

Transmission loss of rectangular silencers using meso-porous and micro-perforated linings

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Summary

The transmission loss of a prototype rectangular shaped silencer is investigated, by measurement using a four-microphone method and comparing with simplified prediction models assuming locally reacting linings. Different cases with symmetrical linings of a glass wool type is tested, in particular the effect of transforming this material into a meso-perforated material, also called a double porosity material, is investigated. This transformation is performed either by drilling holes or cutting slits in the porous material. Furthermore, a single case of an unsymmetrical lining is tested, one side lined with a porous material, the other side being a resonator type of lining. For the symmetrical case, where the linings on opposite sides are identical, the effect of using a double porosity material with slits is reasonably well predicted, whereas the fit between measured and predicted results is less good in the other cases tested. However, the effect of transforming the homogenous material into a meso-porous one is generally positive.

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1. Introduction

The work here concerns the attenuation of sound in rectangular ducts with lining on two walls, see Fig. 1, and for the predicted results we shall only seek solutions for the least attenuated mode, which normally gives a conservative estimate of the attenuation. Two cases will be treated, the first when the lining on the two walls are identical, the other case when the linings have different properties, i.e. the normal input impedances are different for the two walls. The basic type of lining used here is mineral wool, glass wool of relatively high density. The effect of transforming this material into a meso-perforated material, also called a double porosity material, is investigated, i.e. by drilling holes or cutting slits in the mineral wool. The basic theory for calculating the acoustic properties of such materials is presented below. For unsymmetrical linings, only one case is treated, a porous lining on one side and a resonator type of lining on the other side in the form of a micro-perforated plate backed by an air cavity. We shall further assume that the linings on the walls are locally reacting, i.e. we assume that there is no sound propagation along the duct inside the lining itself. This implies that, especially in the case of the resonator type of lining, the cavity

behind the plate must be subdivided in the x -direction to minimize flanking transmission in the cavity.

Measurement results on a prototype silencer are presented in Section 4, using the set-up described in Section 3. As far as possible the measurement results are compared with predicted results.

2. Theory

The theory outlined below firstly treats the simple case of a rectangular type of silencer with the same type of porous material lining the two walls. As indicated on Fig. 1, the porous material is in practice covered by a fabric or a perforated plate. The effect of such coverings is evaluated by using models for these coverings to calculate the input impedance added to the impedance of the porous lining. This is not given here as all measurements are performed primarily to evaluate the effect of modifying the porous linings. Modifying the porous material is primarily performed by making a double porosity material by drilling holes or cutting slits in lining material. The modeling of such a material is given in Section 2.1.1.

Finally, Section 2.2 treats the general case of an asymmetrical lining, further specializing to the case of a porous material on one side and a resonator type on the other side.

2.1 Rectangular duct with identical lining on two walls

With the assumptions given above and furthermore that the sound field in any cross section is the same in the z -direction, the equation for the complex wave number k_y in the crosswise direction may be written, see e.g. Frommhold and Mechel [1],

$$(k_y \cdot h) \cdot \operatorname{tg}(k_y \cdot h) = j \cdot k_0 \cdot h / Z_{n0} = j \cdot U, \quad (1)$$

where $2 \cdot h$ is the width (or depth) of the air channel and Z_{n0} is the normalised input impedance of the lining at normal incidence (zero degree incidence angle). Eq. (1) follows from the more general case of unsymmetrical linings treated in Section 2.2, setting the input impedances equal. Solving this equation for k_y we may from the total wave number k_0 find the complex wave number k_x in the direction of flow. For the latter, which will give us the attenuation, we may write

$$k_x = \operatorname{Re}\{k_x\} + j \cdot \operatorname{Im}\{k_x\} = \sqrt{k_0^2 - k_y^2}, \quad (2)$$

where $\operatorname{Re}\{\}$ and $\operatorname{Im}\{\}$ signify the real and imaginary part of the wave number. The attenuation for a length ℓ of duct is then given by

$$\Delta L = 20 \lg(e) \cdot \operatorname{Im}\{k_x\} \cdot \ell \quad (\text{dB}). \quad (3)$$

By using an expansion of the left-hand side by a so-called method of continued fractions, reference [1] cites polynomial approximations of the Eq. (1) of various orders, of which we shall use a quadratic one.

