Chapter 1. Literature review

This chapter presents the past and present work that preceded the development of a distributed active vibration absorber. It also presents significant research done to reduce structural sound. Such a literature review cannot be exhaustive and is presented in a condensed manner as the reader is referred to original papers. It is a brief overview of the research relevant to the subject of this thesis.

1.1 Structural radiation control

Traditionally, the sound radiated inside structures such as airplanes or cars is controlled using damping materials on inner panels. This technique finds its limitation because of weight and the poor performance at low frequencies. In 1936, *Lueg* [1] first proposed an active control technique to reduce noise using destructive interference of sound waves (ANC). With the development of digital signal processors (DSP) his invention became commercially practical 50 years later. In 1992 *P.A Nelson and S.J. Elliot* [2] first compiled the active control of sound theory. In most of the applications, the sound is controlled by secondary sources such as speakers. Structure born sound being mainly the problem in aerospace applications, a new approach proposed by *C.R. Fuller* [3-4] has become increasingly popular and is called active structural acoustic control (ASAC). This approach uses the advances in vibration control [5-6] to reduce the emitted sound. Active control techniques have been very successful in reducing noise but their cost and reliability remains a problem for commercial applications. New research is done to combine active control with more traditional passive techniques [7-10]. One of the promising devices investigated is called the tunable vibration absorber (TVA) [10]. Before focusing on TVAs (cf. part 1.2), several other aspect of the current research in

ASAC needs to be highlighted since they are linked to the research presented in this thesis.

The first one is the need of simulation models. In 1990 *A. Berry et al.* [11] presented the response of a plate with arbitrary boundary conditions. They used a variational method, which differs from traditional modal decomposition by the use of trial functions. This method enables the modeling of any boundary conditions. The same year *N.W Hagood et al.* [12] presented a model of piezoelectric actuator for ASAC. They modeled these devices using a state space representation. In 1993, *F. Charette et al.* [13] presented the plate model actuated by asymmetric piezoelectric actuators. This model uses the same variational method used by *A. Berry et al.* and is contrasted to the model developed by *C. R. Fuller* [6]. In 1995 *S. Dedieu et al*. [14] presented a finite element model of a plate excited with piezoelectric actuators. This model ultimately permits the investigation of various shapes of piezoelectric actuators and to optimize their position on various structures such as plates or cylinders. None of the proposed models are the perfect answer to a given simulation problem. They all have their advantages and limitations. Modeling for high frequencies and modally dense structures is generally problematic.

A second aspect of the research conducted in ASAC is the need for new actuators and sensors. Recent emphasis is placed on piezoelectric materials. They present the advantages of being lightweight, with a small size and a distributed action. A popular type of piezoelectric material is lead zirconate titanate (PZT). A typical application is the actuation of plates or beam such as the one presented by *R.L. Clark et al.* [15]. In this paper, PZT is used as an actuator for active structural control of sound. An interesting new device presented by *R. Gentilman et al.* [16] uses the 1-3 motion of PZT to create a piston type radiating structure. Another type of piezoelectric material used in ASAC is the polyvinylidene fluoride (PVDF). A typical application uses the distributed properties of the PVDF to create a modal sensor or actuator [17-20]. The need of fail safe control has pushed the research into developing hybrid actuators using these piezoelectric materials. For example, an active-passive system called the smart skin [21-23] has been developed at Virginia Tech. Acoustic foam with embedded PVDF has been used to increase transmission loss in an aircraft cabin application. Another example of hybrid device is the active constrained layer damping (ACLD) presented by A. Baz and J. Ro [8]. The ACLD has been applied on a clamped free beam.

