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RECENT DEVELOPMENTS IN APPLICATIONS OF MICROPERFORATED PANEL ABSORBERS

Kimihiro Sakagami[1], Masayuki Morimoto[1] and Motoki Yairi[2]

[1]Environmental Acoustics Laboratory, Department of Architecture,
Graduate School of Engineering, Kobe University
Rokko, Nada, 657-8501 Kobe, Japan
saka@kobe-u.ac.jp
[2]Kajima Technical Research Institute, Kajima Corporation
Tobitakyu, Chofu, 182-0036 Tokyo, Japan

Abstract

Microperforated panel (MPP) absorbers are promising as a basis for the next-generation of sound absorbing materials. A microperforated panel absorber is backed by an air-cavity with a rigid-back wall and its typical use is for a sound-absorbing ceiling. However, MPPs have some limitations and disadvantages: its sound absorbing mechanism is limited to a Helmholtz resonator caused by perforations with air-cavity and effective absorption is limited to the resonance frequency range. There is also a problem when MPPs are used as a sound absorbing finish of room interior surfaces because typical MPPs are made out of thin limp materials and are not strong enough. In order to solve these problems, the research at Kobe University has focussed on the followings: (1) application of MPPs for room interior surface finishings, including applications of honeycomb MPPs, (2) multiple-leaf MPP absorbers. The main results from these projects are reviewed in this paper.

1. INTRODUCTION

A microperforated panel (MPP) is promising as a basis for the next-generation of sound absorbing materials. Since the pioneering works by Maa [1-3], many studies have been made on the application of MPPs for various purposes such as attenuating noise in small rooms and for duct silencing [4-6]. Application of thin MPP films in acoustic window systems has recently been studied by Kang and Brocklesby [7]. Application of multiple-leaf transparent MPP absorber to noise barriers is also recently reported by Asdrubali and Pispola [8]. However, since MPPs are typically made of a thin metal panel or film, they do not have enough strength and are in many cases not suitable for an interior finish, especially for finishing room walls. The use of a thin panel to make an MPP is not only to facilitate the manufacturing process, but is important to offer an appropriate range of its acoustic resistance. Also, MPPs have been made out of different materials such as a thin plastic film or a thicker acrylic panel. However, for finishing room walls, it should be thicker than at least 10 mm to make the panel stiff enough. If MPPs can be made stiffer, they would be more widely used for a sound absorbing finishing in buildings.

Another weakness of an MPP absorber is its limited frequency range of absorption. This is because a typical MPP absorber with rigid-back wall solely depends on its Helmholtz-type resonance absorption. In order to obtain wideband sound absorption including low frequencies, another absorption mechanism needs to be introduced. Therefore, in our research project we have been focussing on the following problems:

(i) Application of MPPs for room interior surfaces

It is needed to make an MPP strong enough for room interior surfaces. However, if a thick material is used to make MPPs strong, the acoustical performance will be deteriorated due to its excess acoustic resistance and reactance. Thin MPPs are advantageous to produce optimal acoustic resistance and reactance. It is important to make MPPs strong enough without deteriorating the acoustic performance.

In our project, the following treatments were considered and their acoustical effects were discussed: (1) using an elastic support to stiffen an MPP, (2) thickening an MPP to make it firm enough, and (3) attaching a honeycomb structure to MPPs to stiffen the construction. Among these three treatments, the honeycomb structure shows the most interesting effect which makes resonance absorption shift to lower frequencies and become more significant. This effect can be useful not only to stiffen an MPP but also to improve it. Regarding thickening MPPs, a trial production of thick MPPs were carried out, and it was found that there is a possibility to obtain reasonably good absorption performance with a thick MPP by changing the profile of perforations.

(ii) Multiple-leaf MPP absorbers

A permeable material is known to produce sound absorption by its acoustic flow resistance. A typical example is a single- or multiple-leaf permeable membrane. The similar absorption effect can be expected for an MPP as it can also be regarded as a permeable material with acoustic flow resistance. Based on this idea, in this study, to create an efficient sound-absorbing structure with MPPs alone, a double-leaf MPP (DLMPP) is proposed and studied. A DLMPP is composed of two MPPs set in parallel with an air-cavity in-between without a rigid back wall. In this structure, the MPP on the back side plays the role of the back wall in the conventional setting to cause the resonance-type absorption. Besides, a DLMPP can have high absorptivity on both sides to work efficiently for sound incidence from both sides, and can be effectively used as space absorbers.

The results show (1) that the resonance absorption similar to the conventional type MPP absorbers appears at medium to high frequencies and (2) that considerable “additional” absorption can be obtained at low frequencies. This low-frequency absorption is similar to that of a double-leaf permeable membrane and can be advantageous over the conventional type. A parametric study for optimal design of DLMPP as well as some experimental examples are presented, and a possibility of further development is briefly discussed.

In this paper, the above applications of MPPs for sound absorbing purposes are only considered: There are some applications for other purposes, e.g., sound insulation, floor-impact noise control etc [9], but they are not included in this paper.

2. SOME FUNDAMENTALS OF MPP ABSORBERS

The fundamentals of MPP absorbers are very well explained in detail in Maa's pioneering works[1-3]. Therefore, in this section some fundamental formulae consistently used in the present work are reviewed for the reader's convenience. According to Maa's revised formulae [3], the impedance of an MPP, $z = r - i\omega m$, is given by the following equations:

$$r = \frac{32\eta}{p\rho c}\frac{t}{d^2}\left(\sqrt{1+\frac{x^2}{32}}+\frac{\sqrt{2}}{32}x\frac{d}{t}\right) \tag{1}$$

$$\omega m = \frac{\omega t}{pc}\left(1+\frac{1}{\sqrt{1+\frac{x^2}{2}}}+0.85\frac{d}{t}\right) \tag{2}$$

where

$$x = \frac{d}{2}\sqrt{\frac{\rho\omega}{\eta}} \tag{3}$$

and d, p, t are the hole diameter, perforation ratio and thickness (=throat length) of an MPP, respectively. η is the coefficient of viscosity, ρ is the air density, c is the sound speed, and ω (=$2\pi f$, f the frequency) is the angular frequency of the sound. There is a similar expression for these quantities, e.g. in Ref [10], but since the above formulae have been experimentally validated, they are consistently used in the present work.

