A Survey of Recent Innovations in Vibration Damping and Control Using Shunted Piezoelectric Transducers

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***Abstract*—Research on shunted piezoelectric transducers, performed mainly over the past decade, has generated new opportunities for control of vibration and damping in flexible structures. This is made possible by the strong electromechanical coupling associated with modern piezoelectric transducers. In vibration control applications, a piezoelectric transducer is bonded to, or embedded in a base structure. As the structure deforms, the piezoelectric element strains and converts a portion of the structural vibration energy into electrical energy. By shunting the piezoelectric transducer to an electrical impedance, a part of the induced electrical energy can be dissipated. Hence, the impedance acts as a means of extracting mechanical energy from the base structure. This paper reviews recent research related to the use of shunted piezoelectric elements for vibration damping and control. In particular, the paper presents an overview of the literature on piezoelectric shunt damping and discusses recent observations on the feedback nature of piezoelectric shunt damping systems.**

***Index Terms*—Feedback control, passive control, piezoelectricity, piezoelectric shunt damping, synthetic impedance, vibration control.**

I. Introduction

PIEZOELECTRIC transducers are being used as actuators and sensors for vibration control of flexible structures. Piezoelectric materials in current use include polyvinylidene fluoride (PVDF), a semicrystalline polymer film and lead zirconate titanate (PZT), a piezoelectric ceramic material. These materials strain when exposed to a voltage and conversely produce a voltage when strained. The piezoelectric property is due to the permanent dipole nature of the materials, which is induced by exposing the material to a strong electric field while the material is being manufactured.

For vibration control purposes, piezoelectric transducers are bonded to the body of a flexible structure using strong adhesive material. These piezoelectric elements can be used as sensors, actuators, or both. In a typical active control application, a piezoelectric transducer is used as an actuator, while a sensor is used to measure vibration of the base structure. A control voltage is then applied to the piezoelectric actuator to minimize the unwanted vibration of the base structure.

An alternative approach is passive control, also referred to as piezoelectric shunt-damping. The piezoelectric transducer is shunted by a passive electric circuit that acts as a medium for dissipating mechanical energy of the base structure. In their original work [37] Hagood and von Flotow suggested that a series *RL* circuit attached across the conducting surfaces of a piezoelectric transducer can be tuned to dissipate mechanical energy of the base structure. They demonstrated the effectiveness of this technique by tuning the resulting *RLC* circuit to a specific resonance frequency of the base structure. Furthermore, they proposed a method to determine an effective value for the resistive element that appears to be effective.

This paper surveys some of the recent advances in vibration damping and control using shunted piezoelectric transducers. The paper investigates similarities between the shunt damping systems and collocated active vibration controllers, and demonstrates that the problem of vibration control using shunted piezoelectric transducers can be viewed as a feedback control problem with a very specific feedback structure. This observation will have a significant impact on the field as the standard control design tools can now be used to design electric shunts for vibration control purposes. Among other things, the *ad hoc* shunt design techniques proposed over the past decade will be surveyed and their connections with recently developed shunt design techniques will be clarified. Complications that arise in implementing electric shunts will be discussed and a number of recently developed techniques to address these issues will be introduced.

The remainder of this paper continues as follows. Section II contains a brief overview of electromechanical properties of piezoelectric materials. Section III is concerned with the problem of active vibration control using a pair of collocated piezoelectric actuator and sensor. Section IV reviews the "self-sensing" approach to vibration control. Section V contains an in-depth review of the shunt damping techniques and some recent results on the feedback structure of shunt damping systems. Section VI compares performance of shunt damping systems with that of actively controlled systems. Section VII discusses some open problems, and finally, Section VIII concludes the overall of the paper.

II. Piezoelectric Transducers

This section contains a rather brief overview of the piezoelectric effect. For a more detailed discussion of the electromechanical properties of these materials, the reader is referred to [20], [29], [48], [55], and [57]. The piezoelectric effect was first discovered in 1880 by Pierre and Jacques Curie, who demonstrated that when certain crystalline materials were stressed, an electric charge was produced on the material surface. It was subsequently demonstrated that the converse effect was true. That

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is, when an electric field was applied to a piezoelectric material it changed its shape and size. The piezoelectric effect has been observed on a number of materials such as natural quartz crystals, tourmaline, topaz and Rochelle salt [12]. However, it can be artificially generated in certain ceramic materials.

A piezoelectric ceramic, when manufactured, consists of electric dipoles that are arranged in random directions. The responses of these dipoles to an externally applied electric field would tend to cancel one another. Hence, no gross change in dimensions of the piezoelectric specimen may be observed. To generate an observable macroscopic response, the dipoles are permanently aligned with one another through a process referred to as "poling."

A characteristic of piezoelectric material is its "Curie temperature." When the material is heated above this temperature, the dipoles can change their orientation in the solid phase material. During the poling process the material is heated above its Curie temperature and is exposed to a very strong electric field. The direction of this field is referred to as the "polarization direction," and dictates the direction along which the dipoles are aligned. The material is then cooled below its Curie temperature while the poling field is maintained. As a result of this process the alignment of the electric dipoles is permanently fixed and the material is said to be "poled."

When a poled piezoelectric ceramic is maintained below its Curie temperature and is subjected to an electric field, smaller than that used during the poling process, the dipoles respond collectively to produce a macroscopic expansion along the poling access and contraction perpendicular to that. The response will be opposite if the direction of the applied field is changed. This property is referred to as the "converse piezoelectric effect," the material mechanically strains when placed inside an electric field. This property enables the piezoelectric material to be used in the construction of actuators.

When a poled piezoelectric ceramic is mechanically strained it becomes electrically polarized, producing an electric charge on the surface of the material. This property is referred to as the "direct piezoelectric effect" and is the basis upon which the piezoelectric materials are used as sensors. Furthermore, if electrodes are attached to the surfaces of the material, the generated electric charge can be collected and used. This property is also utilized in piezoelectric shunt damping applications.

The describing electromechanical equations for a linear piezoelectric material can be written as [29]

$$\varepsilon^i = S^E_{ij}\sigma_j + d_{mi}E_m \tag{1}$$

$$D_m = d_{mi}\sigma_i + \xi_{ik}E_k \tag{2}$$

where the indexes $i, j = 1, 2, \ldots, 6$ and $m, k = 1, 2, 3$ refer to different directions within the material coordinate system. In equations (1) and (2) ε, σ, D, and E are the strain, stress, electrical displacement (charge per unit area) and the electrical field (volts per unit length), respectively. In addition S^E, d, and ξ represent the elastic compliance, the piezoelectric strain constant, and the permitivity of the material, respectively.

The "piezoelectric strain constant" d is defined as the ratio of developed free strain to the applied electric field. Of particular importance are the strain constants d_{33}, d_{31}, and d_{32}. The subscript d_{ij} implies that the voltage is applied or charge is collected in the i direction for a displacement or force in the j direction. Consider a typical piezoelectric transducer, which has been poled in the three-direction and is then subjected to an electric field along that direction, as in Fig. 1. For one-dimensional motion, the strain of the piezoelectric element in the z (three) direction can be simplified to

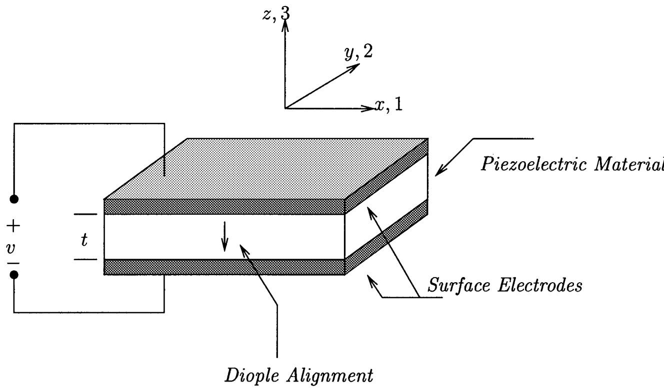


Fig. 1. Schematic diagram of a piezoelectric transducer.

$$\varepsilon^3 = d_{33}\frac{v}{t}$$

while the transducer, now in the actuator mode, will deflect in the z and y directions with the resultant strains

$$\varepsilon^1 = d_{31}\frac{v}{t}$$

and

$$\varepsilon^2 = d_{32}\frac{v}{t}$$

where v is the voltage applied in the three-direction and t is the thickness of the piezoelectric patch, as shown in Fig. 1.

