Optimization of the surface impedance measurement of aeronautical treatments

This article deals with the characterization of acoustic liners for aeronautics applications; the specificity of this application residing in the flow Mach numbers and high sound levels found on these liners. When the test section is small (to limit the size of the air supply compressor but allows the sound environment of a jet engine) recent studies have shown that the application of the conventional Ingard Myers boundary condition to the treatments fails to correctly predict the acoustic behavior and the impedance of the liner, especially with a flow direction opposite to the acoustic propagation. A modified version of the Myers-Ingard condition has therefore been proposed and shows better prediction of surface impedance with grazing flow and regardless of its direction. In fact, the acoustic behavior of liners is better predicted. The experimental method described in this article is based on the use of a microphone array facing the liner to extract the axial wave numbers in the two directions of sound propagation. These are then used with the modified boundary condition to compute the surface impedance. A test section was specially designed so as to reach a Mach number of about 0.5 near the intended application and acoustic sources of high levels have also been implemented to simulate the nonlinear acoustic excitation. Finally, these results are compared with the first results from the direct method recently implemented which involves the use of a closed cavity with two microphones.

1 Introduction

While the use of acoustic treatments (such as "liners") are commonly used in reactor noise reduction applications, the acoustic behavior of such systems in the presence of grazing flow remains a hot topic because of complex interaction between the sound propagation and the flow at the boundary layer near the treated wall.

It was usually considered a potential flow in this area and accepted a continuity of the acoustic normal displacement and acoustic pressure, which leads to a Ingard[1] – Myers [2] boundary condition. This condition has been widely used to calculate the surface impedance from acoustic measurements [3,4,5,6,7]. Aurégan *et al.* [8] then Brambley [9] showed recently that the turbulent and viscous effects near the wall modify this boundary condition. The experimental study of Renou and Aurégan [10] in 2011 shows that the use of the conventional boundary condition does not correctly predict the acoustic behavior and the impedance of the treated wall and particularly when the flow direction is opposite to the acoustic propagation.

A modified version of the Myers-Ingard condition has been proposed [8,10] by introducing an additional term named β_v that can account for visco-thermal effects in the boundary layer of the lined wall. This term is between 0 and 1: when $\beta_v=0$, it is the conventional Ingard-Myers boundary condition (continuity of acoustic displacement) and when $\beta_v=1$, there is a continuity of acoustic mass velocity. The introduction of this additional term is then used to better predict the acoustic propagation in front of liners and better predict the surface impedance with grazing flow and that, whatever the direction of flow.

As part of this study, measures with duct flow are realized with conventional acoustic liner (S-DOF). The first part of this article describes the experimental method used (so-called "K"), which initially determine the axial wave numbers in front of the treatment and, secondly, determine the surface impedance of the liner using the modified boundary condition.

The second part is devoted to experimental realizations, namely the implementation of the method "K" and also the implementation of a standard method called "In Situ" which uses a standard technique of two microphones.

The last part is devoted to the experimental results.

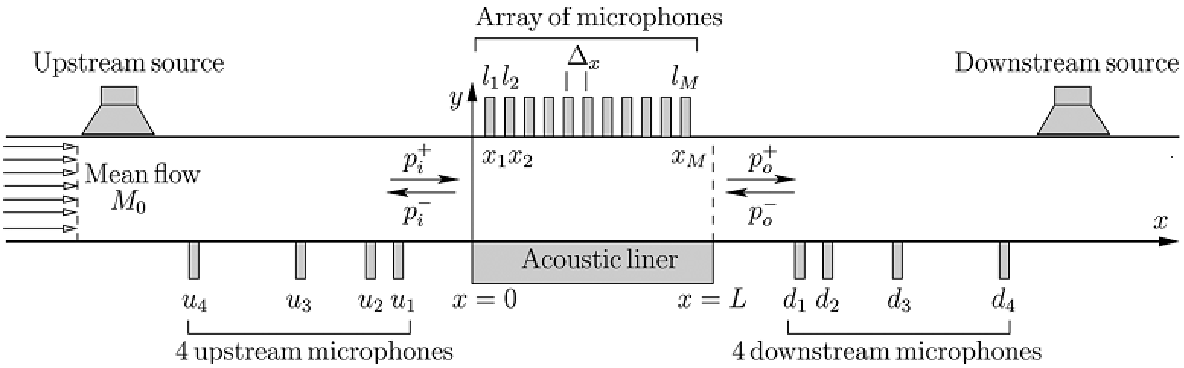


Figure 1 : Schematic view of the experimental setup (from [10])