A typical MPP absorber consists of a single MPP and a rigid-back wall with an air-cavity in-between (cavity depth: D), which is modelled by the equivalent electrical circuit in Fig. 1 (left). A series of Helmholtz resonators is formed by the holes and the cavity, thus the typical absorption characteristics as shown in Fig. 2 have a significant absorption peak. A practical method for desigining a simple MPP absorber is discussed in detail in Maa's recent publication [11].

Maa [1-3] proposed a double-leaf MPP absorber with a rigid-back wall to broaden the absorption range. In this case, two resonators are formed and its equivalent electrical circuit becomes such as Fig. 1 (right). Maa uses the impedance for an air-layer backed by a rigid wall for the first air layer between the two MPPs, which is not strict but gives good approximation. Recently, Zhou et al [12] suggest the Impedance Transfer Method to include the impedance of the air layer between two MPPs correctly and conclude the method offers better prediction.

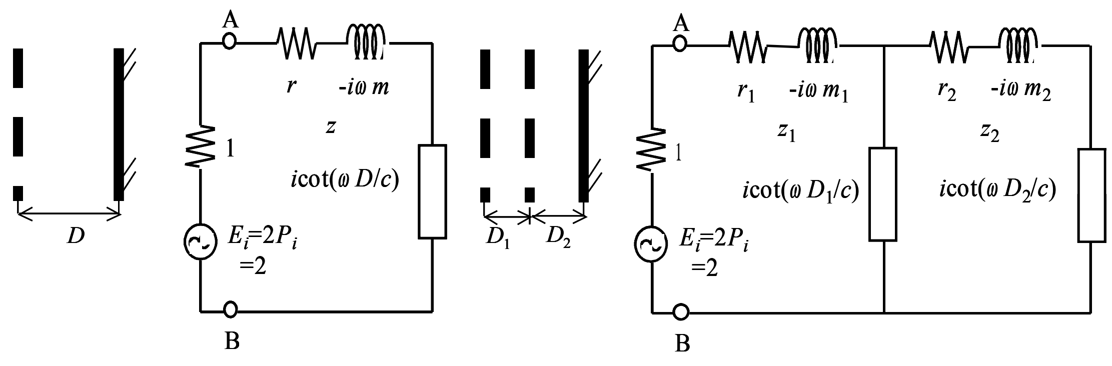

Figure 1. An electro-acoustical equivalent circuits for a typical single MPP absorber (left) and double MPP absorber (right). All impedances are normalised to air impedance ρc.

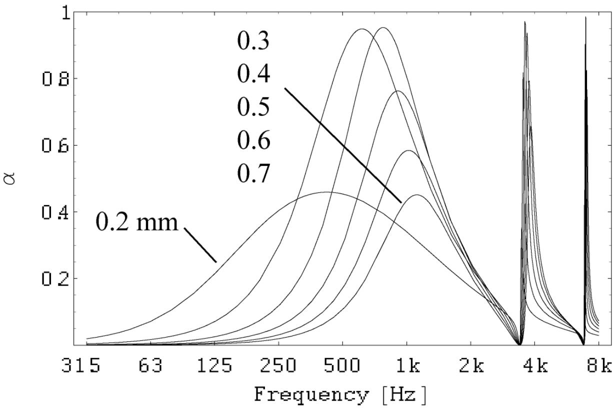

Figure 2. Examples of absorption characteristics of a typical simple MPP absorber. Hole diameter as a parameter. Hole separation 3.5 mm, thickness 0.4 mm, air cavity depth 50mm.

Maa's formulae are based on the wave propagation in a tube, but a new model was recently proposed by Atalla et al [13]. The model deals with an MPP as a rigid porous material. It is rather complicated and beyond the scope of this paper, but it can be applied to various complicated configurations. Interested readers should refer to [13].

3. APPLICATION OF MPPS FOR ROOM INTERIOR SURFACES

It is necessary to make an MPP strong enough to be used for room interior surfaces. However, if a thick material is used to make strong MPPs, the acoustic performance will be deteriorated due to its excess acoustic resistance and reactance. Thin MPPs are advantageous to produce optimal acoustic resistance and reactance. It is important to make MPPs strong enough without deteriorating the acoustic performance.

In this project, the following treatments were considered and their acoustical effects were discussed: (1) using an elastic support to stiffen an MPP, (2) thickening an MPP to make it firm enough, and (3) attaching a honeycomb structure to MPPs to stiffen the construction.

Among these three treatments, the honeycomb structure shows an interesting effect which makes resonance absorption shift to lower frequencies and become more significant. This effect can be useful not only to stiffen an MPP but to also improve its acoustical performance. Regarding thickening an MPP, a trial production of thick MPPs were carried out and it was found that there is a possibility to obtain reasonably good absorption performance with a thick MPP by changing the profile of perforation.

3.1 Effect of an elastic support

In order to use MPPs as an interior finish of room walls, they must be fixed to an exterior wall or structural body by ribs, joists or other supporting elements. In previous studies, the effect of such supporting elements have been neglected, neither has the effect of sound induced vibration of an MPP leaf itself been discussed. Regarding the sound induced vibration, the authors have published the results of a simplified analysis in Ref [14]: the vibration can affect the absorption peak if the MPP is very lightweight, but in many cases the effect is not serious. However, in the same study the effect of the support was not considered. The supporting system can work as a spring to form an additional mass-spring system, of which the resonance can cause a significant effect.

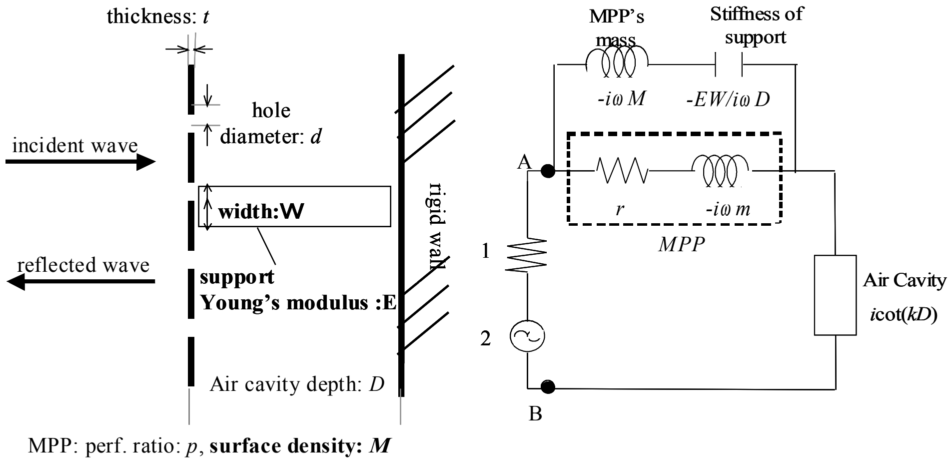

Figure 3. Model of an MPP absorber with an elastic support (left), and its electro-acoustical equivalent circuit for theoretical analysis (right) [15]. All impedances in the circuit are normalised to the air impedance, ρc, except for the MPP's mass and stiffness of the support.

