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PDF issue: 2025-12-05

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(Citation)
Applied Acoustics,70(8):1131-1136

(Issue Date)
2009-04-11

(Resource Type)
journal article

(Version)
Accepted Manuscript

(URL)
https://hdl.handle.net/20.500.14094/90000855

A note on the relationship between the sound absorption by microperforated panels and panel absorbers

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Keywords: Microperforated panel absorber, panel/membrane-type absorber, absorption mechanism, electro-acoustical equivalent circuit model

Abstract

The sound absorption mechanism of microperforated panel (MPP) absorbers and panel/membrane-type absorbers is both based on a certain resonance system and utilising its resonance effect. However, the relationship between the absorption mechanisms of MPPs and panel/membrane-type absorbers has not been discussed: it is not clarified whether they can occur simultaneously, or how they interfere each other. On the other hand, in a previous study there is an attempt to cause both absorption mechanisms simultaneously [Lee et al, *CD-ROM Proceedings of International Congress on Sound and Vibration (ICSV14)*, 2007]. In this paper, using an electro-acoustical equivalent circuit model, their sound absorption mechanisms and their relationship are discussed. The results suggest that the microperforated panel absorption, which is Helmhotz-type resonance, and the panel/membrane-type absorption can be regarded as phenomena of the same kind which can be smoothly transformed into each other by changing a parameter, and can be consistently modelled and comprehensively discussed.

1. Introduction

Microperforated panel (MPP) [1-3] is recently recognised widely as one of the most promising alternatives of next-generation sound absorbing materials. An MPP is a thin panel or membrane less than 1 mm thick with perforation of less than 1 % perforation ratio. MPPs are usually used with air-back cavity and a rigid backing to form Helmholtz resonators with their holes and the cavity. On the other hand, panel/membrane-type sound absorbers have been used in architectural acoustics and other field in acoustics for low-frequency sound absorbers for some time, and have been studied by many authors [4-8]. Panel/membrane-type absorbers absorb sound energy by the resonance of the mass-spring system composed of the mass of the panel or membrane and the stiffness of the air-cavity. Due to this resonance the absorber causes sound absorption due to various energy losses in the system, e.g., loss by supporting edges, absorptivity on the panel/membrane and/or back wall surfaces, and any other energy loss in the vibrating system.

Both MPP and panel/membrane-type absorbers cause frequency-selecting sound absorption by a resonance caused by a resonance system formed in the sound absorbing system. Therefore, it can be stated that they should have some similarity: they both absorb sound energy by some kind of resonance. They both are non-porous sound absorbers, and recently used in various situations, e.g., room interior surface, muffling system, etc., as a next-generation sound absorbing system.

MPPs are made by making perforations in a panel or membrane, and it also causes sound induced vibration. Therefore, there have been some studies dealing with sound absorption characteristics considering the sound induced vibration of an MPP itself [9-11]. There even is a proposal for a new-type sound absorber with an MPP by positively forcing it to vibrate to cause panel absorption as well [12].

Although, in the sense that both MPPs and panel/membrane-type absorbers are sound absorbers utilising resonance effect, there could be some relationship between them, i.e., whether the both (MPP absorption and panel/membrane-type absorption) can occur simultaneously, or how they are related, or how they interfere each other. However, these problems have not been discussed enough and clarified.

In this paper, important previous studies concerning the above problems will be reviewed, and some novel considerations on this point will be made to discuss the relationship between MPP absorption and panel/membrane-type absorption. Although in Ref [11] the effect of the eigenmode in the case of finite-sized MPP absorbers is discussed, the effect of eigenmode of finite plates is not discussed in this paper. Rather, we concentrate on the basic physical insight into the relationship between MPP and panel/membrane-type absorption. This is achieved by employing electro-acoustical equivalent circuit model analysis. More detailed and complicated problems of coupling of the vibration mode with that of the cavity are not discussed here: these are phenomena that are very localised to some eigenfrequencies. This paper deals with rather basic insight into more global relationship between them.