2 "K" Method

The Figure 1 shows the principle of the experimental setup: we consider a rectangular duct partially treated in which propagates an acoustic wave where an airflow is superimposed. According to the duct dimensions, only two acoustic modes are considered in the frequency range studied: the plane wave and the first order mode linked to the largest transverse dimension. As the microphones are mounted in the center of this larger, only the plane wave mode is measured.

Upstream and downstream of the liner, anechoic terminations (not shown), acoustic sources and microphones are arranged. We recognize the classic device of scattering matrix measurement method with two sources.

In front of the liner, a microphone array is also placed so as to determine the axial wavenumbers. These are obtained from a modal decomposition of the acoustic pressure field at the wall opposite to the liner:

$$p_m = \sum_{n=0}^{\infty} b_n^+ e^{-ik_n^+(x_m - x_1)} + \sum_{n=0}^{\infty} b_n^- e^{-ik_n^-(x_m - x_1)}, m = 1 \ldots M \tag{1}$$

where $k_n^\pm$ are axial numbers in the treated part, $b_n^\pm$ are the complex amplitudes of the acoustic waves and M the number of microphones used.

From the hypothesis of a locally reacting liner, its impedance Z_w is expressed as :

$$Z_w = \frac{p}{v_w} \tag{2}$$

where p and v_w mean respectively the pressure and the normal velocity at the lined wall.

The use of Ingard-Myers condition (continuity of acoustic displacement) leads to the following dispersion relation:

$$k_y^2 = (\omega - M_0 k)^2 - k^2 \tag{3}$$

and writing the sound pressure leads to the relation:

$$k_y tan(k_y) = \frac{(i\omega - iM_0 k)^2}{i\omega Z_w} \tag{4}$$

where ω, M_0 mean respectively the pulsation and the Mach Number.

The equations (3) and (4) lead to the impedance surface Z_w from the axial wave number k.

In the following, the impedance of the lined wall is calculated from the predominant mode propagating in both directions, namely the plane wave mode $k_0^\pm$.

Considering the direction of propagation, two wall impedances can be therefore calculated, which according to Renou and Aurégan [10] are equal without flow but different with flow, which shows that the conventional boundary condition is not appropriate. Thus, a modified version of the condition of Ingard-Myers is proposed that leads to modify the relationship (4) by :

$$k_y tan(k_y) = \frac{(i\omega - i(1-\beta_v)M_0 k)(i\omega - iM_0 k)}{i\omega Z_w} \tag{5}$$

The parameter β_v is obtained by forcing the model so constructed to give a single effective wall impedance said Z_{eff} regardless of the acoustic propagation direction.

Refer to the article Renou and Aurégan[10] which details the modeling.

3 Experimental Implementations

3.1 "K" Method

The Figure 2 presents the design of the test section in its central part: it is a rectangular section of dimensions 20 mm x 50 mm equipped with a sample holder containing the liner to test, whose dimensions are 100 mm x 200 mm (only a 50 mm x 200 mm surface is useful). In front of the latter, 11 microphones Brüel & Kjaer type ¼" pressure are mounted and spaced of 20 mm to measure the axial wave numbers.

