Chapter 2

Background

This chapter provides background information applicable to the objectives of this study. First, piezoelectric materials are further defined with an explanation of the piezoelectric theory and the possible applications of piezoelectric materials. Next, the literature search conducted in the areas related to this research is discussed. Finally, the details of the shunt design for this study are presented.

2.1 Piezoelectric Theory

Pieozoceramics are materials that demonstrate what is known as the *piezoelectric effect*:

> *Piezoelectric Effect; appearance of an electrical potential across some faces of a crystal when it is under pressure, and of distortion when an electrical field is applied. Pierre Curie and his brother Jacques discovered the effect in 1880. It is explained by the displacement of ions, causing the electric polarization of the crystal's structural units. When an electrical field is applied, the ions are displaced by electrostatic forces, resulting in the mechanical deformation of the whole crystal. Piezoelectric crystals are used in such devices as the transducer, record-playing pickup elements, and the microphone.*
>
> -*Encarta Concise Encyclopedia[3]*

This effect occurs naturally in quartz crystals, but can be induced in other materials, such as specially formulated ceramics consisting mainly of Lead, Zirconium, and Titanium (PZT). Because they are ceramics (piezoceramics), they can be formed to most any shape or size. In order to "activate" the piezo properties of the mix of metals, the material is first heated to its Curie temperature. There, a voltage field of a sufficient strength is applied in the desired direction, forcing the ions to realign along this "polling" axis. When the ceramic cools, the ions "remember" this polling and act accordingly.

Much reference is made to piezo axes and their relation to the poling axis. Convention and the IEEE Standard on Piezoelectricity [4] state that the poling axis be termed the "3" direction with the same positive/negative sense as the applied voltage field. The remainder of the coordinate system is analogous to a right-handed orthogonal system, mapping x-1, y-2, and z-3 , as shown in Figure 2.1 [5].

