Chapter 1

Introduction

1.1 Motivation

With the recent expansion of both Active Noise Control (ANC) and Active Vibration Control (AVC), transducers have been widely developed since they are an important element of any practical control system. Transducers are divided into two major categories: sensors and actuators. Sensors are needed for measurements to provide information to the controller (e.g.: determine the performance of control). Actuators, driven by control signal, may be used to modify the system response. For this purpose various actuators have been used for many different applications. In the automobile industry, electromagnetic vibration actuators have been used, for instance, to isolate the engine from the car chassis [1-3]. Recent research to reduce the cabin noise has been conducted with piezoelectric actuators mounted into a new speaker design [4]. These actuators are also widely used in aircraft industry. They have been used to reduce rotor vibrations of a helicopter [5].
Compared to significant recent advances in controller design in terms of the software, hardware and control algorithms, there is a technology gap in transducer design. Bridging this “gap” is made more difficult in the case of piezoelectric actuators since it is only recently that their complex properties have begun to be analyzed and understood. However, in order to perform active control, it is fundamental to choose an actuator appropriate for the system to be controlled. This choice depends on various characteristics of the system itself. The requirements may be the control authority of the actuator (i.e. amount of control force, displacement), its power consumption, its “actuating” frequency range, or may be related to physical constraints such as size or mounting conditions in the case where a static pre-load is needed.

For example the design of actuators used in adaptive optics, specifically, deformable mirrors (an element of some high magnification telescopes), is driven by both the desired stroke and the actuator stiffness [6]. To characterize high authority electro-ceramic actuators used for adaptive structures, critical stroke and force output are of considerations and they include as many different parameters as hysteresis, resolution, range, temperature, linearity, sensitivity … etc [7]. In the case of electro-magnetic actuators, other than size, reliability and life expectancy, the basic set of requirements includes peak force, continuous force, stroke and power consumption [8]. To face advances in material sciences leading to the development of very low temperature actuators made of terbium and dysprosium, a test instrument was developed to investigate the test performance characteristics of this new material [9]. This instrument, referred to as a “cryogenic dilatometer” was designed for measuring linear displacements at low temperatures (around 10K) in order to characterize magnetostriction under variable pre-loads as a function of magnetic field.

All these parameters that are usually taken into account are very important to characterize actuators. They give good insight to possible applications for a given actuator and they are also good metrics for the design of actuators once their desired application is determined. However, these characteristics are generally only valid for static applications and in most experimental applications, actuators are used dynamically. As it will be seen
in the next section, these common characterizations of actuators are no longer reliable for dynamic applications.

1.2 Difference Between Static and Dynamic Behavior of an Actuator

A large amount of work has been conducted in order to characterize the behavior of various piezoelectric actuator configurations. Both point actuators such as stack actuators [10] and distributed actuators such as asymmetric wafer actuators (layer of piezoelectric actuator bonded to the surface of a structure that induces strain to the structure when a voltage is applied across its electrodes) [11-12], are typically analyzed using a static approach rather than a dynamic approach which leads to much more complicated models [13-14].

In terms of control authority, two standard tests are commonly conducted to determine two important mechanical properties of an actuator. They are both static tests and are (i) the blocked force and (ii) the free displacement of an actuator. The blocked force represents the amount of force output the actuator can generate while it is constrained from moving. The free displacement corresponds to the maximum displacement generated by the actuator when it is totally unconstrained.

Determining the suitability of an actuator with these two test results assumes the following linear relationship between the force and the displacement of the actuator:

\[ f = -\left(\frac{f_b}{x_f}\right) \cdot x + f_b \]  

where variables \( f \) and \( x \) are the force and displacement, respectively. The first constant, \( f_b \), is the measured blocked force and the second constant \( x_f \), is the measured free displacement. The ratio \( f_b/x_f \) is also known as the internal stiffness \( k_i \) of the actuator. With the knowledge of the required force and displacement for the system to be
controlled, equation (1.1) can be used to determine whether an actuator is suitable or not for a specific task. Illustrating this approach, Figure 1.1 represents the kind of plots provided by actuator manufacturers to characterize their actuators. It shows plots of force, $F$, versus strain, $\varepsilon$, for different voltages. These plots are basically straight lines from the free displacement case (when $F=0$) to the blocked force case (when $\varepsilon=0$). Therefore, using these plots, a potential customer who needs an actuator for a case where, for example, voltage and displacement are constrained, can choose the most suitable actuator that would give him the force output required for his application.

Figure 1.1: Bounded configuration diagram for different voltages of the actuator model QP15W from ACX

This approach is valid as long as the actuator is used for static cases and it also implies that what is being driven is non-dynamic, but is no longer valid when the actuator is driven dynamically. Indeed as soon as we consider dynamic behavior, the load is no
longer a simple real value but a complex mechanical impedance defined as the ratio of its force and velocity \((Z=f/v)\). This mechanical impedance has a magnitude and a phase which varies as a function of frequency, \(Z(\omega)\). For dynamic cases, where actuator dynamics are coupled to structure dynamics, characterization of an actuator is not as easy as static cases since it requires more parameters to define the load condition. The force and displacement requirements for static cases have been replaced by magnitude and phase requirements that vary with frequency for dynamic cases.