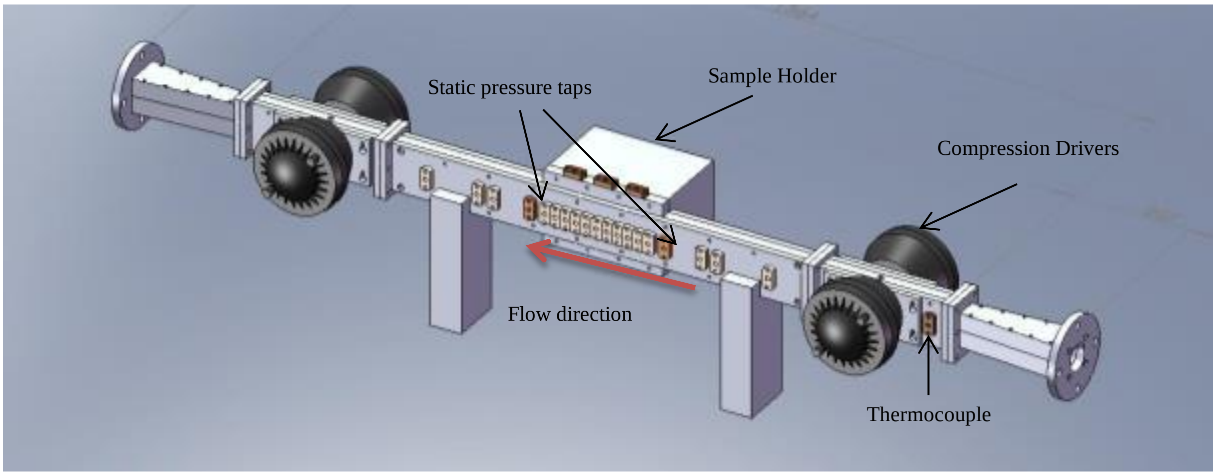


Figure 2 : Design of the test section

Three microphones of same kind can be mounted on either side of the sample holder; they allow the measurement of the scattering matrix of the test element. On both side, a pair of compression drivers are mounted in order to obtain high acoustic excitation levels on the frequency band 800 to 5000 Hz. Finally, section adjustments are provided on each side which allow connection to an existing cylindrical duct of 50 mm diameter. A duct of length of one meter was then added between the adjustment section and the first pair of compression drivers in order to ensure an established flow downstream of the first adaptation section.

The flow is carried out upstream by means of a compressor Roots, a cooler and a volume plenum. In the duct configuration described above, a Mach number of 0.5 can be obtained close to the intended application.

The Figure 3 shows a view of the installation and Figure 4 the top view of the lined part.

Figure 3 Overview of the central part

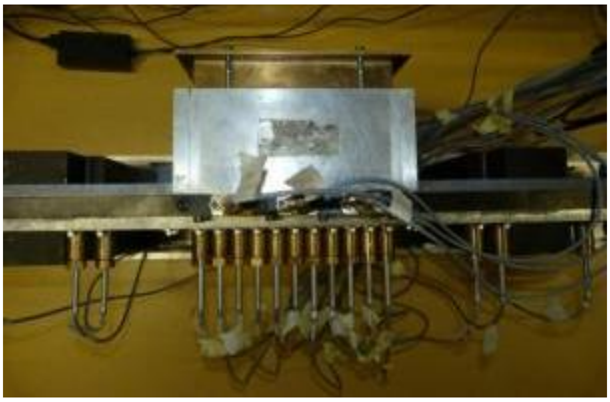


Figure 4 Top view of the lined and equipped part

3.2 In-Situ Method

In addition to the measurement described above, a direct measurement of the surface impedance has been implemented whose schematic drawing is depicted in Figure 5. This is a historical method [11] using two microphones, one flush with the surface for measuring the pressure and the other at the bottom of the cavity where the acoustic pressure is proportional to the acoustic velocity. The main goal of the implementation of this method is to overcome the high frequency 5000Hz limitation of the previous method; this extension is required for the study of liners for small engines.

In this simple configuration, the normalized impedance is deduced directly from the transfer function between the two microphones [12] :

$$z = \frac{p_{face-sheet}}{u_{face-sheet}} = -i\left|\frac{p_{face-sheet}}{p_{back-wall}}\right| e^{i\varphi} sin^{-1}(kh) \qquad (6)$$

where h is the height of the cavity and φ the phase of the cross spectrum between the two microphones.

The direct measurement system is designed to be mounted in place of one compression driver. Two 1/8" microphones are used (Bruel & Kjaer 4138), one of which is mounted with its grid flush to the perforated plate tested and the other is placed in the bottom of the cavity. The cavity depth is 19 mm for a diameter of 29 mm.