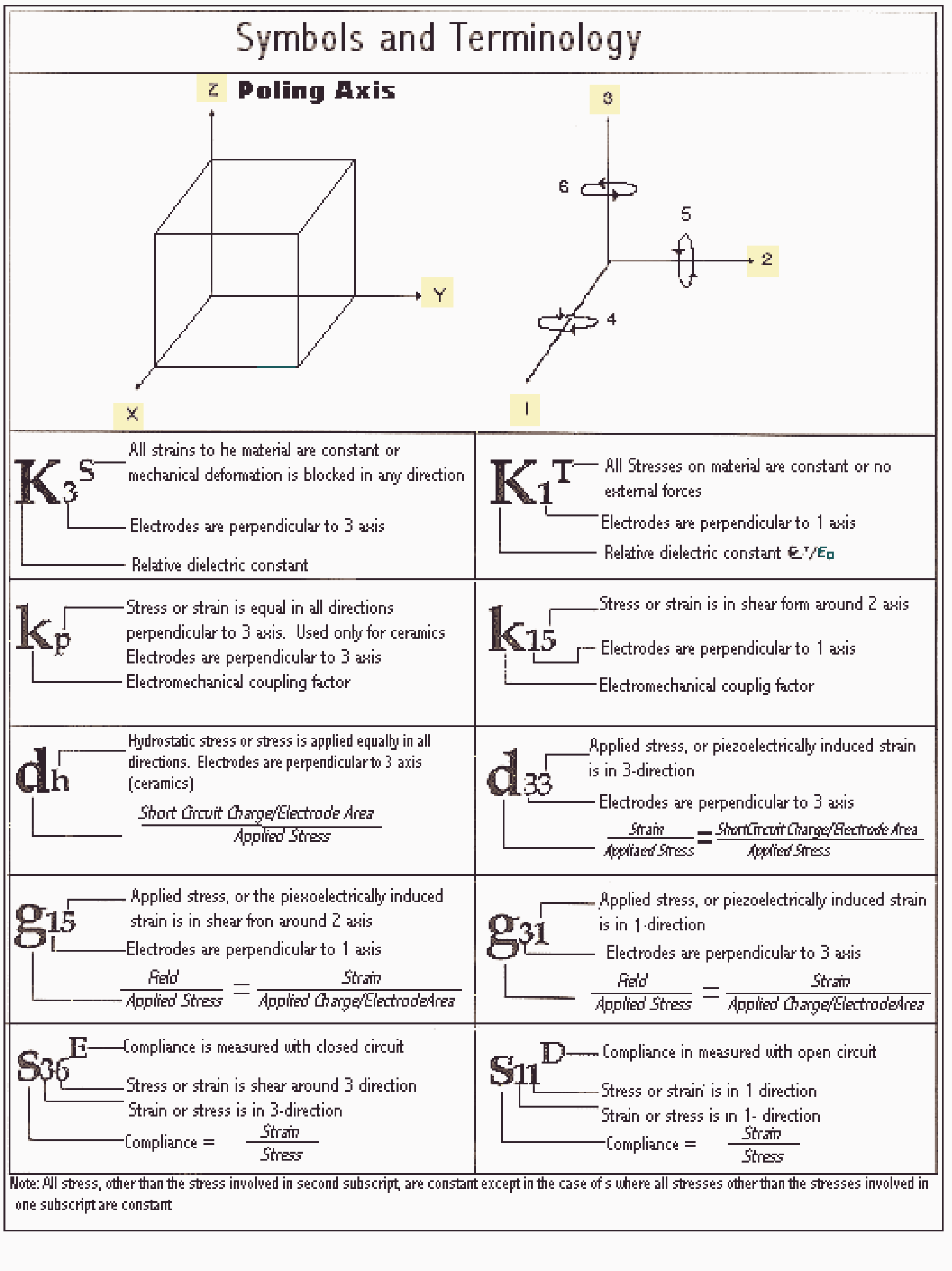


Figure 2.1. Basic Symbols and Terminology in Piezoelectricity

2.2 Applications for Piezoceramics

The piezoelectric effect provides the ability to use these materials as both a sensor and actuator. Strain, for example, can be measured by capturing the voltage created across the material when it is strained. As a sensor, these materials can also be used for damage detection in structures in which they are imbedded. Piezoceramics can be used as actuators because they can strain or displace when an electric voltage is applied across the poling axis. This makes PZTs good candidates for valve actuation or active control systems. Piezoceramics are also used as structural dampers because of their ability to efficiently transform mechanical energy to electrical energy and vice versa. When a piezoelectric element, PZT, is used for passive vibration suppression, the force from the vibration strains the PZT, which generates a voltage difference. This voltage, electrical energy, can then be dissipated through a resistive circuit [6]. For example, the use of piezoelectric elements for passive electronic damping has already been proven to work effectively in commercial products such as the K2 ski. The K2 ski designers used a resistor and capacitor (RC) shunt circuit to dissipate the vibration energy absorbed by piezoelectric devices imbedded into the skis [7]. Active Control eXperts, Inc. developed the Copperhead ACX bat that has shunted piezoceramic materials that convert the mechanical vibration energy into electrical energy. This method of damping significantly reduces the sting during impact and gives the bat a larger sweet spot [8].

2.3 Literature Search

A literature search was conducted to investigate past research related to the use of smart materials to control structural vibration and noise. The specific areas that were considered for the literature search included the utilization of smart materials for passive damping, increasing transmission loss, and reducing vehicle vibration and noise, as shown in Figure 2.2. Two databases, INSPEC and AppSciTechAb™, were used for the literature search. INSPEC is a leading database for physics, electronics, and engineering research, and AppSciTechAb™ is another source for applied science and technology literature.

The search was conducted using the keywords of the primary areas of interest, which were “structural vibration” and “smart materials”, as shown in Figure 2.2. The smart materials were searched as “PZT,” “piezoceramic,” and “piezoelectric” in order to maximize the number of matching research topics. The literature search resulted in a large number of articles in general areas such as “structural vibration” and damping with smart materials. As such, all the works that were reviewed were taken from the results of the search areas highlighted in Figure 2.2. A summary of the search results is provided next.

