Acoustic optimization of anechoic termination with and without superimposed flow

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Abstract: This paper deals with the optimization of anechoic terminations of two types: full-flow and resistive terminations that can be used for the first one with flow and for the second one without flow only. In both cases, analytical models are made to predict the reflection coefficient of the terminations. This is used to make an optimization and the chosen configurations are validated by measurements. For a full-flow termination of 1m length, a reflection coefficient lower than 20% is reached from 170 Hz and, for the resistive termination, a null reflection coefficient is obtained up to 500 Hz and lower than 10% up to 2000 Hz.

Keywords: Anechoic termination, reflection coefficient, full-flow termination, resistive termination, prediction.

1. Introduction

Acoustic characterization of elements - such as exhausts, filters, flexible pipes, etc. - is usually performed on dedicated test benches for transfer matrix or radiated noise measurements. The reliabilities of these measurements are generally improved by employing anechoic terminations at the ends of the test rig. Traditionally, absorbing materials are placed at the end of the duct in the case without flow or around a perforated duct in the case with flow. To date, little studies have been performed on the subject and while a standard [1] that governs the conception of some terminations exists, the solutions are not optimized. Thus, the anechoic terminations are usually empirically designed and, at low frequencies, the reflection coefficient remains often too high.

In this paper, two kinds of anechoic termination are investigated. With air flow, a through flow termination is designed with the help of an analytical model of gradual perforations covered with a resistive material. Without flow, a resistive termination is developed based upon the basic idea to adapt the duct end impedance to the characteristic impedance of the pipe. In both cases, an analytical model is developed to predict the reflection coefficient of the terminations and the configurations are validated with measurements.

In the first part of this paper (section 2), a brief description of the impedance test bench is given. Then, in section 3, after few results about the open duct, a first solution is presented: a very long pipe. The section 4 is dedicated to the full-flow termination, where an analytical model is developed. This model allows a parametrical study where the main parameters are the number and the diameter of the perforations, the total length of the termination and the resistance value of the material placed in front of the hole. In this section, several configurations are also tested. Lastly, section 5 concerns the resistive termination issued from a prior study is studied.

2. The impedance test bench

Classically, the reflection coefficient of a termination is measured by the technique of two-microphones flush-mounted on a duct. This technique is widely spread and described in the ISO standard 10534-2 [2] for the well-known Kundt tube. The main drawback of this technique is linked to the separation between the two microphones: a large separation is needed for low frequencies in order to have sufficient phase shifts, but a large separation introduce indefinite frequencies located to the multiple of the half of length-wave. Therefore, for high frequencies, a small distance between microphones is required. Thus, to cover a wide frequency range, this technique imposes to perform the measurement in two steps with two separations or the use of at least three microphones.

By using a sensor with a known volume velocity source developed by the LAUM together with the CTTM (Figure 1), it is demonstrated that the impedance can be obtained from 10 to 5000 Hz by performing only one measurement [3]. The impedance measurement setup proposed uses a piezo-electric buzzer as a source. This buzzer is loaded on its back by a closed cavity and is connected to the front of the measured pipe. The pressure p at the input of the pipe is measured by a microphone and a second microphone measures the pressure in the back cavity, this pressure being at first order proportional to the volume velocity U delivered by the source. The impedance $Z = P/U$ is thus at first order proportional to the transfer function between the two microphones. To obtain accurate data, a complete model of the sensor is however considered. For more details see reference [3] and [4].

Figure 1 : Impedance Transducer with duct for absorbing materials.

3. Open-duct behaviour and basic solution

3.1 The open-duct

To introduce this study, we should remind the behavior of the open-duct. The Figure 2 describes the reflection coefficient of an open-duct of 32 mm diameter as a function of the frequency.