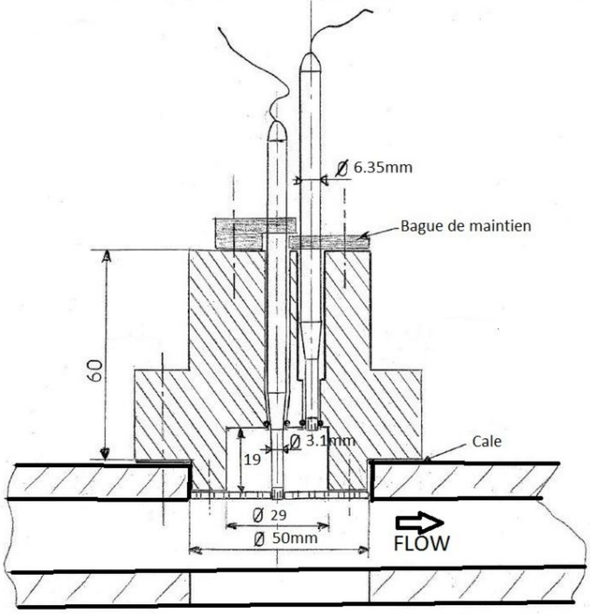
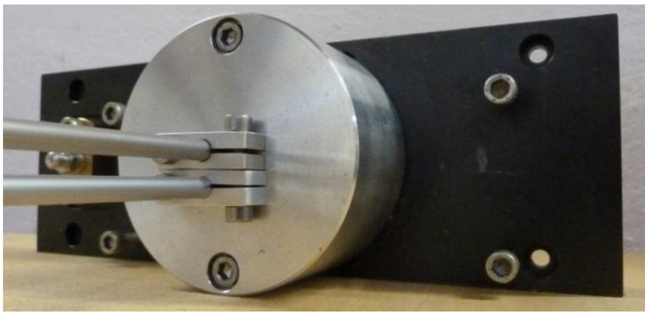


Figure 5 Schematic drawing of the measurement system with two microphones



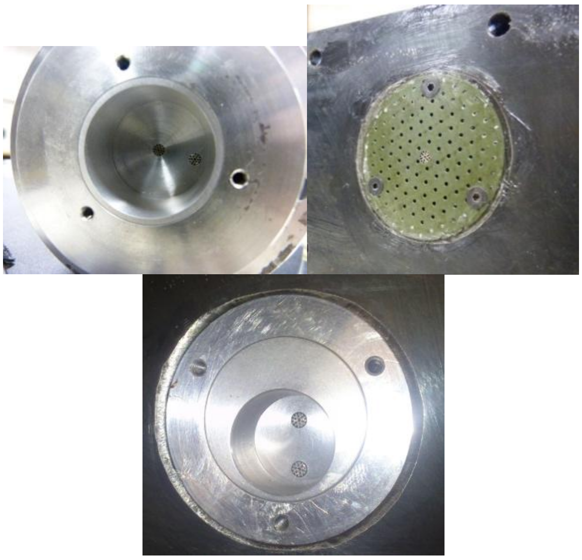


Figure 6 Implementation of the device

The Figure 6 shows several views of the measuring device called "InSitu". The left-view where the two microphones are flush mounted at the bottom of the cavity corresponds to the situation for the relative calibration of the two microphones when they are placed at the end of a Kundt tube with the same diameter (29mm). The bottom view shows an adaptation of the mounting with a ring insert reducing the cavity diameter to substantially increase the desired measuring range towards higher frequencies.

The Figure 7 shows the location of the system on the test section: downstream of the section of adaptation (gray area), there is the section of 1 m duct (for flow establishment), the section containing the two compression drivers for the acoustic excitation, the section containing the in-Situ installation and an anechoic termination.

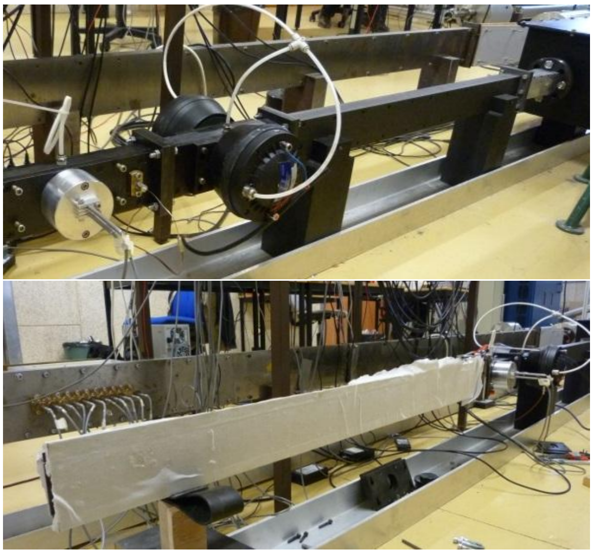


Figure 7 InSitu system installed

3.3 Liner tested

The liner, whose results are presented in this article, is a standard treatment consisting of a honeycomb core and covered with a perforated sheet.