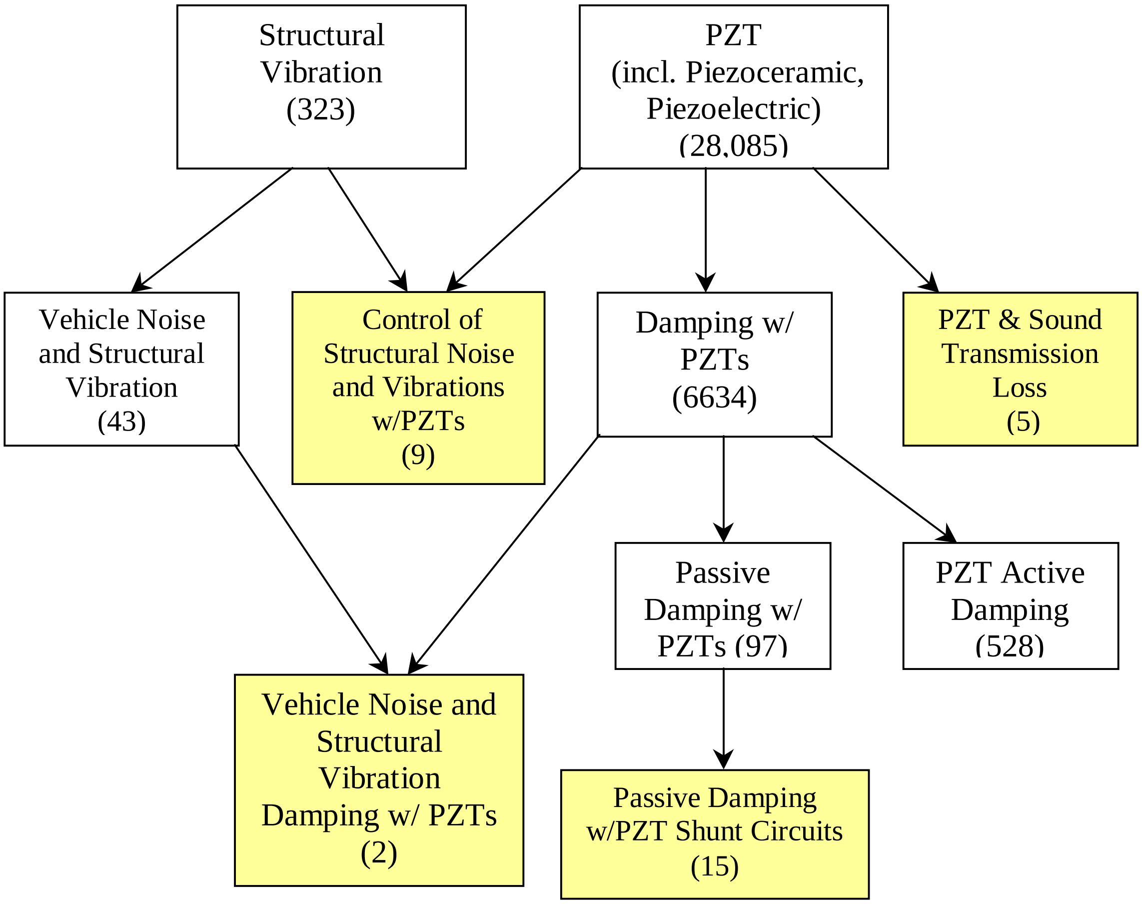


Figure 2.2. Literature Search Flowchart

2.3.1 Control of Structural Noise and Vibrations with Smart Materials

Structural controls have recently been used to reduce acoustic radiation from vibrating structures, also referred to as structure-borne noise. Almost all of the studies have involved the implementation of an active control system. Sun *et al.* used piezoelectric actuators to reduce the structural vibrations and interior noise of a uniform cylindrical shell that models a fuselage section [9]. Two distributed piezoelectric actuators were developed based upon the understanding of structural-acoustic coupling properties of the system.

Control of sound radiation from a plate in an acoustic cavity using smart materials was investigated by Shields *et al.* [10]. They applied a patch of active piezoelectric damping composites to the center of a 29.8-cm square plate made of thin aluminum. The patch was made of PZT fibers embedded in resin. Using a derivative feedback controller, they obtained a 70% attenuation of vibration and sound pressure levels. Active control of sound radiating from a plate was also demonstrated by Varadan *et al.* on a thin square metal plate [11]. The structural vibrations of the plate responsible for the sound/noise radiation were actively controlled with piezoelectric sensors and actuators. This effective method of active noise control was demonstrated for the interior noise of a cabin enclosure by Varadan *et al.* [12]. They used discrete piezoelectric actuators and sensors for the active vibration control of the walls of the enclosure. They were able to achieve significant global noise reduction within the cavity for the dominant modes of the radiation panel.

2.3.2 Vehicle Vibration and Noise Control Using Smart Materials

Lecce *et al.* demonstrated vibration active control in a vehicle by using piezoelectric sensors and actuators [13]. The active structural acoustic control was developed by integrating piezoceramic materials as sensors and actuators into some structural elements of the car. By controlling the vibrations, the structure-borne noise was reduced. A simple feed forward control system was implemented to control the floor panel vibrations.

