Journal of Sound and Vibration 361 (2016) 2–19

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Aircraft panel with sensorless active sound power reduction capabilities through virtual mechanical impedances

R. Boulandet [a,*], M. Michau [a,b], P. Micheau [a], A. Berry [a]

[a] Groupe d'Acoustique de l'Université de Sherbrooke, Université de Sherbrooke, Sherbrooke, Canada J1K 2R1
[b] Laboratoire de Mécanique et d'Acoustique, UPR CNRS 7051, F13402-Marseille cedex 20, France

ARTICLE INFO

Article history:
Received 17 November 2014
Received in revised form
15 September 2015
Accepted 27 September 2015
Handling Editor: J. Lam
Available online 21 October 2015

ABSTRACT

This paper deals with an active structural acoustic control approach to reduce the transmission of tonal noise in aircraft cabins. The focus is on the practical implementation of the virtual mechanical impedances method by using sensoriactuators instead of conventional control units composed of separate sensors and actuators. The experimental setup includes two sensoriactuators developed from the electrodynamic inertial exciter and distributed over an aircraft trim panel which is subject to a time-harmonic diffuse sound field. The target mechanical impedances are first defined by solving a linear optimization problem from sound power measurements before being applied to the test panel using a complex envelope controller. Measured data are compared to results obtained with sensor–actuator pairs consisting of an accelerometer and an inertial exciter, particularly as regards sound power reduction. It is shown that the two types of control unit provide similar performance, and that here virtual impedance control stands apart from conventional active damping. In particular, it is clear from this study that extra vibrational energy must be provided by the actuators for optimal sound power reduction, mainly due to the high structural damping in the aircraft trim panel. Concluding remarks on the benefits of using these electrodynamic sensoriactuators to control tonal disturbances are also provided.

1. Introduction

Noise reduction in aircraft cabins is a major challenge for the competitiveness of an aerospace manufacturer. To decrease structural weight and reduce fuel consumption, the use of composite materials is becoming more widespread. The combination of high stiffness and low mass, however, decreases the sound insulation capability of the cabin against outside noise. In a stiff, light structure like a honeycomb sandwich panel, critical frequencies are also found to be lowered which has the effect of increasing the radiation efficiency of the structure. Porous materials can provide both visco-thermal dissipation and structural damping, but still penalized by added mass and a poor efficiency at low frequencies. Many active methods, including active structural acoustic control (ASAC) strategies, have been specifically developed to reduce sound radiation and transmission through panel-like structures [1], including radiation modes estimation and control [2] and wavenumber sensing [3]. When the variables involved in the actuation and sensing are dual, an ideal collocation of the sensor and actuator ensures, theoretically, the absolute stability in closed loop for passive broadband feedback control [4–6]. Such

* Corresponding author.
E-mail address: romain.boulandet@usherbrooke.ca (R. Boulandet).

http://dx.doi.org/10.1016/j.jsv.2015.09.042
0022-460X/

control units can be considered as two-port systems that directly control the power flow to the structure to which they are attached. In this case, a velocity feedback with collocated point force can be set without causing instability, thus providing active damping to the structure. When flexural structures made up of a large number of resonant modes and a low structural damping are considered, active damping is most often the best option since the reduction in the amplitude of the resonance peaks causes a decrease in the radiated sound power [6–8]. However, the implementation of active damping by velocity feedback does not take into account the vibroacoustic coupling between the vibration of the panel and the radiated sound power. In the context of active structural acoustic control, it is commonly agreed that the minimization of the kinetic energy of the structure usually results in sound power reduction [9]. It can be shown, moreover, that the maximization of the energy absorbed by the control units is almost equivalent to the minimization of the flexural kinetic energy [7]. In the case of flexural structures with a high inherent structural damping like the composite panels commonly used in aircraft cabins, it has been shown that adding damping does not allow the noise transmitted to be reduced optimally [10]. Unlike the damping approach in which a velocity feedback is achieved so as to provide additional viscous damping, the implementation of active mechanical impedances may be necessary to optimally minimize the radiated sound power. As first shown experimentally by Guicking et al. [11], structural vibration can be effectively reduced by impedance control, provided that the mechanical input impedances can be set to target values, spanning a wide range of real parts and imaginary parts. On the footsteps of [11], other methods based on impedance control have been developed to reduce the transmission of noise induced by turbulent boundary layers in aircraft cabins [12], including the virtual mechanical impedance approach [13]. The challenging task is therefore to define the optimal impedances values by solving a linear optimization problem so that mechanical vibrations [14] or sound power radiated [10] can be reduced optimally, and implement them using stand-alone control units. The implementation of decentralized control strategies for which no communication between the control units is permitted is particularly relevant since the stability is ensured. Previous work on decentralized control has focused on achieving collocated active damping on flexible structures, either by velocity feedback [15,16] or piezoelectric shunts [17]. Examples of practical implementation can be found in [18] to modify the modal distribution of high-radiation efficiency modes by using a state observer in a centralized control, or in [14] where tuned resonant controllers are involved in a decentralized control strategy.