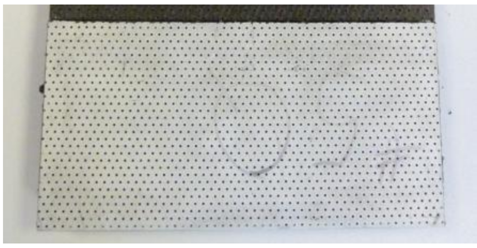


Figure 8 Tested liner

The liner of dimensions 200 mm by 100 mm, as shown in the previous figure, is mounted in the sample holder (Figure 4) for the method "K" measurement and a diameter of 50 mm of the perforated plate is placed in the "In Situ" measuring device (Figure 6).

4 Results

In a first step, we present the pressure levels measured along the treatment with the upstream pair of compression drivers in operation during the measurement using K method (Figure 9). The acquisition is realized by step sine with an increment of 10 Hz between 800 and 5000 Hz, the level is not controlled.

Three levels of excitement are targeted:

- Low level : about 120 dB (green curves)
- Intermediate level : about 140 dB (blue curves)
- Maximum level : about 160 dB (mauve curves)

Moreover, for each level, we represent three curves corresponding to the microphones at the beginning, middle and end of treatment.

It is noted that, logically, the pressure levels decrease along the liner in the frequency range where the absorption is the best. Thus, in order to impose a constant overall acoustic level to the sample, a sinus wave of 791 Hz (outside the frequency range of to study) was superimposed with other sources operating on either side of the rectangular duct.

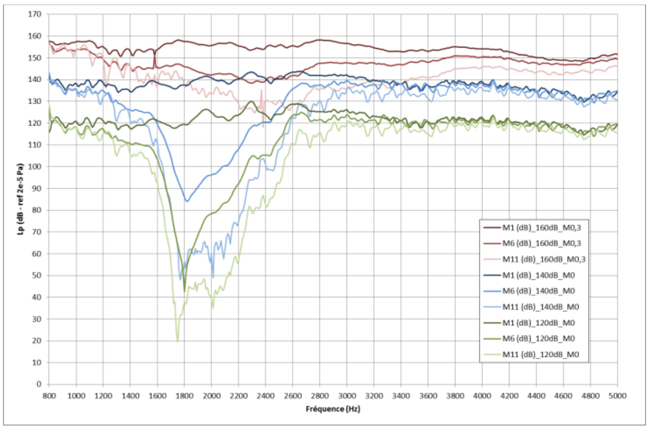


Figure 9 Level Pressure –K Method

The Figure 10 shows the resistance obtained by the K method on four flow rates (Mach = 0, - 0,2 - 0,3 - 0.45) and on two or three levels of acoustic excitation (120 dB - 140 dB - 160 dB).

In general, an increase in the resistance to the flow rate is observed and / or the level of acoustic excitation. The measurement is degraded for frequencies below about 1300 Hz, which is attributed to the relationship between the wavelengths and the sample size in its largest dimension (200 mm). Moreover, in some cases, the signal to noise ratio deteriorates in some situations where the pressure level measured along the treatment is the same order of magnitude or lower than the level of flow turbulence pressure.

The impact of flow and acoustic excitation on the reactance is more moderate (Figure 11) : little or no impact on the pressure level and a downward trend when the flow rate increases.