By convention when a field, which is relatively small in value compared to the poling field, is applied to the piezoelectric transducer in the same direction as the poling vector, as shown in Fig. 1, the element will expand in the z (three) direction. Furthermore, due to the Poisson coupling, at the same time, the element will contract along the x and y directions. Therefore, d_{33} constant is typically specified as a positive value while d_{31} and d_{32} are negative for piezoelectric ceramics.

When a piezoelectric transducer is attached to a base structure, it may be used as an actuator, a sensor, or both. To obtain a dynamical model of the composite system, the strain/stress properties of the piezoelectric wafer must be coupled with the dynamics of the base structure. A variety of methods for obtaining such models have been proposed; see for example [2], [3], [15], [29], [60].

Piezoelectric materials in current use include PVDF, a semicrystalline polymer film, and PZT, a piezoelectric ceramic material. There are notable differences between PVDF and PZT materials. For instance, on average, PZT is roughly four times as dense, 40 times stiffer, and has a permitivity 100 times as great as that of PVDF. Therefore, PVDF is much more compliant and lightweight, making it more attractive for sensing applications. In contrast, PZT is often more favored as an actuator since the piezoelectric strain constant, d_{31} is typically five times greater

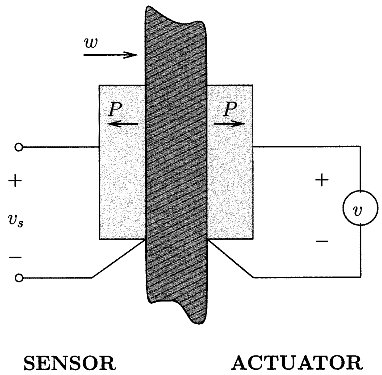


Fig. 2. Flexible structure with a collocated pair of piezoelectric transducers.

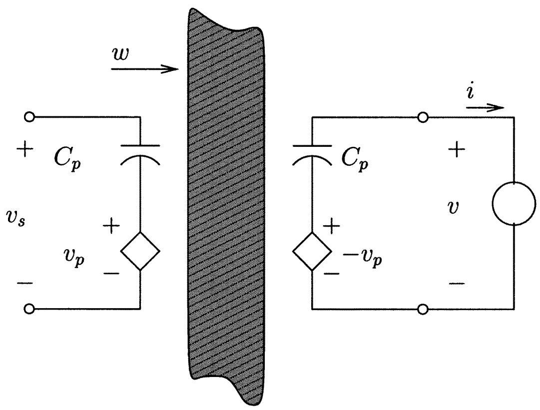


Fig. 3. Electrical equivalent of the system in Fig. 2.

than PVDF. Thus, for a given applied electric field, one would expect a greater induced strain.

III. Active Feedback Control

Piezoelectric actuators and sensors have been used extensively in active vibration control applications (e.g., see [19], [30], [31], [35], [46], and [47]). This provides the motivation to first present an overview of this area, before proceeding to the main topic of this review.

Consider the system depicted in Fig. 2, demonstrating a flexible structure which is subject to some form of disturbance, w with a collocated pair of piezoelectric transducers. In a typical active vibration control application, one transducer is used as an actuator, while the other is employed as a sensor to generate the measurement that is needed in any feedback regulator system. Therefore, in Fig. 2, the transducer on the left would serve as the sensor, while the one on the right-hand side of the base structure would be the actuator. The voltage v would be manipulated based on the signal measured at the sensing piezoelectric transducer such that the effect of the disturbance w on the structure is minimized.

To delineate the underlying mechanisms, the electrical equivalent of the system of Fig. 2 is sketched in Fig. 3. The main assumption here is that both piezoelectric transducers are identical and collocated. The collocation implies that as one transducer expands, when the base structure bends, the other contracts. Therefore, considering orientations of polarization vectors of the two piezoelectric transducers, the voltages induced in them will be equal, but 180° out of phase, as demonstrated in Fig. 3. Now, assuming $w(t) \equiv 0$, the voltage measured at the sensing piezoelectric transducer v_s is related to the voltage applied to the actuating piezoelectric transducer v via a transfer function G_{vv}. That is

$$\begin{aligned} v_s(s) &= v_p(s) \\ &= G_{vv}(s)v(s). \end{aligned} \tag{3}$$

The transfer function $G_{vv}(s)$ is of the form

$$G_{vv}(s) = \sum_{i=1}^{M} \frac{\gamma_i}{s^2 + 2\zeta_i\omega_i s + \omega_i^2} \tag{4}$$

where

$$\gamma_i \geq 0, \qquad \text{for } i = 1, 2, \ldots$$

and $M \to \infty$. In practice, however, M is a finite, but an arbitrarily large number [41], [42]. Notice that the condition $\gamma_i \geq 0$ above, is a consequence of having collocated actuators and sensors [38]. This property only holds for "collocated" and "compatible" actuators, e.g., point force and displacement. The condition $\gamma_i = 0$ can only arise if the piezoelectric transducer is mounted at a location where the ith mode is unobservable. Also, if $v(t) \equiv 0$, the measured signal at the sensing transducer will be related to the disturbance via a transfer function $G_{vw}(s)$. That is

$$\begin{aligned} v_s(s) &= v_p(s) \\ &= G_{vw}(s)w(s). \end{aligned} \tag{5}$$

Since the underlying system is linear, in general, we may write

$$v_p(s) = G_{vw}(s)w(s) + G_{vv}(s)v(s). \tag{6}$$

One would expect the transfer function G_{vw} to have a very similar structure to $G_{vv}(s)$. In particular, it is quite possible that the two transfer functions would share quite a large number of poles. However, since the disturbance w, in general, is not collocated with the sensor, the zeros may be quite different.

It can be observed that if the disturbance w acts to perturb v_s, by an appropriate choice of v its effect can be alleviated. Having made the above observations the corresponding regulator system can be identified as in Fig. 4. The feedback control problem depicted in Fig. 4, although tractable, may prove quite challenging. This can be attributed to two factors: the highly resonant nature of the underlying system $G_{vv}(s)$ and its very high order.

The transfer function $G_{vv}(s)$ consists of a large number of lightly damped modes. Hence, it possesses poles that are very

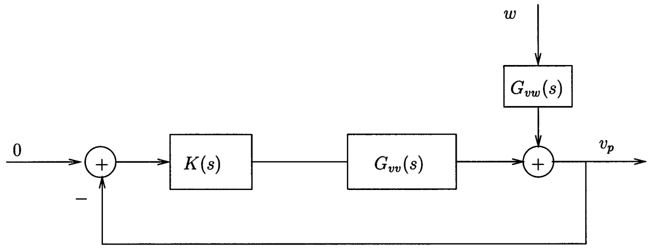


Fig. 4. Active control problem with a pair of collocated piezoelectric transducers.

