SOUND ABSORPTION CHARACTERISTICS OF A SINGLE MICROPERFORATED PANEL ABSORBER BACKED BY A POROUS ABSORBENT LAYER

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A microperforated panel (MPP) is usually used with an air-back cavity backed by a rigid wall to form a Helmholtz-type resonance absorber. In the case of a common perforated panel with larger perforations, a porous absorbent is usually located behind the panel to add acoustic resistance for efficient sound absorption. In the case of an MPP, if a porous layer is inserted in the cavity, the absorption may be deteriorated by the large acoustic resistance due to the porous absorbent. However, if the resistance is suitably adjusted, it is expected that a porous layer can widen the absorption frequency range by the additional damping by the porous absorbent. In this study, a single-leaf MPP absorber backed by a rigid-back wall with a porous absorbent layer in the cavity is analysed using an electro-acoustical equivalent circuit model and its absorption characteristics are discussed through the numerical examples.

INTRODUCTION

A microperforated panel (MPP) was proposed by Maa [1-4] as a 'next-generation' alternative for porous sound absorbers which has various problems in health, sanitary and environmental aspects. Many studies have since been performed on MPPs [5-8]. The basic form of an MPP absorber is composed of an MPP and a rigid-back wall with an air-back cavity in-between. The microperforations and the air cavity form Helmholtz-type resonators. Comparing an MPP absorber with the traditional Helmholtz resonators and perforated panels (with larger perforations), MPP absorbers with microperforations in a very thin panel realise the optimal acoustic resistance and reactance. This results in a relatively wide sound absorption frequency range of around 2 octaves [9-11]. However, even though the sound absorption frequency range is much wider than usual resonance-type absorber, MPPs are still frequency-selective absorbers and no absorption can be expected except for the resonance frequency range.

Considering these circumstances, the authors have been trying various attempts to make more wideband sound absorbers with MPPs [12-16]. These methods, however, have shortcomings. For example, using more leaves than single absorbers, the system becomes more complex. Therefore, if it is possible to obtain a wider absorption frequency range with a simple method, it will be more efficient both in cost and practical aspects.

In this study, the effect of a porous material inserted in the back cavity of an MPP sound absorber is investigated. In the case of a common perforated panel with larger perforations, the acoustic resistance of the perforation is very low. Therefore, in order to add resistance and to obtain higher sound absorption, it is common practice to place a porous layer behind a perforated panel [17] (with larger perforation which is commonly used in room interior surfaces). On the contrary, in the case of an MPP, the acoustic resistance and reactance are in general already optimised. Therefore, additional resistance due to the porous layer may cause a too large resistance resulting in lower sound absorption. Furthermore, the resonance system may be damped by the additional resistance due to porous layer, and resonance-type absorption can be deteriorated. Porous-layer backed perforated panels have been investigated by many previous authors. Mechel [18, 19] studied porous-backed perforated panels in details, however the perforation considered in his studies is much larger than that of an MPP (which is typically of diameter and thickness less than 1 mm). The acoustic properties and behaviour of a typical perforated panel and an MPP are substantially different.

In the case of an MPP, the effect of the acoustic resistance on the peak absorption appears rather soft, and the optimal value is not very critical [13]. In other words, when the parameters are chosen properly, additional acoustic resistance by the porous layer can make the absorption frequency range broader without deteriorating the peak absorption.

An MPP is originally proposed as a substituting material for porous absorbers, it may seem a contradiction to use a porous layer in MPP absorption systems. However, new-type porous absorbents with sanitary and environmentally superior properties have been recently proposed [20]. In addition, in many cases using a porous layer behind an MPP does not deteriorate the advantageous design of MPPs. Therefore, using a porous layer behind an MPP can be considered to be one of the possible alternatives for improving the sound absorption performance of MPP sound absorption structures.

In this study, the case of the most basic form of an MPP absorber corresponding to a single-leaf MPP backed by a cavity and a rigid wall, with a porous layer inserted in the cavity, is analysed using a electro-acoustical equivalent circuit model.

As a preliminary study, the effect of an end-correction of the open ends of the perforations is initially investigated. Mechel's work gives a physical insight into this problem for a typical traditional perforation panel [18, 19]. However, his work is not applicable for MPP cases. Therefore, the end-correction for an MPP backed by a porous layer is derived using traditional theory [21]. The sound absorption characteristics of the porous-backed MPP and the possibility of wideband sound absorption are discussed through numerical examples.