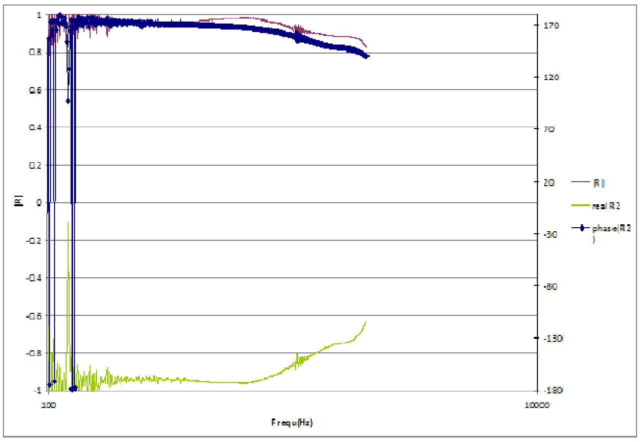

Figure 2 Reflection coefficient of the open-duct

Because this parameter is a complex value, three curves are displayed: the purple one is the modulus of the reflection coefficient, the green one stands for the real part (scale on the left) and the blue one represents the phase (scale on the right). One can observe that in low frequencies (below 750Hz), the reflection coefficient is purely real with a value near -1. The phase is therefore near 180°. This behavior indicates that the acoustic wave in low frequencies is totally reflected at the end of the pipe with a reversal of the phase. Consequently, it is necessary to treat the end of the duct as the acoustic waves remain trapped in the duct and will generate stationary waves unwanted for reliable measures.

3.2 The infinite tube

A first solution consists in using an infinite tube of the same diameter as the measurement duct. Indeed, for a desired reflection coefficient R at the frequency f, the required length L_t of the termination of radius r is defined as:

$$|R| = e^{-2\alpha L_t} \Rightarrow L_t = \frac{-\ln(|R|)}{2\alpha} \qquad [1]$$

$$where: \alpha = 3\times10^{-5}\frac{\sqrt{f}}{r}$$

α is the absorption coefficient per unit length of the duct due to viscothermal losses near the walls.

For example, in order to have a reflection coefficient lower than 10% beyond 100Hz for a pipe of 35mm diameter, the length should be at least 67m.
This solution is classically used for capillary tubes – i.e. the termination is rolled up - but not convenient for largest diameters. Moreover, in presence of flow, the pressure losses might be too large.

As a consequence, for larger diameters, two types of solutions are possible depending or not of the existence of flow.

4. The full-flow termination

4.1 Introduction

For test benches with flow that need to be anechoic at each end of the ducts, the terminations must not introduce added pressure loss. Therefore, this kind of terminations is called through-flow or full-flow termination.

4.2 The gradual slit termination

A simple solution find in the standard 5136 [1], consists to adapt the duct end impedance by the use of a gradual slit covered with a resistive material:

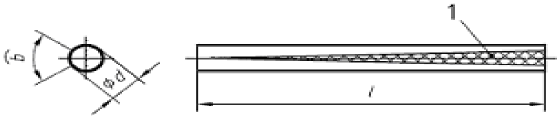

Figure 3 The gradual slit termination (from [1])

The length of the slit l is equal to nine diameters, and at the end of the duct the chord $\widehat{b}$ must be equal to the sixth of the diameter. Moreover, according to the standard, the slit must be covered by a material of hydraulic resistance of around 400 Rayls MKS (near the characteristic impedance of the air in normal conditions).

For previous applications, this kind of termination was realized in a PVC tube of 35 mm diameter (Figure 4).

Figure 4 Gradual slit termination and metallic wire mesh

The resistive material that covers the slit is a metallic wire mesh from the society Haver & Boecker in Germany, material usually found in aeronautic applications. The selected product has a theoretical resistance of 230 Rayls MKS which value was verified on the air flow resistance test bench of CTTM.

This termination was measured with the impedance measurement setup and the results are displayed on Figure 5. For all the results present within this document, the data in very low frequency (below 100 Hz) are noisy and that was due to unoptimized acquisitions (not enough level and not enough averages). Nevertheless, the trends are observed.

