大阪
inter.noise 2011
Osaka Japan September 4-7

DESIGN AND ASSESSMENT OF AN ELECTRODYNAMIC LOUDSPEAKER USED IN A VARIABLE ACOUSTIC LINING CONCEPT

Hervé Lissek[1], Anne-Sophie Moreau

[1] Ecole Polytechnique Fédérale de Lausanne, Station 11, CH-1015 Lausanne, Switzerland

ABSTRACT

The acoustic impedance at the diaphragm of an electroacoustic transducer can be modified using a range of active control strategies, amongst which is “direct impedance control”. This technique employs a combination of feedbacks, one on the acoustic pressure and the other on the diaphragm velocity, to the loudspeaker electric terminals, allowing significant modifications of the acoustic resonator properties of the diaphragm within a specified range. This concept has been specifically adapted to a novel concept of active acoustic liners for aircraft engines within the European project OPENAIR. One of the objectives of active acoustic liners is the achievement of real-time modifications of the acoustic impedance of a 1 degree of freedom resonator. These properties should then match variable target impedances, specified by phases of flight. The paper presents the development of a specific electrodynamic loudspeaker for use as active liners, with an emphasis on integration issues, as well as acoustic performances. The general concept of direct impedance control is first introduced, followed by design considerations on the loudspeakers side, and then experimental assessments of performances are presented.

Keywords: acoustic liners, electroacoustic absorber, electrodynamic loudspeaker.

1. INTRODUCTION

Despite the continuous efforts in developing engine technologies with low fuel consumption, carbon emission and noise pollution, there still remain numerous challenges to overcome before the European Air Transport industry can reach the ambitious ACARE environmental objectives for 2020[2]. In this frame, the European aeronautics industry has implemented, in the last decades, several ambitious research programs. These programs have allowed achieving “Generation 1” engine noise reduction technologies, demonstrating the capability to achieve the 5dB first-step reduction set for 2010, assuming simultaneous progress in the area of noise abatement operational procedures. In the frame of these projects, research activities were conducted in various fields, among which Active Noise Control Developments [1, 2], and leading to successfully assessed prototypes. As a result, many of these assessed technologies are now advanced enough for further integration work, aimed at addressing some identified trade-offs issues, such as performance improvement and weight reduction.

In the following research projects, the ACARE objective of noise reduction are then coupled with the necessity to be emissions neutral, and account potential performance and weight penalties that might be induced by the implementation of novel noise reduction concepts. In this new integrated approach, the active/adaptive technologies developers of the ongoing programs have two main and complementary criteria to fulfill in the achievement of their “Technology Readiness Level”, one on the acoustic performances, the other on the powerplant integration of these technologies (mechanical, aerodynamic and electronics).

In this frame, a novel concept of “electroacoustic absorber” has been retained in FP7-OPENAIR, after preliminary validation at laboratory scale [3]. This concept is potentially a good candidate for the aircraft industry since it doesn’t need a priori power supply as opposed to usual active noise control techniques, thus leading to a lowering of equipment weight. This concept has also been proven to be effective for reducing modal behavior of closed spaces. The described technique has also a high

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[1] herve.lissek@epfl.ch

[2] http://www.acare4europe.org/docs/Vision%202020.pdf

integration potential, with the help of MEMS-based electrodynamic transducers. This paper presents the underlying concept of electroacoustic absorbers, together with simulation and experimental results on a prototype of electroacoustic absorber, envisaged as an active liner concept.

2. THE VARIABLE ACOUSTIC LINING CONCEPT

2.1 ACOUSTIC LINERS SPECIFICATIONS IN OPENAIR

The noise generated by a jet engine is mainly caused by the jet exhaust and the fan, and acoustic liners are used inside the jet engines to reduce the noise radiation. These liners usually consist of one or several layers of perforated plate backed with honeycomb structure, acting as noise dampers within grazing flow. They are typically placed upstream and downstream of the fans to absorb sound propagating out of the ducts. However, the overall acoustic performances of such materials are usually determined by construction, thus presenting limited performances in terms of frequency bandwidth, and can only be made variable by mechanic and/or fluidic actuation.