Figure 3 shows the model of an MPP absorber with an elastic support and its equivalent electrical circuit. In the analysis, the total impedance of the system is derived from the equivalent circuit to obtain the absorption coefficient.

An example of the calculated result for a square-sectioned rib-like elastic support of 50 mm width is shown in Fig. 4. The effect of the elastic support appears around the absorption peak: When the support is stiff (Young's modulus: 10^9 Pa), the peak is raised to nearly unity, but when the Young's modulus is reduced to 10^7 Pa, the peak is lowered and a significant dip occurs. This dip takes place at the resonance frequency of the system consisting of the MPP's mass and the stiffness of the support.

Unless this resonance frequency is in the absorption peak region, the effect is not very significant. A stiff support can somewhat increase the peak absorption, but the material of support should be chosen so that the resonance does not occur in the absorption peak region.

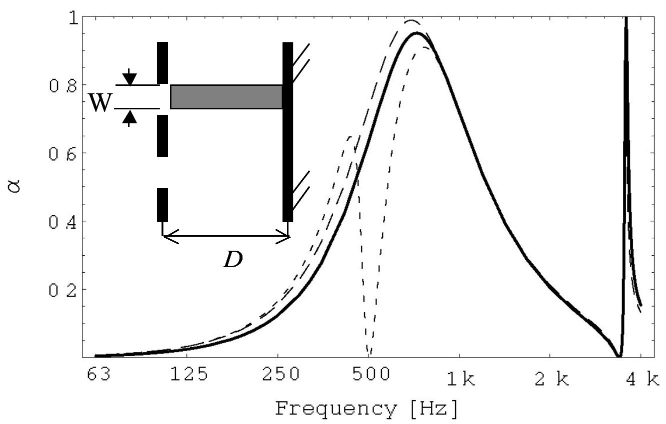

Figure 4. Effect of the Young's modulus of the elastic support on the absorption coefficient [15]. The Young's moduli are 10^7 (dotted line) and 10^9 (dashed line) Pa, compared with an MPP without support (solid line). MPP's parameters are: hole diameter 0.4mm, thickness 0.4mm, perforation ratio 0.8%, cavity depth 0.05m, surface density 1kg/m^2. The elastic support is dimensioned to W (width)=0.05m and D (cavity depth)=0.05m.

3.2 Analysis of thick MPPs

MPPs are usually made of thin panels. This is mainly for manufacture ease since making submillimetre perforations in thick panels is quite difficult. Besides, small perforations in a thick panel tend to produce a too large acoustic resistance.

Figure 5 shows an example of absorption coefficient of a thick MPP panel, calculated by Eqs (1)-(3). The absorption characteristics of a typical thin MPP (hole diameter 0.4 mm and thickness 0.4 mm) are dramatically changed if the thickness is increased to 10 mm: the peak shifts to much lower frequencies and the value becomes very low. If the hole diameter is enlarged to 4 mm in the case of 10 mm of thickness, the characteristics greatly improve with a high peak value, however, the frequency range of the effective absorption becomes very narrow. These examples show the difficulty in making effective wideband absorbers using thick MPPs. This is mainly caused by the excess acoustic resistance or reactance of their holes. Therefore, it is needed to adjust the acoustic resistance and/or reactance of the holes to their optimal values by some means.

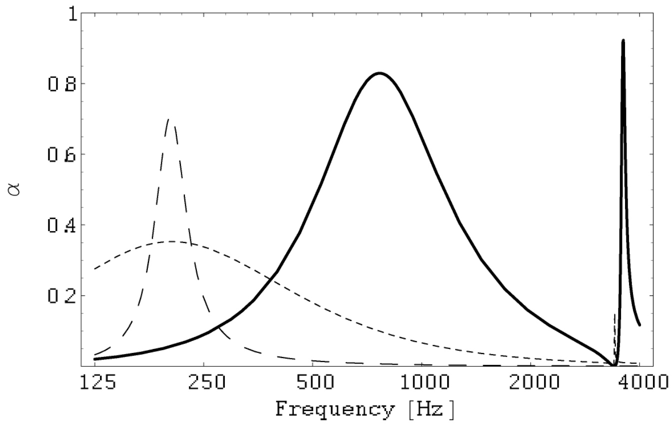

Figure 5. Calculated example of the absorption characteristics of a thick MPP [15,16]. Solid line: hole diameter 0.4mm, thickness 0.4mm; Dotted line: hole diameter 0.4mm, thickness 10mm; Dashed line: hole diameter 4mm, thickness 10 mm. Other parameters: perforation ratio 1.0%, cavity depth 0.05m.

As a pilot study, trial production of thick MPPs was made with normal straight and tapered perforations [15,16]. Since the sound absorption performance of thick MPPs deteriorates due to their high acoustic resistance and/or reactance, it is difficult to improve their performance by simply adjusting the hole diameter or perforation ratio. However, there is a possibility to improve their acoustic performance by adjusting the hole shape or profile. Randeberg [17] examined MPPs with horn-shaped orifices, and suggests its possibility to improve the acoustical performance despite its longer throat than ordinary MPPs. Therefore, there can be a possibility to adjust the acoustic resistance and/or reactance with orifice design in the case of a thicker panel as well.

The results of the normal absorption coefficient measured in an impedance tube (using the transfer function method: ISO 10354-2) of three specimens (thickness: 10 mm) are shown in Fig. 6. The specimen with 0.5 mm perforation shows quite low absorptivity. A second specimen with 0.8 mm perforation shows much higher peak absorptivity, but with a narrower absorption region: large perforations cause large acoustic reactance, which makes the absorption peak sharper. The specimen with a tapered perforation (hole diameter is varied from 0.8 mm at the exposed side surface to 0.5 mm at the back side surface) shows a reasonably high absorption peak and wide frequency absorptive range. This suggests that even a thick MPP can offer reasonably high absorption performance with tapered perforations.

