



Article title: Space sound absorbers with next-generation materials: additional sound absorption for post-pandemic challenges in indoor acoustic environments

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Coverletter to the revised version

Kobe, 22 October 2020

Dear Editors and Reviewers

We appreciate that we have received two reviews from the reviewers, and open comments on our preprint, which we found very useful and helpful for us to improve the quality of our paper.

Here, we are pleased to submit the revised version addressing the all points raised in the reviews and open comments. The revised sentences are marked with red fonts. Also, we summarise the points of revision below:

From the comments by Gioia Fusaro:

1. Page 5, raw 8, *It has been reported that masks affect the acoustic characteristics of voices rather drastically [3].*

From the Literature Review reference, it is clear how the safety mask use affects the speech intelligibility; however, it seems that also the SPL of the voices is quite lowered down. Perhaps I would include some discussion or considerations on how the designed acoustic systems for the post-pandemic “new style” indoor conditions would answer to this issue.

Thank you very much for the comments. We added some comments on the results from Ref [3] as follows (added sentences are italicised):

According to the results [3], the effect of a face mask appears at 1 kHz and above as reduction of 3-7 dB ca., which is smaller than that of a face shield which is more drastic (3-12 dB): the authors consider that both the effect is considered to be large. These results indicate that face shields and masks reduce high frequency components of voices, which affects the loudness and timbre, and eventually deteriorates. This point is clearly showed in their demonstration recordings available in [3]. Not only is there an effect on speech intelligibility, but also on the sound quality of musical performances. Although in music this may be a matter of subjective preference for performers and listeners, it becomes more than a matter of individual preference when the intelligibility of speech is affected. *According to the authors' questionnaire survey (performed in June 2020, unpublished) to university students, some students pointed out that face masks deteriorates speech intelligibility and speech communication quality. As most people experienced that it is rather difficult to speak clearly with face masks, which is also another cause of effect due to a face mask on the*

speech intelligibility. Therefore, regarding speech intelligibility, it is already deteriorated in many cases before it is affected by room acoustic characteristics. In this respect, improving the room acoustic condition can save the further deterioration of speech communication ability.

2. Page 9, raw 22, *observed* should be spelt as observed

Many thanks for this comment. We have corrected.

3. Page 13, raw 23, *In such cases, a 3D-PMA can be more efficient, as the equivalent sound absorption areas are **higher in the case of the 3D-MPA**.*

I think it would sound better written as something like “In such cases, a 3D-PMA can be more efficient, as its equivalent sound absorption areas are higher than standard systems with comparable volume.”

Many thanks for your suggestion. We agree with the reviewer’s suggestion, and have amended this sentence as suggested.

4. Page 14, raw 12, *However, by introducing this additional sound absorption, the acoustics of the room can be somewhat improved, even though **some elaboration** will be needed.*

I think that adding some words about which sort of elaboration the authors mean would give to the text more completeness

Thank you very much for this comment. We added the following sentences after this part:
For example, when these absorbers are used among the users of a room, they should be designed not to disturb the users. Such a consideration will need some more design consideration, such as a shape and colour, etc, based on ergonomics. Some elaboration will be needed also in adding additional function: e.g., the sound-absorbing lampshade proposed in [] has been improved to provide better luminescence distribution, however, may need some more design consideration to optimise it as a lighting equipment according to rooms of different purposes.

5. Page 14, raws 28-33, *In this study, we introduced and summarised the nature of three-dimensional microperforated and permeable membrane space sound absorbers of various types. We also **demonstrated** their typical absorptive characteristics. As these absorbers*

*have displayed not only practical absorption performance, but also a wide applicability and **the additional value of aesthetic designability**, they may pose a more efficient solution to the acoustical challenges of 'new style' built environments.*

I think you should specify that the data analysis work was done previously as it could be mistaken from the audience as your key research question. Whereas I think the key point of this paper is the “**the additional value of aesthetic designability**” which, in my opinion, could be further highlighted and discussed (perhaps adding some more applicability examples or including ergonomics consideration).