BASIC ELECTRO-ACOUSTICAL EQUIVALENT CIRCUIT ANALYSIS: MAA'S THEORY

Figure 1 shows the model of a single-leaf MPP sound absorber backed by a rigid wall and a back-cavity filled with porous absorbent in-between. The figure also shows its electro-acoustical equivalent circuit model. The MPP has the following parameters: thickness *t*, hole diameter *d*, perforation ratio *p*. The depth of the back-cavity is *D*. The normal incidence of a plane sound wave of unit amplitude is assumed.

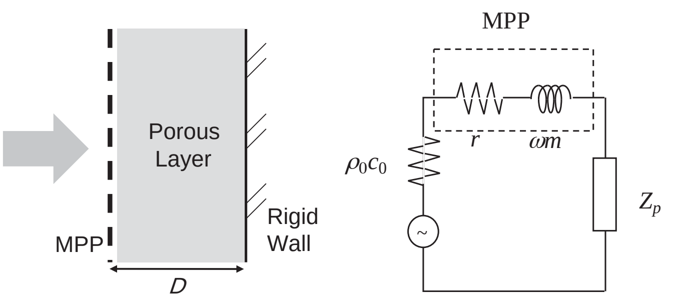

Figure 1. Geometry of a porous layer-backed single MPP absorber (left) and its electro-acoustical equivalent circuit model (right)

The specific acoustic impedance of the MPP, $Z_{mpp} = r - i\omega m$, is derived by the following formulae proposed by Maa [2]. These impedances are normalised to the air impedance $\rho_0 c_0$.

$$r = \frac{32\eta t}{p\rho_0 c_0 d^2}\left(\sqrt{1+\frac{K^2}{32}}+\frac{\sqrt{2}}{32}K\frac{d}{t}\right) \quad (1)$$

$$\omega m = \frac{\omega t}{\rho c_0}\left(1+\frac{1}{\sqrt{9+\frac{K^2}{2}}}+0.85\frac{d}{t}\right) \quad (2)$$

where

$$K = d\sqrt{\frac{\omega\rho_0}{4\eta}} \quad (3)$$

ρ_0 is the air density, c_0 is the sound speed in air, ω is the angular frequency, η is the viscosity of the air (1.789×10^{-5}[Pa.s]).

The impedance of the back-cavity with the depth D is given by the following formula with the propagation constant γ (Note that, in the case of air back-cavity, $\gamma = -ik_0$ with $k_0 = \omega/c_0$, and $Z_a = \rho_0 c_0$):

$$Z_p = Z_a \coth \gamma D \quad (4)$$

From these impedances, the total acoustic impedance of the equivalent circuit Z_{total} is derived, from which the absorption coefficient of the absorption system α is obtained by $\alpha = \mathrm{Re}[Z_{total}] / [\{\mathrm{Re}[Z_{total}]+1\}^2 + \{\mathrm{Im}[Z_{total}]\}^2]$.

PRELIMINARY STUDY: END-CORRECTION FOR AN MPP BACKED BY A POROUS LAYER

The radiation impedance of the open end of a tube, Z_r, where the open end is regarded as a piston, is presented. The radiation impedance of the piston, Z_r, is expressed as follows [21]. (Note that Z_r is not normalised to the air impedance.)

$$Z_r = Z_k\left(\frac{(kd)^2}{8} - i\frac{4}{3\pi}kd\right) \quad (5)$$

k and Z_k are the wavenumber in the surrounding media to which the sound is radiated, and its characteristic impedance, respectively.