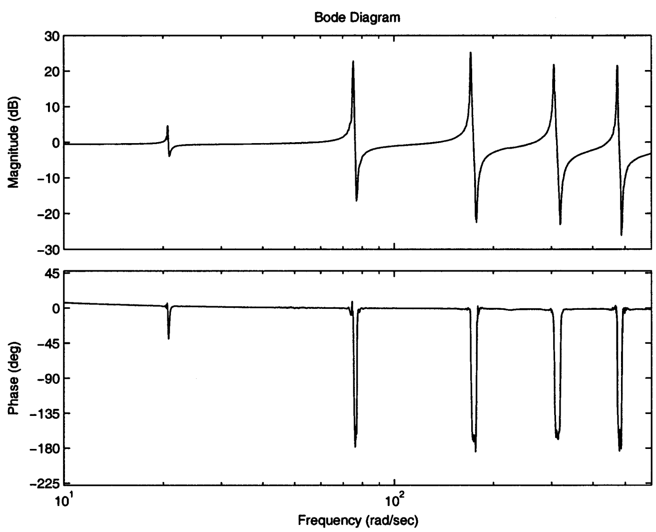


Fig. 5. Bode plot of G_{vv} associated with a simply supported flexible beam with a pair of collocated piezoelectric transducers (see [50] for more details).

close to the $j\omega$ axis (see Fig. 5).[1] Feedback control problems for systems of this nature are inherently difficult to handle (see, for example, [64] and [33, Sec. 1.5.4]). Furthermore, a controller is often designed with a view to minimizing vibration of a limited number of modes that fit within a specific bandwidth. If such a controller is then implemented on the real system (4), the resulting closed-loop system may be destabilized as a result of the spillover effect [7], [8]. The collocated structure is particularly of interest as it allows a specific form of control design which guarantees closed loop stability in presence of the modes that were neglected during the design phase. This point will be further clarified in Section V, however, the reader is referred to [38] and references therein for further discussions.

IV. SELF-SENSING TECHNIQUES

In a typical active vibration control application, piezoelectric elements are often used as actuators, or sensors. In this case, the piezoelectric device performs a single function; either sensing, or actuation. The piezoelectric self-sensing actuator, or sensori-actuator, on the other hand, is a piezoelectric transducer used simultaneously as a sensor and an actuator. This technique was developed concurrently by Dosch *et al.* [21]; and Anderson

[1]Particularly notice that poles and zeros interlace, and that the phase is between 0 and 180°. Low-frequency distortions in the phase are mainly due to the finite input impedance of the measurement device.

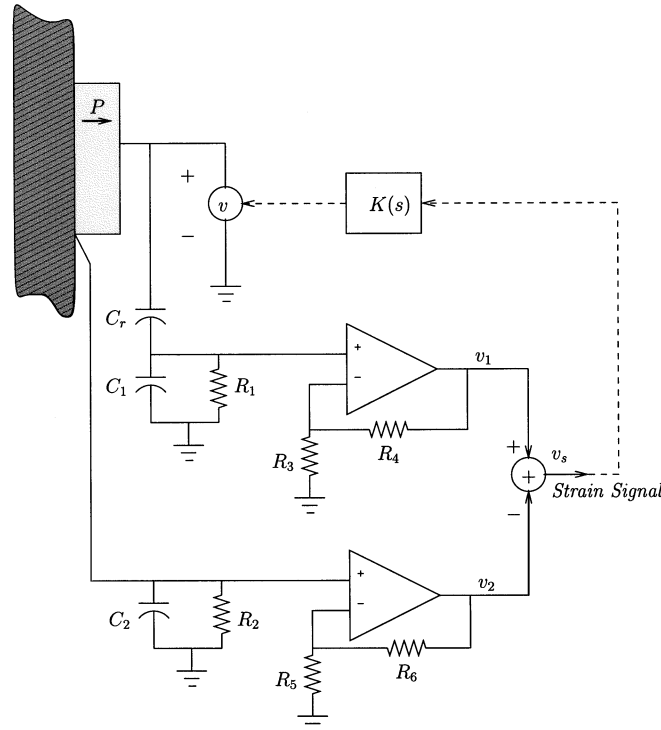


Fig. 6. Piezoelectric-based sensori-actuator, generating an estimate of the mechanical strain.

et al. [6], who made the observation that with the capacitance of the piezoelectric device known, one can simply apply the same voltage across an "identical" capacitor and subtract the electrical response from that of the sensori-actuator to resolve the mechanical response of the structure.

The key idea, here, is to replace the function of a sensor in the feedback loop by estimating the voltage induced inside the piezoelectric transducer, v_p. Since this voltage is proportional to the mechanical strain in the base structure, the estimated signal would provide a meaningful measurement for a feedback compensator. Furthermore, by estimating v_p, one would effectively replace the role of the collocated piezoelectric transducer in Fig. 2 by the additional electronic circuitry. In this way one would, ideally, expect to design feedback controllers that possess appealing properties associated with compensated collocated systems.

Two realizations for the piezoelectric sensori-actuator, as proposed in [6], are sketched in Figs. 6 and 7. The two circuits have rather similar functions; they use a signal proportional to the electrical charge or current and subtract that from the signal proportional to the total charge or current to produce a signal proportional to the mechanical strain, or its derivative. This signal is then used for feedback.

In the strain measurement circuit of Fig. 6, assuming that the leakage resistors R_1 and R_2 are very large and that the gain of each op-amp voltage follower is one, we may write

$$v_1 = \frac{C_r}{C_1 + C_r} v$$
$$v_2 = \frac{C_p}{C_2 + C_p} (v - v_p)$$

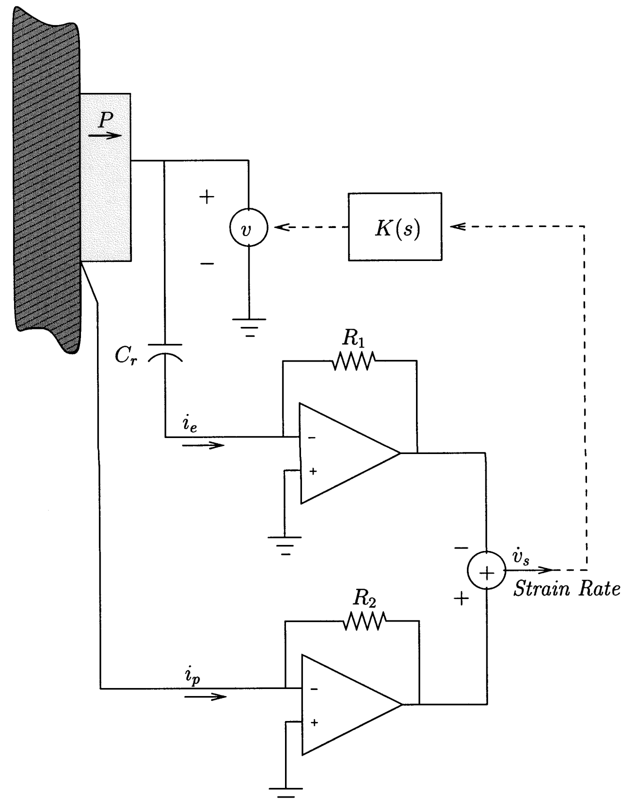


Fig. 7. Piezoelectric-based sensori-actuator, generating an estimate of the strain rate.

where v_p and C_p are, respectively, the voltage induced in and the capacitance of the piezoelectric transducer (refer to Fig. 3). The voltage v_p is proportional to the mechanical strain. Subtracting v_2 from v_1, we obtain

$$\begin{aligned} v_s &= v_1 - v_2 \\ &= \left(\frac{C_r}{C_1 + C_r} - \frac{C_p}{C_2 + C_p}\right) v + \frac{C_p}{C_2 + C_p} v_p. \end{aligned} \tag{7}$$