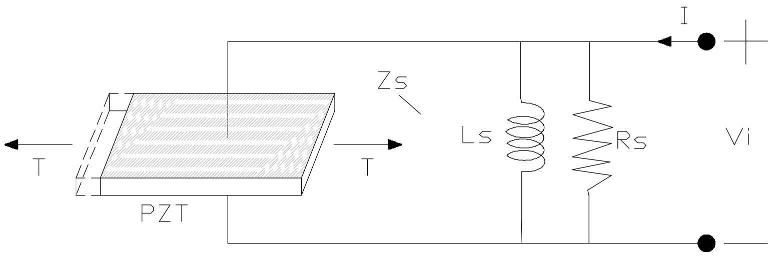
2.3.3 Increasing Transmission Loss with Piezoceramics

Active control using piezoceramics has been implemented to control the sound transmission through a panel. Henrioulle *et al.* added a flexible honeycomb structure with a piezoelectric PVDF (polyvinylidene fluoride) layer to a double panel partition [14]. With active control of the PVDF, they were able to increase the transmission loss by 10 dB at frequencies below 400 Hz. Xiaoqi *et al.* used active control with piezoelectric actuators and sensors to increase the transmission loss through a thin aluminum plate [15]. The plate was actively controlled at the resonance frequencies of the passive plate where the isolation performance was poor. With one sensor and one actuator, a global sound reduction of 15-22 dB was achieved at the first three resonance frequencies.

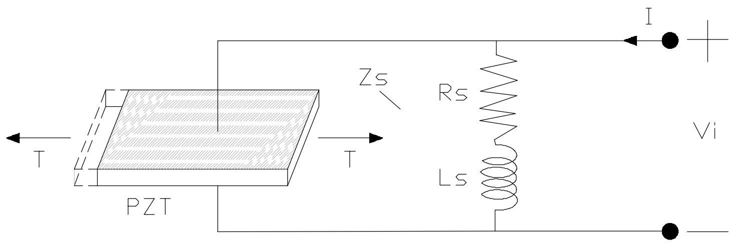
2.3.4 Passive Damping Using Shunted Piezoceramics

In addition to the K2 ski designers, many researchers have investigated the use of passive electric shunts as a potential way to suppress vibrations. In 1979, Forward was the first to suggest the possibility of using passive electrical shunts with piezoelectric elements for vibration damping and control [16]. Forward experimentally investigated the effect of using inductive shunting with a piezoelectric element on a metal beam. Hagood and von Flotow developed the first quantitative analytical models for piezoelectrics shunted with two types of circuits, a resistor circuit (RC) and a resistor and inductor circuit (RLC) [6]. They showed that when a PZT was attached to a resistor circuit, the frequency dependence of the PZT was similar to visco-elastic damping materials. A PZT shunted with the inductor and resistor had an electrical resonance that could be tuned to be similar to a vibration absorber. Hagood and von Flotow validated both circuit models experimentally on a cantilevered beam and developed techniques that analyzed shunted systems. Further piezoelectric theory was developed by Davis and Lesieutre on the damping performance prediction of shunted piezoceramics [17]. They developed a method where the damping is predicted from the effective fraction of the modal strain energy stored in the PZT, the effective piezoelectric material loss factor, and the frequency shaping factor. They determined the strain energy factor using finite element methods, the loss factor to be related to the electromechanical coupling coefficient, and the frequency shaping factor from the dynamic response of the shunting circuit.

Since Hagood and von Flotow's initial research, many have worked to understand, optimize, and improve shunting techniques. Edberg *et al.*, for instance, replaced the heavy commercial inductor used by Hagood with a lightweight electronic circuit [18]. They also showed that it was possible to simultaneously dissipate two vibration modes using one tuned shunt circuit. Hollkamp also expanded the piezoelectric theory to show that it was possible to suppress multiple modes using a single PZT [19]. However, due to mutual loading effects between multiple shunts, it was experimentally difficult to simultaneously tune the shunts to different modes. Wu analyzed the piezoelectric shunt theoretically using a PZT shunted with a parallel resistor and inductor circuit for passive structural damping and vibration control [20]. This design, illustrated in Figure 2.3a, proved easier to tune than the shunt design investigated by Hagood and von Flotow, shown in Figure 2.3b. The load resistor and inductor of the new shunt design could be changed independently, and adjusting the load resistor had no effect on the circuit resonance frequency. Wu used this modified shunt circuit design to develop a method for damping multiple vibration modes using a single piezoelectric patch. They employed "blocking" circuits that consisted of a parallel capacitor-inductor anti-resonant circuit. This circuit was placed in series between shunt circuits designed for one structural mode. These "blocking" circuits were designed to be open-circuited at all frequencies except the resonant frequency to which their branch shunts circuit is tuned. This method proved to be more reliable and easier to tune and optimize than method used by Hollkamp. Wu demonstrated this method by suppressing the first two to three modes of a two-wing cantilevered beam with a single PZT.



