1

Introduction

Smart materials that can damp mechanical vibration in an intelligent way have long been heralded as the dawn of a new era in the construction of automotive vehicles, airplanes and other structures that have to meet ever more demanding performance requirements. This has largely not happened, at least not in the commercial arena. In this context, dynamic behavior is one main design criterion for many kinds of load-carrying structures, as undesirable large-amplitude vibrations often impede the effective operation of various types of mechanical systems, including antennae, spacecrafts, rotorcrafts, automobiles, and sensitive instruments. It is therefore desirable to introduce structural damping into a system to achieve a more satisfactory response and to delay fatigue damages [GZA01]. Many types of smart materials are currently available or are at various stages of development. Applications are largely focused on spacecraft, aircraft and military industries. A few companies have been applying the smart damping technology to commercial products such as smart ski, smart bat, electronic water-ski and smart tennis racquet but the emphasis seems to be more on the marketing value rather than on provable benefits.

This thesis focuses on smart damping materials using piezoelectric transducers. It demonstrates that connecting a shunt circuit to a piezoelectric transducer leads to a simple and low cost vibration controller that is able to efficiently suppress unwanted structural vibration without the need for sensors. The present thesis is a result of the EMPA project *Adaptive Werkstoffe* and in particular the project *PiezoDamp* between the Swiss Federal Laboratory for Material Testing and Research (EMPA[1]) in Dübendorf, the Centre of Structure Technologies (IMES[2]) at ETH Zürich and the Automatic Control Laboratory (IFA[3]) at ETH Zürich.

[1]www.empa.ch
[2]www.imes.ethz.ch/st/
[3]www.control.ethz.ch

1.1 Piezoelectric Actuators and Sensors

In vibration control, piezoelectric actuators and sensors are widely used. Piezoelectricity (from the Greek word $\pi\iota\grave{\epsilon}\zeta\omega$ (*piezo*) that means to press) is defined as a change in electrical displacement D_z across the piezoelectric crystal resulting from a change in applied stress T_z on the crystal. This phenomenon was originally discovered by the brothers Jacques and Pierre Curie in 1880 and is referred to as the direct piezoelectric effect. This effect is mostly used for sensing applications. The inverse piezoelectric effect is the change in strain S_z of the piezoelectric crystal when the applied electric field E_z changes. Referring to Figure 1.1 a), a piezoelectric transducer can be described by the following equation

$$\begin{bmatrix} D_z \\ S_z \end{bmatrix} = \begin{bmatrix} \epsilon^T & d_{33} \\ d_{33} & s^E \end{bmatrix} \begin{bmatrix} E_z \\ T_z \end{bmatrix}, \tag{1.1}$$

where D_z, S_z, E_z, T_z are the electrical displacement (charge/area), the material engineering strain, the electrical field in the material (volts/meter) and the material stress (force/area). The parameters ϵ^T, d_{33}, s^E correspond to the dielectric constant, the piezoelectric constant and the compliance of the piezoelectric material. Equation (1.1), where an electrical field along the z-axis generates a strain along the z-axis, is referred to as the 3-3 effect.

Normally, piezoelectric actuators for vibration control are used as monolithic patch actuators exploiting the 3-1 effect. This is shown in Figure 1.1 b). Due to the applied voltage U, the transducer strains along the z-axis. Because of the poisson effect, the material also strains along the x-axis. The resulting strain S_x along the x-axis