In the case of radiation to air

The wavenumber of air is k_0 and its characteristic impedance is $\rho_0 c_0$. Therefore, the radiation impedance of the open end (to the air), $Z_{r(air)}$, is expressed by Eq. (6), by using the acoustic resistance r_{air} and reactance ωm_{air}, in the following equation (note that $Z_{r(air)}$ is not normalised to the air impedance):

$$Z_{r(air)} = r_{air} - i\omega m_{air} \quad (6)$$

where

$$r_{air} = \frac{\rho_0 c_0}{8}(k_0 d)^2 \quad (7)$$

$$\omega m_{air} = \rho_0 c_0\left(\frac{4}{3\pi}k_0 d\right) \quad (8)$$

In the case of radiation to a porous layer

The wavenumber is k_1, propagation constant γ, and characteristic impedance is Z_a. The wavenumber and the propagation constant have the following relationship:

$$\gamma = -ik_1 \quad (9)$$

For the porous layer, the characteristic impedance and propagation constant are given by Miki's formulae [22] with its flow resistivity. (Note: Z_a is not normalised to the air impedance):

$$Z_a = \rho_0 c_0 (E_1 + iE_2) \quad (10)$$

$$\gamma = k_0 (E_3 - iE_4) \quad (11)$$

where

$$E_1 = 1{+}0.07\left(\frac{f}{R}\right)^{-0.632} \tag{12}$$

$$E_2 = 0.107\left(\frac{f}{R}\right)^{-0.632} \tag{13}$$

$$E_3 = 0.16\left(\frac{f}{R}\right)^{-0.618} \tag{14}$$

$$E_4 = 1{+}0.109\left(\frac{f}{R}\right)^{-0.618} \tag{15}$$

The radiation impedance of the open end of a tube to a porous layer $Z_{r(porous)}$ is in general expressed by Eq. (16) using the acoustic resistance r_{porous} and reactance ωm_{porous}, which are obtained by using Eq. (5) with k and Z_k of the medium and Eqs. (9) to (15) (Note: $Z_{r(porous)}$ is not normalised to the air impedance):

$$Z_{r(porous)} = r_{porous} - i\omega m_{porous} \tag{16}$$

where

$$r_{porous} = \rho_0 c_0 \,(E_1F_1 - E_2F_2) \tag{17}$$

$$\omega m_{porous} = -\,\rho_0 c_0 \,(E_1F_2 + E_2F_1) \tag{18}$$

$$F_1 = \frac{4E_3}{3\pi}\,k_0 d + \frac{1}{8}\,(k_0 d)^2\left(E_4{}^2 - E_3{}^2\right) \tag{19}$$

$$F_2 = \frac{1}{4}\,(k_0 d)^2\,E_3E_4 - \frac{4E_4}{3\pi}\,k_0 d \tag{20}$$

MPP impedance using the end-correction derived from the radiation impedance from the open end

In the case of an MPP backed by air, the MPP impedance Z_1 is expressed using the acoustic resistance r_1 and reactance ωm_1. Replacing the second term in brackets of Eq. (1) and the third term in brackets of Eq. (2), which express the end-correction, with Eqs. (7) and (8), respectively, results in the following equation for the radiation impedance of the open end:

$$Z_1 = r_1 \text{ - } i\omega m_1 \tag{21}$$

where

$$r_1 = \frac{32\eta t}{p\rho_0 c_0 d^2}\sqrt{1+\frac{K^2}{32}} + \frac{1}{4p}\,(k_0 d)^2 \tag{22}$$

$$\omega m_1 = \frac{\omega t}{\rho c_0}\left(1+\frac{1}{\sqrt{9+\frac{K^2}{2}}}\right) + \frac{1}{p}\,\frac{8}{3\pi}\,k_0 d \tag{23}$$

For an MPP backed by a porous layer, the MPP impedance Z_2, with acoustic resistance r_2 and reactance ωm_2, the end-correction terms in Eqs. (1) and (2), that is, the second term in brackets of Eq. (1) and the third term in brackets of Eq. (2), are now replaced by Eqs. (7), (8), (17) and (18), resulting in the following equation for the radiation from the open end of the tube:

$$Z_2 = r_2 - i\omega m_2 \tag{24}$$

where

$$r_2 = \frac{32\eta t}{p\rho_0 c_0 d^2}\sqrt{1+\frac{K^2}{32}} + \frac{1}{8p}\,(k_0 d)^2 + \frac{1}{p}\,(E_1F_1 - E_2F_2) \tag{25}$$

$$\omega m_2 = \frac{\omega t}{\rho c_0}\left(1+\frac{1}{\sqrt{9+\frac{K^2}{2}}}\right) + \frac{1}{p}\,\frac{4}{3\pi}\,k_0 d - \frac{1}{p}\,(E_1F_2 + E_2F_1) \tag{26}$$

COMPARISON BETWEEN MAA'S THEORY AND THE PRESENT THEORY

From the above discussion, two different theories for the end-correction have been given (for the air-backed case given by Eqs. (1) and (2), and for the porous-backed case given by Eqs. (24) to (26)). The first theory is the end correction included in the Maa's formulae, and the second theory is the present theory obtained from the radiation impedance from the open end of a tube. The results from both theories for the case of an MPP backed by the air and a porous layer are compared in what follows.