Hence, if $C_1 = C_2$ and $C_r = C_p$, (7) reduces to

$$v_s = \frac{C_p}{C_2 + C_p} v_p. \tag{8}$$

Therefore, under the above ideal assumptions, the estimated voltage is proportional to v_p. Now, consider the sensori-actuator in Fig. 7. The voltage v is applied to both the piezoelectric transducer and the reference capacitor C_r. A current i_e flows through the upper path, while i_p flows through the lower path. Each signal is converted to a voltage using an op-amp. The two signals are differenced, resulting in a voltage proportional to the derivative of v_p; i.e., the strain rate. To be more precise, if the two resistors R_1 and R_2 are both equivalent to R, v_s is found to be

$$v_s = R(C_r - C_p)sv + RC_p s v_p.$$

Again, it can be observed that if $C_r = C_p$, the first term will disappear, and v_s will be proportional to the strain rate. For practical reasons, however, very often the capacitive and resistive elements are chosen differently; see [6] and [21] for more details.

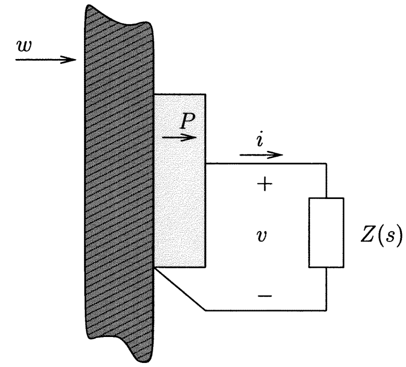


Fig. 8. Piezoelectric laminate shunted to an impedance $Z(s)$.

The two sensori-actuator schemes in Figs. 6 and 7 should perform well under ideal assumptions. Having estimated v_p, or perhaps $\dot{v}_p$, the signal produced by the sensori-actuator can now be used for feedback. Several applications for this method have appeared throughout the literature (see, for example, [4], [11], [36], [44], [67], and [73]). In practice, however, there are a number factors that limit the performance of the sensori-actuator, the foremost being the choice of the reference capacitor C_r, that is directly related to the size of piezoelectric capacitance C_p. The piezoelectric properties are influenced by variations in environmental conditions and operation. This requires a continual effort to tune the circuits in Figs. 6 and 7. A primary obstacle for implementation of the piezoelectric sensori-actuator is the difficulty in obtaining an accurate estimation of the capacitance of the piezoelectric device, C_p. This may not severely affect the open-loop performance of the sensori-actuator, however, if v_s is used as measurement for feedback, such variations may destabilize the closed-loop system.[2] An attempt to address this problem was made in [1], [16], [17], and [68], where the authors suggest an adaptive sensori-actuator implementation based on the least mean square (LMS) algorithm [23], [69].

The sensori-actuator is a linear estimator that generates an estimate of the strain signal, or its derivative. Structure of the estimator, however, is rather crude and is largely dependent on the added electronic circuitry. Often a nominal model for the underlying system is at hand. Therefore, it should be possible to construct better estimates of the required signals using an optimal estimation method such as a Kalman filter [5], [49]. The issue of uncertainty associated with the varying piezoelectric capacitance can then be addressed using the recent advances in robust state estimation and Kalman filtering (see [58] and references therein). It is rather surprising that this alternative approach has not been attempted in the literature.

V. Passive Control

The key idea of passive control is to use the piezoelectric transducer as a medium for extracting mechanical energy from the structure. Consider the system depicted in Fig. 8, in which

[2]In fact, it can be shown that the transfer function estimated by the self-sensing circuit is $G_{vv}(s) + \delta$, where δ is proportional to $C_p - C_r$. This additional fee-through term does not alter poles of the open-loop system. However, it does perturb the open-loop zeros, and this could be detrimental to the closed-loop performance and stability of the system.

a piezoelectric transducer is bonded to the surface of a flexible structure using strong adhesive material. The piezoelectric transducer is shunted by an electrical impedance Z. As the structure deforms, possibly due to a disturbance w, an electric charge distribution appears inside the piezoelectric crystal. This manifests itself in the form of a voltage difference across the conducting surfaces of the piezoelectric transducer v, which in turn causes the flow of electric current i through the impedance. For a strictly passive impedance, this causes a loss of energy. Hence, the electric impedance can be viewed as a means of extracting mechanical energy from the base structure via the piezoelectric transducer.

This approach to vibration control and damping has been under investigation for almost a decade [13], [35], [36], [39], [40], [45], [62], [65], [66], [71], [72], [74]. The two main questions associated with this technique are: how may one go about designing an efficient shunt impedance circuit? and what issues may arise in implementation of such a shunt? This section presents an overview of the field and addresses the above questions. Furthermore, it will be demonstrated that the problem of passive control can be interpreted as a feedback control problem, allowing for the use of modern and robust control methods in designing a shunt impedance.

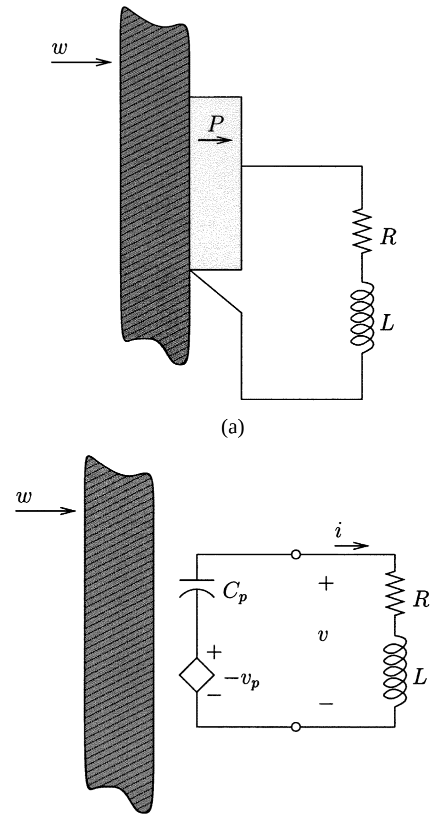
A. Impedance-Based Methods

One of the first researchers to work in this area was Forward [28], who proposed the idea of inductive (*LC*) shunting for narrow-band reduction of resonant mechanical response. In particular, he demonstrated that the effect of inductive shunting was to cancel the inherent capacitive reactance of a piezoelectric transducer. Later, Hagood and von Flotow [37] interpreted the operation of a resonant shunted piezoelectric transducer in terms of an analogy with a tuned mass damper, in which a relatively small second-order system is appended to the dynamics of a larger system. Moreover, they addressed the situation in which a resistive element is added to the shunt network, resulting in an *RLC* tuned circuit. This system, and its electrical equivalent are depicted in Fig. 9. The resulting *RLC* circuit is tuned to a specific resonance frequency of the composite system. That is, if the vibration associated with the ith mode is to be reduced, then L is chosen as

$$L = \frac{1}{\omega_i^2 C_p}.$$

By adopting a proper value for R, the resonant response at, and in the vicinity of ω_i can be reduced. However, one should keep in mind that due to the passive nature of the shunt, there will be hard constraints on the achievable level of performance. Nevertheless, reference [37] suggests a method for choosing the resistive element that appears to be effective. A more systematic method, based on optimizing the H_2 norm of the shunted system is proposed in [9].

The work of Hagood and von Flotow inspired a chain of publications addressing a variety of similar problems. For instance, Wu [70] demonstrated that if the series *RL* shunt is replaced by a parallel *RL* shunt, the resulting shunt circuit will have similar performance, with the added benefit of the performance being far less sensitive to changes in the resistive element.