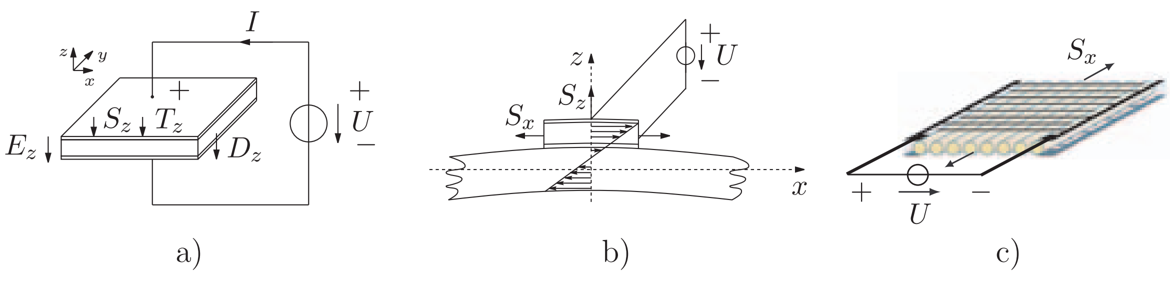


Figure 1.1: a) Piezoelectric stack actuator. b) Piezoelectric transducer on a mechanical structure. Due to the applied voltage U, the transducer bends the mechanical structure. c) Integrated piezoelectric fiber composite structure.

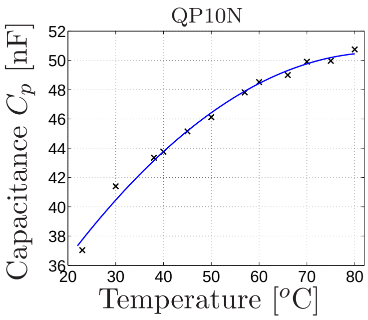


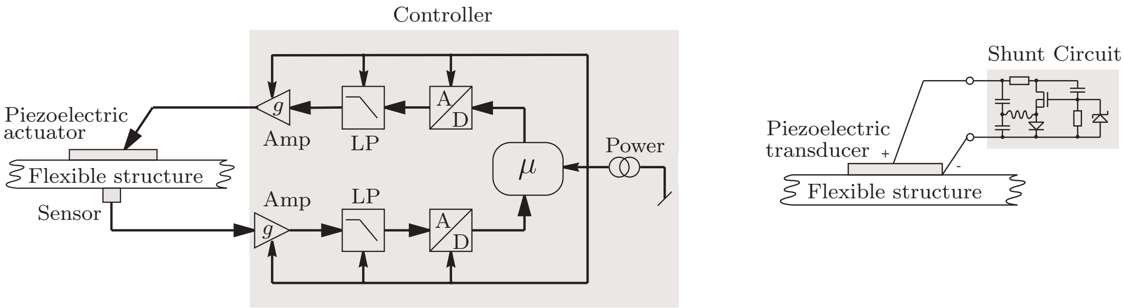
Figure 1.2: Measured temperature dependency of the piezoelectric capacitance.

bends the underlying mechanical structure where the transducer is bonded. Such patch actuators composed of PZT (lead (lat. Plumbum) zirconate titanate) are commercially available from Midé[4], CeraNova[5], TRS Ceramics[6] and other companies. In this thesis, we will mostly use these types of piezoelectric transducers.

Recently, *Active Fiber Composites (AFCs)* have been proposed for smart damping materials [BH93]. As illustrated in Figure 1.1 c), piezoelectric fibers are aligned in the same direction and embedded in a epoxy resin. They are electrically connected to interdigitated electrodes that deliver the electrical field along the longitudinally oriented PZT fibers. Thus, fibers strain along the x-axis, when a voltage U is applied. The main advantages of piezoelectric fibers are their high conformability and integrability in complex curved structures. Furthermore, they achieve greater actuation energy density by exploiting the 3-3 effect along the fibers, whereas standard monolithic piezoelectric stack actuators are based on the less effective 3-1 effect via the poisson effect. Applications and a discussion of AFCs for vibration control will be presented in Chapter 7.

Material parameters of piezoelectric transducers are highly variable with temperature and other environmental factors [Han02, BNP$^+$04]. Figure 1.2 shows the measured temperature dependency of the piezoelectric capacitance of a QP10N patch from Midé, where the capacitance changes by 40% within a temperature range of 58^o C. Chapters 3, 4 and 7 will show that this fact is very important for the design of smart damping materials, because it could make the damping performance very sensitive or even lead to instability of the controlled system.