Active and adaptive noise control reduction technologies have been studied in earlier EU research programs and national research programs at low TRL[3] [2]. OPENAIR intends to further develop these active/adaptive technologies following two main and complementary routes with a view to increasing their TRL: on one hand the acoustic performances of the active/adaptive technologies are to be improved, on the other hand the integration issues (mechanical, aerodynamic and electronics) will be addressed. The following will only focus on the acoustic specifications, but the integration specifications should be understood as driving the choice of small and light transducers and electronic conditioners.

An acoustic liner (be it passive, active or potentially adaptive) can be characterized by the acoustic impedance that its surface presents to the acoustic field. When the surface is a diaphragm behaving as a rigid piston, under a given frequency limit determined by the mass density and mechanical stiffness of the diaphragm, this acoustic impedance is defined as the ratio of the pressure p at the diaphragm, over the inward velocity v of the diaphragm.

In the case of the development of variable acoustic liners, it has been required to assess the capability to change the acoustic impedance of the diaphragm of an electroacoustic transducer from a fixed frequency-dependent function (denoted as “passive”, determined by construction) to a prescribed frequency-dependent function, determined by the application. In our case, the specified acoustic impedance is similar to the one of a single degree of freedom acoustic resonator, with resonance frequency f_s, normalized acoustic resistance r_s, and quality factor Q_s. The specified normalized impedance (z/r_s) as a function of the normalized frequency (f/f_s) is given in Figure 1.

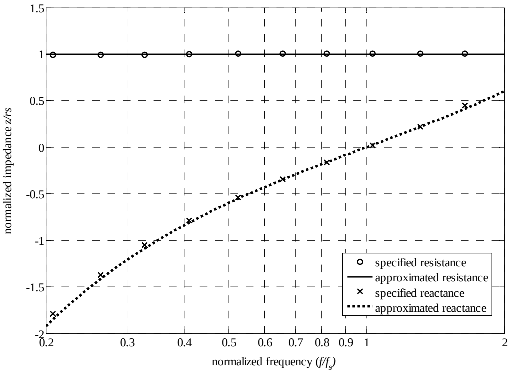

Figure 1: acoustic specifications for the acoustic liner

This impedance corresponds to the following normalized acoustic impedance:

$$\frac{z}{r_s} = 1 + jQ_s\left(\frac{f}{f_s} - \frac{f_s}{f}\right) \tag{1}$$

The objective of the study is to develop an electroacoustic system capable of reaching such prescribed acoustic impedance, with the help of active acoustic impedance control concepts, as described in the following.

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[3] Technology Readiness Level (see http://en.wikipedia.org/wiki/Technology_readiness_level)

2.2 THE ELECTROACOUSTIC ABSORBER

Let us consider an electrodynamic loudspeaker of known constitutive parameters (also known as “Thiele Small parameters”), the electric terminals of which can be either shunt with a passive load or connected to an external amplifier, providing a feedback voltage on acoustic quantities (in our case, a combination of proportional feedback on acoustic pressure p and diaphragm velocity v). It has been demonstrated in [3] that such conditioning of the loudspeaker allows tuning the acoustic impedance of its diaphragm as an active acoustic resonator, the parameters of which are obviously its acoustic resistance, its resonance frequency and its quality factor.