Thank you very much for pointing out our rather misleading paragraph. We have amended this paragraph as follows:

*In this study, we introduced and summarised the nature of three-dimensional microperforated and permeable membrane space sound absorbers of various types, **which resulted from our on-going project for these several years. We presented their typical absorptive characteristics out of the published results from our projects.** As these absorbers have displayed not only practical absorption performance, but also a wide applicability and **the potential value of aesthetic designability**. By adding some considerations about ergonomics, lighting, and other purpose-oriented design considerations, we believe that these absorbers can offer an alternative solution to the acoustic challenges of the "new style" built environment.*

From the comments by Tin Obermann

Response and summary of revision:

Many thanks for your thoughtful and constructive comments on our commentary paper. We have revised the manuscript accordingly to address all your concerns and summarise the revisions as follows:

- As for the point about the C-19 connection, this context is necessary because these acoustic problems discussed in this paper probably would not occur without the pandemic caused by C-19. We remarked out this point in Introduction.
- Although suspended sound absorbers from the ceiling have been used in the past, they are more difficult to set up and remove than floor-mounted ones, and the authors pointed out that they are not as flexible as floor-mounted ones. It is emphasized in the text that this flexibility will become even more important for future interior planning.
- For the historical background, the use of resonant absorption has been practiced for a long time, which is briefly mentioned in this article by citing a book by Bruel. Since

there is a very large number of studies on ongoing metamaterials, we have narrowed the discussion to MPPs and cited some review articles by Herrin et al that may be useful to readers. Whether or not it is for residential use is based on the premise of adding value-added applications for residential use, taking into account that it is necessary to select an appropriate sound absorption treatment according to the scale of the target space.

- Because the hygienic properties of materials other than plate or membrane materials depend on their characteristics, the authors suggest that there may be other materials that can be used, as pointed out by the reviewer.
- As pointed out, the effectiveness of this proposal depends largely on the size of the space and the existing sound absorption capacity. Therefore, it is pointed out that there may be cases that are not as simple as those discussed in "Simple Examples", and it is suggested that there is a limit to the application of this paper.
- A more detailed explanation of the face-covering issue has been added, as noted by another reviewer, with some limited discussion of its relationship to 3D-PMA.
- The title has been revised to suggest that this point is based on considerations from the Japanese context. The title is now: Some considerations on the use of space sound absorbers with next-generation materials reflecting COVID situations in Japan : additional sound absorption for post-pandemic challenges in indoor acoustic environments

From the Open Comments

Francesco Aletta:

I think this is an important and timely contribution - one aspect that could be further elaborated upon in my view is the fact that the modular elements proposed in these study offer the necessary flexibility for making different spatial arrangements in indoor contexts; they also represent a "reversible" design solution. This is important to highlight as we don't know what future scenarios we are facing due to the constant evolution of the pandemic.

Response:

Thank you for your positive comments. As you pointed out, the sound absorbers discussed here are movable, so they can be rearranged as needed. In addition, it can be easily removed when it is no longer needed. Given the difficulty of predicting how long the 'new style' will last, we believe that a method of controlling the sound field without major modifications to existing buildings can be used. In other words, it is a flexible and reversible design method. This is a concept that will be required in some form for newly designed buildings. We will try to explain these points in the text.

In response to this comment, we added the last paragraph of the Concluding remarks:

As pointed above, the sound absorbers are movable, so they can be rearranged as needed. In addition, it can be easily removed when it is no longer needed. Given the difficulty of predicting how long the 'new style' will last, it is considered that a method of controlling the sound field without major modifications to existing buildings will be needed. This can be a concept that will be required in some form for newly designed buildings as well. In any case, such a flexible and reversible design can be considered of some use, even if the 'new style' may only last short and the lifestyle gets back in pre-pandemic style.

A sentence of similar meaning is added also in the subsection relevant to space sound absorbers.

Other revision:

Article note is revised to include new information: the Guidelines for operation of events of performing arts etc were in part revised in September 2020.

Coverletter to the original version

Kobe, 7 Sep. 2020

Dear Editors

We are pleased to submit a manuscript entitled as 'Space sound absorbers with next-generation materials: additional sound absorption for post-pandemic challenges in indoor acoustic environments,' for a possible publication as an open commentary in UCL Open Environment.