2. The case in which only mass reactance of MPP is considered

To begin with, as the simplest model, an electro-acoustical equivalent circuit model of a single MPP considering sound induced vibration only with the mass reactance of the MPP is considered (Fig. 1). The MPP is dealt with as just a mass reactance to sound induced vibration, and connected parallel to the MPP's acoustic impedance R and M in the circuit [10]. Here, as the simplest case, no resistive component for vibration is given in the model. This assumption corresponds to neglecting the energy loss at the supporting edges when the MPP is regarded as a membrane. When the MPP is regarded as an elastic plate, the internal energy loss is also neglected in this case. The impedance of the air-back cavity (depth: D) is $Z(D)=i\cot(kD)$ (normalised to the air impedance ρc, and k is the wavenumber), and no absorptivity is given to the panel and the back wall surfaces. Therefore, acoustic resistance is only at the perforation of the MPP (R).

An example of the results calculated by this model is shown in Fig. 2. These are the results for various surface densities of the MPP panel. The absorption peak (Helmholtz resonance) shifts slightly to a higher frequency with decreasing surface density, but the change in the peak frequency is not very large. When the surface density is very small, the peak value decreases. The change is very little in the realistic range of the surface density. Therefore, sound induced vibration causes a drop in resistance (flow resistance) of the perforation of the MPP. The total acoustic resistance of the system becomes too low when the surface density is too small, which results in the lower absorption peak.

It is obvious from the results that is no other peak except the Helmholtz resonance of MPP absorption. Any peak by the panel/membrane-type absorption does not occur. This is because, in this model, only a mass reactance is attached parallel to the MPP's acoustic impedance, which does not form an additional resonance system and cause mere change in total impedance. Therefore, in this case, panel/membrane-type absorption does not take place independently, and only MPP absorption is caused.

3. The case in which the losses of the panel is considered: the Kang and Fuchs Model[9]

A more sophisticated model including the losses of the MPP's panel vibration is proposed by Kang and Fuchs [9] and is shown in Fig. 3. They model the MPP perforation's resistance and reactance with not only a mass reactance but also resistance caused by the panel losses in vibration. The mass reactance and the vibrational resistance are connected in series and this series impedance is connected in parallel with the MPP's acoustic impedance. Since Kang and Fuchs regard the MPP as a membrane without the rigidity rather than an elastic plate, the losses expressed by this resistance is mainly considered as the mounting losses by caused by friction.

An example of the results by Kang and Fuchs is shown in Fig. 4, which presents the calculated results for various perforation ratio of MPP (microperforated “membrane”). A large absorption peak appears even when the perforation ratio is 0 % (i.e., the “membrane” is no longer an MPP but a mere membrane-type absorber). This shows that membrane-type absorption occurs. Interestingly, when the perforation ratio is increased, the absorption characteristics drastically changes. The absorption peak shifts to higher frequencies with increasing perforation ratio. This means that the characteristics gradually changes from the membrane-type (panel) absorption , which takes place when the perforation ratio is zero, to MPP Helmholtz resonance absorption. This infers that the two absorption phenomena are related to each other. The peak frequency and value are different even though the perforation ratio is the same, but this is explained by the change in the MPP's acoustic reactance and resistance which change with the perforation ratio. In these calculations Kang and Fuchs use R_M=1 (normalised to the air impedance ρc) for the resistance of the panel (membrane).

Another example is shown in Fig. 5 (a): this shows Kang and Fuchs' calculated results for various surface densities of the panel (membrane). Also shown in Fig. 5 (b) are the results that we calculate under the same condition as Fig. 5 (a) but R_M=0. In these results the perforation ratio is fixed at 0.83 % and the surface density of the panel (membrane) is changed from 0.19 to 1.9 kg/m^2. In these cases the perforation ratio is not zero, that is, there are perforations and the absorption is caused by not panel/membrane-type absorption but MPP Helmholtz resonance absorption. However, the absorption peak shifts to lower frequencies and the peak value becomes lower with increasing the surface density of the panel (membrane). The change in this case is larger than that of the previous example without the additional resistance shown in Fig. 2. Comparing Figs. 5 (a) and (b), regardless of the resistance of the panel (membrane) R_M, the amount of the shift in the peak frequency is almost the same. Thus, the fact that the shift of peak frequency is larger in this case than that in the previous example in Fig. 2 is not related to whether the panel (membrane) has resistance due to vibration loss or not, but rather it depends on other parameters, e.g., hole diameter, perforation ratio, etc. Besides, the characteristics are quite different from those in Fig.2, which means that the characteristics are largely dependent on the total resistance of the entire system including R_M, i.e., the peak becomes large under the condition where the total resistance becomes the optimal.