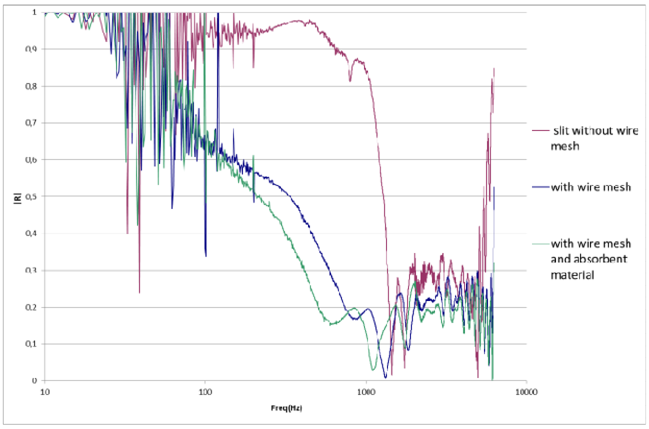

Figure 5 Reflection coefficient of the slit termination

The purple curve stands for the modulus of the reflection coefficient of the termination without resistive material – i.e. only the slit. One can observe that the termination becomes anechoic only above 1400 Hz. With the wire mesh (blue curve), the reflection coefficient is better in low frequencies, but the reflection coefficient only becomes lower than 20% beyond 700 Hz. Because the resistance of the wire mesh is lower than the one suggested by the standard – i.e. a resistance around 400 Rayls MKS – we added a layer of absorbent material (green curve). Unfortunately, the reflection coefficient remains almost the same in low frequencies.

In order to improve this kind of termination, that is a full-flow termination, a model was established on another type of gradual opening: a termination designed with perforations, a configuration easier to model.

4.3 Model of the termination with perforations

The principle of termination with perforations is described on Figure 6. A first part of length L_{in} without hole allows the assembly with the impedance sensor. The second part is composed with N segments of constant length ΔL each containing a hole of variable diameter. The total length of the termination is L_t.

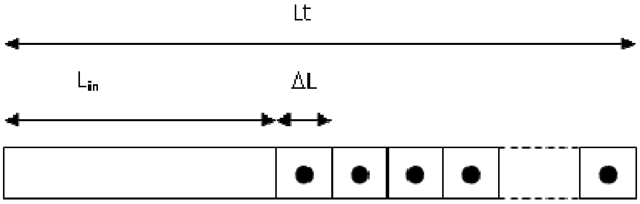

Figure 6 Sketch of the termination with perforations

The transfer matrix formalism in the frequency domain is used to model the behaviour of this system. See for example reference [5].

The Figure 7 shows an electroacoustic representation of the system: the termination is seen as a transfer matrix [MAT] closed by a radiation impedance Z_r. The variables (P_e,U_e) and (P_s,U_s) are the pressure and the flow rate respectively at the inlet and at the outlet of the termination.

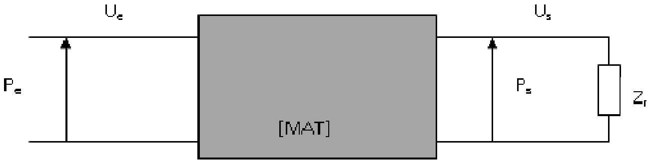

Figure 7 An electroacoustic representation of the termination with perforations

The matrix [MAT] is the product of the matrices of all elements in series, i.e. first the transfer matrix of the duct without hole of length L_{in} [Duct_L_{in}] and the transfer matrixes of each part with hole $[SEG]_i$:

$$[MAT]=[Duct\_L_{in}].\prod_{i=1}^{N}[SEG]_i \qquad [2]$$

The transfer matrix of a cylinder of cross-section S and length l is as follows [5]:

$$[Duct\_l]=\begin{bmatrix}\cos(kl) & jZ_c\sin(kl)\\ \frac{j}{Z_c}\sin(kl) & \cos(kl)\end{bmatrix} \qquad [3]$$

Where $Z_c=\rho c/S$ is the characteristic impedance of the pipe.

The transfer matrix of each segment with hole can be composed as the product of the transfer matrix of a cylinder of length ΔL with the transfer matrix of the hole only (that have no length):

$$[SEG]_i=[Duct\_\Delta L]\cdot[Mhole]_i \qquad [4]$$

According to reference [5], the transfer matrix of the hole is:

$$[Mtrou]_i=\begin{bmatrix}1 & 0\\ Y_t & 1\end{bmatrix} \qquad [5]$$

Where $Y_t=1/Z_t$ is the admittance of the hole.

