With the ACARE directives on aircraft noise reductions for 2050, aircraft turbofan engines acoustic liners will have to overcome contradictory goals: to guarantee an efficiency at low frequencies while reducing treated surface area and liners thickness. The purpose of this paper is to present some concept reviews in the development of transducers-based acoustic liners. The use of transducers enables the coupling of several physical domains: acoustics, mechanics and electronics. As shown in former work, this can lead to highly efficient devices enabling low frequency absorption with thin liners with or without flow. The present work aims to better understand the key phenomena governing acoustic absorption and frequency range available for a given liner thickness and several transductions such as electrodynamic, electrostatic and piezoelectric. The effects of adding an electronic shunt circuit and using several transduction principles on the absorption level and bandwidth are discussed. In order to study several types of transductions, Finite Element Method and Lumped Element Method modelisations have both been developed but only the second one is used in this paper. The transductions are compared considering absorption efficiency due to the shapes of the devices on one hand and to the possibilities offered by the connection to an electrical impedance in terms of absorption enhancement and/or frequency shift on the other hand. Some perspectives are given in terms of structures optimization, electrical shunt impedances choices and expected absorption efficiency.

Keywords: Aeronautics, Transducers, Modelisation, Absorption

1. Introduction

Several papers have been published during the last decades on perfect sound absorption. The use of porous materials is very common approach in automobile, aeronautic or structures problematics. The book by Allar & Atalla [1] deals with the notion of porous materials as acoustic absorbers. Later, Groby et al. investigated the principle of perfect sound absorption by the use of porous materials and periodic structures as metamaterials [2] [3]. Another mechanism of absorption has been investigated by Novak et al. [4] with viscothermal losses into slots. This work highlights the fact that a mechanical structure including acoustic slots, can also be used as an efficient acoustic absorber. The use of a Helmholtz resonator is well known and used to create acoustic treatment on aircraft engines.

Recently, Houdouin et al. [5] also investigated the use of electrodynamic transducers for acoustic absorption. This work was based on a semi-passive concept which means that there is no control loop.
into the system. Active control loop system has been also studied by Lissek [6] and recently been applied to aeronautics applications [7] i.e. for grazing incidence with flow.

The aim of this paper is to introduce optimal electrical shunt circuit with different types of transductions, in order to have a perfect absorption and also the possibility to shift the resonance frequency. This kind of electrical shunt circuit is based on the work of Haggod & Von Flotow [8] which is considered as the first example of shunt circuit on acoustic absorption effect.

The work presented hereafter deals with the comparison of electromechanical absorbers efficiency based upon the choice of several transduction principles. The comparison is based upon their respective absorption coefficients measured with an impedance tube with no flow. In order to get information only about transductions efficiency, the same mechanical-acoustic structure is used for all devices.

In order to have a perfect absorption, the normalized reflexion coefficient \( R(\omega) \) (Eq. 1) has to vanish, which means that \( Z_{sys}(\omega) = 1 \). The imaginary part of \( Z_{sys}(\omega) \) gives information on resonance frequency when \( Im(Z_{sys}(\omega_0)) = 0 \).

\[
R(\omega) = \frac{Z_{sys}(\omega) - 1}{Z_{sys}(\omega) + 1}.
\]  

\section{Physical considerations}

The same mechanical-acoustic system will be considered hereafter. Considering a mechanical structure with an impedance denoted \( Z_m \) and a resonance frequency \( f_m \) coupled to an acoustic load through an acoustic impedance \( Z_{ac} \) and a resonance frequency \( f_{ac} \), the lumped element circuit associated to such device can be represented as shown below in Fig. 1. An acoustic source with a \( P_{wave} \) pressure and a \( w_{ac} \) flow rate arriving on a moving part with an acoustic radiation impedance noted \( Z_{rad} \). The moving part of \( Sd \) surface is represented by a mechanical impedance \( Z_m \) with a \( F_{wave} \) force and \( v_m \) velocity due to the acoustic excitation. Finally the mechanical system radiates into an acoustic load \( Z_{ac} \) due to the coupling.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig1.png}
\caption{Lumped element circuit of the mechanical acoustic coupling.}
\end{figure}

The work done by Houdouin [5] allows to link absorption and lumped element circuit as shown considering a unique acoustic velocity localized on the transducer surface \( (Sd) \) radiating into a fluid (with a characteristic impedance denoted \( Z_0 \)) and proportional to a surface ratio \( \sigma = Sd/Sw \) with \( Sw \) corresponding to the wall surface where the transducer is located. In order to evaluate the acoustic reflexion (Eq. 1) the expression of the global acoustic impedance \( Z_{system} \) is needed (Eq. 2). The graph in Fig. 2 highlights the absorption of the mechano-acoustic system when \( \sigma = 4\% \).

\[
Z_{system} = \left[ Z_m + (Z_{ac} + Z_{rad})Sd^2 \right] \frac{1}{\sigma Z_0 Sd}.
\]
3. Transduction model

Amongst the many kinds of transduction principles we will consider here the three that we considered as the best suited ones for this study: the electrodynamic, piezoelectric and electrostatic ones. Each one of the following sections will introduce the associated lumped elements circuit associated and the general impedance acoustic which allows to study the acoustic absorption. This impedance is also normalized by $Z_0$ which is the characteristic impedance of the fluid.