The aim of the comparisons is twofold: One is to confirm that the two theories give almost the same results in absorption coefficients for the air-backed case. The other is to observe how much difference is caused in the results of the absorption coefficients for the porous-backed case. For the second purpose, first it is needed to confirm that the results using the two theories are in agreement for a certain MPP parameter in the air-back case. Then, the results using the two theories are compared for the same parameter in the porous-backed case.

The results of the comparison of the two theories in the air-backed case are presented in Fig. 2. Typical values are given for the MPP parameters. There is a small discrepancy at around the resonance peak. However, they show very good agreement in general.

As the theory with the radiation impedance is dependent on the MPP parameters d and t, it is found that differences may occur according to the change in these parameters. However, as long as $d/t < 1$, Maa's theory and the present theory are in fairly good agreement. Therefore, the comparison of the two theories in porous- backed case will have to be made within this range of the MPP parameters.

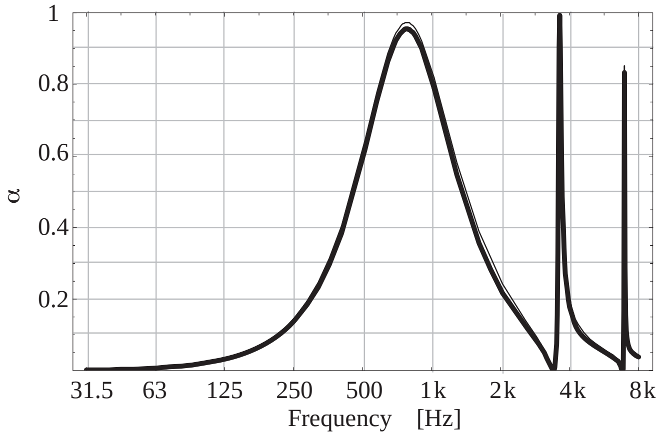

Figure 2. Comparison of the absorption coefficient using the impedance derived from the present theory and Maa's theory in the air-backed case: d=t=0.3 mm, p=0.8%, D=50 mm. Thick line: derived by the present theory, Eqs. (21) to (23); Thin line: Maa's theory, Eqs. (1) and (2)

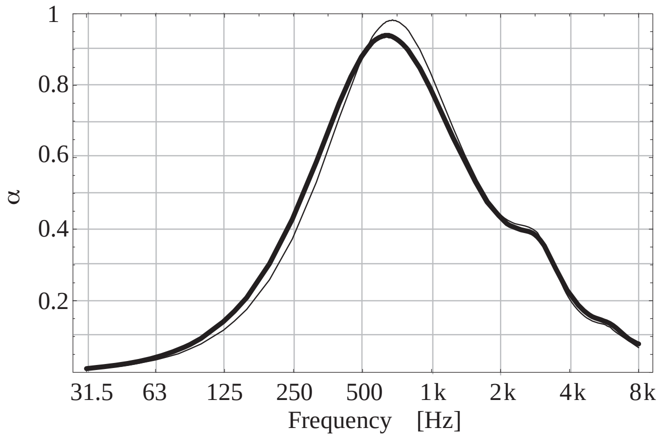

Figure 3. Comparison of the absorption coefficient using the impedance derived from the present theory and Maa's theory in the porous layer-backed case. d=t=0.3 mm, p=0.8%, D=50 mm, R=10 kPa.s.m^{-1}. Thick line: the present theory, Eqs. (24) to (26); Thin line: Maa's theory, Eqs. (1) and (2)

Figure 3 shows the comparison of the two theories in the porous-backed case for the same MPP parameters as in Fig. 2. In this case, the discrepancies between the two theories are slightly larger than those in the air-backed case. However, it can be observed that Maa's theory also offers a good approximation for the porous-backed case of an MPP. Therefore, in the following section, Mas's theory is used for calculation, through which the absorption characteristics of a single-leaf rigid wall-backed MPP with porous absorbent in the cavity will be discussed.

