scanning the laser.

Further research is needed to continue to develop the hybrid laser and PZT sensor method for vibration suppression. Specific tasks suggested are to (1) build a next-generation faster scanning mirror with a 100 Hz bandwidth and ±15 degrees of rotation to allow control of the higher modes of vibration, (2) investigate other control techniques and develop a new control law for use with a scanning laser vibrometer sensor, the control law should compensate for time delay and the laser position should be determined to compute the full state or output feedback vector, and the control should be robust to instability, (3) simulations should be conducted using a more detailed FEM of the beam to optimize the controller design, (4) testing must be performed for different input conditions and the results compared with predictions, (5) the hybrid control system should be tested on another type of structure such as a wing section in a wind tunnel, and (6) ways to reduce speckle noise should be investigated to improve performance at higher frequencies and faster scan rates. Another possible use of the laser that can be investigated is to locate damage to a structure.

ACKNOWLEDGMENTS

This work was sponsored by the Army Research Office under the research grant DAAH04-96-1-0048 (technical monitor, Dr Gray Anderson), by the Army Research Office under the equipment grant DAAG55-97-1-0299 (technical monitor Dr Thomas L. Doligalski), and by the NASA Center of Aerospace Research at NCA&TSU under the grant NCC-1-255. This support is gratefully acknowledged.

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