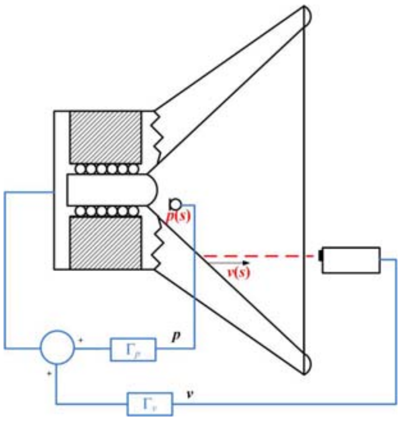

Figure 2: description of direct impedance control on a loudspeaker

It is indeed always possible to represent a feedback on acoustic quantities feeding a loudspeaker as a function of an electric quantity. We have chosen an electrodynamic loudspeaker, of constitutive parameters $(R_e, L_e, R_{ms}, M_{ms}, C_{ms}, S, Bl)$, the electric input being loaded with a combined acoustic pressure/diaphragm velocity feedback with gains Γ_p and Γ_v, such that the feedback voltage U_{fb} is a linear combination of sound pressure at the diaphragm p and diaphragm velocity v as (direct impedance control):

$$U_{fb} = \Gamma_p p + \Gamma_v v \qquad (2)$$

When the loudspeaker is fed back by this electric voltage, the feedback is seen at the electric side as a variable acoustic impedance device (see [3] for further details). This closed-loop electroacoustic device presents then the following acoustic impedance at its diaphragm:

$$z_{EA}(f) = \frac{p}{v} \approx r_{EA}\left[1 + jQ_{EA}\left(\frac{f}{f_{EA}} - \frac{f_{EA}}{f}\right)\right] \qquad (3)$$

where r_{EA}, f_{EA} and Q_{EA} are the acoustic resistance, the resonance frequency and the quality factor of the electroacoustic absorber, resulting from the active feedback. It is especially shown that these three quantities are only function of the Thiele-Small parameters (determined by construction) and the feedback gain Γ_{v} and Γ_{p}. One should notice that, when applying only proportional feedback as described in Eq. (2), the resonance frequency is hardly modified, but the control still allows a modification of the acoustic resistance of the resonator, and the quality factor (ie. the slope of the imaginary part of the impedance around the resonance frequency). But the 2 degrees of freedom of the control (Γ_{v} and Γ_{p}) should allow reaching the target acoustic impedance, assuming the resonance frequency is accurately tuned for the passive resonator (ie. without control).

3. DESIGN OF THE ELECTROACOUSTIC ABSORBER

3.1 DESCRIPTION OF THE ACTIVE CONFIGURATION

We have chosen to develop an electrodynamic loudspeaker with a resonance frequency tuned around f_s, and then change the resistance and quality factor by direct impedance control. Figure 3 shows the chosen transducer design. The driver uses a standard ring magnet made of neodymium-iron-boron, with an inner diameter $\varnothing_{in}$=16 mm, an outer diameter $\varnothing_{out}$=26,70 mm and a height h=5 mm.

The use of ABS (Acrylonitrile butadiene styrene)[4] material for the diaphragm is chosen to ease the design of the transducer (3D printer for prototyping). We have also decided to design a single piece for the suspension and the coil support, which has also been chosen accordingly to environmental specifications (heat, humidity, static pressure).

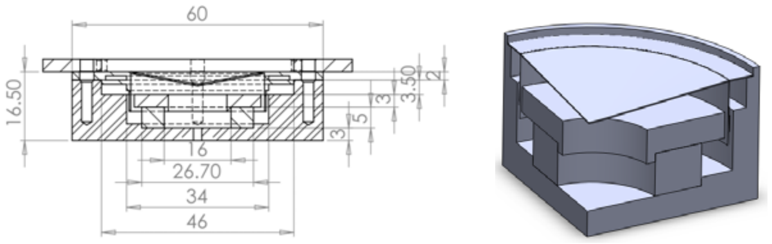

Figure 3 - design of specific circular electrodynamic loudspeaker for use as active liner.

A finite-element model of the transducer has been developed on COMSOL Multiphysics with the Acoustic Module, in order to characterize and optimize the design accordingly to the acoustic specifications. The model is developed with 2D axisymmetry, with acoustic/structure interaction on the diaphragm side, and ac/dc coupling on the electric side, to account for the active load at the transducer electric terminals.

