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Vibration Suppression Utilizing Piezoelectric Networks

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15.1 Introduction

Because of their electromechanical coupling characteristics, piezoelectric materials have been explored extensively for structural vibration control applications. Some of the advantages of piezoelectric actuators include high bandwidth, high precision, compactness, and easy integration with existing host structures to form the so-called *smart* structures. In a purely active arrangement, an electric field is applied to the piezoelectric materials (which can be surface bonded or embedded in the host structure) based on sensor feedback and control commands. In response to the applied field, stress/strain will be induced in the piezoelectric material and active control force or moments can thus be created on the host structure to suppress vibration.

In recent years, a considerable amount of work has been performed to further utilize piezoelectric materials for structural control by integrating them with external electrical circuits to form piezoelectric networks. Such networks can be utilized for passive, semi-active, and active-passive hybrid vibration suppressions (Lesieutre, 1998; Tang, Liu, and Wang, 2000). Many interesting phenomena have been explored and promising results have been illustrated. The objective of this chapter is to review these efforts and assess the state-of-the-art of vibration control treatments utilizing piezoelectric networks. The basic concepts and development of passive and semi-active networks are discussed in Section 15.2. With the introduction of active actions, various issues, and recent advances regarding active-passive hybrid networks are presented in Sections 15.3 through 15.5.

15.2 Passive and Semi-Active Piezoelectric Networks for Vibration Absorption and Damping

In a purely passive situation, piezoelectric materials are usually integrated with an external shunt circuit (Hagood and von Flotow, 1991; Lesieutre, 1998). As the host structure vibrates, the piezoelectric layer will be deformed. Because of the electromechanical coupling characteristic, electrical field/current will then be generated in the shunt circuit. With proper design of the shunt components (inductor, resistor, or capacitor), one can achieve the so-called electrical damper or electrical absorber effects.

Soon after Hagood and von Flotow provided the first quantitative analysis of piezoelectric shunt networks, Hagood and Crawley (1991) applied the resonant shunt piezoelectric (RSP) network to space truss structures. An important feature of that work is the usage of a synthetic inductor, which is essentially a circuit with an operational amplifier feeding back current rate, thus simulating the effect of an inductor. For small piezoelectric capacitance and low structural modes, the optimum RSP requires a large inductance with low electrical resistance, which could be difficult to realize. The introduction of the synthetic inductor can effectively circumvent this problem and, more importantly, ease the tuning of the circuit because the inductance can be changed by varying the gain of the feedback current rate. Following along the same line, Edberg et al. (1992) developed a simulated inductor composed of operational amplifiers and passive circuitry connected as a gyrator, which can produce hundreds or thousands of henries with just a few simple electronic components. Because the value of simulated inductance may be easily changed by a variable resistor, it may be possible to have passive damping circuits monitor the frequencies to which they are subjected and alter their own characteristics in order to optimize the behavior.

From the power-flow point of view, the effect of inductance in the RSP is to cancel the inherent capacitive reactance of the piezoelectric material. As proposed by Bondoux (1996) the same effect can be expected by introducing a negative capacitance. Although this negative capacitance is impossible to achieve passively, it can be realized by using a small operational amplifier circuit similar to the synthetic inductor. Bondoux compared the negative capacitance shunting and the RSP and found that the use of a negative capacitance provides a broadband efficiency allowing multiple-mode damping. A similar conclusion was also drawn by Spangler and Hall (1994) and Bruneau et al. (1999). In general, the negative capacitance can increase the electromechanical coupling coefficient and enhance the efficiency of piezoelectric damping in both the resistive shunt and RSP network. The disadvantages are that the negative capacitance can generate electrical instabilities (Bondoux, 1996), and the high ratio of capacitance compensation is difficult to achieve in practice without adding a sensor to the circuit to account for the thermal changes of the piezoelectric capacitance (Bruneau et al. 1999).

A common thread of the aforementioned studies is the usage of an electronic circuit with operational amplifiers. Although they are not true semi-active approaches, these studies laid down a foundation for semi-active (adaptive/variable) absorption and damping research that continues today. An immediate application of the tunable nature of the synthetic inductor is a self-tuning piezoelectric vibration absorber developed by Hollkamp and Starchville (1994) (see Figure 15.1, case a). An RSP network is formed as an electromechanical vibration absorber and the shunt inductance are controlled through varying the resistance of a motorized potentiometer in the synthetic inductor, which enables on-line adjustment of the RSP tuning to maximize the performance function. In their approach, an ad hoc performance function was selected as the ratio of the RMS voltage across the shunt and the RMS structure response. If the ratio increases, the change in the inductance is in the proper direction and the inductance is again changed in that direction. If the ratio decreases, the direction is reversed. Although one deficiency of this simple control scheme is that the absorber will never settle on a single tuning value, it is effective for slow time-varying systems which can tolerate the tuning fluctuations and the time it takes to initially tune the absorber.

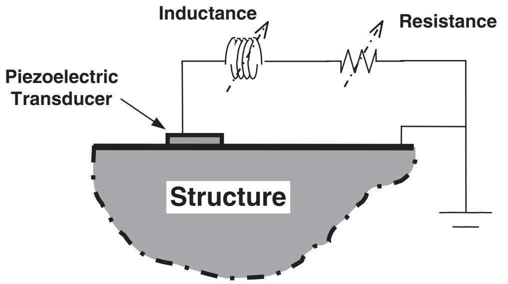

FIGURE 15.1 Schematics of some semi-active RSP damper/absorbers. Case (a): R = inherent resistance in the circuit; L on-line adjusted. Case (b): R and L on-line adjusted.