Kang and Fuchs compared the calculated results from their model with experimental results, and concluded that they showed good agreement. However, in their experiment only a few specimens were used and the range of their parameters is limited, and they do not show any data which support the tendency shown in Figs. 4 and 5. Furthermore, they do not discuss how the results change by the sound induced vibration, or whether or not including sound induced vibration improves the agreement with experiments. That is, they do not compare the results with vibration and those without vibration. Therefore, here, using their model, we make some parametric studies. The calculated results for various surface density M_M are shown in Fig. 6. The peak frequency shifts to higher frequencies with decreasing M_M, which is the same tendency as is usually observed in panel/membrane-type absorbers. The decrease in the peak value is due to the decrease in total resistance of the vibration loss and MPP perforation.

The effect of the loss of the panel (resistance R_M) is shown in Fig. 7. In this case the perforation ratio is 0.8 %, which causes MPP Helmholtz resonance absorption significantly. The MPP's acoustic resistance of its perforation is nearly optimal, showing a typical absorption peak is shown. Therefore, there is no effect of R_M. In this case the MPP perforations have enough acoustic resistance to cause clear Helmholtz resonance absorption, the loss of the panel due to the resistance R_M shows no effect. In the case that the perforation ratio is zero and R_M is changed, only a panel/membrane-type absorption peak occurs and its peak value is dependent on R_M. The peak takes maximum value when R_M=1, and decreases if R_M is larger or smaller than unity. This is the typical tendency of a panel/membrane-type absorber.

Figure 8 (a) shows the results for various perforation ratios (R_M=1). The absorption peak shifts to higher frequencies with increasing perforation ratio. This is because the volume of the air-cavity per each perforation is decreased with increasing perforation ratio, resulting in higher Helmholtz resonance frequency. The result for the zero perforation ratio corresponds to those for a panel/membrane-type absorber: In this case, the peak value of absorption is unity because R_M=1. The peak value decreases with increasing perforation ratio: this is dependent on the acoustic resistance and reactance of MPP perforation.

Figure 8 (b) is calculated using the same condition as Fig. 8 (a) but R_M=0. In this case there is no vibrational loss in the system. No panel/membrane-type absorption takes place when the perforation ratio is zero, which results in zero absorption at all frequencies. However, once there is non-zero perforation ratio, MPP absorption occurs, and a tendency similar to the case of R_M=1 (Fig. 8 (a)) is observed.

From the discussion above, the relationship between panel/membrane-type absorption and MPP Helmholtz resonance absorption is summarised below:

(a) Panel/membrane-type absorption and Helmholtz resonance absorption by an MPP are related phenomena. The panel/membrane-type absorption occurs when the perforation ratio is zero, and it is transformed into Helmholtz type MPP absorption with increasing perforation ratio. The peak frequency shifts with it accordingly, and the characteristics change gradually and smoothly.

(b) The resistance due to the vibrational loss of the panel (membrane) and the amount of the peak frequency shift have no consistent relationship. They are almost the same regardless to the value of the resistance.

(c) Regarding the change in the absorption peak value, its behaviour is determined by the total acoustic resistance of the system including vibrational loss. If there is no vibrational loss, the acoustic resistance of the perforation of MPP changes due to the sound induced vibration, which causes drastic change in the absorption peak value.

(d) When the panel/membrane does not have vibrational loss, panel/membrane-type absorption does not occur. Therefore, in this case, the characteristics change gradually and smoothly from zero absorption when the perforation ratio is zero to the MPP absorption by Helmholtz resonance with perforations, according to the increase in the perforation ratio.

From the above discussion, panel/membrane-type absorption and MPP's resonance absorption are both caused by some acoustic resistance (in this case, perforation's acoustic resistance, or panel's vibrational loss, or the combined resistance of the both) in the system and the reactance of the system (that of the perforation or panel's mass reactance, or combined reactance of the both) and the stiffness of the air-cavity in a certain resonance system composed of them. Therefore, both phenomena are considered to have the similarity.