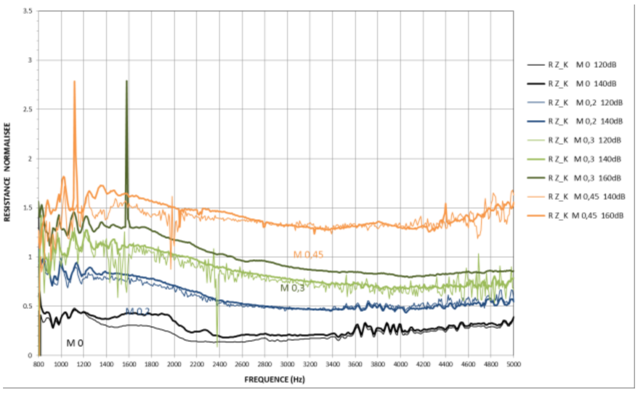


Figure 10 Resistances –K Method

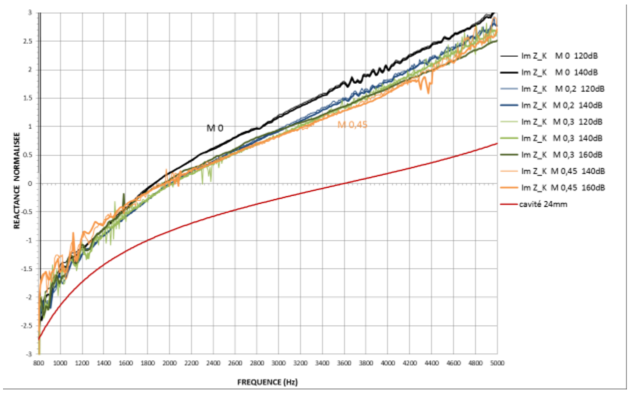


Figure 11 Reactances –K Method

The following figure shows the resistance measured with the In Situ method on three levels of excitement and without flow (blue curves) and compared to the resistances obtained by K method on two levels of excitation (purple lines). We see that the measurements obtained with the In Situ method are very swinging and hardly comparable to the K method. The observed oscillations are to be compared with changes in excitation levels experienced during measurements with the In Situ method (Figure 13 « curves Front (dB) »). For example, with the strongest level of excitement, resistance becomes very sensitive to the level of pressure: the shape of the resistance curve follows the shape of the level of excitement.

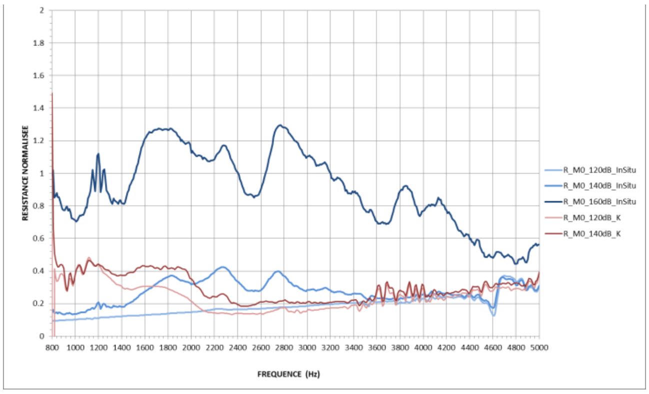


Figure 12 Resistances – Mach0 –K + InSitu Methods

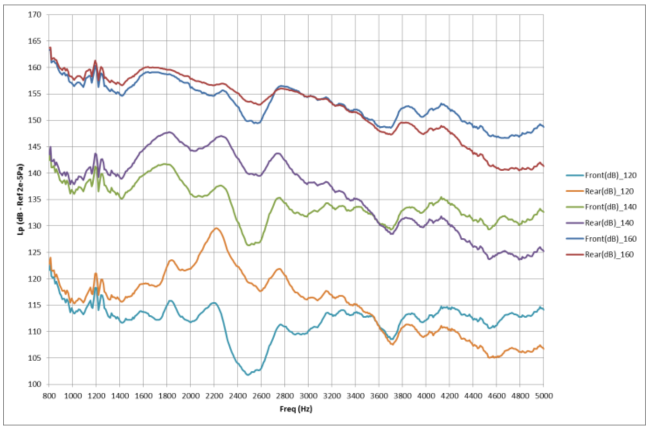


Figure 13 Excitation levels – Mach0 – InSitu Method

Comparisons on the reactance (Figure 14) are made solely on the perforated sheet by subtracting the contribution of resonant cavities (cotan (kH)) due to differences in cavity depth (24 mm on the sandwich panel and 19 mm on the InSitu system). Significant differences are observed, and contrary to the resistances, the change in excitation level has little impact on reactances.