4.4 Termination with 80cm perforated length

With the aid of the model, we defined a termination of a perforated length of 80cm. It is composed of 80 segments of length 10 mm with holes diameters varying linearly from 0.2 to 10 mm. In practice, the 10 first holes have a diameter of 1mm and the next four segments have a hole of 0.5 diameter largest than the previous ones, and that up to the hole of diameter 10mm.

The results obtained with the impedance sensor are displayed on Figure 8.

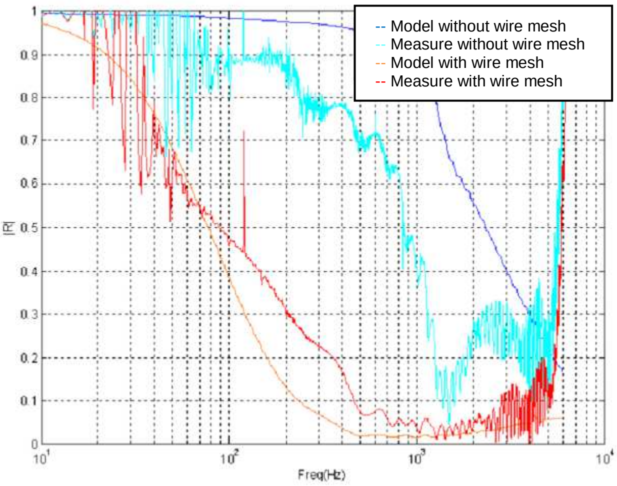

Figure 8 Reflection coefficient of the 80 cm perforated termination

The two configuration – with and without wire mesh - are presented and for each case the model is compared with the measurements. One can observes first, that the behaviour is correctly predicted by the model. The differences observed can be attributed to the fact that the first holes of 1mm diameter are too small compared with the mesh size of the resistive material. Indeed, the model assumes implicitely a hole size far more larger than the mesh size in front of it. For the configuration without wire mesh, the model predicts roughly the behaviour but with wire mesh, the model is more accurate.

Nevertheless, the reached performances are interesting as the reflection coefficient becomes now lower than 20% beyond about 350 Hz.

4.5 Influence of the first and last holes

Because one of the aims is to reduce the size of the overall termination, the model predicts that the performances are identical if the first and last holes are plugged. Thus a configuration, where the holes of a diameter lower than 3.5 mm and larger than 9mm are closed, is tested. In the model, the plugged segments are replaced by a cylinder of equal length but without perforation.

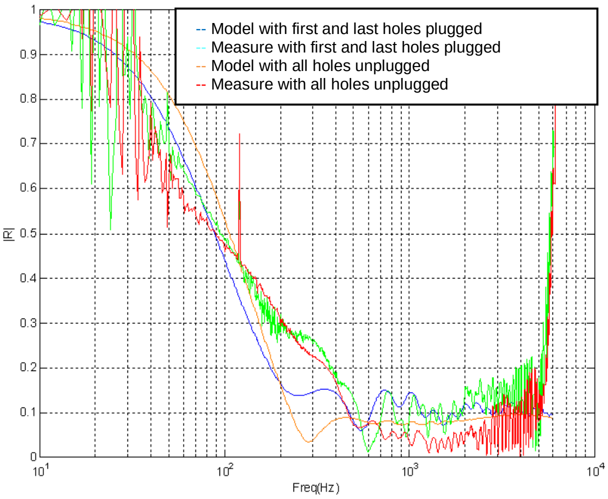

Figure 9 Reflection coefficient of the 80 cm perforated termination with first and last perforations plugged

Actually, the Figure 9 shows that the first and last perforations have a little impact on the previous performances.

Lastly, as the last part of the termination with plugged holes is not useful, the last configuration tested corresponds to the one where the last section is cut (Figure 10).