4. The case in which the sound absorption of the back wall surface is considered

The model by Kang and Fuchs includes the vibrational loss of the panel or membrane as the acoustical resistance in the electro-acoustical equivalent circuit model. However, according to the previous studies on panel/membrane-type absorption [6,8], the acoustic admittances on the panel/membrane surface and/or back wall surface play an important role in panel/membrane-type absorption. In that case, for example, if the surface of the back wall has acoustic admittance, the electro-acoustical equivalent circuit model does not include the resistance at the panel or membrane, but the air-cavity impedance includes this absorptivity of the back wall surface. Therefore, the circuit model is the same as in Fig. 1: the panel/membrane does not have any vibrational loss and is expressed by pure mass reactance. However, the air-cavity impedance is changed to the following equation because it includes specific acoustic admittance of the back wall's surface, A:

$$Z(D)=\frac{1+A+(1+A)\exp(2ikD)}{1+A-(1-A)\exp(2ikD)} \tag{1}$$

Here, an attempt is made to understand panel/membrane-type absorption and MPP resonance absorption consistently in this case through numerical examples.

First, the effect of the acoustic admittance of the back wall surface A is shown in Fig. 9. In this example the perforation ratio is 0.8 %, and the absorption peaks are produced by the MPP's

Helmholtz resonance. When A is small, A does not greatly affect the peak value, but affects the absorptivity at low frequencies (lower than the peak frequency). The tendency of A to affect the characteristics at frequencies lower than the peak frequency is similar to panel/membrane-type absorber, except that in the case of a panel/membrane-type absorber, the peak values are also affected. It is explained by considering the general behaviour of a single-degree-of-freedom resonance system. In general, in a single-degree-of-freedom resonance system force transmissibility becomes unity below its resonance. In this case, the acoustic energy transmits more easily into the cavity at lower frequencies. When A becomes larger and becomes nearly 1.0, the peak value decreases and the peak eventually disappears. This is because the back wall eventually becomes perfectly absorptive and has no acoustical effect. Therefore, the resonance no longer occurs, and the characteristics become the same as the transmission coefficient of the MPP.

Figure 10 shows the results for various perforation ratio with A=0.026 (which corresponds to the normal absorption coefficient of 0.1). When the perforation ratio is zero the absorption is solely caused by panel/membrane-type absorption. In this case the absorptivity on the back wall surface affects the absorption as the only dissipative component in the resonance system, and causes a resonance peak. When the perforation ratio is increased, the peak value also increases. The absorption mechanism is transformed into the MPP Helmholtz resonance absorption and its typical characteristics are observed.

From the discussion above, even if the panel or membrane itself does not have any energy loss, when the back wall surface has absorptivity, the similar tendency to that discussed in the preceding section that MPP's Helmholtz resonance absorption and panel/membrane-type absorption can be transformed into each other by changing parameter can be observed. Therefore, in any case, panel/membrane-type absorption and MPP Helmholtz resonance absorption are similar and can be transformed into each other with a parameter change.

5. Concluding remark

The model analysis of the MPP absorber with sound induced vibration was made and the relationship between MPP Helmholtz resonance absorption and panel/membrane-type absorption has been discussed. In conclusion, both absorption phenomena can be understood as absorption phenomena of the same kind and transformed into each other by changing the perforation ratio. This suggests that MPP absorption and panel/membrane-type absorption can be consistently modelled and discussed.

Acknowledgements

This work was in part supported by the Grant for Scientific Research from Takahashi Industrial and Economic Research Foundation. The authors thank Dr Nicole Kessissoglou for her constructive comments on this work.

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Figure Captions

Figure 1: Typical configuration of a MPP absorber (left) and its electro-acoustical equivalent circuit model considering MPP's mass reactance (right). *R* and *M* are the MPP's acoustic resistance and reactance, *m* is the surface density of the MPP. *Z*(*D*) is the acoustic reactance of the air-back cavity of depth *D*. [10]

Figure 2: Effect of the mass of MPP on its absorption characteristics. Calculated with the model in Fig. 1. The surface density of the MPP is 0.1 ... 2 kg/m^2. The immobile case is also shown for reference. MPP's parameters are: hole diameter 0.4 mm, thickness (throat length) 0.4 mm, perforation ratio 1.0 %. The depth of the cavity is 50 mm. [10]

Figure 3: Kang and Fuchs' model of an MPP absorber considering MPP's mass reactance and mechanical loss [9]. R_L and M_L are the resistance and reactance of perforations, R_M and M_M are those of the panel (membrane), respectively.