(a) Shunt Circuit Concept Used by Wu



(a) Shunt Circuit Concept Used by Hagood and von Flotow

Figure 2.3. Shunt Circuit Design Concepts Used by Hagood and Wu

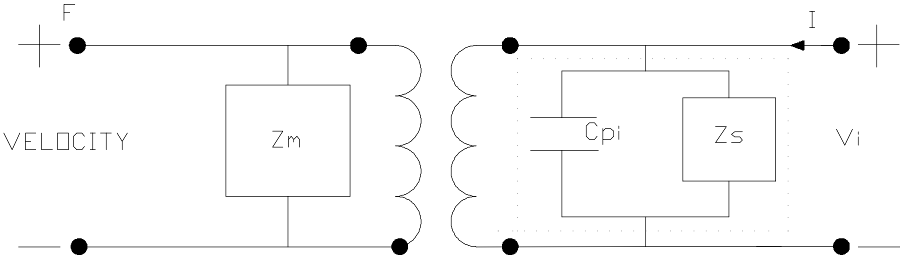
Later, Wu and Bicos demonstrated multimode shunting on a composite plate structure [21]. In addition to Wu and Bicos, the application of passive smart damping on a plate has been researched by others as well. For example, Hollkamp and Gordon compared the damping effectiveness of a piezoelectric vibration absorber with constrained layer damping treatment on an electronic chassis box [22]. The results showed that the piezoelectric absorber could provide vibration suppression comparable with that obtained with the constrained layer damping. Ghoneim investigated the application of shunted piezoelectric damping on a cantilevered plate [23]. His investigation was mainly analytical and qualitative with preliminary experimentation. Ghoneim argued that the shunted piezoelectrics were more effective at suppressing resonant vibration amplitudes with a wider effective range of vibration control than constrained layer damping.

Passive piezoelectric damping has also been applied to space structures in research conducted by Aldrich *et al.* [24], and Edberg and Bicos [25]. Aldrich *et al.* implemented 0.5 kg of piezoelectric material to damp a 5000-kg structure. Their study included active and passive damping using piezoelectric materials. Resistive piezoelectric shunting provided the necessary broadband damping. Edberg and Bicos investigated implementing shunted piezoelectric materials in structural struts that may be installed in a truss structure.

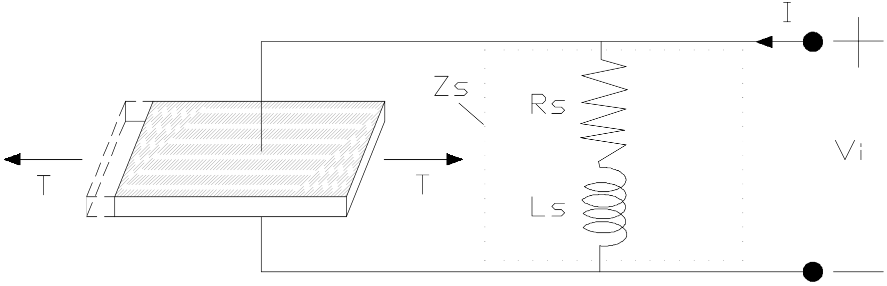
Another aspect of shunted piezoelectric damping that has been researched is the methodology of tuning the shunt circuit for optimal response. Piezoelectric materials shunted with resonant circuits are designed to minimize structural vibrations at a specific frequency. This frequency, however, may shift in practical applications thus reducing the effectiveness of the tuned vibration absorber. As such, researchers such as Hollkamp and Starchville [26], and Davis and Lesieutre [27] have investigated implementing active self-tuning circuits. Hollkamp and Starchville used a cantilevered beam mounted with PZTs attached to resonant shunt circuits to demonstrate active tuning. The PZT vibration absorbers were designed to tune themselves to a particular mode and track the mode as it varies in frequency. The control system achieved this by comparing the structural response of the beam to the shunt circuit response. Davis and Lesieutre demonstrated active tuning for a piezoelectric vibration absorber with a passive capacitor shunt circuit. They developed a control scheme that estimated the desired tuning frequency from sensors and determined the appropriate shunt capacitance. The shunt circuit was tuned using a relay-driven parallel capacitance ladder circuit designed to tune the shunt in ten discrete steps over the tuning range. With their actively tuned shunt design, Davis and Lesieutre were able to achieve a 10 dB improvement in vibration reduction over passive resonant shunt damping.