(b)

Fig. 9. Piezoelectric transducer with an *RL* shunt and the equivalent electrical circuit.

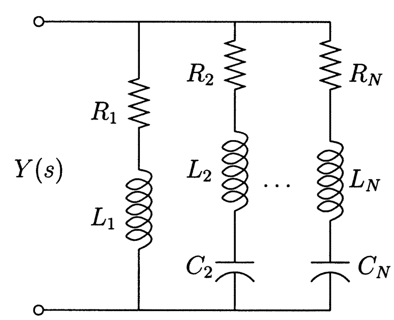


Fig. 10. Hollkamp circuit.

A question puzzling the researchers since [37] has been: how can one extend this method to allow for multiple mode vibration suppression? A trivial choice is to attach a number of piezoelectric transducers to a structure, each one shunted by an *RL* circuit tuned to a specific mode. This is clearly not a viable option as one would quickly run out of space over which transducers can be mounted. The main focus in this area, therefore, has been on finding multiple-mode vibration damping methods using a single piezoelectric transducer.

Hollkamp [39] suggested a specific resonant structure, depicted in Fig. 10. The shunt circuit consists of a number of parallel *RLC* shunts, with the very first branch being an *RL* circuit. For one mode, Hollkamp's circuit reduces to the one proposed by Hagood and von Flotow. However, for each additional mode, an *RLC* branch has to be added. When an extra branch is added, the previous resistive and inductive elements must be retuned

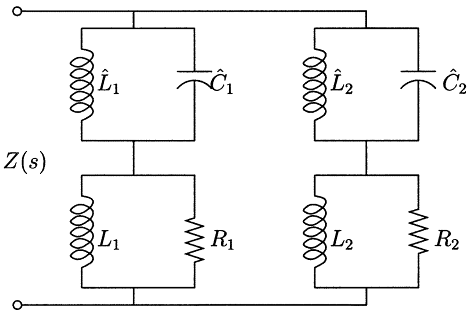


Fig. 11. Two-mode shunt damping circuit [71].

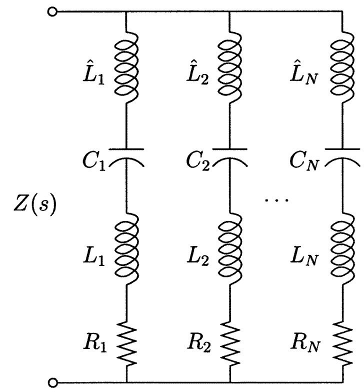


Fig. 12. Multimode shunt damping circuit [10].

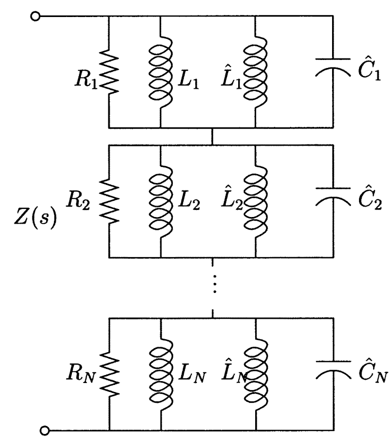


Fig. 13. Dual of the multimode shunt damping circuit of [10].

to ensure satisfactory performance. No closed-form tuning solution has been proposed for this technique. However, in [39] values for the shunt circuit electrical elements are determined using numerical optimization, based on minimizing an objective function. Given that all circuit elements are to be determined numerically, for a large number of modes this procedure may result in a complicated optimization problem. Nevertheless, the method has been applied to a cantilevered beam in [39], in which vibration of the second and third modes were reduced by 19 and 12 dB, respectively.

Another technique was proposed by Wu *et al.* [71], [72], [74]. Their idea is centered at using an *RL* (either parallel, or series) shunt for each individual mode, and then inserting current blocking *LC* circuits into each branch. The electric shunt circuit for a two mode system is depicted in Fig. 11. If vibration of the first two modes of the base structure are to be reduced, then L_1C_p is tuned to ω_1 while L_2C_p is tuned to ω_2. Furthermore, $\hat{L}_1\hat{C}_1$ is tuned to ω_2 while $\hat{L}_2\hat{C}_2$ is tuned to ω_1. Therefore, L_1R_1 and L_2R_2 are effectively separated at ω_1 and ω_2. For three modes, two current blocking circuits are inserted inside each branch, and so on. The difficulty with this method is that the size of the electric shunt increases very rapidly with the number of modes that are to be shunt damped, seriously complicating the task of implementing the required circuits. This issue will be further discussed in the sequel.

A recent method for multimode piezoelectric shunt damping is proposed in [10]. The shunt circuit, as depicted in Fig. 12 consists of *RL* branches, each tuned to a specific mode, with current-flowing series *LC* circuits inserted in each branch. The two inductors in each branch can be combined, resulting in a series *RLC* circuit in each parallel arm of the shunt circuit. Compared to the circuit proposed by Wu *et al.* [71], [72], [74], the resulting shunt circuit is of a considerably lower order. Furthermore, in comparison with the technique proposed in [39], this is a more systematic way of designing a shunt impedance circuit. A dual of the impedance proposed in [10] is depicted in Fig. 13. The circuit can be simplified by combining the two parallel inductors inside each series portion of the shunt.

B. Implementation Issues

The methodologies discussed so far result in electric shunt circuits that are realizable with passive circuit components such as resistors, capacitors, and inductors. Complications arise when low frequency modes of a structure are to be shunt damped. Very often a situation arises where a number of very large inductors, possibly in the order of hundreds of Henries, are to be used. For example, in [9] it is shown that to minimize vibration of two low-frequency modes of a beam using a PIC151 piezoelectric patch, one requires three rather large inductors: 43 H, 20.9 H, and 45.2 H. Such inductive elements are often implemented using Gyrator circuits, requiring two op-amps per inductor [63]. This may be acceptable for a single mode shunt circuit in which only one inductor is utilized, however, such an implementation for multimode shunt circuits would be painstakingly difficult. Consider, for example, the multimode shunt circuit proposed by Wu *et al.* [71]. If the number of modes to be shunt damped is n, it can be verified that one would need $2n(2n-1)$ op-amps to implement all necessary inductive elements. Hence, for five modes, 90 op-amps are needed! Other methods, such as that proposed in [10], require a considerably smaller number of op-amps—$2n$ for n modes, to be precise. However, such op-amp-based circuits have to be finely tuned on a regular basis as they go out of tune regularly. Therefore, more reliable and effective methods are desired.