This work is a purely commentary, overviewing the main results from our recent research project on three-dimensional microperforated panel (MPP) / permeable membrane (PM) space sound absorbers to propose the use of them for resolving acoustical challenges in built environment, which are likely to be caused in the post-pandemic 'new style'.

First, we discussed the acoustical challenges in the post-pandemic 'new style' in which various acoustical deficiencies can be caused by new operations in built environments, due to social distancing. Next, we give some general ideas on sound absorption technology. Then, we give a summary of the main results of our recent project on three-dimensional MPP/PM space absorbers, which are suitable alternative to control the room acoustics and of the merit from the hygiene point of view.

Therefore, this work is fully based on the previously published materials, but with additional newly elaborated discussions and examples. In this sense, we consider that open commentary is the suitable article type for this work.

We believe that this work brings some idea to improve the acoustics in built environments in post-COVID 'new style' everyday life.

We hope that this work can find a space in your journal.

Kindest regards

Kimihiro Sakagami, corresponding author

Some considerations on the use of space sound absorbers with next-generation materials reflecting COVID situations in Japan: additional sound absorption for post-pandemic challenges in indoor acoustic environments

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ABSTRACT

In this study, we first point out the possible acoustic problems associated with the post-pandemic operation of built environments. Particularly, we focus on the problem of acoustic deficiency due to the lack of absorption. This deficiency, which is likely to be encountered in most enclosed spaces in a range of establishments, is due to the reduced number of audience members or users of the space as a result of social distancing. As one of the promising solutions to this problem, we introduce a sound absorption technique using three-dimensional space sound absorbers developed through our recent research projects. Significantly, the type of sound absorber proposed herein is made of materials that are especially suited to hygiene considerations. The materials are microperforated panels (MPPs) and permeable membranes (PMs), both of which are easily washable and sanitised. Furthermore, we point out that three-dimensional MPP or PM space absorbers possess the additional value of aesthetic designability.

Keywords: sound absorption, microperforated panel, permeable membrane, post-pandemic 'new style', indoor acoustic environment

Introduction

Background: Sound absorption and the 'new lifestyle'

Among the built environments in cities, there are various types of public spaces used for different purposes. For example, in railway stations, airports, schools and meeting rooms in community halls, acoustical problems are often encountered due to insufficient sound absorption. This occurs not only in public spaces, but also in private spaces, such as dwellings, meeting rooms and offices in commercial premises. These spaces often also suffer from excessive reverberations, caused by insufficient sound absorption, resulting in various acoustical deficiencies, e.g., lower speech intelligibility, higher noise levels, the feeling of 'noisiness', etc.

In order to avoid these problems, additional sound absorption treatment is the only effective method of passive treatment. However, sound absorption treatments are usually made on the interior walls of rooms, which leads to a change in the design of the interior surfaces. Furthermore, conventional porous and fibrous materials for sound absorption are not suitable for interior surfaces unless appropriate facings are applied. This can also cause a problem due to insufficient strength or textural design of the interior surfaces; thus, in many cases, it may be desirable to avoid these methods.

In the current situation, following the COVID-19 outbreak, most people's activities are conducted according to a set of suggested guidelines known as the 'new style', 'new lifestyle' or 'new normal' in each country. For example, in Japan, several new guidelines for the conduct of everyday activities have been proposed [1]. According to these guidelines, people must maintain a distance from other people, and this results in limitation of the use of public spaces. For example, the Ministry of Health and Labour in Japan suggests that all gathering activities should be held in a space with the capacity for a group twice as large as the number of people actually gathering. Guidelines for various types of events and activities have been published [2]. This is applied not only to live performances or events in large auditoriums, but also to small performance spaces and non-performance spaces such as meeting rooms in practice. (See also Article Note 1.)

As an example of this 'new style' of operation of smaller multi-purpose spaces, Figure 1 shows a seat arrangement in a multi-purpose room in a municipal hall, where concerts and performing arts gatherings are regularly held, in a certain city in Japan. In this case, the room can usually hold 60 audience members, but after the COVID-19 outbreak, the number of audience members is limited to 20. This drastic reduction of the audience is likely to affect the acoustics of this room.