Wang et al. (1996) proposed a semi-active RSP scheme with variable inductance and resistance (see Figure 15.1, Case b). Their focus was on an improved control law that can handle not only quasi-steady-state scenarios but also structures with more general disturbances such as nonperiodic and transient loadings. They found that in such a semi-active configuration, the rates of the total system energy (the main structure mechanical energy plus the electrical and mechanical energies of the RSP) and the main structure energy are dependent on the circuit resistance, inductance, and inductance rate. It was recognized that an effective approach would be to reduce the total system energy while constraining the energy flowing into the main structure. Because two objectives were to be accomplished and they could contradict each other, an algorithm using variable resistance and changing rate of inductance as control inputs was developed to balance the energies. By selecting the total system energy as a Lyapunov functional, one can guarantee system stability through ensuring a negative rate of the system energy, while at the same time maximizing energy dissipation of the vibrating host structure.

Davis et al. (1997) and Davis and Lesieutre (1998) studied the possibility of tuning a mechanical absorber using shunted piezoelectric materials. The idea was initiated from the inertial piezoelectric actuator concept developed for structural vibration control (Dosch et al., 1995) where the forcing element in a proof mass actuator was replaced by a piezoelectric element with dual-unimorph displacement amplification effect. An important finding is that in such a configuration, the absorber stiffness is dependent on the ratio of the electrical impedance of the open circuit piezoelectric capacitance to the electrical impedance of the external shunt circuit. Therefore, by varying the impedance of an external shunt circuit, the natural frequency and, in some cases, the modal model damping of the vibration absorber will vary (Davis et al. (1997). Based upon this, Davis and Lesieutre (1998) developed an actively tuned solid-state piezoelectric vibration absorber. Because their goal was to maintain minimum structural response at a certain (may be varying) frequency, they adopted a capacitive shunting scheme without a resistive element, as damping is not needed in such applications. It should be noted that depending on different performance requirements, different shunting schemes could be optimally designed. To obtain variable capacitance, a “ladder” circuit of discrete capacitors wired in parallel was used. At a given time, the controller switches on some or all of the capacitors in parallel with the piezoelectric element, thereby changing the absorber stiffness and tuning the absorber frequency to the favorable value. The range of the adjustable stiffness is nevertheless limited by the piezoelectric electromechanical coupling coefficient. On a benchmark experimental setup, Davis and Lesieutre (1998) achieved a ± 3.7% tunable frequency band relative to the center frequency. Within the tuning band, increases in performance (vibration amplitude reduction) beyond passive performance were as great as 20dB. In addition, the averaged increase in performance across the tunable frequency band was over 10dB.

Piezoelectric materials realize a significant change in mechanical stiffness between their open-circuit and short-circuit states. This property was exploited by Larson et al. (1998) to develop a high-stroke acoustic source over a wide frequency range. By switching between the open-circuit

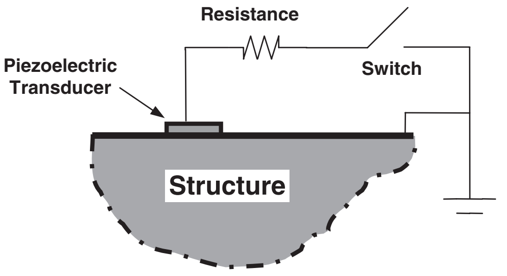

FIGURE 15.2 Schematics of some semi-active piezoelectric switching dampers. Case (a) Switching between open and short circuit states, R = 0. Case (b) switching between open circuit and resistive shunting, R = optimal passive value.

and short-circuit states, the acoustic driver's stiffness (and, therefore, its natural frequency) can be changed, allowing it to track a changing frequency with high amplitude. While Larson et al. (1998) proposed a practical realization of such a state-switched source for applications in active sonar systems, underwater research, and communication systems, Clark (1999a) found it is also useful in forming a semi-active piezoelectric damper. Using a typical energy-based control logic (Leitmann, 1994), Clark (1999a) illustrated how a piezoelectric actuator can be switched between the high and low stiffness states to achieve vibration suppression (see Figure 15.2, Case a). When the system is moving away from equilibrium, the circuit is switched to the high-stiffness state (open circuit), and the circuit is switched to the low-stiffness state (short circuit) when the system is moving toward equilibrium. This has the effect of suppressing deflection away from equilibrium, and then at the end of the deflection quarter-cycle, dissipating some of the stored energy so that it is not returned to the structure. In the open-circuit case, deflection stores energy by way of mechanical stiffness and the piezoelectric capacitance effect. When the system is switched to the short-circuit state, the charge stored across the capacitor is shunted to ground, effectively dissipating that portion of the energy. Clark (1999b) further studied the case that used a resistive shunt instead of a pure short circuit at low-stiffness state (see Figure 15.2, Case b), and compared the state-switching control with an optimally tuned passive resistive shunt. It was shown that for the example used in the study the optimal resistive shunt performed better for suppressing transient vibrations. The state-switching approach, however, provided better performance for off-resonance (particularly low-frequency) excitations, and was very robust to changes in system parameters.

Richard et al. (1999) also developed a piezoelectric damper using the switching concept (see Figure 15.2, Case a). The switch itself consisted simply of a pair of MOSFET transistors and little power was needed. The main difference between their approach and that proposed by Clark (1999a, 1999b) is in the switching law. Instead of switching between open and short circuits at different quarter-cycles of vibration, Richard et al. (1999) proposed to maintain the open circuit as the nominal state, and briefly switch to the short-circuit state to dump the electrical energy only when the structure displacement reaches a threshold value. Although no analytical results were available, they found that the best vibration suppression was achieved for a threshold corresponding to a maximum and a minimum of the displacement or output voltage in one vibration period. The time interval corresponding to the short-circuit time is also important and can be tuned. It was experimentally shown that the shortest time led to the best damping efficiency. They demonstrated enhanced damping performance of the proposed device over the passive resistive shunt.