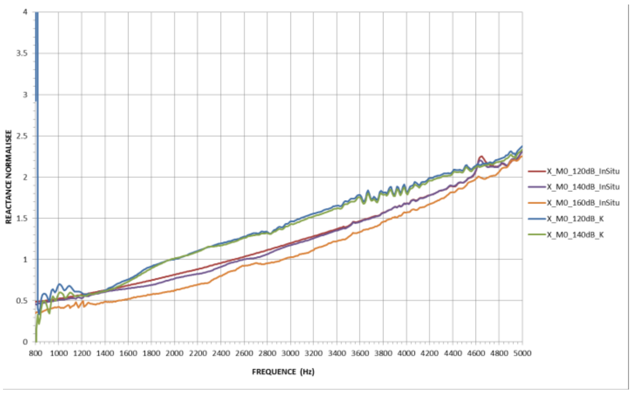


Figure 14 Reactances - Mach0 –K + InSitu Methods

The following figures illustrate the results recently obtained by implementing a standard driving process and designing a dedicated anechoic termination. The Figure 15 presents normalized impedances measured up to 6400 Hz without flow using the signals from the two microphones and with four stabilized levels of excitation (100 - 120 - 140 and 150 dB). It is then found much better results with the new procedure implemented. They nonetheless degrade at high frequencies and are proving to be definitely related to the acoustic field disturbed at these frequencies in the cavity due to the crossing of the center microphone. The Figure 16 shows the results obtained by using only the central microphone which is moved in a second measurement when the latter is placed at the bottom of the cavity. These results seem less disturbed by high frequency despite some sensitivity observed at low excitation level.

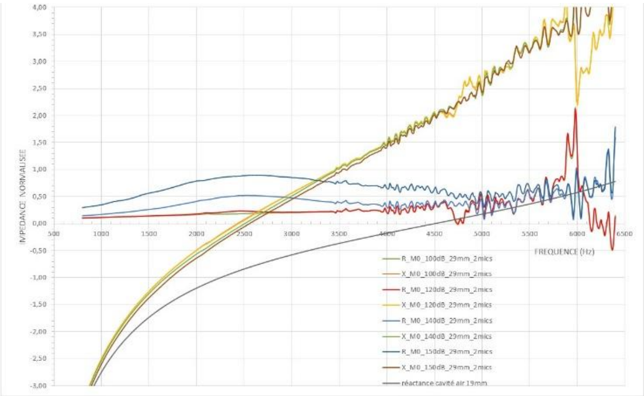


Figure 15 Impedances - Mach0 –InSitu
Two microphones treatment

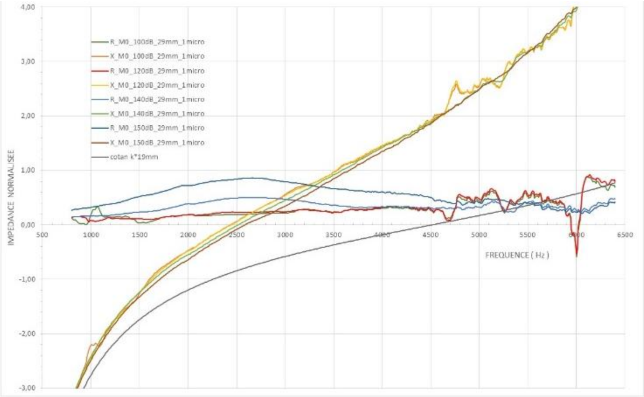


Figure 16 Impedances - Mach0 –InSitu
Mobile microphone

5 Conclusion

This paper deals with the measurement of impedance of aeronautical liners under grazing flow. A dedicated test section is designed to achieve acoustic excitation levels and significant flow rates close to the target application. An innovative method optimized by LAUM is presented and implemented (K method). The results obtained by this method are very satisfactory. An additional method with two microphones to characterize treatment beyond 5000Hz is tested (In Situ method). The first results obtained did not give complete satisfaction due to the high sensitivity of this method to the variation of the level of acoustic excitation when the standing wave ratio is important in the measurement area. To solve this problem, an anechoic termination and a dedicated driving level have recently been implemented. The first results are very encouraging and allow considering the extension of the measurement to the higher frequencies.

Acknowledgments

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