[4]http://www.mide.com
[5]http://www.ceranova.com
[6]http://www.trsceramics.com



a) b)

Figure 1.3: a) Conventional vibration control and b) the piezoelectric shunting technique. The latter approach is described in the present thesis.

1.2 Conventional Vibration Control

During the last two decades there has been increasing research interest in smart damping materials and their applications, because damping with passive materials (e.g. mufflers, damping plates, etc.) is not very effective at low frequencies and requires more space and weight. The vast majority of research in smart damping materials has concentrated on the control of structures made from composite materials with embedded or bonded piezoelectric transducers. Controllers to damp vibration were implemented mostly in a purely active arrangement, i.e. an electrical field is applied to the piezoelectric materials based on sensor feedback and control commands [FEN96, PKPM99, SC98]. This is shown in Figure 1.3 a), where the active controller produces an actuator-signal based on a sensor-signal from an accelerometer, velocity or strain sensor. Normally, active controllers are implemented in microprocessors that are connected to the sensors and actuators by special amplifiers as illustrated in Figure 1.3 a). These approaches have several disadvantages. First, every sensor and actuator needs bulky amplifiers (Amps) and the implementation with a digital microprocessor implies the use of anti-aliasing and reconstructing filters (LP) and A/D-, D/A-converters. This hinders the integration of the controller into the structure, which exactly would be required for smart damping materials. Additionally, the large instrumentation overhead raises the costs and extra power-supplies for amplifiers, filters, converters and the microprocessor are needed. This makes the system more sensitive to failures and the wiring of the power supply also becomes difficult.

To account for the drawbacks of common vibration control techniques described in the last section, a new control approach for smart damping materials is required. The demands for novel smart damping materials can be summarized as proposed in [KPVG97]:

- External power source is not required for operation.
- Device does not need to be tuned to a specific frequency.
- Device operation is not affected by changes in modal frequency.
- Device suppresses vibration over a number of modes, i.e. it is multi-modal.
- Weight and size of the device should be minimized.
- Device is to be a self-contained unit.

This thesis will focus on these points and it will be shown that there are ways to fulfill these demands.

1.3 Vibration Control via Piezoelectric Shunting

The large instrumentation overhead of conventional vibration control in Figure 1.3 a) can be significantly reduced by a new method that involves attaching an electrical shunt controller across the terminals of one piezoelectric transducer with the view to minimizing structural vibrations, as it is shown in Figure 1.3 b). This approach is referred to as piezoelectric shunt damping [For79, HA91, EBF+92, BMF03] and is known as a simple, low-cost, lightweight and easy-to-implement method for vibration damping. Thus it seems that it may fulfill the demands for novel smart damping materials described in the last section.

The idea of shunt damping is that the passive shunt circuit dissipates electrical energy that is transformed by the piezoelectric material. Therefore, the shunt withdraws vibration energy from the mechanical system and damps the vibration. Additionally, the shunt circuit can store electrical energy and supply it back to the mechanical system at the right time to counteract vibration. In Chapter 3, we will see that the shunt circuit parameterizes a feedback controller that controls mechanical vibration. As the piezoelectric transducer is both actuator and sensor, the controlled system is ideally collocated.

The shunt damping method has several advantages compared to conventional vibration control. In particular, it requires no feedback sensor, the implementation is very easy as only a few electronic components are needed, and in some circumstances, it may not require any support electronics or power supply. Moreover, it offers the benefits of stability, robustness and performance without the need for complex digital signal processors, and in many cases it does not require parametric models for design purposes.