Warkentin and Hagood (1997) studied a nonlinear piezoelectric shunting scheme with a four-diode full-wave rectifier and a DC voltage source. If the vibration amplitude is small, the voltage produced by the accumulation of charge on the piezoelectric capacitance is less than the DC voltage. Under this condition, all the diodes are reverse biased and no current will flow through the shunt, and the system is at the open-circuit condition. For larger motions, the diodes are turned on, current flows through the shunt, and the piezoelectric voltage is clipped at positive and negative DC voltage

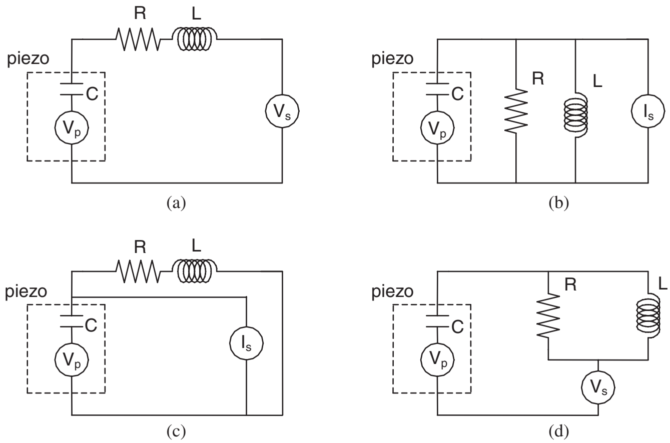

FIGURE 15.3 Schematics of active-passive hybrid piezoelectric networks. V_p: equivalent voltage generator attributed to the piezoelectric effect; V_s: voltage source; I_s: current or charge source; C: piezo capacitance; R: resistance; L: inductance. (From Tang, J., Liu, Y., and Wang, K. W., *Shock and Vibration Digest*, 32(3), 189–200, ©2000, Sage Publication, Inc.)

by the rectifier and the voltage source. The arrangement of the diodes ensures that the current always flows into the positive terminal of the DC source. If the DC source is implemented as a rechargeable battery or a regulated switching power circuit, the vibration energy removed from the structure may thus be recovered in a usable electrical form. The different stiffness exhibited at the open-circuit and short-circuit phases, combined with the voltage offset from the shunt voltage source, will produce a mechanical hysteresis. Although its performance was not as good when compared with the loss factor achieved by a conventional resistive shunt operating at optimum frequency, the rectified DC shunt is a frequency-independent device and its potential energy recovery ability remains an attractive feature. Warkentin and Hagood (1997) also studied resistive shunting with variable circuit resistance. An optimization approach was used to determine the ideal periodic resistance time history. The effective loss factors obtained in the simulations assuming sinusoidal deformation exceeded twice the values achieved by the fixed resistive shunt.

15.3 Active-Passive Hybrid Piezoelectric Network Treatments for General Modal Damping and Control

While the earlier investigations in RSP networks mostly focused on passive applications, it is clear that shunting the piezoelectric does not preclude the use of a coupled piezoelectric materials–shunt circuit as active actuators. That is, by integrating an active current or voltage control source with the passive shunt, one can achieve an active-passive hybrid piezoelectric network (APPN) configuration (Figure 15.3). The passive damping can be useful in stabilizing controlled structures in the manner analogous to proof mass actuators (Miller and Crawley, 1988; Zimmerman and Inman, 1990; Garcia et al., 1995). Hagood et al. (1990) developed a general modeling strategy for systems with dynamic coupling through the piezoelectric effect between a structure and an electrical network. Special attention was paid to the case where the piezoelectric electrodes are connected to an arbitrary electrical circuit with embedded voltage and current sources. They obtained good agreement between the analytical and experimental results, and concluded that the inclusion of electrical circuitry between the source and the structure gives the designer greater ability to model actual effects and to modify the system dynamics for closed-loop controls.

Niezrecki and Cudney (1994) addressed the power consumption characteristics of the piezoelectric actuators. The electrical property of a piezoelectric actuator is similar to a capacitor, which

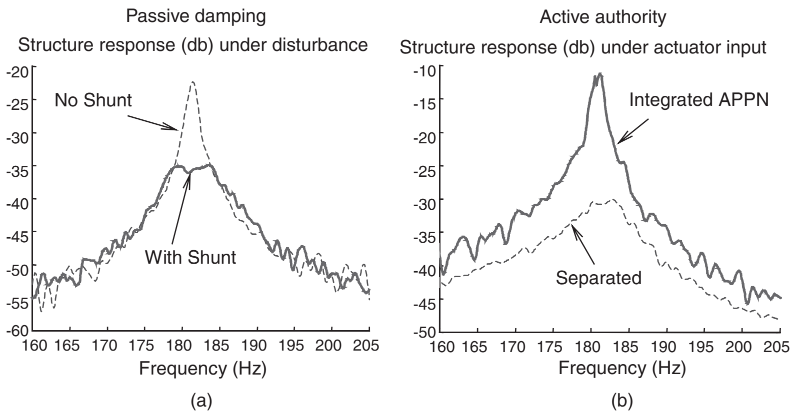

FIGURE 15.4 Experimental results on system passive damping and active authority of APPN. (From Tang, J., Liu, Y., and Wang, K. W., *Shock and Vibration Digest*, 32(3), 189–200, ©2000, Sage Publication, Inc.)

leads to a reactive current that provides only an electromagnetic field and does not perform work or result in useful power being delivered to the load. Therefore, the power factor of a piezoelectric actuator is approximately zero. Niezrecki and Cudney (1994) proposed to add an appropriate inductance to correct the power factor to unity within a small but useful frequency range. They studied two cases: adding inductors in parallel and in series with the piezoelectric actuator. In both cases, a resonant LC circuit was formed, and around the resonant frequency the reactive elements cancelled and the phase between current and voltage became zero, resulting in a unity power factor. They incorporated the internal resistance of the piezoelectric actuators and inductors in their analysis. Implementing the parallel LC circuit reduced the current consumption of the piezoelectric actuator by 75% when compared to the current consumption of the actuator used without an inductor. Implementing the series LC circuit produced a 300% increase in the voltage applied to the actuator compared to the case when no inductor was used. In both cases, the apparent power was reduced by 12dB.