3.1 Electrodynamic transduction

This well-known transduction is based upon the interaction between a coil and a magnet. It is due to the Lorentz and Laplace forces which are presented by Merhaut [9], as the lumped element circuit presented in Fig. 3. This type of circuit can be expressed by a unique impedance $Z_{\text{dyn}}$ formulation as show in Eq. (3). In that case, $Z_{\text{elec}}$ is considered as a combination of an inductance ($Z_{Le}$) and a resistance ($Z_{Re}$) due to the presence of a coil and $Bl$, the coupling term.

$$Z_{\text{dyn}} = Z_m + (Z_{ac} + Z_{rad})Sd^2 + BL^2 \left( \frac{1}{Z_{shunt} + Z_{Re} + Z_{Le}} \right) \frac{1}{\sigma Z_0 Sd}. \quad (3)$$

Figure 3: Lumped element circuit of the electrodynamic transduction.
3.2 Electrostatic transduction

Mainly used for measurements due to its high sensitivity over a large frequency bandwidth, this transduction is based on the principle of a variable capacitance. The motion of an electrode due to an acoustic excitation will change the distance between the two polarized electrodes and thus create a differential potential voltage. The governing equations are also known and can be found in Bruneau’s book [10] in order to express the lumped element circuits in the same way as the electrodynamic transduction’s one. In previous works, Lavergne et al. [11] also considered the whole mechanical electrostatic structure in order to increase the accuracy of the lumped element model. However, this is not the aim of this paper, which is focused on the transduction impact. The lumped elements circuit can be seen in Fig. 4 and the corresponding impedance $Z_{\text{stat}}$ formulation in Eq. 4, where $k_b = C_0 U_0 / d_0$ is the coupling term ($U_0$ the polarized voltage and $d_0$ the distance between the electrodes) and $R_g$, the input resistor of the preamplifier ($R_g \to \infty$).

\[
Z_{\text{stat}} = \left( Z_m - \frac{k_b^2}{j \omega C_0} + (Z_{ac} + Z_{rad})S_d^2 + k_b^2 \frac{Z_{\text{shunt}}Z_{C_0}Z_{R_g}}{Z_{\text{shunt}} + Z_{C_0} + Z_{R_g}} \right) \frac{1}{\sigma Z_0 S_d}.
\] (4)

3.3 Piezoelectric transduction

The piezoelectric effect is a reversible process involving mechano-electric physics. The generation of an electrical charge is the result of an applied mechanical force and a mechanical strain is the result of an applied electrical field. The state equations of the piezoelectricity are available in Brissaud book [12]. In a same way as for the previous transduction, it is possible to establish the lumped element circuit of the piezoelectric transduction in Fig. 5 where the coupling term $k_p = e_{13} S_{\text{piezo}} / t_{\text{piezo}}$ is a relation between the piezoelectric parameter $e_{13}$, the thickness $t_{\text{piezo}}$ and the surface of piezoelectric $S_{\text{piezo}}$. The general impedance $Z_{\text{piezo}}$ formulation of a piezoelectric transducer is presented in Eq. 5

\[
Z_{\text{piezo}} = \left( Z_m - \frac{k_p^2}{j \omega C_p} + (Z_{ac} + Z_{rad})S_d^2 + k_p^2 \frac{Z_{\text{shunt}}Z_{C_p}Z_{R_g}}{Z_{\text{shunt}} + Z_{C_p} + Z_{R_g}} \right) \frac{1}{\sigma Z_0 S_d}.
\] (5)

4. Effect of electrical impedance variation

In this section the focus is on the addition of an electrical shunt impedance to drive the absorption level and the resonance frequency of the considered system.
Figure 5: Lumped element circuit of the piezoelectric transduction.

Figure 6: Absorption curves for different kinds of resistive shunt circuits and transductions: (a) Electrodynamic - (b) Electrostatic - (c) Piezoelectric.
Table 1: Transduction parameters used for the models implementation.

<table>
<thead>
<tr>
<th>Transduction type</th>
<th>Electrodynamic</th>
<th>Electrostatic</th>
<th>Piezoelectric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>$B_l = 0.1 N.A^{-1}$</td>
<td>$d_0 = 1 mm$</td>
<td>$\text{thickness} = 50 \mu m$</td>
</tr>
<tr>
<td></td>
<td>$L_e = 50 \mu H$</td>
<td>$R_g = 10 M \Omega$</td>
<td>$e_{31} = 0.58 C.m^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$R_e = 25 \Omega$</td>
<td>$C_0 = 28 pF$</td>
<td>$C_0 = 500 pF$</td>
</tr>
</tbody>
</table>

The real part of the impedance controls the absorption performance and the frequency bandwidth. The way to tune the real part of the impedance is by adding a resistor or a negative resistor. The imaginary part of the impedance allows to tune the system to a specific frequency when the reactance is vanishes. The corresponding electrical elements that allow to change the imaginary part are the inductance and the capacitance.