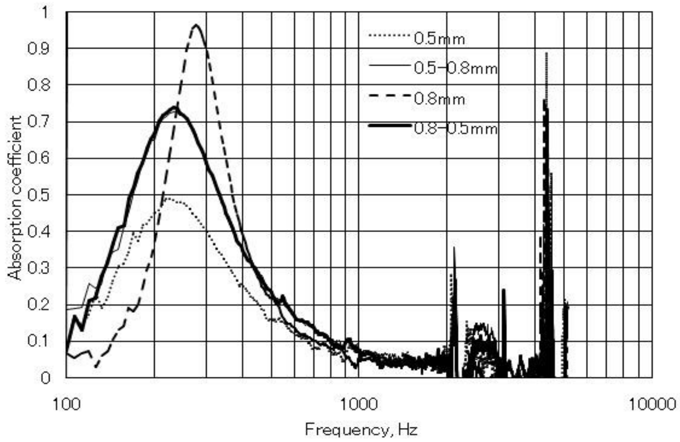

Figure 6. Results of the measured normal absorption coefficients of thick MPP specimens [15,16]. All specimens are 10mm thick. Hole diameters are: 0.5mm (dotted line), 0.8mm (dashed line), and tapered hole with diameter 0.8-0.5 mm (thick line) and 0.5-0.8mm (thin line: overlapped with thick line). The depths of the air-back cavity were determined so that the resonance frequencies became around 250 Hz. The cut-off frequency of the test tube is 2 kHz.

Interestingly, the tapered specimen showed exactly the same absorption characteristics when it was reversed (i.e., the hole diameter was 0.5 mm on the exposed side, and 0.8 mm on the back side), as shown in Fig. 6. This infers that only the resistance and reactance affect the characteristics, and there is no such an effect like 'impedance matching'. As Randeberg[17] suggested, the parameters of hole profile do not have a monotonic effect and each has its optimal value. Further investigation is needed to clarify the effect of hole profile.

3.3 Effect of a honeycomb structure attached behind an MPP

Although a thick MPP has proved its potential as a sound absorbing material, manufacturing a thick MPP is still difficult and costly. Considering the acoustical performance as well as the manufacturing process, thin MPPs are much more efficient. Therefore, it will be the more effective if it is possible to strengthen MPPs whilst keeping them as thin as typical MPPs. In this section, the attachment of a honeycomb structure behind an MPP is investigated, and appears to be a promising and effective solution [15,18,19].

A honeycomb structure can provide strength, yet it is quite lightweight. A honeycomb is known to have an acoustical effect that can improve the absorptivity of porous layers when attached behind the porous layer [20]. This effect is attributed to a honeycomb in the cavity resulting in an acoustical condition similar to a local reaction. A similar effect can also be expected when it is used in the back cavity of MPP absorbers. A model of an MPP absorber with a honeycomb structure behind the MPP and its electro-acoustical equivalent circuit for analysis is shown in Fig. 7. The model was built by considering the results of a preliminary experiment made in a small parallelepiped reverberation chamber and impedance tube. The honeycomb is modelled as many tubes in which traditional theory of sound propagation in tubes is applied [21]. The impedance of the air layer (of thickness D_2) behind the honeycomb is described by $z_t = i\cot(k_0 D_2 \cos\theta)$ including angle factor ($k_0=\omega/c$: wave number, θ: angle of incidence). Thus, the impedance of the honeycomb (of thickness D_1), z_h, with air layer behind as the terminal impedance, z_t, is given by:

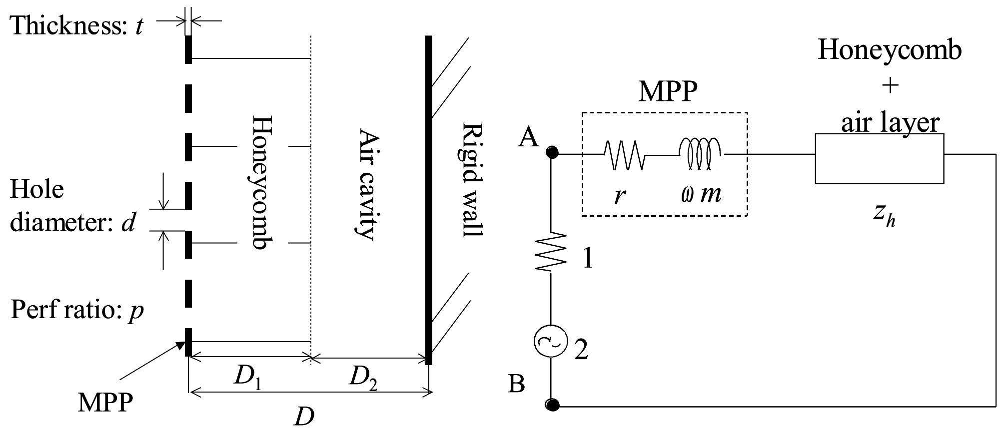

Figure 7. Model of an MPP absorber with a honeycomb structure behind the MPP (left) and its electro-acoustical equivalent circuit for analysis (right) [15,18,19].

$$z_h = \frac{z_t - i \tan k_0 D_1}{1 - i z_t \tan k_0 D_1} \tag{4}$$

Since the honeycomb does not affect the normal absorption coefficient both in calculated and measured results, a comparison of the computational and experimental results of reverberation sound absorption coefficient is shown in Fig. 8. The results show that the peak of reverberation sound absorption coefficient becomes higher and shifted to lower frequencies. The experimental results shown in this figure are obtained from a separate experiment carried out in a reverberation chamber of volume 164 m^3. As the test specimen was small (3.24 m^2), severe area effect is observed and the value exceeds unity at some frequencies. Therefore, the theoretical and experimental results do not agree quantitatively, however, the general trend of the experimental results are confirmed by the theoretical results.

The reason for the quantitative discrepancy is also owing to the extra resistance caused by the honeycomb: if the resistance of the honeycomb estimated from its absorption coefficient is included in the calculation, the theory offers better prediction than the calculation with one estimated by the well-known theory [22]. Thus, the model can appropriately give a physical insight into the acoustical phenomenon caused by the honeycomb. This suggests that the honeycomb makes the back cavity ‘locally reactive’ so that the characteristics approach those of normal incidence. Regarding the size of honeycomb cells, it was shown to have only negligible effect when the cell size is less than 50 mm.