NUMERICAL EXAMPLES AND DISCUSSION

In this section, numerical examples of the calculated results for the absorption characteristics of single-leaf MPP absorbers backed by rigid back-wall and porous layer in-between. In the preceding section it was confirmed that Maa's theory can give reasonable approximation even in the porous-backed case, therefore in this section, the calculated results by Maa's theory are presented, and the absorption characteristics of the porous-layer backed MPP absorber are discussed through the numerical examples.

First, the basic feature of the porous layer-backed MPP is shown in comparison with the results for that backed by air-cavity. Figure 4 compares the typical numerical results for the single-leaf MPP absorber with an air-cavity and that with an absorbent-cavity.

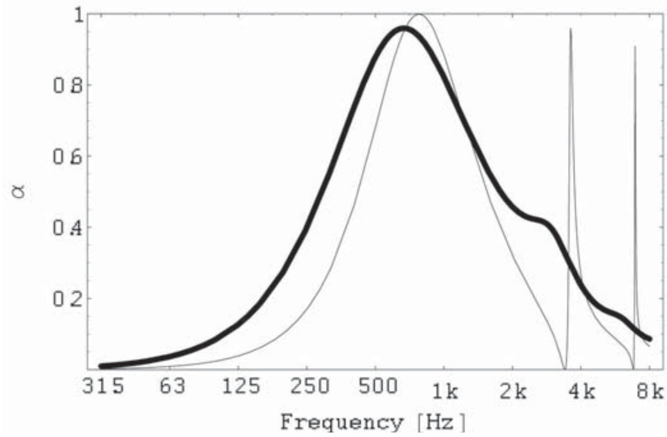

Figure 4. Comparison of the absorption characteristics of an MPP absorber backed by an air cavity (thin line) and that backed by a porous absorbent layer (thick line). Hole diameter d=0.3 mm, thickness t=0.3mm, perforation ratio p=0.8%, flow resistance of the absorbent R=10 kPa.s.m^{-1} and cavity depth D=50 mm

The results for the case of an MPP backed by an absorbent cavity show that, although the peak absorption coefficient is slightly lower than that for an MPP backed by an air cavity, the peak becomes broader and covers a wider frequency range. The peaks due to the higher resonance modes at around 4 kHz and 8 kHz observed in the air-cavity case disappear in the absorbent-cavity case. This is because the resonance in the cavity is damped by the porous absorbent. Thus, inserting a porous absorbent layer in the back cavity makes an MPP absorber more wideband.

The above effect of the porous absorbent can be varied with its acoustical parameters. In this study, the characteristic impedance and propagation constant are given by Miki's formulae, hence the only affecting parameter of the porous absorbent is its flow resistivity. The effect of the flow resistivity of the porous absorbent in the cavity of a single MPP absorber is discussed. As observed in Fig. 5, the peak becomes broader with increasing flow resistivity. However, whilst the peak is from 0.9 to 1.0 when the flow resistivity is from 5 to 20 kPa.s.m^{-1}, the peak value gradually decreases if the flow resistivity becomes higher, and the value becomes as low as around 0.7 when the flow resistivity is 80 kPa.s.m^{-1}. Therefore, in order to keep the high absorption as well as wideband absorption, the flow resistivity of the porous absorbent should not be too large. In this example, it should be lower than 20 kPa.s.m^{-1}. It should be noted that this tendency depends on the total acoustic resistance. Therefore, when the acoustic resistance of the MPP itself is already optimised, the additional resistance makes the total resistance too large. This results in deteriorated absorption performance. Therefore, the suitable range of the flow resistivity of the porous absorbent, which affects the total resistance, should be considered in each case of MPP parameter.