Considering the mechano-acoustic system seen previously (Fig. 2) in a $Z_0$ medium, means that $Z_m$ and $Z_{ac}$ are known (as well as $Z_{rad}$, $Sd$ and $\sigma$ which depend of these impedances). Due to parameters such as sound pressure level and Mach number, the average acoustic particle displacement is of the order of 1 mm. That leads to a minimum distance $d_0$ between the electrodes (for electrostatic transduction) of 1 mm in order to avoid collapse phenomena due to the polarization voltage. The following table (Tab. 1) sums up the transduction parameters that will be used for the next simulations.

### 4.1 Perfect absorption

In order to tune the performance of the system without shifting the resonance frequency, it is necessary to adjust the real part of the impedance. As said in the introduction, the impedance has to be equal to 1 in order to have perfect absorption. This leads to different expressions of the optimal shunt impedance for each transduction in order to have $Z_{system}(\omega) = 1$. The following graphs show the difference between the systems for three different configurations and for three different kinds of transductions: electrodynamic (Fig. 6a), electrostatic (6b) and piezoelectric (Fig. 6c and 6d).

The optimal shunt circuits shown above are using a negative resistor ($R_s = -23.1 \Omega$) for the electrodynamic transduction and a positive one for the electrostatic and piezoelectric ones. It is necessary to notice that the polarized voltage for the electrostatic transduction has to be very high ($\approx 1500 V$) in order to minimize coupling factor. In pratical case, the electrostatic shunt circuit could not be set up due to the polarization voltage and the low current flowing through the shunt ($\approx nA$) and the high input impedance of the preamplifier. The piezoelectric transduction can be improved by using a negative capacitance in order to vanish the $Z_{C_0}$ impedance and adapt the coupling factor conversion.

### 4.2 Shifting frequency

In a same way as in the previous section, the focus is set on the imaginary part of the impedance. In other words, the aim of this study is to show the possibility of the addional shunt circuit to shift the resonance frequency. Considering that the system is tuned to $\omega_1$ and the goal is to tune it to $\omega_2$, the condition that has to be satisfied is $Im(Z_{system}(\omega_2)) = 0$. The following curves below are simulated with the same transduction parameters as shown in Tab. 1 and only the electrical shunt circuit is adapted. Some results can be seen on the figure underneath with the three kinds of transductions: electrodynamic (Fig. 7a), electrostatic (Fig. 7b) and piezoelectric (Fig. 7c).

The addition of a capacitance in the electrodynamic shunt circuit produces a resonant circuit (LC). The system then behaves like a double degree of freedom one. In that way it is possible to tune the value of $C_s$ in order to reach another frequency or tune the damping ratio (value of $R_s$) to increase the...
Figure 7: Absorption curves for different type of reactive shunt circuits and transductions: (a) Electrodynamic - (b) Electrostatic - (c) Piezoelectric (Without $L_s$) - (d) Piezoelectric (With $L_s$).

For the electrostatic and piezoelectric transductions, the negative capacitance allows the system to decrease the value of stiffness in order to reach lower frequencies. By the end, for the piezoelectric transduction, the strategy is quite different from the electrostatic’s one. Indeed, the shunt inductance value required for electrostatic transduction is too high ($\approx MH$) to be set up. But for the piezoelectric transduction, the use of a synthesized inductance is possible in order to create an electrical resonant circuit with the natural capacitance of the piezoelectric transducer. Then it is possible to adjust three parameters ($R_s, L_s, C_s$) in order to get a wide absorption band, which is not the case for the electrodynamic transduction since only two parameters ($R_s, C_s$).

5. Conclusion

This paper highlights several types of transduction which can be used on a mechanical structure in order to create acoustic absorbers. There are also a passive and semi-passive strategies set up that show the existence of an optimal electrical shunt circuit, depending on the electrical component used and the targeted effects. In some cases, it is difficult to put in practice the optimal shunt due to different reasons as the voltage polarization, the low value of electrical current which passes through the circuits or the precision needed for the value. Nevertheless, the ability to use an electrical transduction in order to enhance the absorption performance, the bandwidth, or to shift the resonance frequency of the system is demonstrated.

In further work it will be preferable to have a mechano-acoustic structure that meets the needed
specifications. In that way the transduction part could be used in order to increase the performance of the absorption, shifting the frequency of interest, enhancing the bandwidth or measuring the acoustic field pressure.

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REFERENCES