2.1.1 Linings of single and double porosity media

The lining material used in the symmetrical cases is, as mentioned above, a common glass wool type, either used in the normal way or made into a double porosity material by drilling holes or cutting out slits of the material. In all calculations it is assumed that the frame of the material is rigid, which for example measurements of the absorption coefficients of samples clearly indicate is not the case, indicating frame resonances. However, the effects of changing the linings into a double porosity type are reasonably well predicted using the theoretical rigid type of models. In the case of the duct wall lined with a porous material of thickness d backed by hard wall, the normalized impedance to be used calculating the variable U ; see Eq. (1), is

$$Z_{n0} = Z_{an} \coth(\Gamma_a d) \quad (4)$$

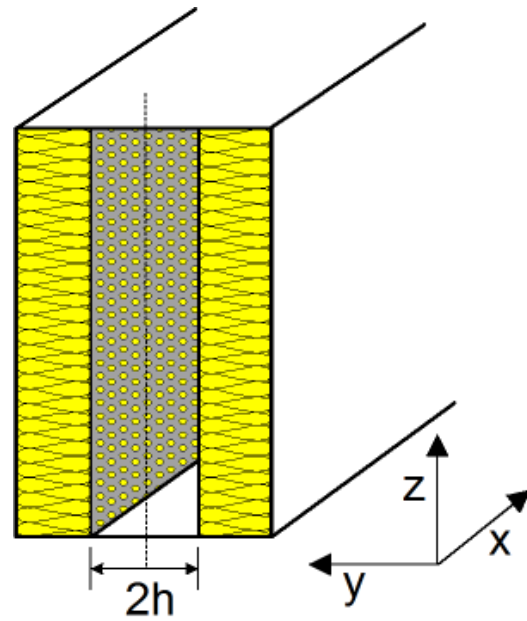


Figure 1. Rectangular duct silencer .

where Z_{an} and Γ_a are the normalized characteristic impedance and the propagation coefficient of the material, respectively. A number of different models for these variables exist in the literature, see e.g. Allard and Atalla [2], often expressed by the effective density ρ_{eff} and the bulk modulus K_{eff}

$$Z_a = \sqrt{\rho_{\text{eff}} \cdot K_{\text{eff}}} \quad \Gamma_a = j \cdot \omega \sqrt{\rho_{\text{eff}} / K_{\text{eff}}}, \quad (5)$$

Following Sgard et al. [3], we shall calculate the input impedance of the double porosity lining from Eq. (5), indicating the double porosity medium by using the index “dp” instead of “eff”. The effective density is then expressed by the dynamic permeability Π_{dp}

$$\rho_{\text{dp}} = \frac{\eta}{j \cdot \omega \cdot \Pi_{\text{dp}}}. \quad (6)$$

where η is the dynamic viscosity coefficient of the fluid in the pores (air). The dynamic permeability may be expressed as a sum being

$$\Pi_{\text{dp}} = (1 - \phi_p) \cdot \Pi_m + \Pi_p, \quad (7)$$

where Π_p represent the permeability of a fictive medium with a network of macro-pores, being e.g. holes or slits, where the micro-porous part is replaced by an impermeable medium. Here we shall use macro-pores in the form of long slits and expression for Π_p for such a case is given by Olny and Boutin [4]. Similarly, the expression for the

bulk modulus of the doubly porosity medium will be given by

$$K_{dp} = \left[\frac{1}{K_p} + (1 - \phi_p) \cdot \frac{F_d(\omega)}{K_m} \right]^{-1}, \quad (8)$$