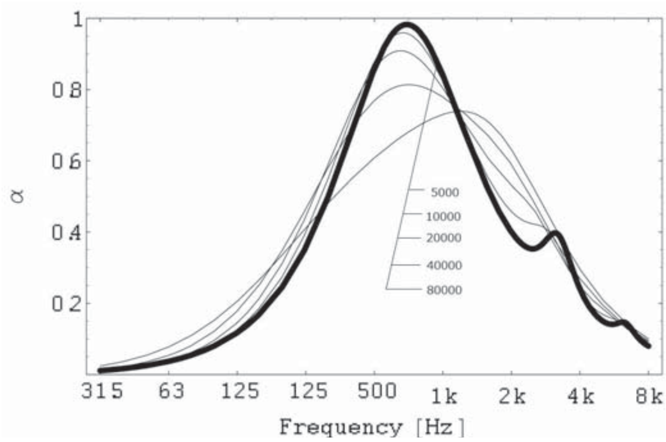

Figure 5. Effect of the flow resistance of the porous absorbent layer in the back cavity. Flow resistance of the absorbent R= 5 to 80 kPa.s.m^{-1}. Hole diameter d=0.3 mm, thickness t=0.3mm, perforation ratio p=0.8% and cavity depth D=50 mm.

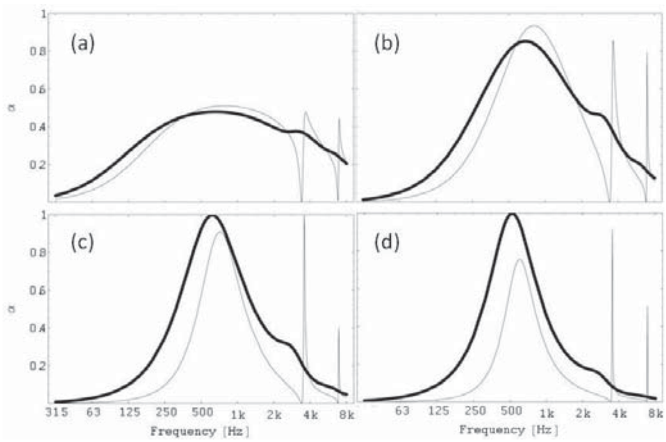

Figure 6. Effect of the hole diameter of the MPP of a porous layer-backed single MPP absorber. Thick line: porous layer-backed MPP; Thin line: air layer-backed MPP. Hole diameter d=0.1 mm (a), 0.2 mm (b), 0.5 mm (c) and 1.0 mm (d). Thickness t=0.3 mm, perforation ratio p=0.8%, flow resistance of the absorbent R=10 kPa.s.m^{-1} and cavity depth D=50 mm.

A numerical calculation is now performed to investigate how the effect of the porous layer changes with changing MPP parameters. Figure 6 shows the effect of the hole diameter when the flow resistivity of the porous layer is 10 kPa.s.m^{-1}.

When the hole diameter is 0.1 mm, the acoustic resistance of the MPP itself is too large which results in low absorption. Therefore, the porous layer does not have a significant effect. When the hole diameter is 0.2 mm, the absorption coefficient becomes lower when a porous layer is inserted. This is because the total acoustic resistance becomes too large due to the additional resistance of the porous layer. On the other hand, when the hole diameter is 0.5 and 1.0 mm, the peak becomes higher than that with air cavity. The peak also becomes wider. Thus, when the acoustic resistance of the MPP itself is unsatisfactorily low, the effect of the porous layer becomes significant and the absorption performance can be improved.

A similar tendency is observed when the thickness of the MPP is varied, that is, the effect of the porous layer becomes significant when the thickness is small (with low acoustic resistance), as shown in Fig. 7.