The design parameters (dimensions and physical properties of ABS) are used to optimize the transducer, in order to achieve a desired resonance frequency for the mechanical resonator, targeting the specified value of f_s. This resonance frequency is assessed on COMSOL Multiphysics, by computing the acoustic impedance presented by the transducer diaphragm to the acoustic field, according to ISO 10534-2 standard. In that view, a simulation of an impedance tube configuration is developed, as described in [4].

3.2 ELECTROACOUSTIC ABSORBER MODEL

Figure 4 shows the real and imaginary parts of the acoustic impedance processed on the COMSOL model of the transducer after the method of ISO 10534-2 standard, with no feedback (passive case), and with feedback (active case in), compared to the required impedance.

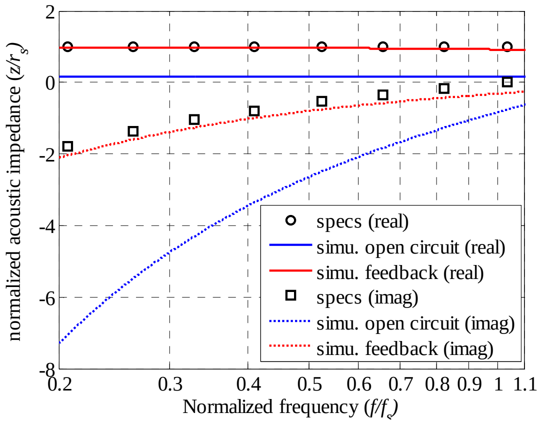

Figure 4 : simulated normalized acoustic impedance for the open-circuit case (blue) and an ideal acoustic feedback setting (red).

At passive stage, the computed real part of the acoustic impedance is of the same order of magnitude of the specifications, but the imaginary part is far from the required one, thus legitimizing the development of active means. The simulation obtained with active feedback show that the resistance can be slightly increase, up to the specified value, and the slope of the reactance is also significantly decrease so as to attain the specified reactance.

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[4] See http://en.wikipedia.org/wiki/Acrylonitrile_butadiene_styrene

3.3 DEVELOPMENT OF THE ELECTROACOUSTIC ABSORBER PROTOTYPE

For the prototype, we have frozen the design of Figure 3. The coil is made of two layers of copper wires and is in overhang configuration. The coil wire has a diameter $\varnothing_{\text{wire}} = 0.1$ mm.

The membrane, suspension and coil support are made in one piece with a 3D printer for prototyping. This piece is airtight owing to a special resin. The design of the suspension, made of several little stiffeners that can be cut one by one, allows the fine-tuning of the resonance frequency of the loudspeaker once designed.

Figure 5 shows each sides of this piece, highlights the stiffeners suspending the diaphragm to the body of the transducer.

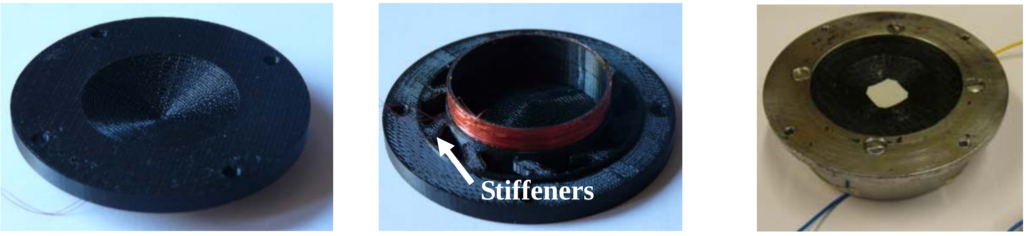

Figure 5 - Views of each sides of the ABS piece (left – middle), and whole transducer (right).