where K_p the dynamic modulus of the fictive medium with macro-pores where the micro-porous part have been replaced by an impermeable medium and K_m is the modulus of the micro-porous medium. The function $F_d(\omega)$, is a frequency dependent function giving the ratio between the average pressure in the micro-porous domain to the pressure in the pores. In the work conducted here, determining the transmission loss of silencers using meso-porous material with slits, measurement results are compared with predictions using the expressions above, which assumes a porous material with a rigid frame. It should be pointed out that a model for a double porosity material with an elastic frame is proposed by Dazel et al. [5], adopting Biot theory to account for the frame deformation. This model is, however, not implemented here.

2.2 Rectangular duct with unsymmetrical lining

The “idea” behind lining a duct unsymmetrically, i.e. the input impedance is different on the two sides is, as cited by Mechel [6], “the anti-symmetrical mode is used, together with the symmetrical mode, to make up the sound field, and due to its higher attenuation it will increase the attenuation of the least attenuated mode in such ducts”.

For this unsymmetrical case, where the normalized input impedance Z_{n0} on the two sides is different, following Mechel [6], we get the characteristic equation

$$\begin{aligned} (z \cdot \cot(z) + j \cdot U_2) \cdot (z \cdot \tan(z) - j \cdot U_1) + \\ (z \cdot \cot(z) + j \cdot U_1) \cdot (z \cdot \tan(z) - j \cdot U_2) = 0 \end{aligned} \quad (9)$$

In the case of symmetrical lining, i.e. $U_1 = U_2$, we get the simpler Eq. (1). For the unsymmetrical case we shall use an approximate 4th order equation.

In our case, we shall be interested in a combination of silencer duct walls, one being lined with a porous material, the other being a micro perforated plate backed by an air cavity, i.e.

constituting a Helmholtz resonator to enhance the low frequency properties of the silencer.

In the case of the duct wall lined with a porous material of thickness d_1 backed by hard wall, the normalized impedance to be used calculating the variable U_1 is again by using Eq. (4). For the other duct wall the surface impedance will be a series combination of the impedance of the micro-perforated plate and an air filled cavity.

As for the micro-perforated plate, where we shall use the type with microslits; see e.g. Vigran and Pettersen [7], the normalized surface impedance to be applied is given by

$$(Z_{n0})_2 = \frac{1}{Z_0 \varepsilon} [Z' + j \rho_0 \omega (2\Delta t)] \quad (10)$$

where ε is the perforation rate of the plate, Z' is the impedance of the slit itself having a given width and Δt is the end correction of the slit in the plate of thickness t .

3. Measurement methods

The measuring method used here, which is further detailed below, is based on the ASTM measuring standard E 2611-09 [8], using the so-called two-load method.

The basic type of lining used here is mineral wool, glass wool of density approximately 40 kg/m³. The impedance and the absorption coefficient of this material, also perforated with holes or slits, are measured in a standing wave tube with a square cross section with side length 200 mm, which limits the measurement range upwards in frequency to approximately 850 Hz. Using the two-microphone method in ISO 10534-2 [9], the transfer function of sound pressure between the microphones was deduced from impulse response measurements using the WinMLSTM software, i.e. the impulse responses for the loudspeaker detected at each microphone feeding the loudspeaker with a swept-sine signal.

3.1 Transmission loss

The applied method, given in the ASTM-standard [8], is primarily intended for determining sound transmission of acoustical materials using the transfer matrix method but may equally well be adapted for transmission loss of silencers.