Figure 4: The calculated results by the Kang and Fuchs' model in Fig. 3 [9]: effect of the perforation ratio. Cavity depth: 100 mm, surface density: 0.19 kg/m^{2,}, thickness: 0.17 mm. ....: unperforated; Thick line: hole diameter 0.06 mm and perforation ratio 0.83 %; - - - - : hole diameter 0.3 mm and perforation ratio 0.83 %; Thin line: hole diameter 0.18 mm and perforation ratio 7.43 %; ―――: hole diameter 0.3 mm and perforation ratio 20.65 %. The gradual change in characteristics due to the perforation ratio is observed.

Figure 5: The calculated results by the Kang and Fuchs' model in Fig. 3 [9]: effect of the MPP's surface density. (a) Cavity depth 100 mm, thickness 0.17 mm, hole diameter 0.06 mm, perforation ratio 0.83 %. Thick line: 1.9 kg/m^2, dotted line 0.95 kg/m^2, thin line: 0.19 kg/m^2. (b) the same parameters but with the mechanical loss resistance set to 0.

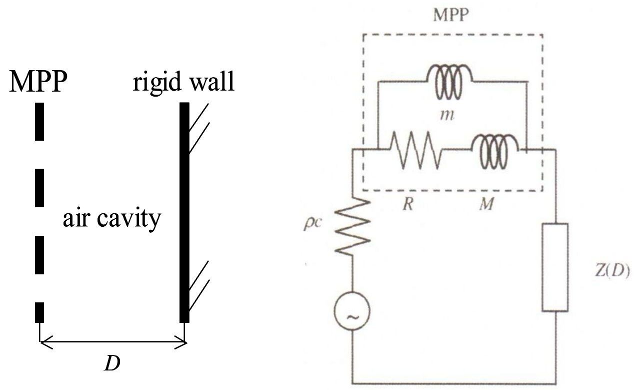
Figure 6: The effect of the surface density of the MPP leaf. Calculated by Kang and Fuchs' model (Fig. 3). Hole diameter and thickness are 0.4 mm, perforation ratio 0.8 %, cavity depth 50 mm, mechanical loss resistance 1.0. (1) 1 kg/m^2, (2) 0.5 kg/m^2, (3) 0.25 kg/m^2, and (4) 0.1 kg/m^2.

Figure 7: The effect of the mechanical loss resistance of the MPP leaf. Calculated by Kang and Fuchs' model (Fig. 3). Hole diameter and thickness are 0.4 mm, perforation ratio 0.8 %, cavity depth 50 mm. Mechanical loss resistance is 0.1, 0.5, and 1, of which all curves are overlapped.

Figure 8: The effect of the perforation ratio of the MPP. Calculated by Kang and Fuchs' model (Fig. 3). Hole diameter and thickness are 0.4 mm, cavity depth 50 mm, surface density 1 kg/m^2. (a) mechanical loss resistance 1.0, (b) mechanical loss resistance 0. Perforation ratio: (1) 0 % (unperforated), (2) 0.1 %, (3) 0.2 %, (4) 0.4 %, (5) 0.8 % and (6) 1.2 %.

Figure 9: The effect of the acoustic admittance of the back wall. Calculated by the model in Fig. 1 with the air-cavity impedance Eq.(1). Hole diameter and thickness are 0.4 mm, perforation ratio 0.8 %, cavity depth 50 mm, surface density 1 kg/m^2. No mechanical loss resistance in MPP leaf is considered. Back wall admittance is (1) 1.0, (2) 0.626, (3) 0.172, (4) 0.026, and (5) 0.

Figure 10:The effect of the perforation ratio. Calculated by the model in Fig. 1 with the air-cavity impedance Eq.(1). Hole diameter and thickness are 0.4 mm, cavity depth 50 mm, back wall admittance 0.026, surface density 1 kg/m^2. No mechanical loss resistance in MPP leaf is considered. Perforation ratio is (1) 0 % (unperforated), (2) 0.1 %, (3) 0.2 %, (4) 0.4 %, and (5) 0.8 %.