From the above work, one may realize that the RSP network not only will increase the system's passive damping, but also will greatly increase the active control authority around the shunt resonant frequency. Agnes (1994, 1995) examined the simultaneous passive and active control actions of an RSP network through open-loop analyses. A modal model was developed to evaluate the hybrid vibration suppression effect, and open-loop experiments were performed for validation. Using Hagood and von Flotow's optimal RSP tuning results (1991) to determine the shunt circuit parameters, it was observed that not only the passive damping effect was significant, the modal response of the structure to the input voltage or current signal is also increased greatly. Using voltage as the driving source (Figure 15.3a), the shunted system frequency response was similar to the nonshunted response below the tuned (shunted mode) frequency, but exhibited greater roll-off above the tuned frequency. For broadband control, this would help prevent spillover because the magnitude of the response is, in general, lower for higher modes. When current source was used (Figure 15.3c), the shunted system's active action was less effective below the tuned frequency when compared to the nonshunted case, but no roll-off was observed in the high-frequency region. Tsai (1998) and Tsai and Wang (1999) also performed experimental investigations to illustrate the shunt circuit's passive damping ability (Figure 15.4a), as well as its active authority enhancement ability (Figure 15.4b) in APPN. Through exciting the structure with the actuator, they compared the open-loop structural response of the integrated APPN and the configuration with separated RSP and a piezoelectric actuator. While the two configurations have the same passive damping ability, the APPN configuration can drive the host structure much more effectively than the separated treatment does (Figure 15.4b), which clearly demonstrated the merit (high active authority) of the integrated APPN design.

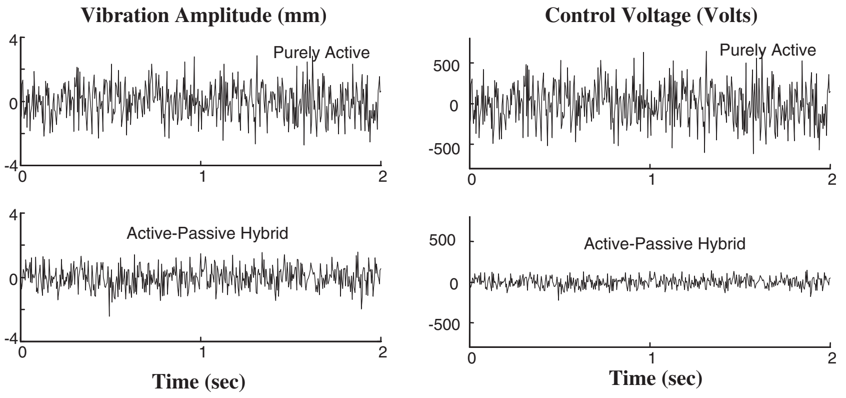

FIGURE 15.5 Comparisons of purely active and active-passive hybrid systems: performance and required voltage for vibration control. (From Tsai, M. S. and Wang, K. W., *Smart Materials and Structures*, 5(5), 695–703, ©1996, IOP Publishing, Inc.)

While Hagood and von Flotow's tuning results (1991) can minimize the maximum frequency response for a passive system, they are not necessarily good choices for an active-passive hybrid system. That is, the question of how to determine the system's active and passive parameters to achieve efficient hybrid vibration control still remains. From the driving voltage (control input) standpoint, the circuit inductance value will determine the electrical resonant frequency around which the active control authority will be amplified, and although appropriate resistance is required to achieve broadband passive damping, resistance in general reduces the active authority amplification effect (Tsai and Wang, 1999). To balance between active and passive requirement conflicts and performance tradeoffs and achieve an optimal configuration, a scheme was synthesized to concurrently design the passive elements and the active control law (Kahn and Wang, 1994, 1995; Tsai and Wang, 1996, 1999). This approach is to ensure that active and passive actions are configured in a systematic and integrated manner. The strategy developed is to combine the optimal control theory with an optimization process and to determine the active control gains together with the values of the passive system's parameters (the shunt circuit resistance and inductance). The procedure contains two major steps: (1) for a given set of passive parameters (resistance R and inductance L), form the system equations into a regulator control problem and derive the active gains to minimize a cost function representing vibration amplitude and control effort via the optimal control theory (Kwakernaak and Sivan, 1972); (2) for each set of the passive control parameters R and L, an optimal control exists with the corresponding minimized cost function, J, and control gains. That is, J is a function of R and L. Therefore, utilizing a nonlinear programming algorithm (Arora, 1989), one can determine the resistance and inductance that further reduce J. Note that as the R and L values are varied during the optimization process, step (1) is repeated to update the active gains simultaneously. In other words, by concurrently modifying the values of the active gains and passive parameters, an "optimized" optimal control system can be obtained.

The APPN system and the control/design scheme have been evaluated on various types of structures. In a multiple APPN ring vibration control problem (Tsai and Wang, 1996), a random sequence was generated to compare the structure displacements and control efforts (voltages) of the uncontrolled, the active, and the active-passive systems. From the results, it is clear that the active-passive action resulted in significant vibration reduction compared to the uncontrolled case (a 25dB reduction in standard deviation). In addition, the hybrid approach also outperformed the purely active system (Figure 15.5). Figure 15.5 also shows that the active-passive hybrid controller requires much less voltage than the active controller does.