4. ACOUSTIC ASSESSMENT OF THE ELECTROACOUSTIC ABSORBER

The developed transducer is employed as an electroacoustic absorber, with direct impedance control feeding back its electric terminals. It is then placed at one termination of an impedance tube with a view to measure its acoustic impedance according to ISO 10534-2. The whole experimental setup is described on Figure 6. The excitation is a low-pass filtered white noise, the magnitude of which is set to 10 Pa (set under anechoic termination), delivered by a loudspeaker positioned at the other termination of the impedance tube.

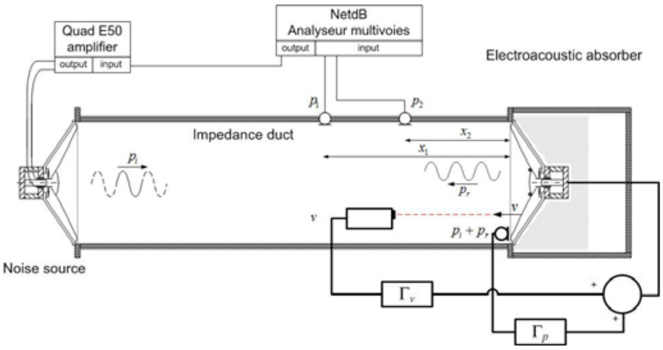

Figure 6: Description of the acoustic impedance measurement after the ISO 10534-2 technique

Figure 7 shows the results of the normalized acoustic impedance $z_{\text{EA}}/r_{\text{s}}$ (real and imaginary parts) vs. normalized frequency f/f_{s}, measured on the electroacoustic absorber fed by direct impedance control of known gains Γ_{v} and Γ_{p}, chosen accordingly to the design guidelines provided in [3]. These results are compared to the specifications (with markers).

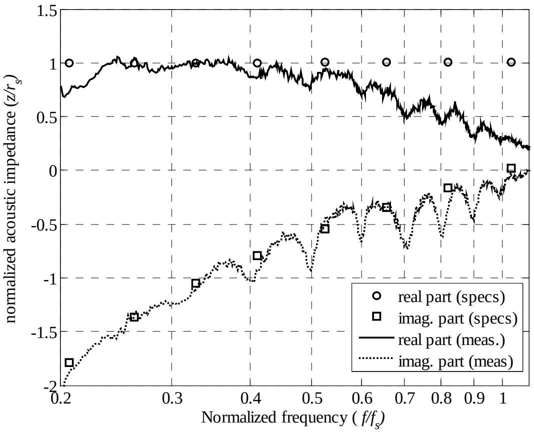

Figure 7 : normalized acoustic impedance of the developed electroacoustic absorber (markers: specifications; plain lines: measurements) – real and imaginary parts.

The obtained acoustic impedance is then significantly modified, from a given resistance and frequency-dependent reactance given in Figure 4 up to the specified resistance and reactance. This result is achieved at least under 0,5.f_s for the resistance, and up to f_s for the reactance, despite some slight discrepancies due to non-linear behavior of the electroacoustic absorber. These non-linear behavior is mainly due to the mechanical stiffness of the diaphragm, and could alleviated by making the diaphragm more compliant, for example by substituting the use of ABS for the suspension for an elastic suspension.

5. CONCLUSIONS

We have shown that applying direct impedance control on a loudspeaker can modify the acoustic impedance presented by its diaphragm, up to the specified acoustic impedance. In our example, this is achieved at least over a limited frequency bandwidth below the target resonance frequency. A way to better fit the specifications is to modify the control, replacing the proportional feedbacks by derivative elements, allowing to modify independently the quality factor and the resonance frequency, which is not directly accessible through the control concept assessed here. Another possibility is to replace the feedback with acoustic quantities with a shunt synthetic electric impedance, mimicking the acoustic sensings and allowing a much broader variety of acoustic impedances (see [3] for further details).

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 234313.

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