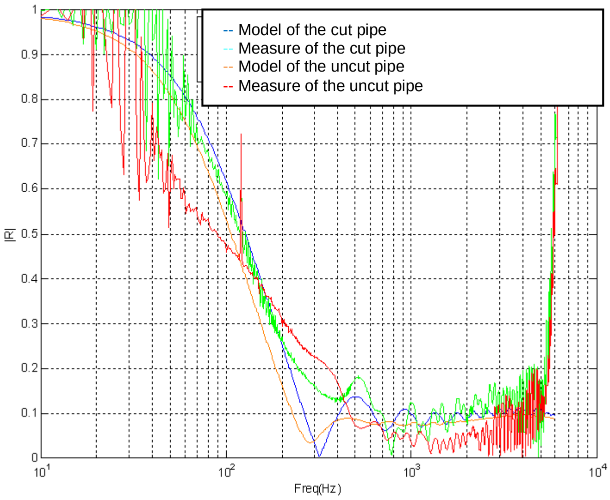

Figure 10 Reflection coefficient of the 80 cm perforated termination with first perforations plugged and last part cut

These lasts results show that the cut configuration is better than the uncut one: the measured reflection coefficient reaches 20% towards 240 Hz.

Finally, 38 cm were earned on the initial 80 cm termination with perforations, which is a reduction of almost the half of the original length with almost the same performances.

4.6 Effect of the segmentation

Since the model gives satisfactory results, one effect is analytically tested. This effect is linked to the length of each segment ΔL or the number of segments that the termination contains. Indeed, the maximal length of the segment is equal to around the half wavelength of the highest frequency observed. For a 35mm diameter duct, the cut-off frequency in normal conditions is about 5800 Hz and the corresponding half wavelength is about 30mm.
The Figure 11 shows the effect of the segmentation on a perforated termination of 1m length (33 segments for one meter correspond to a unit length of about 30mm). The resistance used in this simulation was 230 Rayls MKS, the diameters are in the range 4 – 10 mm in a linear progression. For 10 segments (blue curve), several peaks occur and their position correspond to the multiple of the half wavelength. Below the first peak the reflection coefficient is fairly high (around 40%). For 33 segments (green curve), only one peak appears at the end of the frequency range, and the reflection coefficient obtained is the best (below 20% from 100 Hz). Finally, for a large number of segments (100 – red curve), no peak appears but the performance in low frequency is worse.

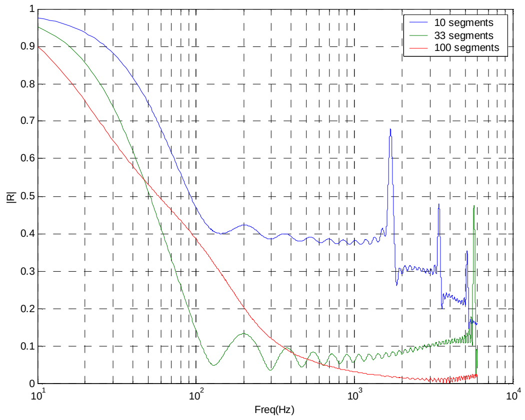

Figure 11 Effect of the segmentation on a perforated termination of 1m length

4.7 Effect of the resistance value

A last parameter is analytically tested: the resistance value of the resistive material placed in front of the hole. For this simulation, the length of the termination is 1m for 40 segments and the diameters are also in the range 4 – 10 mm in a linear progression (Figure 12).

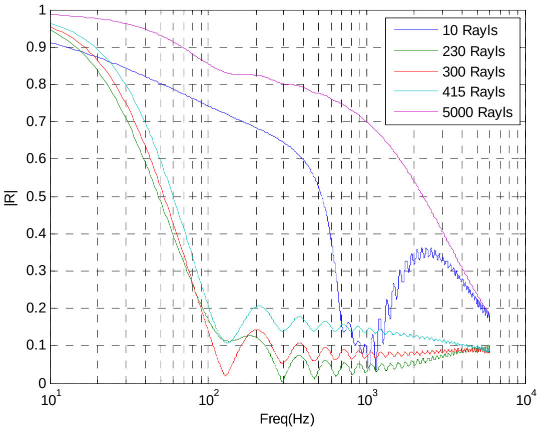

Figure 12 Effect of the resistance on a perforated termination of 1m length

A too small value of resistance (blue curve) or a too large value (purple curve) lead to a behaviour of a tube with perforations respectively unplugged and plugged. For a resistance of 230 Rayls (green curve) – i.e. the same value as the wire mesh – the result obtained seems better than the one obtained for 415 Rayls (light blue curve) – i.e. the value recommended value by the standard [1]. An optimum seems to be reached for 300 Rayls (red curve).