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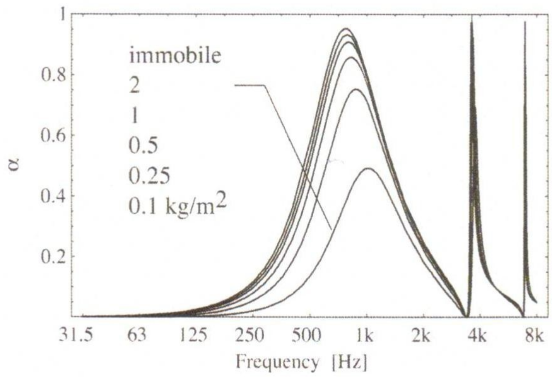

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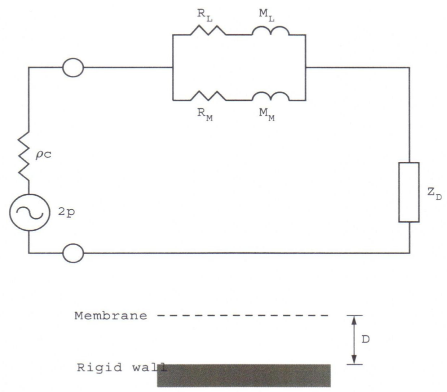

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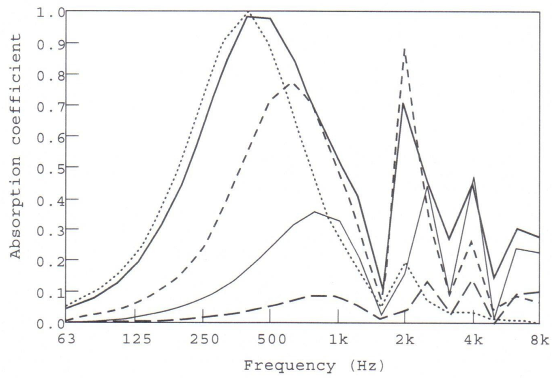

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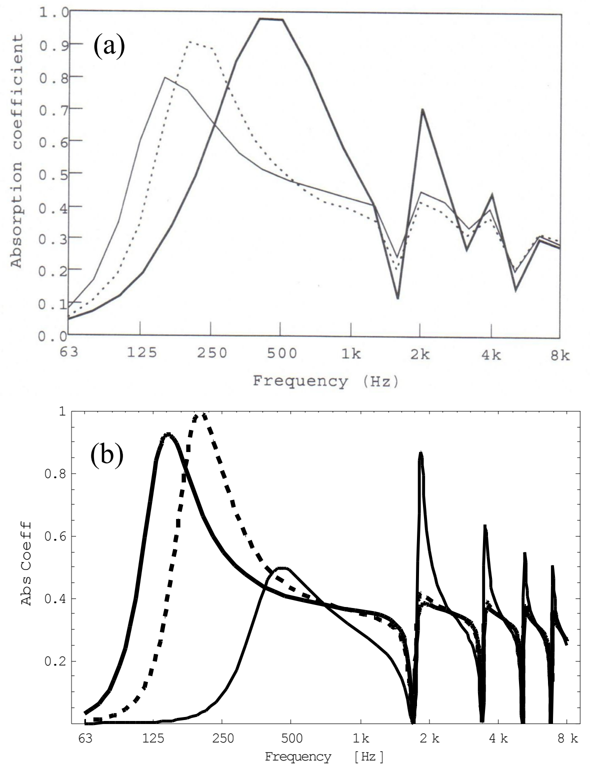

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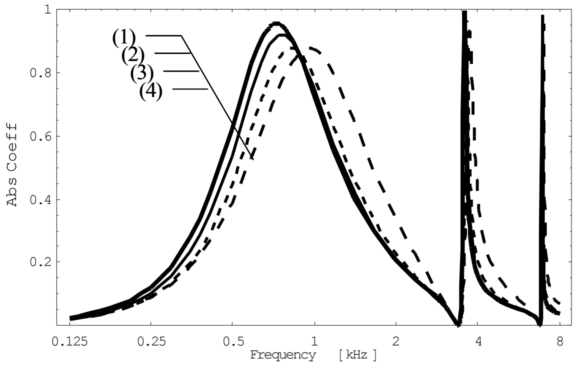