If we consider the system called an actuator-structure, the theoretical static approach refers then to the method using a statically determined equivalent force as the magnitude of the forcing function in order to determine the dynamic response due to the activation of the actuator on the structure [15]. This approach is not accurate since it assumes that the force output of the actuator is frequency independent and, more importantly, does not give a good physical understanding of the interaction between the actuator and the structure. However, the dynamic interaction between the structure and the active element exists and affects the performance of both the structure and the actuator.

An easy way to see the influence of a dynamic load may be to consider two simple cases. When the term “dynamic load” is used, it refers to the structure the system is attached to, if this structure has dynamic behavior. In the first case let us assume the actuator is simply acting as an inertial actuator, fixed on one side to an infinite rigid structure and on the other side driving an inertial mass (Cf: Figure 1.2, Case 1). In this case, the system can be modeled as a single degree of freedom system by a mass on a spring. It then has a single natural frequency. The second case considered differs from the first case in that now the bottom surface of the actuator is no longer rigidly constrained, but has dynamic behavior (Cf: Figure 1.2, Case 2). In this second case, the system has two degrees of freedom since the mass of the structure in motion also has to be taken into account.

Figure 1.3 shows the actuator’s input force to the structure versus frequency when the actuator is driven in the two different cases. These two different behaviors of the structure lead to two different force outputs of the actuator along the frequency axis. It is
therefore obvious that to choose or design a suitable actuator, the behavior of the structure that the actuator will have to act against is an important parameter than cannot be neglected.

Figure 1.2: Two different uses for an inertial actuator: static or dynamic structure

Figure 1.3: Force output of an inertial actuator used in two different cases

Figure 1.3: Force output of an inertial actuator used in two different cases
Therefore, as opposed to the static approach, the impedance method for dynamic analysis of active material systems developed by Liang, C. et al [15] provides a better understanding of the dynamic behavior of piezoelectric element-driven systems. This method essentially relies on the fact that the interactions between an actuator and a structure are governed by the dynamic output characteristics of the actuator and the dynamic characteristics of the structure. As a consequence, this methodology can be used for any actuator and any structure as long as the dynamic output characteristics of the actuators can be determined.

Then, to face the almost infinite range of possibilities that the consideration of dynamic load conditions brings, it becomes necessary to create a test facility with the ability to impose any load conditions to an actuator whose performances would be tested. This test facility, since it is capable of reproducing any possible load conditions realistic to a specific application, should be able to conduct a wide range of tests to verify the accuracy of any actuator model.

To adaptively modify the dynamic load conditions on a tested actuator, an adaptive controller, which uses a secondary control actuator, can be used. This work is concerned with the implementation of such an active control system to allow actuator characterization over a wider range of load impedance conditions.

1.3 Thesis Objectives and Organization

The principal objective of this research is not specifically actuator characterization. It deals more precisely with the realization of an active test set-up capable of creating any desired dynamic load condition (or impedance) an actuator may experience. Using this test set-up, measurements could be taken to characterize the actuator tested. The main idea behind this is to be able to accurately tell from the characterization whether or not an actuator is suitable to a given application. This implies that the test set-up would have been able to reproduce accurately both static and dynamic
load conditions. However, the research presented here is not a straightforward application of active control. Compared to classical active noise control or active control of vibration, there are two main differences. First the objective is not to reduce noise or vibration but to use the controller to reach a desired value by minimizing the difference between a desired impedance and the measured impedance. Second, although a simple Single Input Single Output (SISO) controller is needed, the control has to affect two independent variables (force and velocity) whose ratio is later compared to the desired (desired load or impedance, $Z_d$) (see Chapter 3, Methodology). Therefore, some preliminary work was necessary before performing real time active control. This involved the establishment of a control methodology adapted to the specific case of “impedance control” and different models and simulations were conducted with a preliminary test rig. The aim of these simulations was to help anticipate the various limitations and requirements necessary to successfully apply the active control.

Chapter 2 addresses some theoretical background needed for this work. First it covers the theory of digital filters, as it will be needed for the implementation of the desired impedance into the controller. Then a brief review of the theory of adaptive algorithms and feedforward control is presented to explain the functioning of the adaptive feedforward controller being used for this research. Chapter 3 explains the methodology used to perform the specific control of impedance. Chapter 4 is dedicated to simulations of actuators and the control itself to determine the requirements necessary to design a good test set-up and also investigate possible limitations. Some preliminary work was necessary before the final version of the test rig could be designed and before tests using the new adaptive feedforward impedance controller could be conducted. Without developing any new theory, Chapter 6 proposes a technique for building and testing a linear actuator model that is well adapted to the final version of the test rig. The goal of this model, called a two-port network, is to compensate for the control limitations and also to save numerous experimental manipulations. Finally Chapter 7 presents the overall conclusions drawn from this project and suggests future directions for this research.