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Optimisation of anechoic duct termination using line theory

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ABSTRACT

Anechoic terminations are often required for in-duct measurement. Various solutions have been proposed but rarely an optimisation process is proposed. In the present paper we show how to design and optimize an anechoic termination with perforated holes covered by a tissue of known acoustic resistance. From line theory some rules allowing the optimisation are derived. Experiments show that terminations performance can be predicted with a good accuracy leading to efficient solutions with slim dimensions.

1. Introduction

Acoustic characterization of elements - such as exhausts, filters and flexible pipes - 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. In the absence of flow, traditionally, absorbing materials with the shape of a cone are placed at the end of the duct. This is most often done empirically and the anechoicity is not always controlled. Another solution is the use of calibrated acoustic resistance at the end of the duct as proposed in [1]. An example of application is given in [2]. A solution to be mentioned is also the uses of a long tube [3]. In the presence of flow, some kinds of horns have been designed, leading to efficient but bulky solutions [4,5]. Otherwise a perforated duct covered by a tissue is used. To date, little studies have been performed on the subject and while a standard [6] exists, that governs the conception of some terminations, 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 the present paper we focus on the design of an anechoic termination made with a perforated tube covered by a metallic tissue, i.e. a wiremesh, of calibrated resistivity. We first consider the example of a long tube and that of a tube with a slot of constant width covered by a resistive tissue. These two cases are modelled with the transmission line theory which allows us to derive two simple rules allowing the optimization of the termination. Then, it is shown that the solution can be shortened by using a slot of variable width. Finally, it is shown that the slot can be advantageously be replaced by perforated holes leading to the same result at low frequencies. In order to validate our approach, a termination is realised and measured showing that the reflection coefficient of such a termination can be accurately calculated.

2. Basis

A uniform line can be described by its local characteristics, the series impedance per unit length $\overline{Z}$ and the parallel admittance per unit length $\overline{Y}$. From these quantities the characteristic impedance Z_c and the propagation constant Γ are simply derived:

$$Z_c = \sqrt{\overline{Z}/\overline{Y}} \text{ and } \Gamma = \sqrt{\overline{Z}\overline{Y}}. \tag{1}$$

When such a line of length L is placed at the end of a duct which characteristic impedance is $Z_{c0} \approx \rho c/S$ (ρ the air density, c the speed of sound in air and S the tube cross section), waves coming from the main line are partly reflected at the discontinuity and partly propagate in the line, at the end of which it is reflected (see Fig. 1). So, it can be shown that global reflection coefficient is given by:

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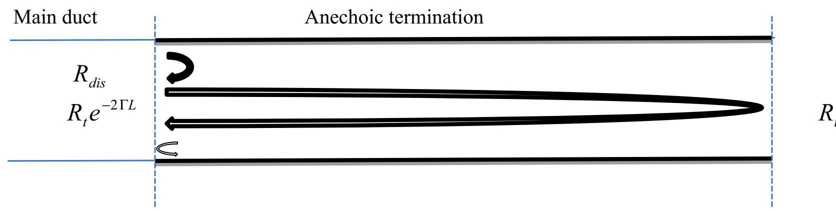

Fig. 1. Scheme of the reflections at the discontinuity and at the end of the termination.

$$R = \frac{R_{dis} + R_t e^{-2\Gamma L}}{1 + R_{dis} R_t e^{-2\Gamma L}} \tag{2}$$

with $R_t = \frac{Z_t - Z_c}{Z_t + Z_c}$ the reflection coefficient at the end of the line (Z_t the impedance at the end of the termination) and $R_{dis} = \frac{Z_c - Z_{c0}}{Z_c + Z_{c0}}$ the reflection coefficient due to the change of characteristic impedance at the junction.

In order to realize an anechoic termination, the objective is to obtain the lowest possible reflection coefficient, or, at least, lower than a given value ε, i.e. $|R| < \varepsilon$. So two conditions are required:

- first, the impedance discontinuity at the junction shall be reduced:

$$|R_{dis}| < \varepsilon_{dis} \tag{3}$$

- second, the damping in the line $\alpha L = \text{Re}(\Gamma L)$, shall be large enough:

$$|R_t| e^{-2\alpha L} < \varepsilon_\alpha. \tag{4}$$

As $|R_t| \leqslant 1$,

$$\alpha L > -\ln(\varepsilon_\alpha)/2 \tag{5}$$

is a sufficient condition for αL.

Globally,

$$\varepsilon_{dis} + \varepsilon_\alpha < \varepsilon \tag{6}$$

is a sufficient condition.