2.4 Shunt Circuit Design

The smart damping technique chosen for this study involved attaching piezoceramic devices that are shunted with passive electrical circuits. When the panel vibrates, as illustrated in Figure 2.4(b), the mechanical energy strains the piezoelectric material and thereby generates electrical energy (i.e. voltage). The shunted electrical impedance then dissipates this electrical energy. The components of these shunt circuits (resistors, capacitors, and inductors) are chosen to produce an effective mechanical impedance at desired levels and frequencies.



(a) Network Analog of Shunt Model



(b) Simple Physical Model of a Uni-Axial Shunted PZT

T- Stress by Plate on PZT
I- Circuit Current
Ls- Shunt Inductance
Zm-Plate Mechanical Impedance

Vi- PZT Voltage
Rs- Shunt Resistance
Zs-Equivalent Shunt Impedance
Cpi-Inherent PZT Capacitance

Electrical Resonant Frequency:

$$\omega_e = 1/\sqrt{LsCpi}$$

Ref. H.W. Hagood, and A von Flotow, " Damping of Structural Vibrations with Piezoelectric Materials and Passive Electrical Networks," Journal of Sound and Vibration, Vol. 146, No.2, pp. 243-268, 1991

Figure 2.4. Shunting of Piezoelectric Materials

As shown in Figure 2.4(a), the shunt circuit that was chosen for this application was an RLC circuit, similar to the one demonstrated by Hagood and von Flotow [6]. Although there have been many improvements made on this shunting concept, this shunt was chosen because it was the established design implemented at the Center for

Intelligent Material Systems and Structures Lab at Virginia Tech. Future studies in this area may select other shunt circuits that are more suitable for their intended applications.

The basic resonant shunt design consists of a resistor, an inductor, and a capacitor. The resistor in the circuit is referred to as the load resistor because it is the mechanism that dissipates the electrical energy. This resistor value ranges from 0 to 14,000 Ω, and dissipates around 0.002 W of energy from the plate at resonant peaks. The electrical resonance of the circuit is determined by the value of the inductance and the capacitance, as in Equation (2.1).

$$\omega_e = \frac{1}{\sqrt{LsCpi}} \tag{2.1}$$

The capacitor, *Cpi*, for the circuit is the PZT itself because electrically, it behaves similar to a capacitor. The capacitance value of the circuit cannot be changed in order to tune the circuit at a desired resonant frequency unless a variable capacitor is added in parallel or series. If the capacitance of the PZT has to be reduced, a variable capacitor can be added in series with the PZT. Alternatively, a variable capacitor can be added in parallel with the PZT to increase the capacitance. Another simpler alternative is to use a variable inductor as the shunt inductor in order to tune the circuit. The inductance for the RLC circuit, *Ls*, was simulated with an operational amplifier circuit as shown in Figure 2.5 [28].

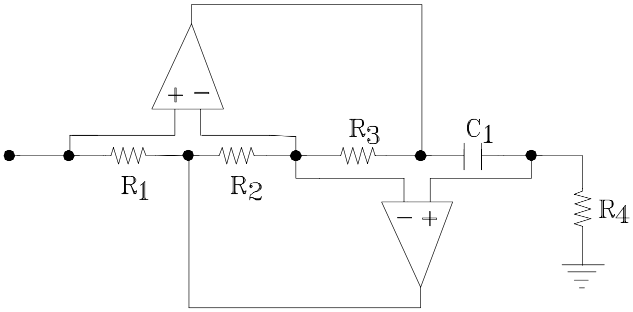


Figure 2.5. Operational Amplifier Circuit Emulating a Variable Inductance

The resistor, R_2, is a variable resistor that can be adjusted in order to change the circuit inductance. The components labeled R_1, R_3, and R_4 are 10kΩ resistors, and C_1 is a 10,000μF capacitor. The details of one of the experimental shunt circuits are pictured in Figure 2.6, where R_L is the load resistor. The leads from the positive and ground poles of the PZT are inserted at the marked nodes. The operational amplifier uses a ±15 Volts power source, but requires less than 1 Watt of power to run. This shunt-power supply configuration is illustrated in Figure 2.7.