The synthetic admittance circuit proposed in [24] and [25], and depicted in Fig. 14 is an efficient method for implementing electrical shunts onto piezoelectric transducers. The circuit is, in fact, a voltage-controlled current source that establishes a specific relationship between the current and voltage at the piezoelectric terminals. The voltage difference across the conducting electrodes of the piezoelectric transducer is measured and a current is supplied that is dictated by the transfer

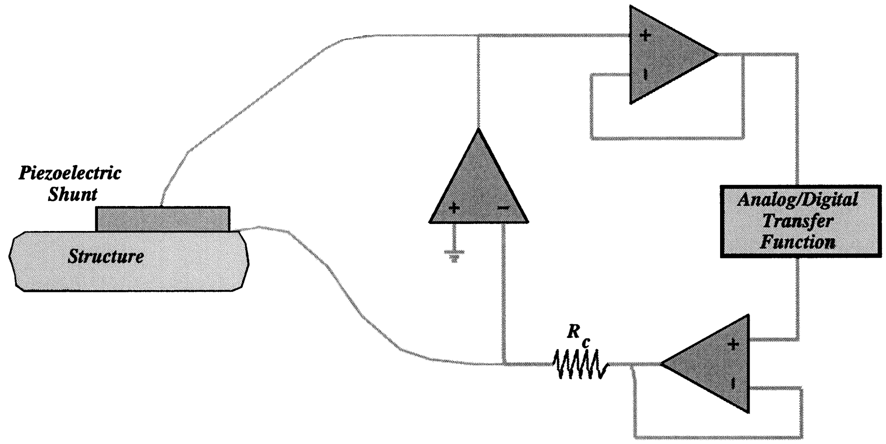


Fig. 14. Synthetic admittance circuit [24], [25].

function programmed into the digital signal processor (DSP) system. Hence, this is a digital implementation of an electrical admittance. Alternatively, one may choose to implement an impedance transfer function digitally; that is, measure the current flowing into the piezoelectric transducer and supply the voltage. The former method, however, is believed to be more advantageous. It is often more straightforward to obtain high-precision voltage measurements from a piezoelectric transducer, while the current can be supplied with the required precision. Another justification for this observation is related to the hysteretic behavior of piezoelectric transducers at higher drives, when driven by a voltage source. It is known that a piezoelectric transducer displays negligible hysteretic nonlinearities if it is driven by a current source instead [18], [32], [56].

The above discussion suggests that, unless otherwise necessary, the use of a synthetic admittance circuit may have to be recommended. However, there are situations where it may be necessary to implement an impedance transfer function. Later, it will be demonstrated that the problem of vibration control and damping using a shunted piezoelectric transducer can be interpreted as a feedback control problem with either $Z(s)$ or $Y(s)$ as the controller. Setting up the problem with $Y(s)$ as a controller may not result in satisfactory performance and robustness at all times forcing the designer to revisit the problem using $Z(s)$ as a controller.

C. Feedback Interpretations

Most of the methods proposed in the literature for the design of impedance shunt circuits, although effective, are based on rather *ad hoc* procedures. It turns out, however, that the problem of piezoelectric shunt damping can be interpreted as a feedback control problem, allowing for modern and robust control design methodologies to be employed in designing high performance impedance structures. The feedback structure associated with shunted piezoelectric transducers are reported in [52] and [53].

Consider the shunted piezoelectric transducer in Fig. 8 and its electrical equivalent in Fig. 15. Compared to active control methods, shunting the piezoelectric transducer with the impedance Z removes the need for an additional sensor. This, however, is achieved at the expense of having to deal with a more complicated feedback control problem.

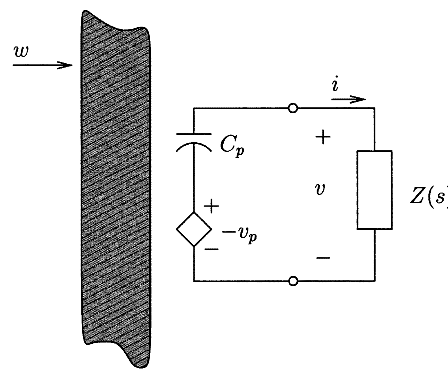


Fig. 15. Electrical equivalent of the system in Fig. 8.

To visualize the underlying feedback control structure, one needs to identify a number of variables such as the control signal, the measurement, the disturbance and the physical variable that is to be regulated. Furthermore, one has to choose either $Z(s)$ or $Y(s)$ as the controller. The feedback structure can be identified by noticing that the current may be written as

$$i(s) = -\left(v_p(s) + v(s)\right) C_p s. \tag{9}$$

Furthermore

$$v(s) = Z(s)i(s). \tag{10}$$

Equations (6), (9), and (10) suggest the feedback structure depicted in Fig. 16(a). The block diagram suggests a rather complicated feedback structure as the controller, $Z(s)$ is itself inside an inner feedback loop.

If $Y(s)$ is chosen as the controller, the block diagram of Fig. 16(a) can be redrawn as in Fig. 16(b). There are specific reasons as to why $Z(s)$ or $Y(s)$ should be chosen as a controller. Some of these reasons were clarified in previous sections.

The reader should notice that the feedback systems depicted in Fig. 16(a) and (b) are very similar to the feedback problem

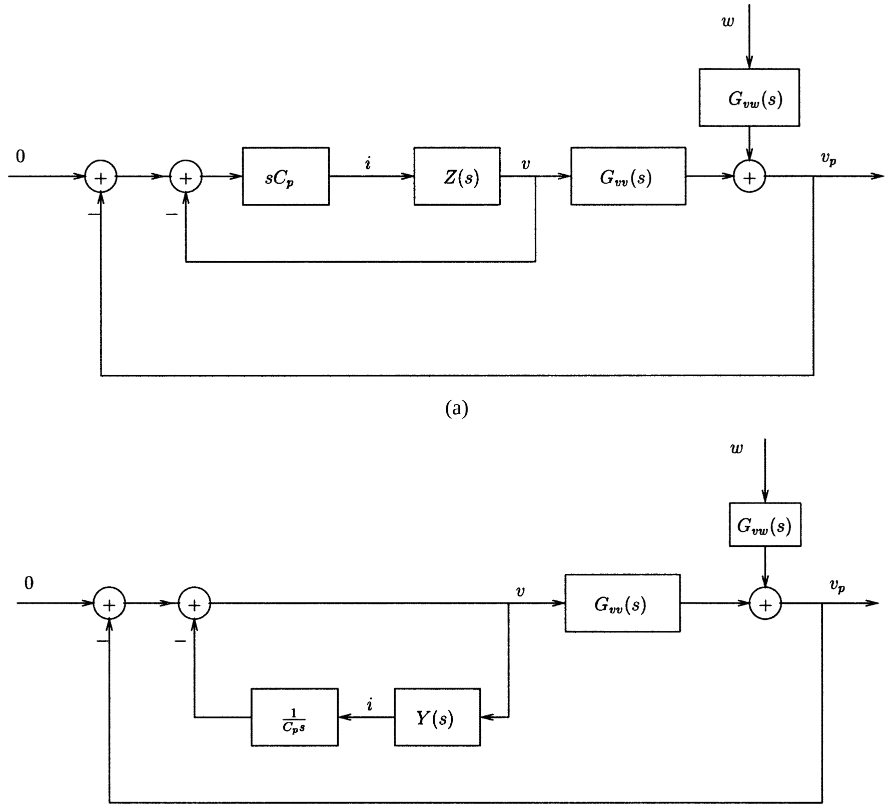


Fig. 16. Feedback structure associated with the shunt damping problem in Fig. 8. (a) $Z(s)$ functions as the controller. (b) $Y(s)$ serves as the controller.

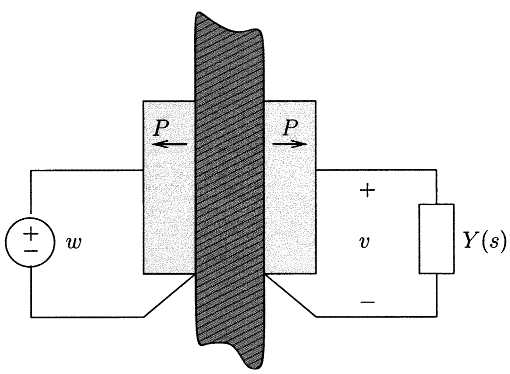


Fig. 17. Structure with collocated piezoelectric transducers.

associated with the collocated system in Fig. 4, if the feedback controller $K(s)$ in Fig. 4 is chosen as

$$K(s) = \frac{sC_pZ(s)}{1 + sC_pZ(s)}$$

or

$$K(s) = \frac{1}{1 + \frac{Y(s)}{sC_p}}.$$

Therefore, it should be possible to see the very close relationship between the collocated feedback control problem and the problem of vibration reduction using shunted piezoelectric transducers. This observation, however, could be misleading as it may lead the reader to the conclusion that having designed a controller for the former system, one may obtain an impedance for the latter. While this may be true in certain cases, such a procedure may result in an impedance, or an admittance transfer function that is not implementable digitally. Therefore, more practical impedance design methods are needed. A number of techniques are discussed in the next section.