Figure 1. An example of a setting for a performing art gathering in a multi-purpose room in a municipal hall. Before the pandemic, the room accommodated 60 audience members, but capacity is limited after the COVID-19 outbreak. One can see only 20 seats for the audience members, in order to maintain social distancing (photo courtesy of T. Soki).

The reduction in audience numbers can result in lower sound absorption within the space, which leads to longer reverberation, lower speech intelligibility, etc., in events requiring verbal communication, such as meetings, symposia, theatrical performances, etc. **Such a situation, in many cases, would not occur without the COVID-19 pandemic: e.g., in performances without audience for broadcasting programmes, one may hear rather reverberant sounds, which would not be in the case without the pandemic.** The problem of lower speech intelligibility can become more critical with larger distances between speakers and listeners. Moreover, face shields or mouth masks, which people are advised to wear during conversation, are often used. It has been reported that masks affect the acoustic characteristics of voices rather drastically [3]. **According to the results [3], the effect of a face mask appears at 1 kHz and above as reduction of 3-7 dB ca., which is smaller than that of a face shield which is more drastic (3-12 dB): the authors consider that both the effect is considered to be large. These results indicate that face shields and masks reduce high frequency components of voices, which affects the loudness and timbre, and eventually deteriorates. This point is clearly shown in their demonstration recordings available in [3].** Not only is there an effect on speech intelligibility, but also on the sound quality of musical performances. Although in music this may be a matter of subjective preference for performers and listeners, it becomes more than a matter of individual preference when the intelligibility of speech is affected. **According to the authors' questionnaire survey (performed in June 2020, unpublished) to university students, some students pointed out that face masks deteriorate speech intelligibility and speech communication quality. As most people have experienced, it is rather difficult to speak clearly with face masks, which is also another cause of effect due to a face mask on the speech intelligibility. Therefore, regarding speech intelligibility, it is already deteriorated in many cases before it is affected by room acoustic characteristics. In this respect, improving the room acoustic condition can save the further deterioration of speech communication ability.**

Sound absorption technology

The sound absorption technique is practically the only passive solution to controlling the acoustics of an enclosed sound field [4]. Therefore, it has been studied extensively [5]. There are three main types of sound absorbers: (1) porous and fibrous type absorbers, (2) panel- or membrane-type resonant absorbers, and (3) Helmholtz resonator type absorbers (including perforated panels).

All of these methods can obviously contribute to the improvement of the above mentioned problem of lower absorption. However, nowadays we must consider which type of absorber is the best from a hygiene point of view. Considering the nature of porous and fibrous materials, they are obviously not suitable in this regard. Washable or easily sanitised

materials are more advantageous for post-pandemic applications. Therefore, sheet- or panel-like materials are advantageous, as they can be cleaned by applying (e.g., spraying) disinfectants relatively easily. Therefore, panel- or membrane-type resonant absorbers, or perforated (including microperforated) panels are likely to be good choices.

There are recently developed materials such as metal wool or porous metal, which can be more advantageous than traditional porous/fibrous material in this regard, however, in this commentary we focus on the panel or membrane materials, which are in many cases lightweight and flexible.

However, panel-like materials are usually used with a rigid-back wall and an air cavity placed between the absorber and the wall. This requires a change in the interior surfaces of buildings. In many cases it is difficult to make a permanent change of the interior surface to accommodate sound absorption materials, as it can require substantial renovation of the building. In such a case, space sound absorbers, which can be placed mainly on floors are one of the alternative methods used to control the acoustics of the room, to reduce excessive reverberations. This is an effective alternative of flexible and reversible design not only for temporary improvements for post-pandemic 'new style' but also in multipurpose spaces, etc, in 'usual' situations. Another way of the usage is to suspend those absorbers from the ceiling, which is widely known, however this usage is likely to require more constructive cost and effort than floor-mounted types. In the following, some basic ideas about space sound absorbers with panel- or sheet-like materials are presented.