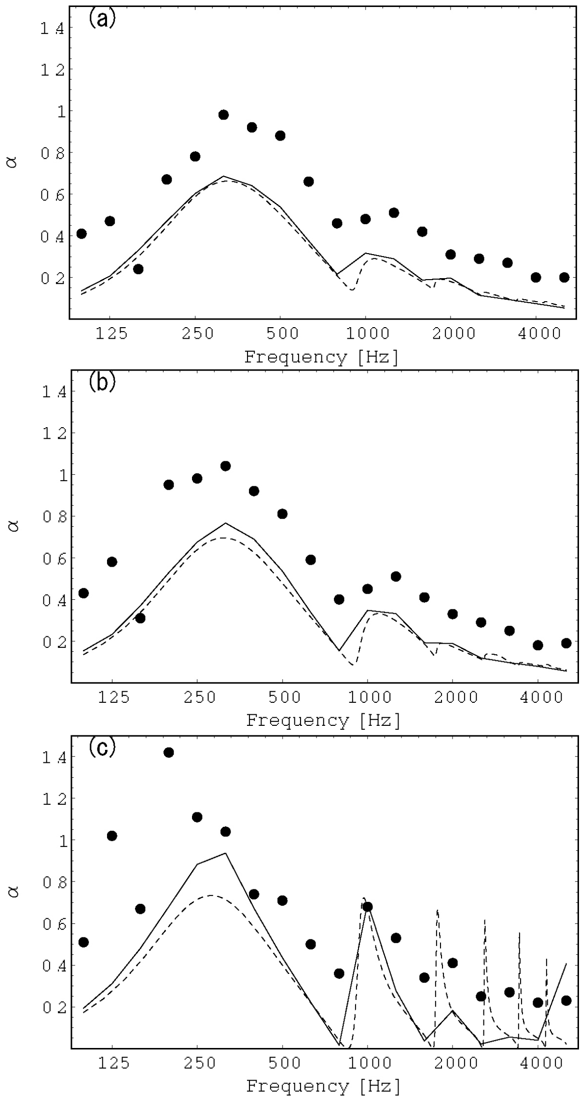

Figure 8. Comparison of the measured and calculated results [15,18,19]. Dots indicate the measured results, dashed line the calculated results with theoretical value of the acoustic resistance of the honeycomb, and solid line indicates the calculated results with the honeycomb resistance estimated from its absorption coefficients. (a) D_1=50, D_2=150, (b) D_1=100, D_2=100, and (c) D_1=200, D_2=0 [mm]. MPP is of 0.5 mm thick with 0.5 mm perforation (perforation ratio: 0.64%).

4. MULTIPLE-LEAF MPP ABSORBERS

Multiple-leaf MPP absorbers were first proposed by Maa [1-3]: Maa proposed a double-leaf MPP backed by a rigid-back wall with an air-cavity. This absorber is intended to produce two resonators so that a broader absorption frequency range is obtained. However, as long as MPP has a back wall, its absorption is caused only by the Helmholtz resonance and this results in the absorption limited to its resonance frequency region.

In order to broaden the frequency range, especially to extend it to lower frequencies, it is needed to introduce another absorption mechanism that is effective at low frequencies. Acoustic permeability of MPPs can possibly be utilised for this purpose.

A permeable material is known to produce sound absorption by its acoustic flow resistance. A typical example is a single- or multiple-leaf permeable membrane [23-25], which shows moderate absorption (absorbing up to 50% of incident energy) at low frequencies. A similar absorption effect can be expected for MPPs, as an MPP can also be regarded as a permeable material with acoustic flow resistance. Therefore, in the authors' previous study [26], to create an efficient sound-absorbing structure with MPPs alone, a double-leaf MPP *without* a back wall (DLMPP) was proposed and studied with a simplified model.

A DLMPP is composed of two MPPs, placed in parallel with an air-cavity in-between, without a rigid back wall. In this structure, the MPP on the back side plays the role of the back wall in the conventional setting to form the Helmholtz resonator. Thus, a DLMPP is supposed to work as a Helmholtz type absorber at mid-high frequencies, as well as, a permeable structure with acoustic resistance to absorb sound energy at low frequencies. A DLMPP works for sound incident on both sides and can be effectively used as space absorbers or a sound-absorbing screen/partition. This feature can be useful in various situations in which a rigid backing is not available for setting MPPs against and also it can enable MPPs for application to different parts of interior in buildings.

In the previous paper [26], an electrical equivalent circuit model was used for simplified analysis. Although equivalent circuit analyses are useful to gain a physical insight into the absorption mechanism, it is inevitable to use an approximate expression for air cavity and this leads to exaggeration of resonance behaviour causing an error in the results. Therefore, the authors later revisited the acoustic properties of DLMPPs with strict theory using a Helmholtz integral formalism. In this section, main results from the authors' recent studies on DLMPPs are shown: the theoretical solution derived from a Helmholtz integral formalism is introduced. Numerical examples, as well as some experimental examples are shown to demonstrate the effect of the parameters on the acoustic properties of a DLMPP.

4.1 Theoretical considerations

Figure 9 shows the model for a DLMPP. MPP1 and MPP2 are of infinite extent, and they are placed in parallel with an air-cavity of depth D in-between. A plane sound wave of unit pressure amplitude is assumed to be obliquely incident upon MPP1. Both leaves have submillimetre perforation which is characterised by the following parameters: hole diameter (d), perforation ratio (p), and panel thickness (=throat length, t).

A Helmholtz integral is used to represent the pressures on the exposed side surface of MPP1 and the back side surface of MPP2. The sound field in the cavity is represented in the standard form, which gives the pressures on the back side surface of MPP1 and the front surface of MPP2. They include the impedance of MPPs, and are coupled with the sound induced vibration of the leaves.

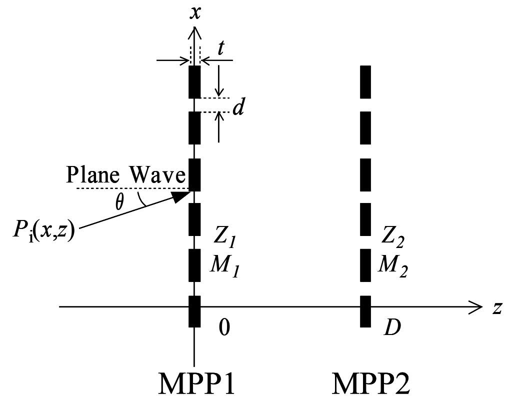

Figure 9. Model of a DLMPP for theoretical analyses. Z_1 and Z_2 are the impedances, and M_1 and M_2 are the surface densities of MPP1 and 2, respectively.