Based on this simultaneous optimal-control/optimization strategy, Tsai (1998) and Tsai and Wang (1999) performed a detailed parametric analysis for the APPN design, showing that the optimal resistance and inductance values for the hybrid system could be quite different from those of the passive system, especially when demand on performance is high and/or when the number of actuators is much smaller than the number of controlled modes. For the APPN configuration, when the weighting on control effort increases, the optimal resistance (*R*) and inductance (*L*) values using the concurrent design will approach those derived from the passive optimization procedure. In general, when demand on control performance increases, the resistance value becomes smaller to enhance the active authority amplification effect, and inductance reduces to cover a wider frequency bandwidth. The excitation bandwidth also plays an important role, as it determines to which mode the *RL* values will be tuned.

Tsai and Wang (1998) addressed the robustness issue in systems controlled by APPN. They developed an algorithm with coupled μ synthesis (Zhou et al., 1996) and an optimization process to design a robust hybrid controller. In their example, they found that the structural uncertainty level that the hybrid controller can tolerate (the maximum uncertainty level at which the μ synthesis approach can find a solution) is much higher than what a purely active controller can tolerate, and thus the hybrid controller is much more robust than a purely active system.

Tang and Wang (1999a) applied the active-passive hybrid piezoelectric networks to rotationally periodic structures. Consisting of identical substructures, a rotationally periodic structure is essentially a multi-degrees-of-freedom system. The coupling between the substructures will split the otherwise repeated substructure frequency to a group of frequencies, which creates the problem of how to tune the shunt. By utilizing the unique property of rotationally periodic structures, Tang and Wang (1999a) developed an analytical method to determine the passive and active parameters for the control design, where the active control was used to compensate for the mistuning effect due to substructure coupling. The overall effect of the active and passive actions minimizes the maximum frequency response for all modes. Identical shunting circuit and control gains were applied to each substructure, which could bring convenience in implementations.

As mentioned earlier, while the resistor in the hybrid control system provides passive damping, it also tends to reduce the active control authority by dissipating a portion of the control power (Tsai and Wang, 1999). To further improve the efficiency of the active-passive hybrid piezoelectric network, Morgan and Wang (1998) proposed using a variable resistor in the circuit. The key feature in this control design was the introduction of a parametric control law to adjust the variable resistor. When electrical energy is flowing into the actuator/structure from the voltage source, the circuit is shorted to reduce the loss of control power. When the energy is flowing out of the actuator/structure, a positive value of resistance is selected for passive energy dissipation. They suggested using a digital potentiometer connected to the parametric controller to achieve the hardware realization. Their analysis showed that the parametric control law can significantly increase the efficiency of the active-passive hybrid control system, especially for narrowband and/or low to moderate gain applications. The reduced control effort could make it an attractive option for applications when minimizing the power consumption is critical.

Tsai and Wang (1999) concluded that the APPN will become less effective when the excitation bandwidth increases, because its passive damping and active authority amplification effects are narrowbanded. To circumvent this, they proposed to integrate the APPN with broadband damping treatments (Tsai and Wang, 1997). Specifically, they studied the integration with the enhanced active constrained layer (EACL) configuration (Liao and Wang, 1996, 1998a, 1998b; Liu and Wang, 1999), to which edge elements are added to the active constraining layer (ACL) (Park and Baz, 1999) to increase the transmissibility and active action authority. They found that adding the hybrid network to a traditional active constrained layer (ACL) treatment will not lead to much extra damping because of low transmissibility between the host structure strain and the piezoelectric coversheet deformation. However, the integration of APPN with EACL can achieve high damping. A comparison of the APPN, EACL, and combined APPN-EACL damping treatments was performed. An objective function was defined to reflect the vibration amplitude and control effort. In general, smaller objective function means better overall performance and thus better hybrid damping

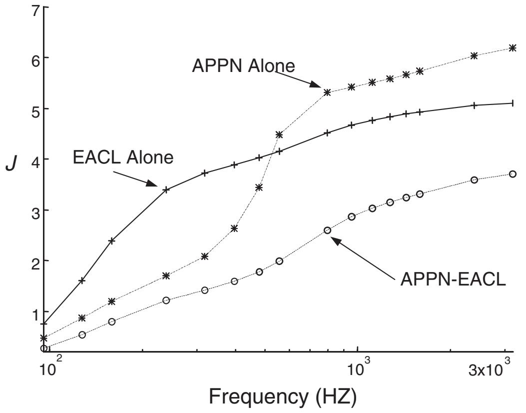

FIGURE 15.6 Objective function (J) comparison between different configurations.

ability. The minimized objective function, J, for different configurations vs. excitation bandwidth was obtained (Figure 15.6). As shown in the figure, APPN outperforms EACL when the bandwidth is small, but becomes less effective than EACL as bandwidth increases. On the other hand, the combined APPN-EACL system can outperform the individual APPN and EACL cases, under both narrowband and broadband excitations.

So far, in most active-passive hybrid piezoelectric network studies, only one of the series configurations has been considered. That is, the resistor, the inductor, and the power source (voltage source) were all connected in series with the piezoelectric actuator (Figure 15.3a). Wu (1996) found that by connecting the resistor and inductor in parallel with the piezoelectric material, one can achieve a similar passive vibration absorbing/damping effect as that of the series configuration proposed by Hagood and von Flotow (1991). Combining parallel and series passive configurations with the parallel and series active driving, one can envision a few different active-passive hybrid piezoelectric network configurations, some of which are shown in Figures 15.3b–d. From the viewpoint of linear system superposition, the structure response is a summation of that caused by external disturbance and that caused by control input. Therefore, for the passive effect to function normally in the absence of the active control input, we should use charge or current control when the power source is in parallel with the shunting elements, such as those shown in Figures 15.3b and c. Although one has to resort to complicated circuit design to obtain a charge source, it has the potential benefit of avoiding the piezoelectric hysteresis (Main et al., 1995). However, it should be noted that different configurations yield roughly the same passive and hybrid damping abilities (Tang and Wang, 2001).