Alternative sound absorption materials and structures suitable for post-pandemic applications

As mentioned above, porous and fibrous materials raise difficulties in their application for the purposes discussed in the present study, whereas membrane and perforated panels are promising alternatives. There are two types of membrane material: impermeable, which does not permit airflow and reflects sound itself; and permeable, which uses acoustic flow resistance. Considering the use of membrane for a space absorber, a permeable membrane is a better and more advantageous choice. Regarding perforated panels, conventional and traditional perforated panels with larger holes (larger than a few millimetres) are not suitable because of their lower absorptivity. Therefore, the most promising alternatives among them are microperforated panels, which are thin flexible panels with submillimetre holes, below a 1% perforation ratio. They are usually used on interior surfaces; however, they can also be used as free-standing space sound absorbers.

Recently, we proposed three-dimensional microperforated space sound absorbers (3D-MPAs) of various types: cylindrical, rectangular and spherical [6–8]. A similar concept has also been applied to permeable membranes, and we have proposed three-dimensional permeable membrane space sound absorbers (3D-PMAs). In the following, the main results of our projects on the 3D-MPA and 3D-PMA designs are introduced. All the absorbers introduced in this commentary can be either put on floors or suspended from ceilings, are made of light-weight plastics or fabrics that are washable or easily sanitised, and are potentially designable, which may be one of solutions for improving the acoustics of built

environments for use in the 'new style'. In this commentary, we consider mainly public spaces such as auditoria, meeting rooms, etc., however, the idea is also applicable in a residential building: in that case, considering the scale of the space, we would suggest to use it with some additional value, e.g., a lampshade, etc, for everyday use which is mentioned later.

Space sound absorbers with next-generation materials

Space sound absorbers with microperforated panels (MPPs)

A micro-perforated panel (MPP) is one of the most promising of the so-called 'next-generation sound absorbing material'. D-Y Maa first produced an MPP in the 1970s and developed theories concerning their potential performance [11–13]. Since then, many studies on MPPs have been conducted [14,15]. MPP absorbers mainly show high sound absorption performance at medium to high frequencies, which are important for the speech transmission performance of architectural spaces [4]. Figure 2 shows a typical example of the sound absorption performance of a conventional MPP sound absorber with a rigid back-wall, which shows a significant peak absorption in the mid-frequency range.

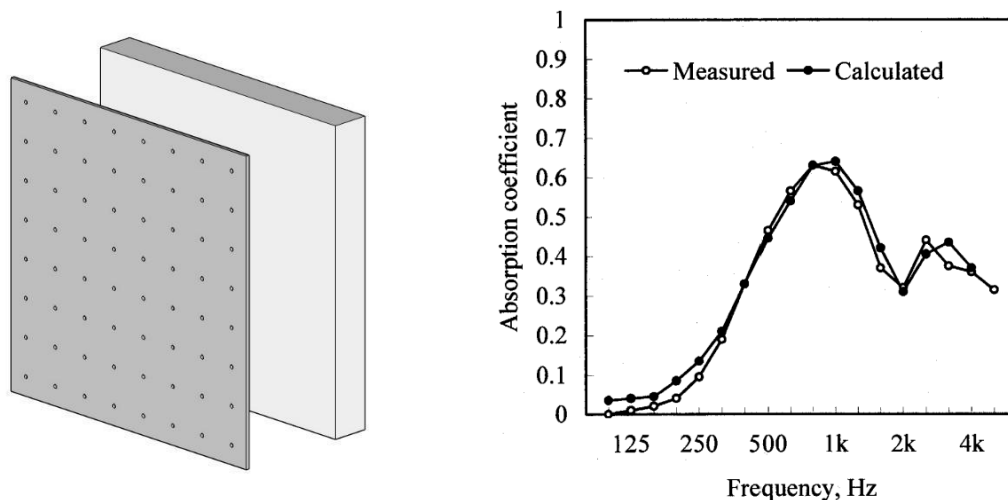


Figure 2. An example of a sketch of a conventional microperforated panel (MPP) absorber (left) and the diffuse-field sound absorption characteristics of a conventional microperforated panel (MPP) (right) absorber. The theoretically calculated value and the measured value are compared. Hole diameter and thickness of the MPP are 0.5 mm, and the perforation ratio is 0.64%. The air-cavity depth between the MPP and the rigid back-wall is 0.05 m.