Solving all the equation gives the reflected pressure p_r and transmitted pressure p_t as:

$$p_r(x,z) = \left[1 + \frac{i\rho_0\omega^2\Gamma_1(k_0\sin\theta) - k_0A_{m1}S\{a_1\Gamma_1(k_0\sin\theta) + a_2\Gamma_2(k_0\sin\theta) + a_3\}}{k_0\cos\theta}\right] \times \exp[i(k_0x\sin\theta - k_0z\cos\theta)] \tag{5}$$

$$p_t(x,z) = \frac{-i\rho_0\omega^2\Gamma_2(k_0\sin\theta) + k_0A_{m2}Q\{b_1\Gamma_1(k_0\sin\theta) + b_2\Gamma_2(k_0\sin\theta) + b_3\}}{k_0\cos\theta} \times \exp[i(k_0x\sin\theta + k_0z\cos\theta)] \tag{6}$$

The parameters $\Gamma_{1,2}$, Q, S, $A_{m1,2}$, $a_{1,2,3}$, and $b_{1,2,3}$ are all somewhat complicated functions including the parameters of MPP1,2 and air cavity depth, etc. More information about the formulation will be found in Ref [27].

The absorption and transmission coefficients are given as $\alpha = 1-|p_r|^2$ and $\tau = |p_t|^2$, respectively. As a DLMPP is a space absorber and it causes sound transmission, it is necessary to eliminate the effect of transmission from the absorption coefficient for evaluating its absorption efficiency. Therefore, the difference of these coefficients, $\alpha-\tau$, which indicates the ratio of the energy dissipated in the system, is used to evaluate the absorptivity unless otherwise noted.

4.3 Numerical examples

4.3.1 Experimental validation

Experiments were carried out to validate the present theory, and also to confirm the efficiency of DLMPP absorbers [28]. The experimental results for two specimens (Table 1) are presented here in comparison with theoretical results. Specimen A was made with a commercial product of steel MPP ceiling panel, whereas Specimen B was made with a microperforated polycarbonate film. The film used in Specimen B is originally prepared for non-acoustical purposes and is not well optimised for sound absorption. Specimen B, therefore, was not expected to show efficient absorption, however it was also measured in the experiment to give a variety in measured data to be compared with the present theory. The measurements were made in a reverberation chamber in accordance with JIS A 1409 (ISO 354 compatible) except for the arrangement of specimen in a chamber. As the specimens were supposed to be used as a space absorber, they were suspended from the ceiling in the middle of the reverberation chamber. According to the previous study on membrane-type space absorbers [29], if a space absorber has the same characteristics on the both side surfaces, the theoretical value of $\alpha - \tau$ for one side surface (of the absorber of infinite extent) should correspond to the measured reverberation absorption coefficient when it is suspended in the room (except for the area effect). Therefore, the values calculated for the two specimens with the present theory are directly compared with the above experimental results.

Table 1. Description of specimens used in the experiment. Note that MPP1 and 2 have the same parameters.

Specimen	MPP1, MPP2				Area (one side) (m^2)
	Hole diameter (mm)	Thickness (mm)	Perforation ratio (%)	Material (surface density)	
A	0.5	0.5	0.64	Steel (ca 4.0 kg/m^2)	1.9
B	0.2	0.2	0.785	Polycarbonate (ca 0.12 kg/m^2)	2.1

*Air cavity depth was 150 mm for both Specimen A and B.

Figure 10 compares the experimental and theoretical results for Specimens A and B. In both cases the experimental values are larger than the theoretical values. Particularly at the peak in Specimen A the difference becomes large. This is due to the small area of the specimens, which caused the area effect so that the peak was enhanced. However, the present theory describes the behaviour of the experimental values and reasonable agreement between theoretical and experimental results are observed at most frequencies. Thus, the present theory can be useful to predict and discuss the acoustical properties of a DLMPP absorber. More experimental results and further discussion are presented in Ref [28].

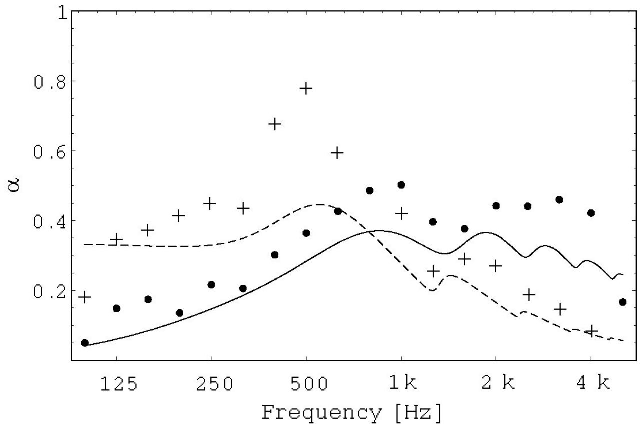

Figure 10. Comparison of experimental and theoretical results of absorption coefficient of a DLMPP [28]. Specimen A: $d = t$ =0.5 mm, p =0.64%, D=150 mm. Dashed line: theory, +: experiment. Specimen B: $d = t$ =0.2 mm, p =0.785%, D=150 mm. Solid line: theory, dots: experiment.

4.3.2 Comparison with equivalent circuit theory

Figure 11 shows an example of the absorptivity (α–τ) of a DLMPP calculated by the present theory (Eqs (5) and (6)), in comparison with that calculated by the electro-acoustical equivalent circuit model [26]. As described previously, the equivalent model tends to exaggerate the resonance behaviour of the air cavity, so that the absorption peak tends to become larger. Also, the resonance peak appears at somewhat lower frequencies than the present theory. This implies that the equivalent circuit analysis can overestimate the resonance absorption, but as shown in the figure, there is no difference at low frequencies. The low frequency absorption is caused by the acoustic resistance of the MPP leaves and the air cavity does not contribute.