4.8 An optimum perforated termination

This analytical study allows to highlight the main geometric parameters:

- The perforated area length determines the anechoic performance in low frequency: for about 1m, the reflection coefficient is below 20% from 100 Hz;
- It is not relevant to begin with small holes or ending with big ones: a diameter range of 4 to 10 mm seems to be sufficient;
- The number of segments must be sufficient in regards with the segmentation effect;
- The resistance value of the resistive layer must be in the order of 300 Rayls.

With these considerations, we define an optimal configuration for which a reflection coefficient of 20% is required at 100 Hz. The geometrical parameters are as follows: a perforated length of 1m, 40 segments (ΔL=25mm), diameters holes from 4 to 10mm in a linear progression. The results are displayed on Figure 13. Experimentally, the reflection coefficient is moved towards high frequency and a value above 20% is obtained only beyond 170 Hz.
This behaviour is perhaps due to an effective value of resistance seen by the holes lower than expected. This might also be due to the weakness of the model.

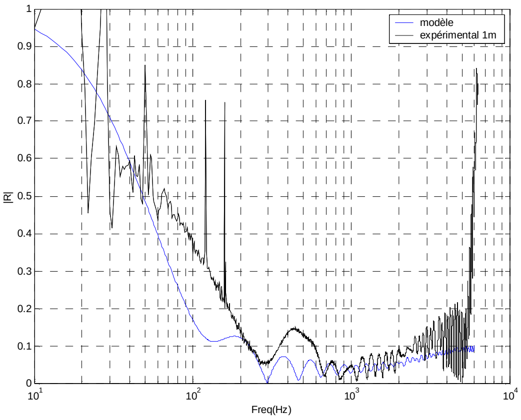

Figure 13 Reflection coefficient of an optimal perforated termination

4.9 Conclusion

This part was dedicated to the optimisation of a full-flow termination which principle is the use of a perforated tube covered by a resistive layer. A simple analytical model yield to define the main geometrical parameters and the results obtained are better than those we can achieve by the recommendations of the standard [1] for a gradual slit termination.

5. The resistive termination

5.1 Introduction: change of media

If we consider the propagation of an acoustic wave inside an open duct of cross-section S, at the end, the wave is reflected in low frequencies (see § 3.1) and partially transmitted for high frequencies (Figure 14). This phenomenon is linked to the change of impedance between the inside $Z_c = \rho c / S$ and the outside $Z_{air} = \rho c$.

In that configuration the reflection coefficient is:

$$R = \frac{Z_{air} - Z_c}{Z_{air} + Z_c} \qquad [6]$$

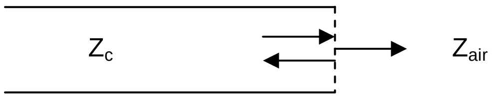

Figure 14 Change of media at the end of a duct

As a consequence, the relation **Erreur ! Source du renvoi introuvable.** shows that the reflection coefficient is null when the two impedances are identical. In other words, an anechoic termination is efficient when the interface impedance is close to the characteristic impedance of the duct.

5.2 The first conception

In 1989, Dalmont & al. [6] applied this principle where the main difficulty at that time was to realize the resistive layer required for the termination. This was achieved with a microchannel plate, i.e. with open capillary tubes:

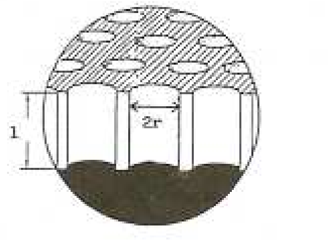

Figure 15 Microchannel plate

Because the microchannel plate supplied had a resistance value of 1600 Rayls, a coupling adapter was defined to keep constant the characteristic impedance of the main tube. The principle was to set up the plate into a larger duct:

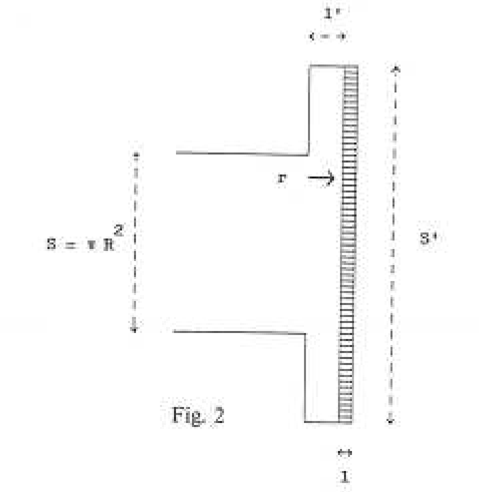

Figure 16 The coupling adapter

The input impedance of the coupling adapter can be represented by the following electrical equivalent circuit:

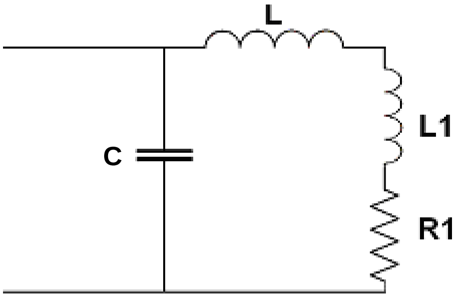

Figure 17 Electrical equivalent circuit of the input impedance of the cavity

The capacity $C=V/\rho c^2$ stands for the compressibility of the volume and the inductance L represents the inertial part linked to the cross-section change. The terms L1 et R1 are respectively the radiation inertia and the resistance of the multichannel plate.
The previous equivalent circuit is simplified in the following way:

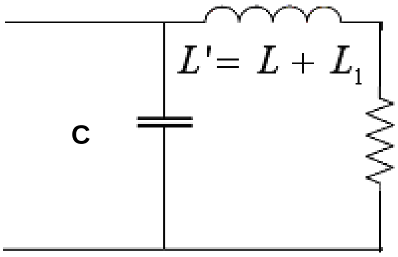

Figure 18 Simplification of the equivalent circuit

In low frequencies, for a well-chosen value of volume so that $L'/C=Z_c^2$, the circuit L'C is equivalent to an added length of duct. In this situation, the behaviour of the termination is like the one of a duct slightly longer and closed by a resistance, where the radiation inertia term is eliminated.

With this first conception, a reflection coefficient below 5% was obtained above 2000 Hz. The main drawback was the cost of the multichannel plate.

5.3 The actual set-up

The set-up used in 1989 is reused by replacing the microchannel plate with the wire mesh pinched between two stiffeners. The volume of the cavity is adjusted by screwing or unscrewing the upper part of the device. The device is simply placed at the end of the duct (Figure 19).

Figure 19 The coupling adapter

In order to avoid an impedance discontinuity between the main duct and the adapter, the inner diameters must match. For the present case, the inner diameter is 35mm.

In order to keep constant the characteristic impedance between the main duct and the cavity, the resistance value must be adjusted. Because the diameter of the present cavity is 68mm, the cross-section ratio is equal to 3.8 and therefore, the resistance of the resistive layer must be multiplied by the same value. Since the impedance of air in normal condition is about 415 Rayls inside the pipe, the resistance of the layer must be around 1570 Rayls. Therefore, 7 layers of the wire mesh were stacked between the two stiffeners.

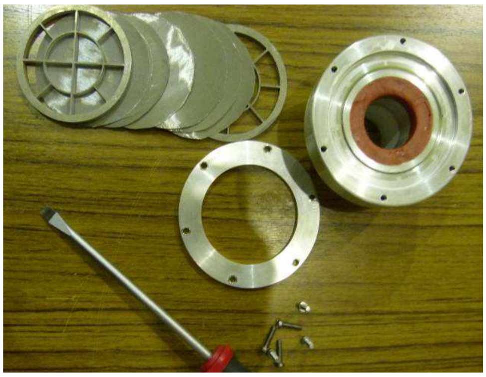

Figure 20 The coupling adapter open

5.4 Adjustment of the volume cavity

First, the volume of the cavity is adjusted to treat the problem of radiation. This is done by simply screw or unscrew the device and perform a measurement. As we can see on Figure 21, three configurations were tested: the maximum volume (black curve), the minimum volume (blue curve) and the optimum volume (green curve) obtained by test when the reflection coefficient is the lowest.