15.4 Active-Passive Hybrid Piezoelectric Network Treatments for Narrowband Vibration Suppression

The focus of Section 15.3 is systems utilizing APPN for general modal damping and control. It has also been found that the APPN configuration could be very effective for narrowband vibration rejection. The active-passive hybrid approach is especially attractive for narrowband disturbances with varying frequencies (an example of this type of excitation is a machine with a rotating unbalance — the frequency variation could be a slow drift due to changes in operating conditions or a rapid spin-up when the machine is turned on), as discussed in this section.

While a passive piezoelectric vibration absorber (piezoelectric materials with passive resonant shunt) is effective for harmonic disturbance rejection (Hagood and von Flotow, 1991), it could be sensitive to frequency variations and system uncertainties. As stated in Section 15.2, semi-active piezoelectric absorber concepts have been proposed to suppress harmonic excitations with time-varying frequencies. The implementation of these semi-active absorbers requires either a variable inductor or a variable capacitor element. While they are conceptually valid, both of these methods have some inherent limitations. For instance, the variable capacitor method (Davis et al., 1997) limits tuning of the piezoelectric absorber to a relatively small frequency range. The variable inductor approach (Hollkamp and Starchville, 1994), which is usually accomplished using a synthetic inductance circuit, can add a significant parasitic resistance to the circuit that is generally undesirable for narrowband applications. In either case, the variable passive elements can be difficult to tune rapidly with high accuracy.

With the above arguments, Morgan et al. (2000) and Morgan and Wang (2000) developed a high-performance active-passive hybrid alternative to the semi-active absorbers, utilizing the APPN configuration. Throughout this study, the system being considered was a generic mechanical system with a single piezoelectric actuator attached. The piezoelectric was shunted with an *RL* circuit as well as an active voltage source (Figure 15.3a). The passive inductance value was tuned to a nominal excitation frequency. Because the interest here is to use the APPN absorber characteristic to suppress vibrations at distinct frequencies, low damping (resistance) is required in the absorber. Therefore, other than the inherent resistance in the circuit, no extra passive resistor was added.

The active control law consists of three modules. The first part of the control law is designed to imitate a variable inductor so that the absorber is always tuned to the correct frequency. In addition, an active negative resistance action is used to reduce the absorber damping (inherent resistance in the circuit) and increase the absorber narrowband performance. To further enhance the robustness of the piezoelectric absorber, the system's apparent electromechanical coupling is increased using the third active action. The advantages of the active inductor include fast and accurate adjustment, no parasitic resistance, and easier implementation compared to a semi-active inductor. To ensure that the active inductance is properly tuned, an expression for optimal tuning on a general multiple-degrees-of-freedom (MDOF) structure was derived. The closed-loop inductance was achieved using this optimal tuning law in conjunction with an algorithm that estimates the fundamental frequency of the measured excitation. Details of the mathematical formulation and derivation can be found in Morgan et al., 2000 and Morgan and Wang, 2000.

The APPN adaptive absorber concept was implemented and experimentally verified on a lab fixture. Details of the test procedure and setup are described in Morgan and Wang (2000). Two test cases were considered: the first case is for an off-resonant excitation, and the second is for an excitation near a resonant frequency of the structure. The baseline system for the resonant excitation case is an optimally damped passive piezoelectric absorber. That is, the absorber is tuned to the resonant frequency and sufficient damping (resistance) is added to give a flat frequency response around the resonant frequency. In the off-resonant case, a passive absorber would be a poor choice for an excitation of varying frequency because of its small effective bandwidth. Therefore, the baseline for the off-resonant case is selected to be the response of the structure with the piezoelectric actuator shorted (no shunt circuit). The inputs to the controller are the structure response signal, the voltage across the passive inductor, and the excitation signal. The controller also contained a frequency estimation algorithm, which uses the measured excitation signal to continually estimate the excitation frequency.

The purpose of this experiment was to study the performance of the system when subjected to a harmonic excitation with varying frequency. The simplest such excitation is a linear chirp signal, which is a sinusoid of linearly increasing frequency. The three parameters that characterize the chirp signal are the nominal frequency f_o, the bandwidth of the frequency variation Δ, and the frequency rate of change $\dot{f}$ (Hz/s). For the linear chirp used here the frequency starts at $(1-\Delta)f_o$ at time t_s and increases at a rate of $\dot{f}$ until it reaches a maximum frequency of $(1+\Delta)f_o$ at time t_f. In this experiment, the nominal excitation frequency and bandwidth were constant in each case and the frequency rate of change was varied. Four tests were carried out for both the near-resonant and off-resonant cases, with the frequency rate of change varying from 2 to 8 Hz per second. The excitation was applied at time $t = 0$, but the data acquisition system was set to have a trigger delay

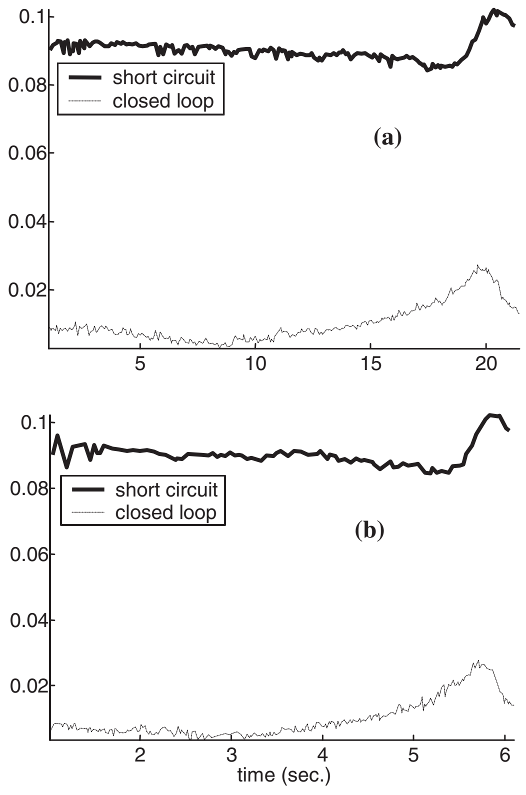

FIGURE 15.7 Experimental response (sensor voltage readings) envelopes (off-resonant case), f_o = 205 Hz. (a) $\dot{f}$ = 2Hz/s, (b) $\dot{f}$ = 8 Hz/s.

of t_s = 1 second. The purpose of this delay is to discard the large transient response caused by initially applying the excitation, which would give a better estimate of the performance of the system under extended operating conditions.