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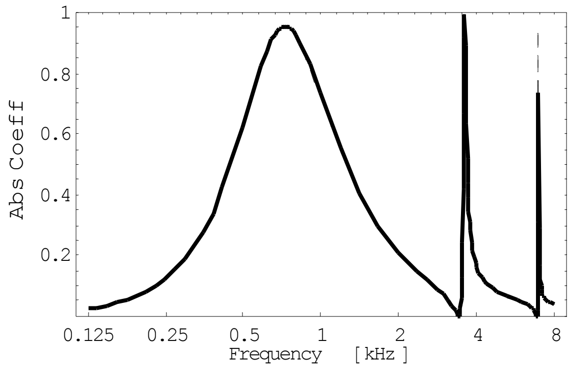

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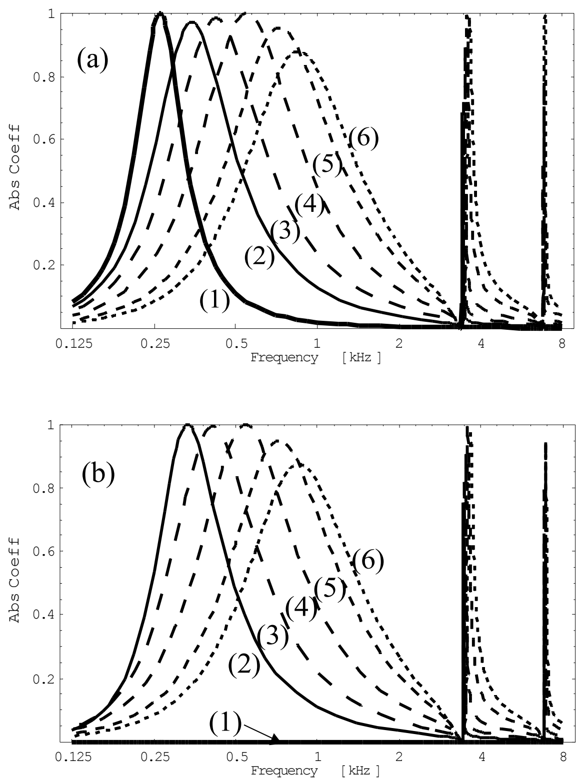

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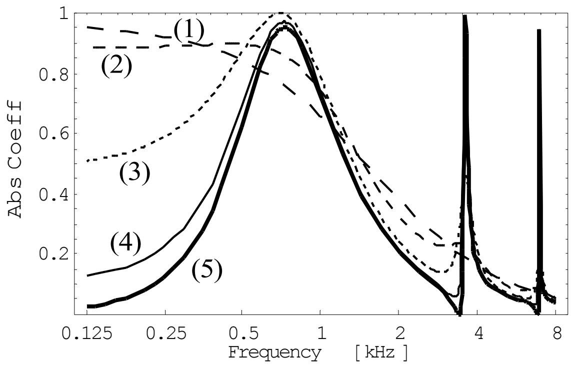

Figure 9: The effect of the acoustic admittance of the back wall. Calculated by the model in Fig. 1 with the air-cavity impedance Eq.(1). Hole diameter and thickness are 0.4 mm, perforation ratio 0.8 %, cavity depth 50 mm, surface density 1 kg/m^2. No mechanical loss resistance in MPP leaf is considered. Back wall admittance is (1) 1.0, (2) 0.626, (3) 0.172, (4) 0.026, and (5) 0.

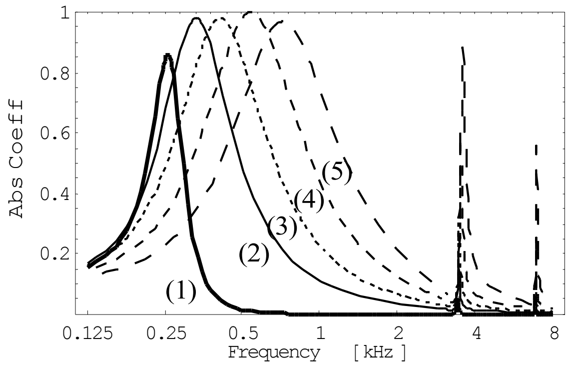

Figure 10:The effect of the perforation ratio. Calculated by the model in Fig. 1 with the air-cavity impedance Eq.(1). Hole diameter and thickness are 0.4 mm, cavity depth 50 mm, back wall admittance 0.026, surface density 1 kg/m^2. No mechanical loss resistance in MPP leaf is considered. Perforation ratio is (1) 0 % (unperforated), (2) 0.1 %, (3) 0.2 %, (4) 0.4 %, and (5) 0.8 %.