Control units comprising a combined electrodynamic inertial actuator with a collocated accelerometer, the signal of which is processed by a time integrator, are commonly used in structural control [6,19], e.g. for a direct and effective control of the local mechanical impedance of the structure [10]. Piezoelectric transducers such as lead zirconium titanate (PZT) and polyvinylidene difluoride (PVDF) are also widely used as strain actuators and vibration sensors in structural control systems. In addition to also deal with dual variables, their mass-loading effect upon the structure is low and does not change much the overall structural behavior [19–21]. Besides the velocity feedback approach, an alternative control strategy commonly referred to as "shunt transducer" has also been developed in the recent decades. In the pioneering work of Hagood et al. [22], the control of mechanical vibration is achieved by shunting the terminals of a structurally bonded piezoelectric actuator with a simple electrical network consisting of a shunt resistor or a resistor–inductor circuit. Drawing on the work of Hagood et al., standard synthesis techniques such as LQG, $\mathcal{H}_2$, and $\mathcal{H}_\infty$ have been applied to allow more complex electrical impedance and admittance to be implemented [14,23,24]. In practice, however, the pairs of actuators and sensors can hardly be collocated in real-world situations. For this reason and also to ensure duality, a number of research have focused on developing self-sensing actuation in recent decades. A self-sensing actuator (also called sensoriactuator) is basically a reversible electromechanical transducer, generally piezoelectric or electromagnetic, which uses simultaneously the dual function of sensing and actuation. The idea of self-sensing actuation was developed concurrently by Hagood et al. [25,26] and Dosch et al. [27] in the early 1990s, where the PZT elements were used as sensors and actuators simultaneously to reduce implementation, cost and complexity, by achieving truly collocated control. The principle is later implemented in different ways to achieve vibration control on a cantilever beam [28], active structural acoustic control on a simply supported plate [29], vibration damping by using piezoelectric patches [14,30,31], electrodynamic shakers [32] or inertial exciters [31], to develop a sensorless technique for active noise control using an moving coil loudspeaker [33], or for biomedical application using an electromagnetic actuator [34].

The general goal of this work is to improve the sound insulation capability of an aircraft composite panel subject to tonal acoustic disturbances. The specific objective is to achieve a virtual impedance control on the panel using stand-alone control units, i.e. self-sensing actuators, instead of control units composed of separate sensors and actuators. The practical implementation is performed digitally using a complex envelope controller, previously developed to achieve harmonic active control of power of rotating machines [35] and successfully applied to the harmonic control of power for mono-cylinder hybrid powertrain [36]. The main originality of method described here is to show that the actuator is capable of sensing the structural dynamic response upon actuation, using a model-based approach, thus achieving sensorless control. The remaining is organized as follow. First, the basic knowledge necessary for modelling the electrodynamic self-sensing actuator is presented. An analytical model is derived from the equivalent circuit model of the voice coil actuator. In Section 3, the baseline concept of the virtual mechanical impedances method is presented in the context of active structural acoustic control, assuming a harmonic acoustic excitation. Experimental results performed on an aircraft trim panel using sound transmission loss facility are provided in Section 4. Measured data are compared to results obtained with sensor–actuator pairs comprising an accelerometer and an inertial exciter, particularly as regards sound power reduction. Concluding remarks on the benefits of using these electrodynamic sensoriactuators to control tonal disturbances are also provided.