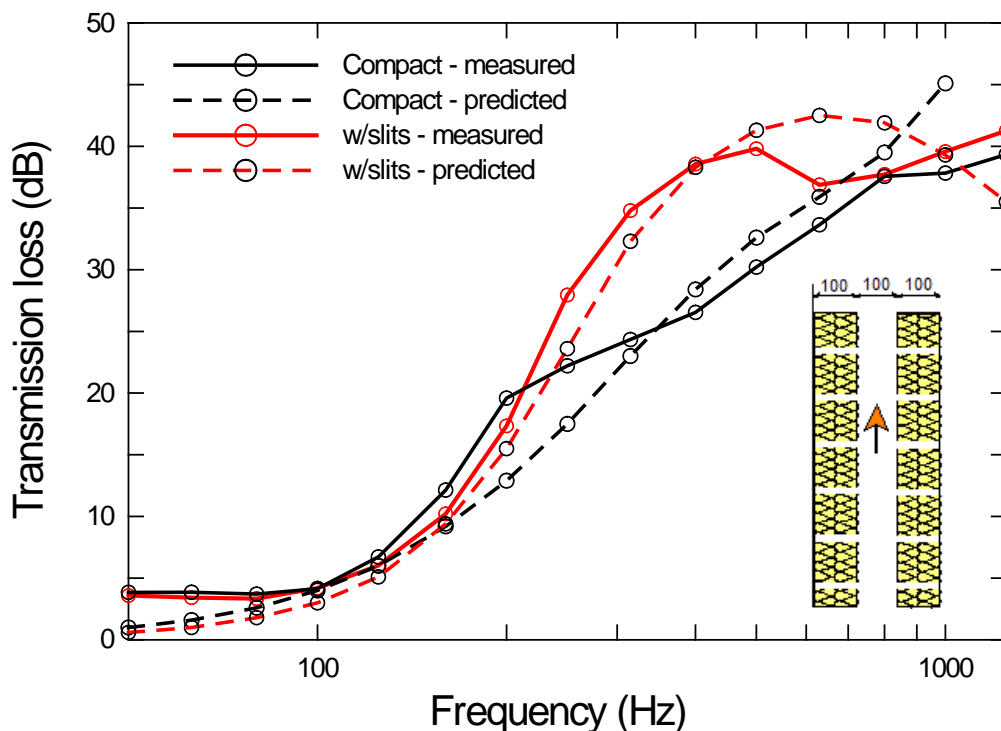


Figure 2. Measured and predicted transmission loss making slits in the porous material. The width of the slits is approximately 25 mm wide giving an effective perforation rate of 10%

The silencer is made by wooden plates, having a length of one meter and placed between two cylindrical plastic tubes of inner diameter 185 mm, each having a length of 2.5 meter. The rectangular free air channel of the silencer, having dimension 100 mm x 280 mm, is connected to the tubes by steel transfer pieces of length 320 mm.

Details concerning the set-up, the formulas used and the measurement equipment are given by Vigran [10] and are not repeated here as the only difference is the type of tubes used. In the latter reference the transmission loss of perforated plates in a tube of uniform square cross section 200 mm x 200 mm were measured.

4. Results and discussion

The primary goal of the investigation on the silencer transmission loss is, for the symmetrical cases, to see the effect of making the porous absorber material into a double porosity one, either by making holes or slits in the material. For the unsymmetrical case, the effect of using a Helmholtz type of resonator on one side and a porous material on the other side is investigated.

It is well known that the primary effect of making a porous material into a double porosity one is to increase the absorption in a certain frequency band, at the same time decreasing the absorption particularly in the low frequency range.

4.1 Transmission loss. Symmetrical case

An example on the measured and predicted transmission loss using the porous material with slits is shown in Figure 2. The slits are indicated on the insert sketch giving an effective perforation rate in this case of approximately 10%. As pointed out above the porous material should better be modelled with a flexible frame but here only a fixed set of parameters are used for a rigid frame model, giving a reasonable fit to the measured data for the non-perforated case. Of primary importance here is the effect of making the slits and this effect is reasonably well predicted.