1.4 Outline

The remainder of this thesis is organized into the following chapters. Chapter 2 reviews several piezoelectric shunting techniques that have been suggested in the past. The different techniques are categorized and analyzed. Chapter 3 introduces a new online-tuning methodology for single-mode and multi-mode resonant shunt circuits. This new methodology is validated with experimental results. Chapter 4 describes how to implement the proposed self-tuning resonant shunt as a simple electronic circuit with only a few analog circuit components. Chapter 5 introduces the application of adaptive resonant shunts for electromagnetic systems. It is shown that a similar adaptive resonant shunt circuit can be applied for vibration suppression using an electromagnetic apparatus. Afterwards, the proposed adaptation technique is compared with a standard adaptation methodology. In Chapter 6, switching shunts are investigated. By using a Hybrid System Framework, an optimal switching law to damp vibration is derived. On the basis of the novel switching law, an autonomous switching circuit is implemented that does not require additional power for operation. Chapters 7 and 8 present new applications using shunt circuits. It is shown that shunt circuits can be applied for active fiber composites. Another promising application are shunted loudspeakers for acoustic noise reduction. We introduce this idea and validate it with experimental results. Finally, Chapter 9 summarizes the thesis and gives an outlook for possible future work in this field.

2

Review of Shunt Damping

This chapter gives an overview of shunt damping. First, we will define the control problem associated with the design of shunt circuits for vibration damping. Afterwards, different shunt topologies that have been proposed in the past are described and we discuss their advantages and drawbacks. Then, some applications are described where shunt damping has been implemented.

2.1 Control Problem Formulation for Shunt Damping

The key problem of the shunt damping technique is to find a very simple shunt circuit that efficiently damps a given structure. The demands of designing a shunt circuit for smart damping materials can be summarized as follows: the shunt circuit should minimize structural vibration, i.e. it should damp mechanical vibration very efficiently. This efficiency should be robust against system parameter variations, and stability should also be guaranteed. Furthermore, the shunt circuit should not require power for operation and the weight and cost of the implemented circuit should be kept to a minimum. Since it is intended to integrate the shunt circuit into the structure, its size should be as small as possible.