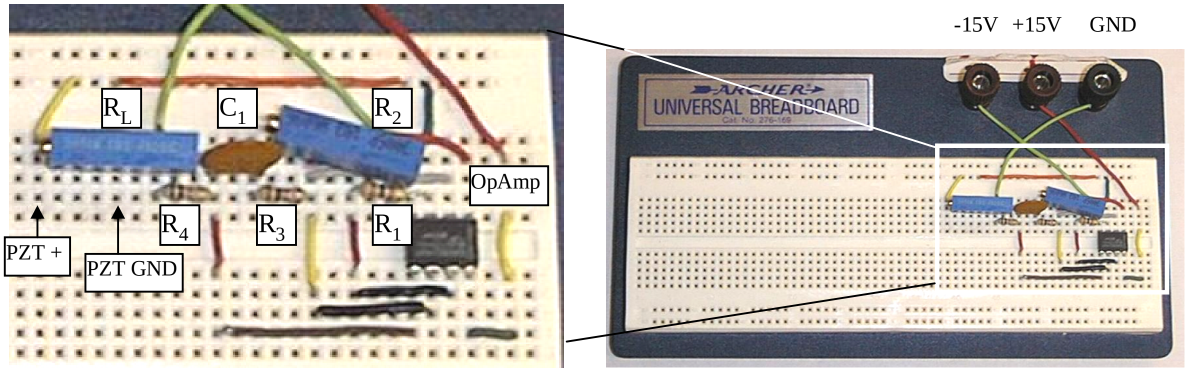


Figure 2.6. Experimental Shunt Circuit Board (Single Shunt)

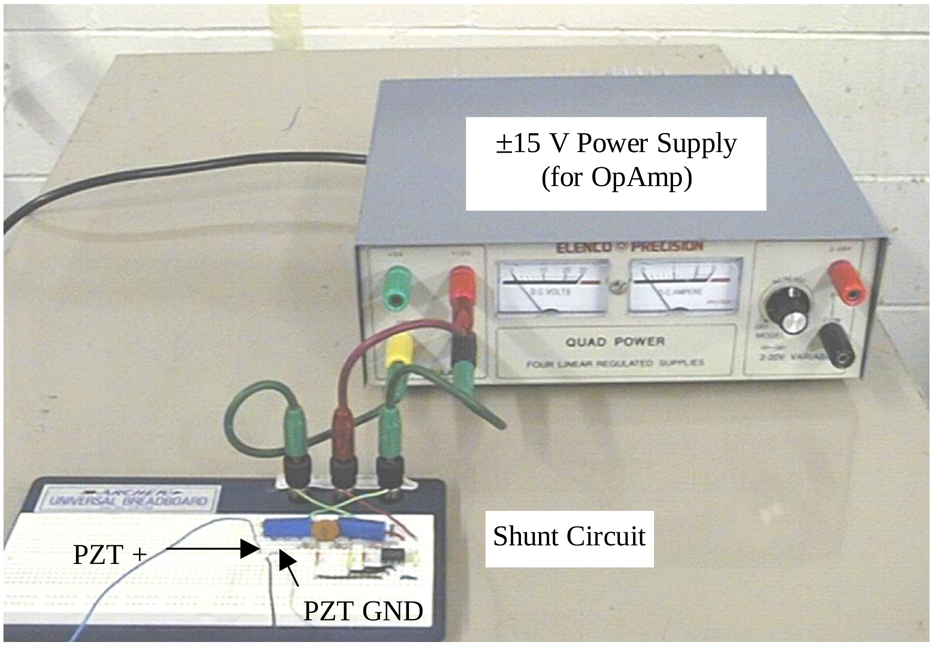


Figure 2.7. Single Shunt Circuit and Power Supply Configuration

2.4.1 Shunt Tuning

The purpose of this section is to describe the methods used for tuning the PZT resonant shunt circuits. The first step is to determine the electrical resonant frequencies required to dissipate the mechanical energy. The second step is to calculate the initial values for the variable resistors in the shunt circuit. The final step is to fine-tune the resistors with testing in order to achieve optimal damping.