4.2 Transmission loss. Unsymmetrical cases

Two cases of results on the transmission loss are shown in Figure 3. As indicated on the insert sketch, one side is lined with the porous material backed by 50 mm airspace, the material being

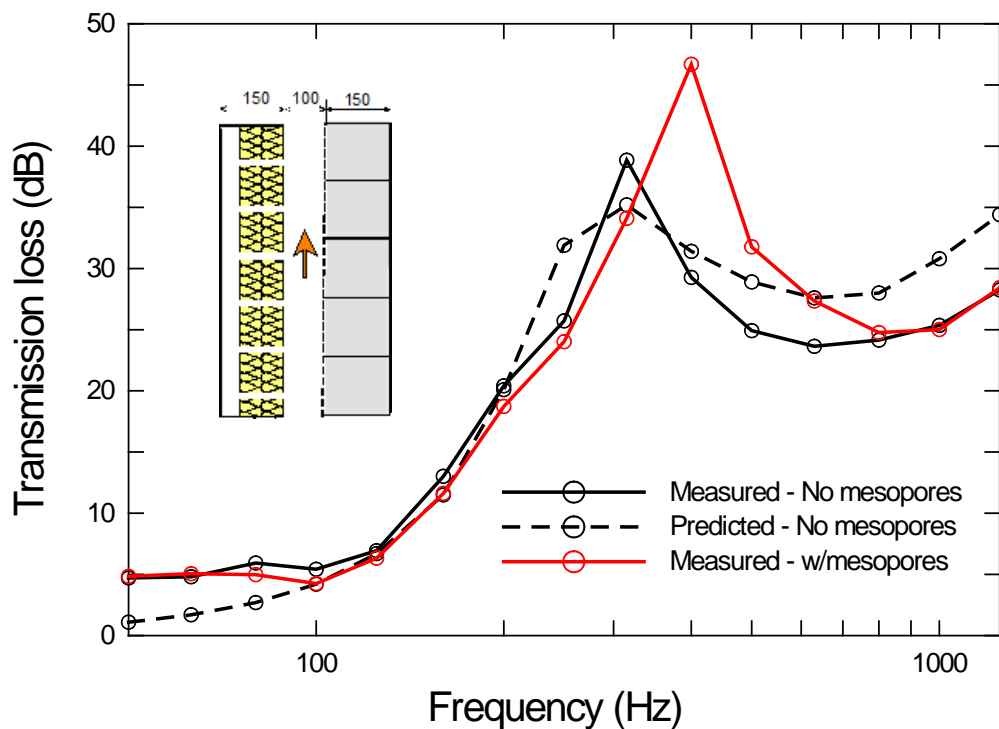


Figure 3. Measured and predicted transmission loss for an unsymmetrical silencer, one side lined with porous material, the other being a Helmholtz resonator with a micro-slit plate in front of an air-space. The measured effect of making one side meso-porous is also shown.

either compact or meso-porous with slits as in Figure 2, the other lined as specified above. The predicted transmission loss, the porous material being compact, reasonably follows the general trend of the measurement data. The increase in the transmission loss making slits in the porous material is quite large in some frequency bands. No predicted results is shown for the latter case as the modelling for this case, porous material with slits combined with an airspace, is not clear.

5. Conclusions

The common type of silencers for ventilation systems are based on using various types of porous material. Here, the effect of making the material into a double porosity one, making holes or slits in the material is tested on a prototype rectangular silencer. For the symmetrical case, where the linings on opposite sides are identical, the effect of using a double porosity material with slits is reasonably well predicted. For a case using holes in the porous material, the predicted transmission loss is higher than the measured result. In this case, however, an airspace of 50 mm is added behind the porous material, probably violating the overall assumption that the lining is locally reacting. For the unsymmetrical case, with a compact porous lining on one side and a

Helmholtz type of resonator on the other side, the general trend for the transmission loss is reasonably well predicted. Using a meso-perforated material on one side is enhancing the transmission loss in an octave-band range.

All measurements are performed without any fabric in front of the porous material, which certainly is needed in practice. Optimisation tools for designing a suitable double porosity material also including such a fabric should be the next step in the work.

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