Now, consider a system consisting of a base structure along with two piezoelectric transducers attached to either sides of the base structure in a collocated manner as in Fig. 17. Such a system is easily realizable in a laboratory. If the two piezoelectric transducers are identical, one may write

$$G_{vw}(s) = G_{vv}(s).$$

Therefore, the block diagram in Fig. 15 may be reduced to that shown in Fig. 18.

Identification of the underlying feedback structure associated with shunt damping is an important step in designing high-performance impedance shunts. In particular, the knowledge of this feedback structure enables one to address issues that would be very difficult to tackle otherwise. This includes problems such as fundamental performance limitations in vibration damping, dealing with actuator saturation, multivariable shunt design, robustness issues, etc. Some of these issues will be discussed in the following section.

D. Impedance Design for Piezoelectric Shunt Damping

An advantage of casting the shunt damping problem into a feedback control framework is that the impedance, or alternatively the admittance transfer function can now be considered

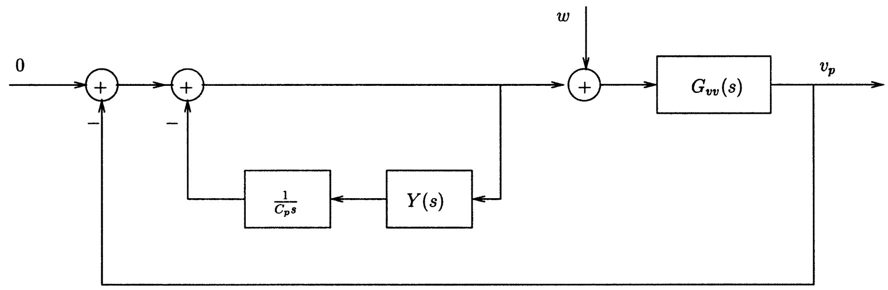


Fig. 18. Feedback structure with the disturbance applied to the collocated piezoelectric transducer.

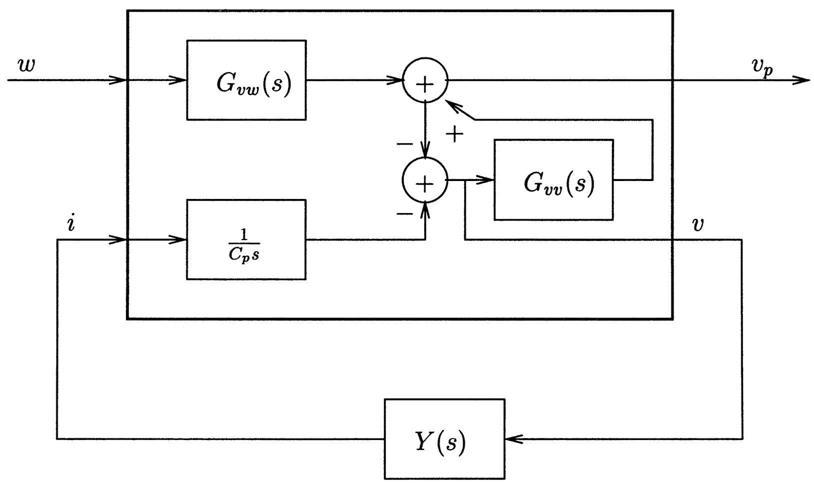


Fig. 19. Feedback problem in Fig. 16(b) cast as a disturbance rejection problem.

as the controller. It is, therefore, possible to use modern and robust control techniques to design high-performance shunt impedances. As an example, the feedback system of Fig. 16(b) can be cast as a disturbance rejection problem, as shown in Fig. 19. This approach removes the need for $Y(s)$ to be a passive electrical network. As a matter of fact, the impedance, or the admittance transfer function can be any transfer function, as long as they satisfy the performance, and robustness objectives of the closed-loop system. The resulting transfer function can, then, be digitally implemented using the synthetic admittance circuit discussed above.

In certain situations the uncertainty in the underlying model of the composite structure can be modeled in an efficient way. The uncertainty may be due to a number of factors, e.g., varying resonance frequencies with changing environmental/operating conditions, imprecise knowledge of damping factors associated with some vibration modes, or the effect of truncated high-frequency modes on the in-bandwidth dynamics of the structure [14], [51], etc. As the dynamics of the underlying system is known, one may attempt to cast the problem into a typical robust control design framework, as demonstrated in Fig. 20. Here, the block Δ contains all uncertain parameters of the system, while P includes all the nominal dynamics of the structure and $Y(s)$ represents the shunting admittance/controller. $Y(s)$ has to be designed in a way that the resulting uncertain closed-loop system is stable, for all admissible uncertainty Δ, and a specific performance objective as defined by w and z and a given performance index is achieved. Once the problem is brought down to this level of abstraction, a range of robust control design methodologies capable of addressing these issues can be used to design a shunt impedance (see, e.g., [22], [34], [59], and [75]).

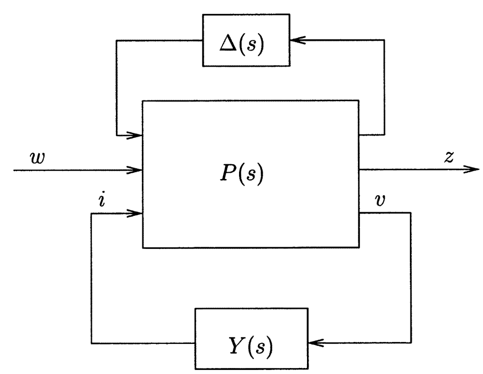


Fig. 20. Casting the shunt damping problem into a robust control framework.

A shunt impedance/controller design methodology has been recently proposed [52], in which the feedback structure associated with the shunt damping problem is utilized to construct robust and high-performance impedance shunts. Inspecting the systems depicted in Fig. 16(a) and (b), one can realize that a controller must internally stabilize the inner, as well as the outer feedback loop. Youla parameterization can be used to obtain a parameterization of all stabilizing controllers for the inner loop, and from there, those controllers that stabilize the system can be determined. In particular, it can be shown [27], [52] that any admittance transfer function possessing the structure