Experimental results for the off-resonant case are shown in Figure 15.7. The excitation bandwidth used for the off-resonant case is ±10% of the nominal frequency, which corresponds to approximately 40 Hz. These plots show the response envelopes for the cases $\dot{f}$ = 2 Hz/s and $\dot{f}$ = 8 Hz/s. From these results it appears that performance of the active-passive absorber is relatively unaffected by the frequency rate of change. This is somewhat surprising because the optimal tuning is determined using a quasi-steady-state assumption, which is only valid for excitations with very slowly changing frequency. The conclusion is that the combination of the quasi-steady-state tuning law and the active coupling enhancement allows the adaptive absorber to achieve good performance even for rapidly varying excitations. The combination of a rapidly changing excitation frequency and a very wide frequency bandwidth is a difficult problem for a semi-active device. However, the active-passive piezoelectric absorber presented here could have the performance and robustness necessary for these applications.

Experimental results for two of the near-resonant cases are shown in Figure 15.8. Once again we see that performance of the active-passive absorber is relatively unaffected by the frequency rate of change. Although the performance of the optimal passive absorber baseline is already much better than the original system (no absorber), the adaptive active-passive absorber still can outperform the baseline system significantly.

Through extensive parametric studies (Morgan and Wang, 2000), the proposed design was also compared with two active and active-passive vibration control methods: the Filter-X algorithm (Fuller et al., 1996) for off-resonant excitation and the concurrent APPN optimal control-optimization process

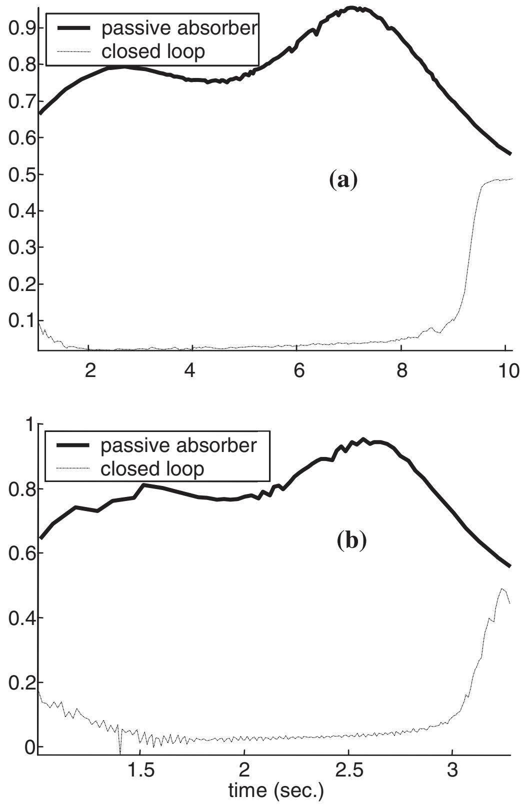

FIGURE 15.8 Experimental response (sensor voltage readings) envelopes (near-resonant case), $f_o = 92$ Hz. (a) $\dot{f}$ = 2 Hz/s, (b) $\dot{f}$ = 8 Hz/s.

(Tsai and Wang, 1999) for near-resonant situation. It was shown that the adaptive active-passive absorber can outperform the two systems significantly while requiring less control effort. These parametric studies also illustrated the effects of the absorber parameters and excitation characteristics on the performance of the adaptive active-passive piezoelectric absorber design.

While promising, the system proposed by Morgan et al. (2000) and Morgan and Wang (2000) is for suppression of excitations with only a single dominant frequency. To further enhance and expand the ability of such a device, a multi-frequency adaptive piezoelectric vibration absorber design was developed (Morgan and Wang, 2001). Building upon the single-frequency disturbance rejection network configuration, multiple circuit branches and an additional active law were added. The active control law effectively decouples the dynamics of the individual circuit branches. This decoupling action allows the tunings of the multi-frequency absorber to be calculated using an analytical optimal tuning law. The proposed design was shown to be effective for simultaneously suppressing two harmonic excitations with time-varying frequencies, and it can achieve better performance while requiring less control power than the Filtered-X algorithm. The design and analysis presented can be extended in a straightforward manner to cases with more excitation frequencies.

15.5 Nonlinear Issues Related to Active-Passive Hybrid Piezoelectric Networks

As mentioned, the piezoelectric network can result in high-performance vibration control through the dual effects (passive damping and active authority enhancements) of the shunt circuit. On the other hand, high performance corresponds to a high electrical field across the piezoelectric material, especially under high loading conditions. When the electrical field level is high, the linear assumption often made in most piezoelectric actuator-based systems (the linear constitutive relation between the stress, strain, electrical field, and electrical displacement of the piezoelectric material) may no longer be valid. This is because the material hysteresis and the high-order nonlinear relationship between the mechanical response and electrical field could become very significant when a high electric field occurs on the piezoelectric actuators.