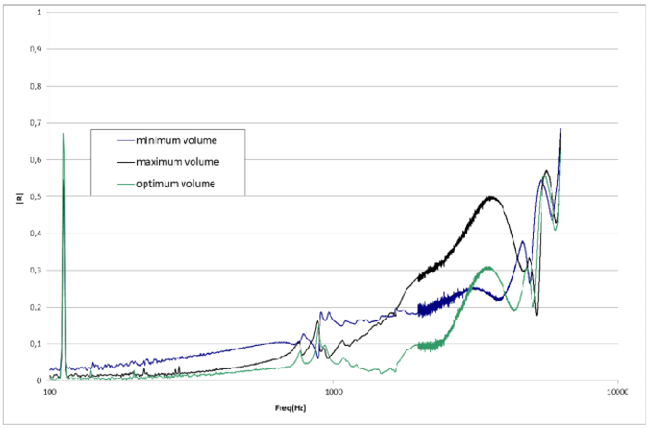

Figure 21 Adjustement of the volume cavity

For this optimum configuration, 7 layers of wire mesh are used and **the reflection coefficient is null up to 500 Hz** and lower than 10% up to 2000 Hz. Beyond 2000 Hz, one can note a strong increase of the coefficient. The oscillation observed at 1000 Hz is certainly due to an unsufficient stiffening of the resistive layers and the peak at 110 Hz is likely due to an acquisition problem.

5.5 Effect of the resistance

Lastly, we tested the influence of 6, 7 and 8 layers (Figure 22). It is clear than the use of 7 layers is the optimum configuration. Compared with the results of 1989, the reflection coefficient is lower and the oscillations are moved from 1000 Hz to 2000 Hz.

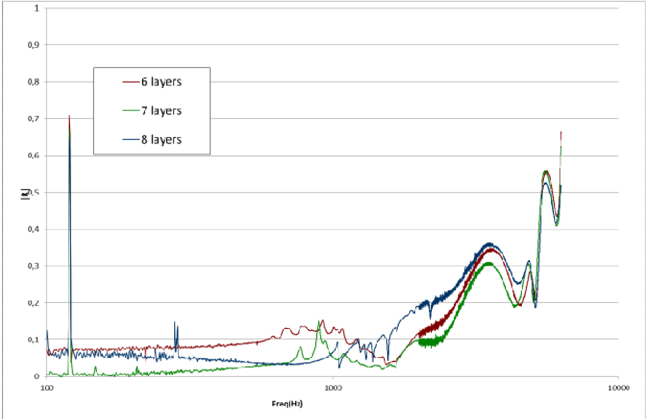

Figure 22 Influence of the number of resistive layers

6. Conclusion and perspectives

In the first part of this paper, we discuss the fair performances of a full-flow termination with a gradual slit covered with a resistive layer which preconisations are given in the standard ISO 5136 [1]. Indeed this termination seems not to be the result of a rigorous optimization. For this reason we decided to make an optimization on a perforated termination type easy to model and to realize. The experimental results are somewhat worse than the predicted ones but far better than the results obtained with a gradual slit. The main parameters are highlighted such as the length of the termination, the size of the perforations, the number and the length of the segments and lastly the resistance of the layer in front of the holes. In function of the application, the model can predict quickly and easily the best compromise. As an illustration, a reflection coefficient lower than 20% from 170 Hz is achieved with a termination of 1m.

Some tests must now be performed with flow at several flow rates. Furthermore, for some applications for automotive industries, terminations are now required for test benches with hot gas and high pressure (turbocharger test facility for example). For testing theses conditions, the termination must be closed by a volume that will change the actual performances of the present termination. Extended experiments are foreseen.

In the second part of this study a solution known in the literature [6] is investigated. The expensive plate of the original setup is replaced by a metallic wire mesh. Results are in accordance with that of the literature [6] and even slightly better. A null reflection coefficient is obtained up to 500 Hz and lower than 10% up to 2000 Hz. After this frequency the values strongly increase. However, for this termination, the stiffness of the resistive layers must be improved in order to avoid oscillations in the reflection coefficient in medium frequencies.

An interesting perspective for this kind of termination consists in coupling the two concepts for a hybrid solution: the medium and high frequencies would be treated by a perforated termination, which would be ended by the resistive termination for the low frequencies.

7. References

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