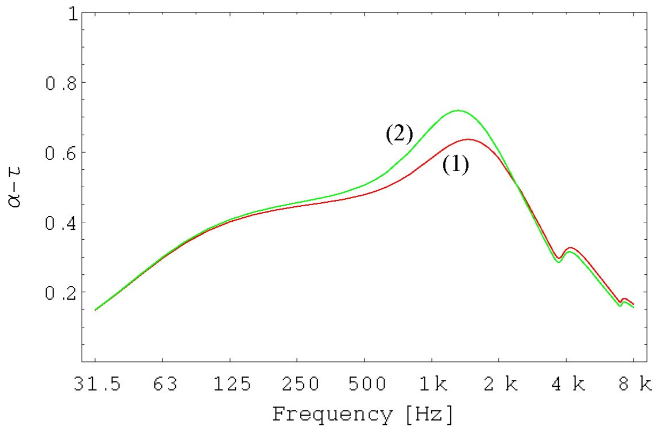

Figure 11. Comparison of the field-incidence averaged absorptivity (α–τ) calculated by the present theory and equivalent circuit theory for a DLMPP. Hole diameter: 0.2 mm, thickness: 0.4 mm, perforation ratio: 1.0%, surface density: 1.0 kg/m^2, for both MPP1 and 2. Cavity depth: 50 mm. (1) Present theory, (2) Equivalent circuit theory.

4.3.3 Parametric survey

Figure 12 shows the effect of the hole diameter of MPPs on the absorption characteristics (α–τ) of a DLMPP. In this example, the absorption peak is maximised when the diameter is 0.15 mm. Smaller or larger diameters give lower peak values. At low frequencies the absorptivity becomes the highest at d=0.2 mm, but it decreases at around 125 Hz. This is because the acoustic resistance of the leaves is decreased by the effect of their sound induced vibration. Thus, the optimal value of each parameter changes accordingly by the effect of the vibration. These tendencies depend on the behaviour of the acoustic resistance of the MPP leaves and the optimal value of each parameter depends on the other parameters. Therefore, similar tendencies are observed when the other parameters, e.g., thickness and perforation ratio, are changed. As pointed out in the author's previous study, the optimal value of the system's total acoustic resistance is around $2\rho c$ to maximise the peak absorption, and $3\rho c$ to maximise the low frequency absorption [26]. Regarding the perforation ratio, it also affects the peak frequency: larger perforation ratio gives higher peak frequency, though too large perforation ratio cannot offer effective peak absorption (Fig. 13). The peak frequency can also be controlled by the cavity depth (Fig. 14).

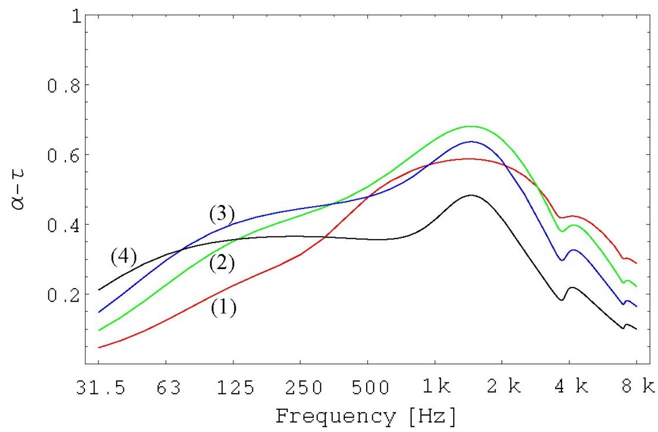

Figure 12. Effect of hole diameter on the field-incidence-averaged absorptivity ($\alpha\!-\!\tau$) of a DLMPP. Hole diameter d=0.1 (1), 0.15 (2), 0.2 (3), and 0.3 (4) mm. Two leaves are given the same parameters. Thickness: 0.4 mm, Perforation ratio: 1.0%, Surface density: 1.0 kg/m^2, Cavity depth: 50mm

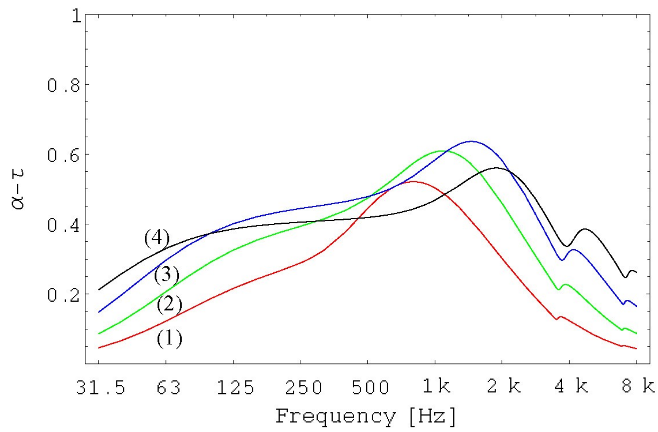

Figure 13. Effect of perforation ratio on the field-incidence-averaged absorptivity ($\alpha\!-\!\tau$) of a DLMPP. Perforation ratio p= 0.25% (1), 0.5% (2), 1.0% (3), and 2.0%. Two leaves are given the same parameters. Hole diameter: 0.2 mm, Thickness: 0.4 mm, Surface density: 1.0 kg/m^2, Cavity depth: 50mm.

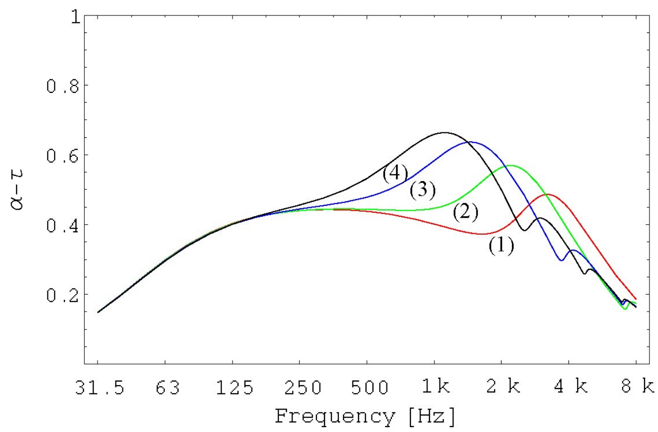

Figure 14. Effect of cavity depth on the field-incidence-averaged absorptivity ($\alpha\!-\!\tau$) of a DLMPP. Cavity depth D= 12.5 (1), 25 (2), 50 (3), and 75 (4) mm. Two leaves are given the same parameters. Hole diameter: 0.2 mm, Perforation ratio: 1.0%, Thickness: 0.4 mm, Surface density: 1.0 kg/m^2.