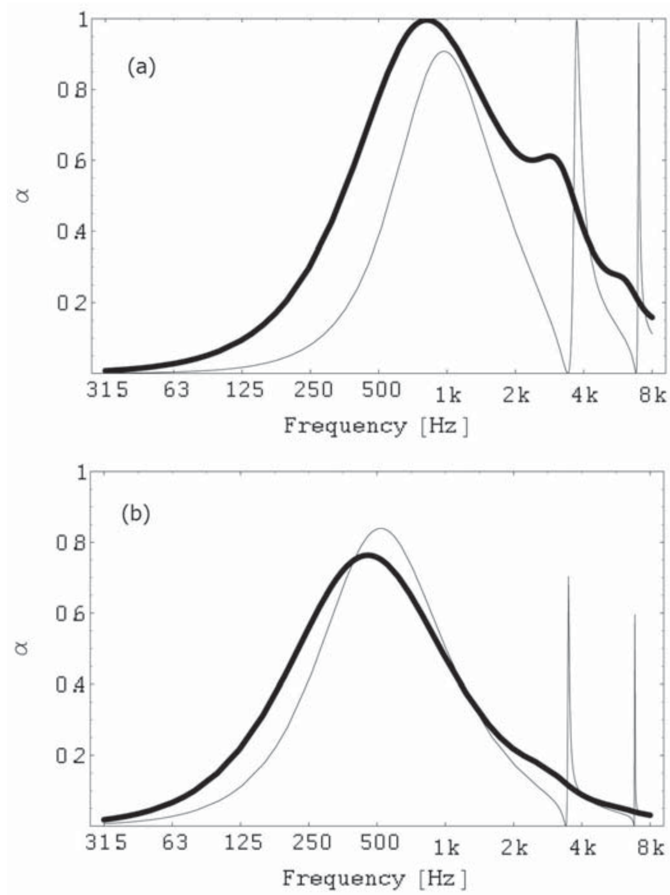

Figure 7. Effect of the thickness of the MPP of a porous layer backed single MPP absorber. Thick line: porous layer backed MPP; Thin line: air layer backed MPP. Thickness t=0.1mm (a), and 1.0 mm (b). Hole diameter d=0.3 mm, perforation ratio p=0.8%, flow resistance of the absorbent R=10 kPa.s.m^{-1} and cavity depth D=50 mm.

A different behaviour is observed when the perforation ratio of the MPP is changed. When the perforation ratio is low, the typical resonance-type absorption characteristics of an MPP can be observed. However, if the perforation ratio exceeds 1.0%, the acoustic properties of the porous layer inside the cavity become dominant to show totally different absorption characteristics and which are similar to those of a porous sound absorber. As an example for an extreme case, the results for the perforation ratio of 5.0% are shown in Fig. 8.

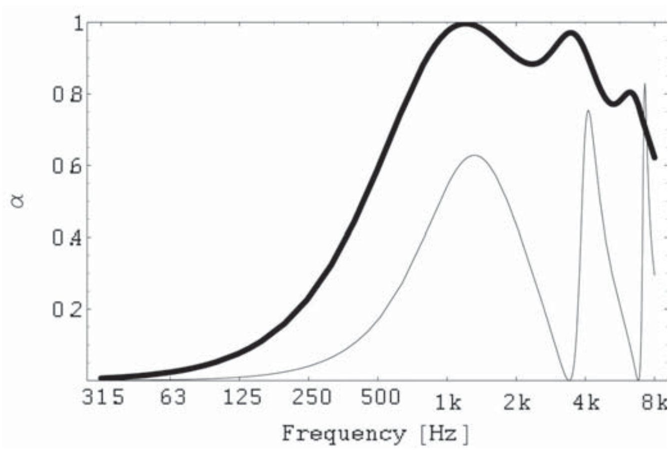

Figure 8. An example of the absorption characteristics of a porous layer backed single MPP absorber with a large perforation ratio. Thick line: porous layer backed MPP; Thin line: air layer backed MPP. Hole diameter d=0.3 mm, thickness t=0.3 mm, perforation ratio p=5.0%, flow resistance of the absorbent R=10 kPa.s.m^{-1}, and cavity depth D=50 mm.

CONCLUDING REMARKS

In this study, the effect of the porous absorbent layer in the cavity of a single-leaf MPP sound absorber backed by a rigid wall is analysed using an electro-acoustical equivalent circuit model. The end-correction for an MPP backed by a porous layer was derived and compared with Maa's theory, which assumes the end-correction for air-backed case. It was observed that Maa's theory offers a fairly good approximation even in porous backed cases. Therefore, in the numerical study, Maa's conventional theory was used for the end correction for an MPP backed by a porous layer, through which the effect of the porous layer in the cavity was discussed. The results showed that inserting a porous absorbent layer in the back cavity, the peak value becomes slightly lower, but the absorption frequency range can be made wider. However, the effect is dependent on the flow resistivity of the porous layer. Hence it is necessary to choose a suitable value of the flow resistivity. Also the effect depends on the MPPs parameters such as hole diameter, thickness and perforation ratio.

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