An optimal electrical resonant frequency must be calculated because the electrical resonant frequency is not exactly the same as the resonant plate frequency due to inherent damping in the plate and added damping of the shunt circuit. An optimal tuning ratio, δ_{opt}, is calculated to determine the electrical resonant frequency of the circuit, ω_e. Several experimental parameters must be determined before δ_{opt} and ω_e can be calculated. These parameters include the natural frequencies of the plate when the PZT is open- and short-circuited; the generalized electromechanical coupling coefficient, K_{31}; optimal tuning inductance and capacitance; and the shunting resistance for each mode. It is difficult to determine these optimal tuning parameters using the conventional shunt circuit theories developed by many researchers for two main reasons. The first is that the PZT capacitance and the shunt inductance have some internal resistances and these are not negligible. The second is that the material parameters of capacitors (PZTs) used in the shunt electric circuit vary 5-10 % from manufacturer's values.

First, the capacitance of the PZT should be determined roughly (since capacitance is dependent on frequency) using Equation (2.2):

$$C_p^T = \frac{K_3^T \times \varepsilon_0 \times A_p}{t_p} \tag{2.2}$$

where C_p^T is the capacitance of the PZT at constant stress, K_3^T is the relative dielectric constant at 1KHz, the constant ε_0 is 8.85×10^{-12} F/m, A_p is the surface area of PZT, and t_p is the thickness of the PZT. These values were provided by the manufacturer, Piezo Systems, Inc. The product of $K_3^T \varepsilon_0$ is called the permittivity of the dielectric denoted ε. The PZT capacitance at constant strain, C_p^S, is obtained from Equation (2.3):

$$C_p^S = C_p^T \left(1 - k_{31}^2\right) \tag{2.3}$$

which is dependent upon the electromechanical coupling coefficient, k_{31}, provided by the manufacturer.

Second, the generalized electromechanical coupling constant for a piezoelectric bonded to a structure can be obtained from the frequency change of the electric boundary conditions [5]:

$$K_{31}^2 = \frac{\left(\omega_n^D\right)^2 - \left(\omega_n^E\right)^2}{\left(\omega_n^E\right)^2} \tag{2.4}$$

Here, ω_n^D and ω_n^E are the natural frequencies of the structural mode of interest with an open circuit piezoelectric and a short circuit piezoelectric, respectively. These frequencies can be obtained from the frequency response function. The other optimum tuning parameters are calculated from the values determined above as follows:

$$\delta_{opt} = \sqrt{1 + K_{31}^2} \text{ and } \omega_e = \delta_{opt}\omega_m \tag{2.5}$$

where δ_{opt} is the optimal tuning ratio, and ω_e is the electrical resonant frequency.

The shunt inductance and PZT capacitance determine the electrical resonance of the circuit as in the equation:

$$\omega_e = \frac{1}{\sqrt{L_s C_p^S}} \tag{2.6}$$

The shunt inductance, Ls, as illustrated in Figure 2.4b, is calculated from ω_e and the PZT capacitance, C_p^S:

$$L_s = \frac{1}{\omega_e^2 C_p^S} \tag{2.7}$$

The equivalent inductance of the op-amp circuit shown in Figure 2.5 is determined to be

$$L_{eq} = R^* C_1 \tag{2.8}$$

where

$$R^* = \frac{R_1 R_3 R_4}{R_2} \tag{2.9}$$

The resistor, R_2, in the inductor circuit shown in Figure 2.5 is a variable resistor that is adjusted in order to change the circuit inductance.

For a desired inductance of L_S, the value of R_2 is determined from the equation:

$$R_2 = \frac{R_1 R_3 R_4 C_1}{L_s} \tag{2.10}$$

To determine the optimal shunt load resistance, R_L of Figure 2.5, the optimal damping ratio, r_{opt}, must be calculated using the value K_{31} from Equation (2.4):

$$r_{opt} = \sqrt{2}\,\frac{K_{31}}{1+K_{31}^2} \tag{2.11}$$

The optimal shunt load resistance, R_{opt}, is then calculated as

$$R_{opt} = \frac{r_{opt}}{C_p^S \omega_n^E} \tag{2.12}$$

The values for the inductor resistance and load resistance were calculated using the m-file included in Appendix A. These values were used for the initial tuning of the shunt circuit; fine-tuning was then performed during testing, as described in Appendix B.

2.5 Summary

This chapter presented background information on piezoelectric materials, including an introduction to the piezoelectric effect and possible application of piezoelectric materials. A literature review was included to present research topics related to this study and to provide additional background information on piezoelectric materials. Finally, the shunt circuit design used for this study was explained in detail.