A third aspect of the research being performed for ASAC is the search for optimization techniques. In order to improve the performance of an active-passive system, most of the configuration of its components need to be optimized. One of the possible optimization tasks is the positioning of actuators and sensors. One interesting method is the use of natural algorithms presented by *K.H. Baek and S.J. Elliot* [24-26]. In an aircraft cabin, many locations can be selected for ANC speakers and with a multiple speakers configuration the number of possible combinations is daunting. The use of genetic algorithms and simulated annealing algorithm demonstrate their ability to find “good” positions for improved ANC performance. This type of optimization process was also investigated for classical ANC and ASAC. *G.P. Gibbs et al.* [25] applied such optimization techniques on an aircraft structure. This type of algorithm has a broad range of applications. It has also been used to optimize the distribution of purely passive devices such as point masses on plates [27].

1.2 Tunable vibration absorber

The word “absorber” is misleading. The device does not work by absorbing the energy of the main structure. It rather creates a reactive force in response to the disturbance and therefore reduces the base motion at the resonance frequency. The classic tunable vibration absorber (TVA) is a vibration device often named after *J.P. den Hartog* [28] who first analytically described its behavior in 1928. This basic analysis is briefly presented in chapter 2. Den Hartog's work was preceded by *H.Frahm* [29] who was used mass spring systems and also the oscillation of water between two tanks to counter the rolling of ships. In 1968, *J.C. Snowdon* [30] presented the action of one and two TVAs on the vibration of cantilever beams. However, after almost a century of development, the typical application remained the suppression of vibration in machinery. TVAs have found many applications in civil engineering for the construction of bridges and earthquake proof buildings. In 1982, *G.B. Warburton* [31] proposed a design procedure for absorbers. His main interest was earthquake engineering. Recently TVAs have been used more specifically for acoustic purposes [32-33] and a new detuning approach was presented by *C.R. Fuller et al*. [34] in 1997. The main factor for a TVA to behave properly is to have its resonance frequency properly tuned (or "detuned") in respect to the frequency of vibration of the main structure. The idea of having an adaptive TVA is simple but also a design challenge that still remains. *M.A Franchek et al*. [35] and *F. Charette et al.* [36] presented adaptive TVAs using stepper motors. The use of electro-rheological fluids and electromagnetic dampers can also provide some design solutions. The new trend is to use an "active" TVA in contrast to an "adaptive" TVA. The advantage of the active TVA is that no moving mechanical part is involved for changing its dynamics thus increasing reliability and adaption speed. In most of the designs the active TVA has an active element in parallel to a resilient part. This type of TVA can enforce the antiresonance of the main system [37]. The absorber properties can be set artificially to desired values in order to obtain maximum attenuation. It also can be considered has a passive device if the electronic circuit attached to the TVA is purely passive. This type of device is presented by *C. Davis et al.* [38]. One similar commercial application of this type of oscillator is the "smart ski" developed by ACX and available under the brand name K2. The definition of passive absorber is therefore ambiguous. According to *R. Herzog* [9] the control theory has a simple answer: passivity is a "stability behavior plus an energy flow condition related to the input/output behavior". The modern TVA is a hybrid device for which electronics and mechanics are combined. Once purely mechanical, the future TVA is likely to become a what is called "smart" device. A very interesting survey of passive, adaptive and active TVA has been realized by *J.Q. Sun et al.* [10] in 1995. This survey which presents various design configuration is a valuable overview of the recent research.

1.3 Distributed TVA

The classic TVA is connected to the main structure at one point. A distributed absorber would have a continuous connection with the structure and would cover a significant surface of this structure. The distributed absorber is a very seductive idea that has never found real application. The main argument is weight. This has to be taken into account but this thesis is here to demonstrate that the weight problem can be overcome. Very few researchers presented distributed type of absorbers. Beam-type vibration absorbers have been studied as a way to cancel multiple modes in a structure. In 1985, *H. Yamaguchi* [39] presented a beam-type vibration absorber. Even if this device is distributed, the connection to the main structure is still a point. *T. Aida et al.* [40] presented in 1992 a beam-type TVA which is continuously connected to the main structure. The same principle was then applied in 1995 [41] for a plate-type TVA. As it will be discussed later in this thesis, such designs can hardly be considered as absorber since the "absorber" and the main structure are of the same nature. Until now, the distributed vibration absorber remains a theoretical oddity.