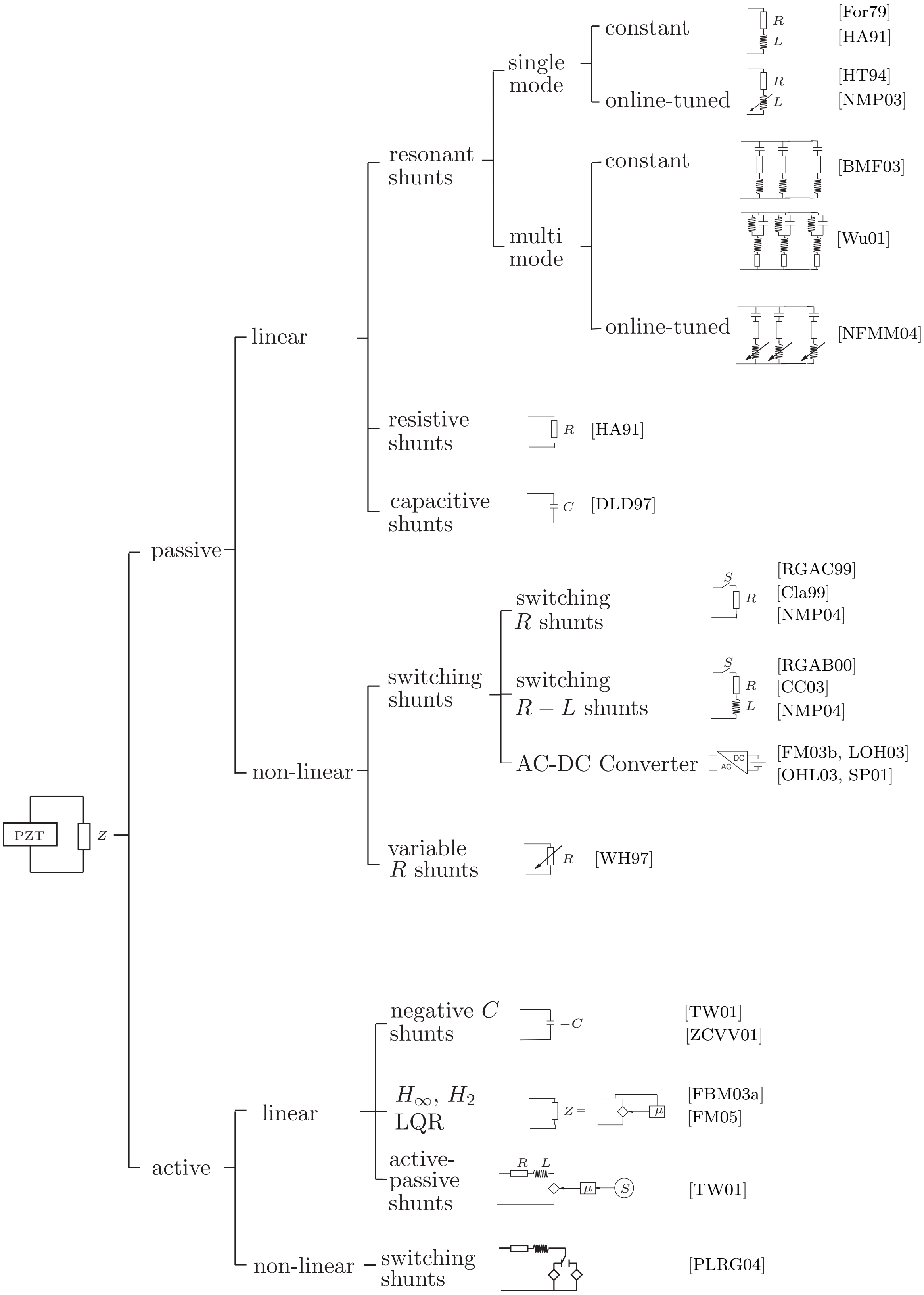
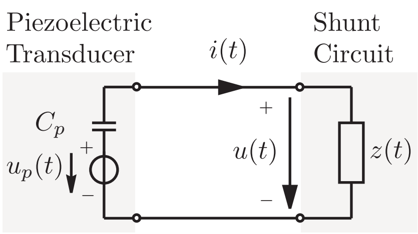
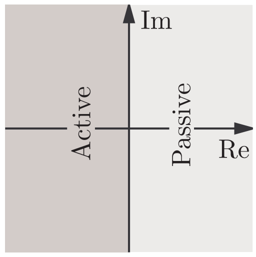


Figure 2.1: Different topologies of shunt networks for shunt damping



a)



b) $Z(j\omega)$

Figure 2.2: Definition of passive and active shunts: a) $z(t)$ shunted to the piezoelectric transducer. b) Passive and active impedance $Z(j\omega)$ in the frequency domain.

2.2 Different Shunt Circuit Topologies

In the last decade, many different electrical shunt topologies have been proposed. These shunts can be divided into passive and active shunts as it is shown in Figure 2.1.

2.2.1 Passive Shunt Circuits

Passive shunts are characterized by the fact that they do not add energy to a system, i.e.

$$\int_0^T u(t) \cdot i(t) dt \geq 0 \quad \forall T, \tag{2.1}$$

where the directions of $u(t)$ and $i(t)$ are defined in Figure 2.2 a). For linear systems, the passivity of the impedance $Z(j\omega)$ is defined in the frequency domain by

$$\Re\left(U(j\omega)I^*(j\omega)\right) \geq 0 \text{ or } \Re(Z(j\omega)) \geq 0 \quad \forall\omega, \tag{2.2}$$

where $I^*(j\omega)$ is the complex conjugate of $I(j\omega)$. The passive and active regions of an impedance are shown in Figure 2.2 b). If a shunt is passive, stability of the whole system is guaranteed, because no energy is added to the system. Passive shunts can be categorized into linear and non-linear shunts.

Linear shunts

Linear shunts are those for which the principle of superposition holds. Assuming zero initial condition, the shunt $f_z(i,t)$, relating voltage and current with $u(t) = f_z(i,t)$,