In recent investigations performed by Tang et al. (1999) and Tang and Wang (1999b, 2000), the nonlinear behavior of the piezoelectric material was investigated experimentally and analytically. Through lab tests, one can clearly see the complexity of the material property, especially at high field levels. This fact suggests that one way to utilize the high field (high authority) regime is to consider the various nonlinear phenomena as uncertainties and develop robust controls to compensate for such uncertainties. By treating the nonlinearity (or part of it) as bounded uncertainties, a constitutive relation is proposed. For example, if the linear constitutive relation is used as the basic model, the actual actuation strain at a certain field will be the linear deterministic value plus some bounded uncertainty (Tang et al., 1999). For one-dimensional structures, the modified constitutive equations can be expressed in the following form,

$$\tau = E_p \varepsilon - h_{31} D$$

$$E = -h_{31}(\varepsilon - \varepsilon_0) + \beta_{33} D$$

where τ, ε, D, and E represent the stress, strain, electrical displacement (charge/area), and electrical field (voltage/length along the transverse direction) within the piezoelectric patch, respectively, and E_p, h_{31}, and β_{33} are the Young's modulus, piezoelectric constant, and dielectric constant of the material. Here, ε_0 represents the uncertainty in the strain-field relation, which is bounded as $|\varepsilon_0| < \varepsilon^*$. The bounds can be selected according to the maximum field level that the actuator will undergo and identified from experimental data.

Given the new constitutive equation and uncertainty bounds, a robust control algorithm based on the of sliding mode theory (Slotine and Li, 1991; Utkin, 1993) was then developed to compensate for the piezoelectric nonlinearities (Tang et al., 1999; Tang and Wang, 1999b, 2000). In general, the dynamics of a system so controlled consist of a reaching mode and a sliding mode. The strategy for designing a sliding mode controller involves: (1) the design of a switching manifold (sliding surface) on which the system will be asymptotically stable (the so-called sliding mode, where fast convergence is desired); and (2) designing a controller which can force the state trajectory to reach the switching manifold in finite time (the so-called reaching mode, where a brief reaching time is desired). When all the nonlinearities were considered as uncertainties, a linear-quadratic regulator (LQR) optimal control formulation (Kwakernaak and Sivan, 1972) was used to set up the sliding surface and ensure stability on the surface (Tang et al., 1999; Tang and Wang, 2000). When the high-order nonlinearity was included in the model and the other nonlinearities were treated as uncertainties, the Lyapunov stability approach was utilized to select the sliding surface (Tang and Wang, 1999b).

The effectiveness of the proposed approach was demonstrated through experimental studies and numerical analyses on vibration control of an APPN-treated cantilever beam structure. For the purpose of comparison, the simulation results of the beam tip displacement for the linear optimal controller are shown in Figure 15.9 (upper plot). The dashed line represents the ideal situation where there are no piezoelectric nonlinearities. However, since the voltage across the piezoelectric material is high, the actual result is given by a solid line, where the piezoelectric nonlinearities are simulated as bounded uncertainty. The performance of the linear controller is obviously degraded by the piezoelectric nonlinearities. The sliding mode control result considering all the piezoelectric nonlinearities as uncertainties (Tang and Wang, 2000) is then illustrated in Figure 15.9 (lower plot),

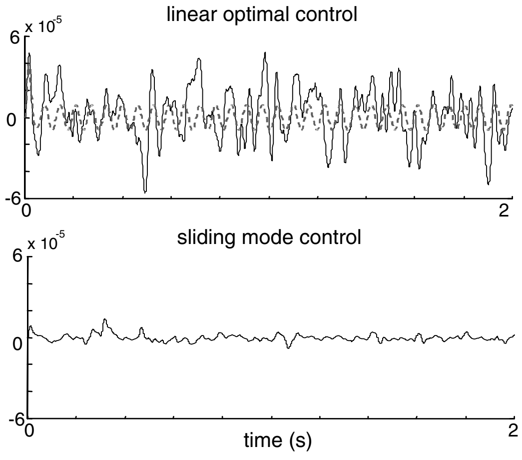

FIGURE 15.9 Beam tip vibration amplitude. Upper plot: linear control (dashed line, ideal case without piezoelectric nonlinearity; solid line, realistic case with piezoelectric nonlinearity). Lower plot: Sliding mode control compensating for piezo nonlinearity.

which clearly shows much better performance. Here, for a fair comparison, the two controllers are designed so that they utilize the same RMS value of control power input. These results illustrate that with such a nonlinear robust controller, one can fully utilize the high authority characteristics of the APPN system.

15.6 Summary and Conclusions

The major findings and achievements to date in vibration control utilizing piezoelectric networks can be summarized as follows:

- Passive and semi-active tuning of piezoelectric circuit elements can be effective in various damping and vibration absorption applications, especially for systems with no variations or under slow/small changes. Most of the control algorithms are based on energy or power analysis, and through adjustable resistance, inductance, and capacitance, as well as open- to short-circuit state switching.
- To further enhance the performance of piezoelectric networks, active voltage or current sources have been added to form an active-passive hybrid piezoelectric network (APPN). Circuit elements not only can provide passive damping, they also can increase the treatment's active authority. To tune the system properly for general modal damping and control applications, one approach is to employ a concurrent optimization scheme and simultaneously synthesize the active gains and passive parameters. Such an APPN approach could outperform a purely active system with less control effort.
- The active actions in an active-passive hybrid piezoelectric network can also be used to tune passive component parameters. Such an approach merely adds a dynamic compensator, with gains emulating the circuit variables and the electromechanical coupling parameter. This feature could be especially effective for rejecting narrowband excitations with variable frequencies, where the APPN adaptive absorber effect is utilized.
- The shunt circuit could significantly increase the APPN active authority through increasing the voltage across the piezoelectric material. That is, high performance corresponds to high electrical field, especially under high loading conditions. When the electrical field level is high, piezoelectric nonlinear characteristics should be considered in designing and controlling the system. One effective approach to utilize the nonlinear high authority features of the

APPN is to synthesize a nonlinear robust controller (e.g., the sliding mode controller discussed in this chapter) to include and compensate for the actuator nonlinearities in the design process.

- Most investigations to date have concluded that a well-designed, self-contained APPN system could have the advantages of both purely active and passive systems and could outperform both approaches.

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