3. Long tube as an anechoic termination

A long pipe is a simple and efficient solution to realize an anechoic termination. For such a pipe the viscothermal losses are sufficient to cancel the wave reflected at the end. In that case, there is no impedance discontinuity since the long pipe has the same diameter as the main duct. The absorption coefficient α is accurately approximated by

$$\alpha = 3.0 \cdot 10^{-5} \sqrt{f}/r, \tag{7}$$

where f is the frequency in Hz and r the radius of the tube in meter. So it is easy to derive from Eq. (5) the minimum length of the tube for a given performance ε of the termination. To fix ideas, considering a tube of 35 mm diameter, to obtain a reflection coefficient lower than $\varepsilon = 0.2$ at 100 Hz, the length shall be 47 m. In practice, such a tube coiled does not take so much place and can be considered as a valuable solution. This is commonly used in capillary tubes. However, in presence of a significant mean flow, pressure losses become too important and another solution have to be found.

4. Tube with a slot covered by a resistive tissue

We consider here a tube with a slot of constant width covered by a resistive tissue of known acoustic resistivity *Res* (homogeneous to ρc) as shown in Fig. 2.

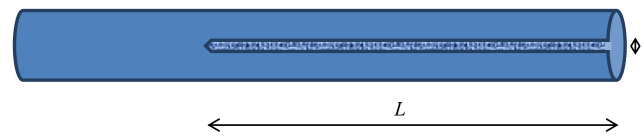

Fig. 2. Scheme of the termination made with a slot covered by a resistive tissue.

In that case, ignoring viscothermal losses in the tube, the series impedance per unit length $\overline{Z}$ and the parallel admittance per unit length $\overline{Y}$ are given by:

$$\overline{Z} = jkZ_{c0} \text{ and } \overline{Y} = jk/Z_{c0} + \overline{G} \tag{8}$$

with $k = \omega/c$, $Z_{c0} = \rho c/S$ the characteristic impedance of the tube of cross section S without the slot and $\overline{G} = e/Res$ the conductance per unit length of the tissue on the slot of width e.

So the characteristic impedance Z_c and the propagation constant Γ are:

$$Z_c = Z_{c0}/\sqrt{1 + \widetilde{G}/jk} \text{ and } \Gamma = jk\sqrt{1 + \widetilde{G}/jk} \tag{9}$$

with $\widetilde{G} = \overline{G} Z_{c0}$.

Considering $\widetilde{G}/k \ll 1$, it comes at first order:

$$\alpha = \text{Re}(\Gamma) \approx \widetilde{G}/2 \text{ and } |R_{dis}| = \left|\frac{Z_c - Z_{c0}}{Z_c + Z_{c0}}\right| \approx \widetilde{G}/4k. \tag{10}$$

It is important to notice that α tends to be constant which implies that the reflection coefficient will not tend to zero with frequency (unless viscothermal losses and radiation are considered).

To fix ideas, let set $\varepsilon_{dis} = \varepsilon_\alpha = 0.1$ at 100 Hz ($k = 1.85$ in standard conditions). This implies $\widetilde{G} = 0.74\ \text{m}^{-1}$ and $L > \ln(\varepsilon_\alpha)/2\alpha \approx$ 3 m which is still rather long.

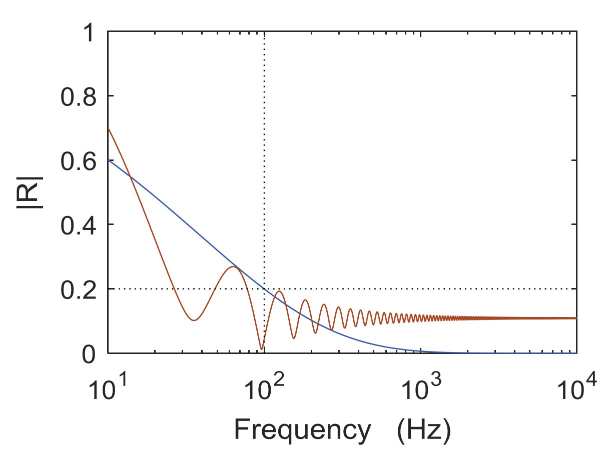

Fig. 3. Modulus of the reflection coefficient. Blue line: tube of 47 m (diameter 35 mm). Red line: tube with a 3 m long slot of constant width covered by a resistive tissue ($\widetilde{G} = 0.74\ \text{m}^{-1}$, viscothermal losses in the tube are ignored). Dotted line indicate the target: $|R| < 0.2$ for $f > 100$ Hz. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)