Since the low frequency absorption depends on the total acoustic resistance, not only those MPP parameters but the mass of the MPP leaves is also important. As known in other permeable structures such as a permeable membrane, the acoustic resistance decreases with decreasing its surface density owing to the sound induced vibration. Figure 15 shows the effect of the surface density of MPPs on the absorption characteristics of a DLMPP. Lightweight MPPs give very small absorption at low frequencies. When the surface density is larger than 2.0 kg/m^2, the characteristics are almost the same as those for immobile leaves. Therefore, to make a DLMPP effective at low frequencies, it is necessary to use a MPP with appropriate weight.

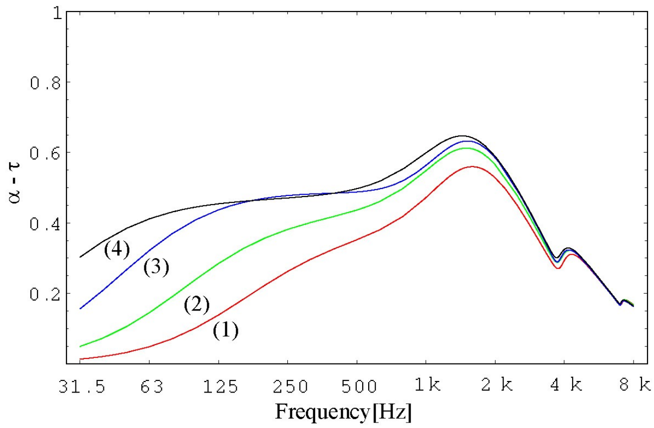

Figure 15. Effect of surface density of MPPs on the field-incidence-averaged absorptivity ($\alpha{-}\tau$) of a DLMPP. Surface density M= 0.25 (1), 0.5 (2), 1.0 (3) and 2.0 (4) kg/m^2. Two leaves are given the same parameters. Hole diameter: 0.2 mm, Perforation ratio: 1.0%, Thickness: 0.4 mm. Cavity depth: 50 mm.

4.3.4 Further considerations

Although a DLMPP shows a resonance absorption peak similar to a conventional MPP absorber, the peak is not as significant as of a conventional type. Enhancing the resonance peak of a DLMPP can be possible by adjusting the acoustic impedance of the second leaf. However, this can result in lower absorptivity at low frequencies and insufficient absorptivity for the sound incident from behind (on the second leaf). Adding one more MPP to a DLMPP to make a triple-leaf MPP absorber (TLMPP), two resonance peaks appear. Thus, the peak can be broadened and absorption range can be somewhat extended to higher frequencies [30,31].

Another possibility to improve the absorptivity of a DLMPP is the use of a honeycomb structure. When a honeycomb is placed in the air cavity of a DLMPP, the same effect as observed as in a conventional MPP absorber with a honeycomb. The absorption peak is shifted to lower frequencies and becomes larger. Examples of experimental results are shown in Fig. 16 in comparison with a DLMPP without a honeycomb [28]. The MPP leaves are the same as Specimens A and B in the experiment in section 4.3.1. The MPPs in Specimen B were not designed for acoustical purposes and not optimised. However, with the effect of the honeycomb it shows reasonably high absorptivity, particularly at mid-low frequencies around 500 Hz. In Specimen A, the effect of the honeycomb is smaller than in Specimen B.

Specimen A is fairly well optimised and shows high absorptivity at the peak. In this case, the increase of the peak value by the effect of a honeycomb can be less significant.

Other configurations, including a combination with an ordinary perforated panel, impermeable and/or permeable materials, have also been studied - there is a possibility to find an efficient combination for a specific purpose [32,33].

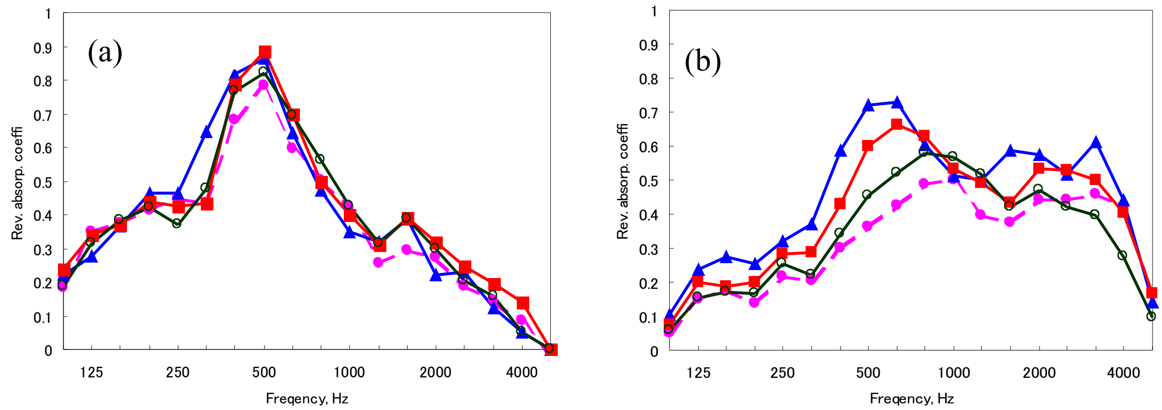

Figure 16. Effect of a honeycomb in the air-cavity on the absorptivity of a DLMPP (experimental results) [28]. (a) Hole diameter: 0.5 mm, thickness: 0.5 mm, perforation ratio: 0.64 % (Specimen A), (b) Hole diameter: 0.2 mm, thickness: 0.2 mm, perforation ratio: 0.785 % (Specimen B). Cavity depth: 150 mm. Honeycomb thickness: 0 mm (closed circle), 50 mm (open circle), 100 mm (square), and 150 mm (triangle). The honeycomb structure is of hexagonal cell of 20 mm diagonal, and is made of polycarbonate.

5. CONCLUDING REMARK

In this paper, the authors' recent work on the application of microperforated panels and sheet materials (MPPs) have been reviewed. These applications are mainly for building purposes, especially for using MPPs for room interior surfaces and absorption treatment in rooms. However, some of them can be also applied to other purposes. MPPs can be made of quite wide variety of materials which allows us attractive alternatives for sound absorption treatment with flexibility and designablity. The authors expect that MPPs will become more widely used in various purposes and will continue to investigate further development in application studies.

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