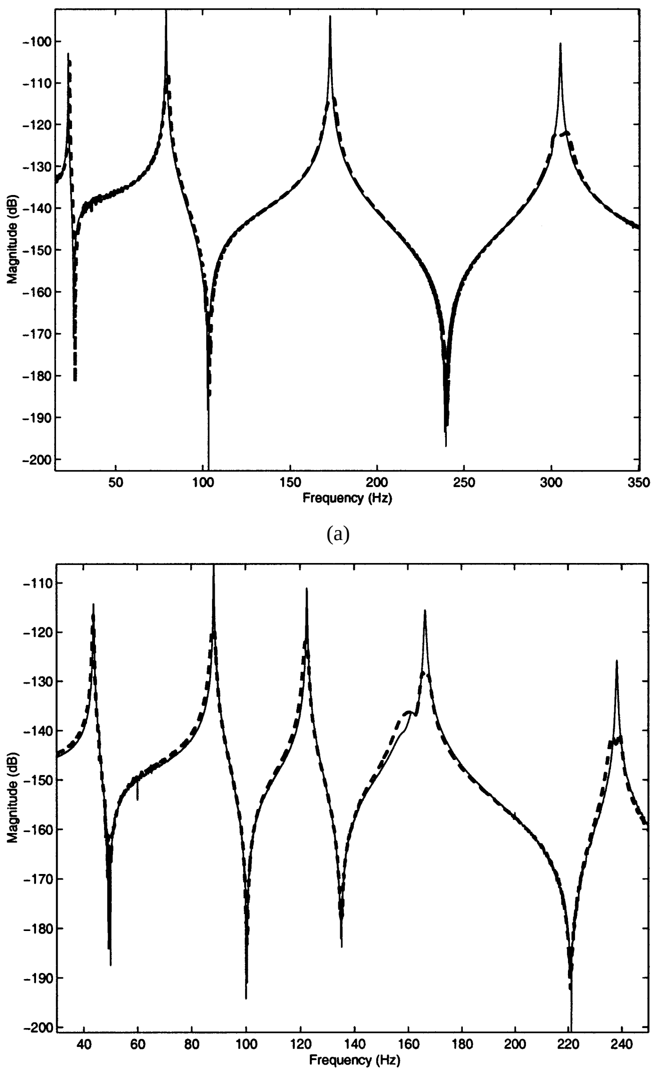


Fig. 21. Shunted and unshunted frequency response of (a) a beam and (b) a plate.

$Y(s) = (H(s)/(1 - H(s)))C_p s$, with $H(s) = 1 - sJ(s)$ and $J(s)$ a strictly positive real system, renders the closed-loop system internally stable. Two admittances have been suggested that have favorable performances. These are

$$Y_1(s) = \frac{\sum_{i=1}^{N} \frac{\alpha_i(2d_i\omega_i s + \omega_i^2)}{s^2 + 2d_i\omega_i s + \omega_i^2}}{1 - \sum_{i=1}^{N} \frac{\alpha_i(2d_i\omega_i s + \omega_i^2)}{s^2 + 2d_i\omega_i s + \omega_i^2}} C_p s \tag{11}$$

and

$$Y_2(s) = \frac{\sum_{i=1}^{N} \frac{\alpha_i\omega_i^2}{s^2 + 2d_i\omega_i s + \omega_i^2}}{1 - \sum_{i=1}^{N} \frac{\alpha_i\omega_i^2}{s^2 + 2d_i\omega_i s + \omega_i^2}} C_p s \tag{12}$$

where in both cases $\sum_{i=1}^{N} \alpha_i = 1$. Interestingly, it can be proved that (11) and (12) are strictly positive real transfer functions [43], and hence, can be implemented using passive circuit components such as resistors, capacitors, and inductors. The task of synthesizing such a passive network, however, does not appear to be straightforward. Nonetheless, these circuits should be implemented digitally, due to the reasons explained previously. These shunts have been experimentally implemented on a number of test beds, and they have proved to be quite efficient in reducing structural vibrations. Fig. 21 demonstrates experimental results obtained from a simply supported beam, and a plate with shunted piezoelectric transducers. In both cases, resonant peaks have been reduced significantly once the shunts were applied to the structure.[3]

The reader should notice that with Y_1 and Y_2 defined above, the shunt damping problem is equivalent to the feedback control problem associated with the collocated system in Fig. 4 with

$$K_1(s) = 1 - \sum_{i=1}^{N} \frac{\alpha_i(2d_i\omega_i s + \omega_i^2)}{s^2 + 2d_i\omega_i s + \omega_i^2}$$

and

$$K_2(s) = 1 - \sum_{i=1}^{N} \frac{\alpha_i\omega_i^2}{s^2 + 2d_i\omega_i s + \omega_i^2}.$$

K_1 and K_2 are, therefore, resonant controllers (see [38], [61]).

It is instructive to consider the situation where only one mode is to be shunt damped. This can be achieved by setting the admittance $Y(s)$ in (11) equal to the ith term. That is

$$Z(s) = \frac{s/C_p}{2d_i\omega_i s + \omega_i^2}.$$

This is equivalent to the parallel connection of a resistor

$$R = \frac{1}{2d_i\omega_i C_p}$$

with an inductor

$$L = \frac{1}{\omega_i^2 C_p}.$$

The parallel *RL* circuit for single mode piezoelectric shunt damping was proposed in [70], in which a similar choice for L is proposed. Also, if $i = 1$ in (12), the series *RL* circuit proposed by Hagood and von Flotow [37] can be recovered.

VI. Performance

An issue that needs to be addressed here is that of achievable performance with shunted piezoelectric vibration absorbers as compared to the active methods. It should be noted that the combination of a piezoelectric transducer shunted by a strictly passive impedance is inherently stable. Therefore, existence of out-of-bandwidth dynamics can not destabilize the closed-loop system. Despite this advantage the very fact that the impedance and, hence, the controller, is passive implies that one should expect a hard limit on the achievable damping from such a system.

In contrast to this, active control methods may offer higher performance levels. However, this may come at the expense of lower stability margins. Therefore, careful design of a controller requires the enforcement of stability robustness by other means. Subsequently, this may lead to a compromise between performance and stability robustness.

[3]For more details, the reader is referred to [54].

A distinct advantage of viewing a shunted piezoelectric transducer as a feedback control system is that control theoretic tools can now be used to design shunt impedances for vibration suppression purposes. Given that the impedance is no longer required to be passive, one may expect to achieve higher performance levels as compared to using strictly passive shunts. Furthermore, using such a structure removes the need for an additional sensor. This is in contrast to active vibration control methods which require sensors, as well as piezoelectric actuators.

VII. Future Directions

The observation that the problem of vibration reduction using shunted piezoelectric transducers is a feedback control problem enables researchers to address a wide range of problems using systems theoretic tools. This includes fundamental problems such as: what is the maximum achievable performance with a passive shunt? how to deal with the problem of saturating actuators? how to formulate the problem of vibration reduction using several shunted piezoelectric transducers? how to accommodate the hysteresis associated with the piezoelectric material at high drives? and other questions that may arise subsequently. All these problems, however, are open and are yet to be addressed.

A number of problems associated with shunt damping systems were not addressed in this review. Most notably, the problem of passive–active control, also known as the hybrid control of vibrations [65]. In this technique a controlled voltage source, or a current source is added to the electric shunt to generate further damping. Considering the shunt damping problem as a feedback control problem, the added controlled voltage, or current source can be viewed as an additional controller that can be combined with the shunt controller.

Another topic that has received little attention is adaptive piezoelectric vibration absorbers [26], [40]. Resonance frequencies of lightly damped flexible structures are known to drift with changing operating conditions. Viewing the electric shunt as a feedback controller, one can adaptively tune the shunt parameters to track the resonance frequencies of the base structure, hence, avoiding performance degradation.

VIII. Conclusion

Piezoelectric transducers have found extensive applications in vibration control systems. In active vibration control problems, these transducers are used as actuators and sensors in feedback control loops designed to suppress vibration of flexible structures. Shunt damping systems remove the need for a sensor by shunting a piezoelectric transducer by an impedance. The resulting system now becomes a feedback control system, in which the impedance transfer function is the controller. The feedback structure is very similar to that of a feedback controller with a pair of collocated, and identical, piezoelectric transducers. The actual controller/impedance, however, is itself inside an inner feedback loop. This observation allows one to use standard control system design tools for designing shunt impedances.

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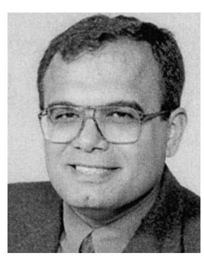

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