An MPP absorbs sound energy in the same way as a conventional perforation panel does, by forming a Helmholtz resonator, which needs a rigid backing and an air cavity behind it. In this sense, it is similar to conventional perforated panels. However, MPPs employ submillimetre holes to realise suitable acoustic resistance for high sound absorption performance. As mentioned above, its conventional application involves placing it in front of

a rigid back-wall. As an MPP is usually thin (less than 1 mm), it lacks the strength required for interior walls in building spaces; therefore, it is commonly used in places which users cannot touch directly. Furthermore, once fixed to the wall as an interior finishing, it is difficult to be cleaned with disinfectant.

As a trial implementation, Hoshi et al. [16] used a honeycomb-backed box-like MPP absorber panel, which was detachable from the main wall and could be suspended from the ceiling, etc., to improve excess reverberation and inferior speech intelligibility (see Figure 3). This method is one possible solution applicable to ‘new style’ built environments.



Figure 3. A photograph of a honeycomb-backed box-like MPP absorber panel installed on the corner of the wall and ceiling of a meeting room. The absorber panel is made of plastic sheets and is very light weight. The surface of the MPP is colored with paint, so that it matches with the existing wall. These absorbers are suspended from a picture rail on the wall.

The concept of 3D-MPAs provides another alternative for the same purpose. This type of absorber can be used to improve the acoustics of an enclosed space without changing the design of its surfaces—it can simply be placed on the floor or suspended from the ceiling. Previously, the main variants of 3D-MPAs were the cylindrical shape (cylindrical MPP space absorber (CMSA) [6], the rectangular shape (rectangular MPP space absorber (RMSA) [7] and the spherical shape (spherical MPP space absorber (SMSA) [8]. The prototypes of these 3D-MPAs and their sound absorptivity are shown in Figures 4 and 5.

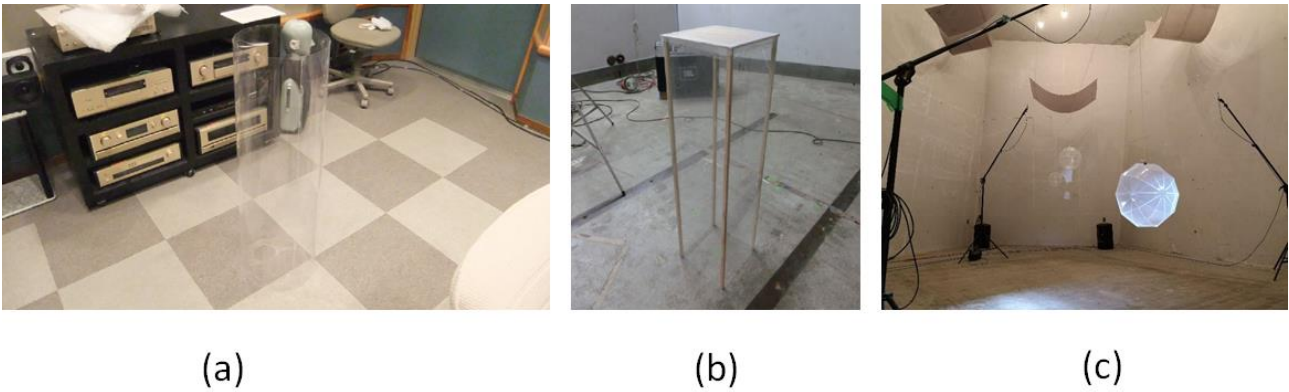


Figure 4. Photographs of the prototypes of (a) cylindrical MPP space absorber (CMSA), (b) rectangular MPP space absorber (RMSA) and (c) spherical MPP space absorber (SMSA). CMSA and RMSA were made out of polycarbonate MPP with a hole diameter and thickness of 0.5 mm and a perforation ratio of 0.785 %. SMSA was made out of a polypropylene sheet with the same parameters.

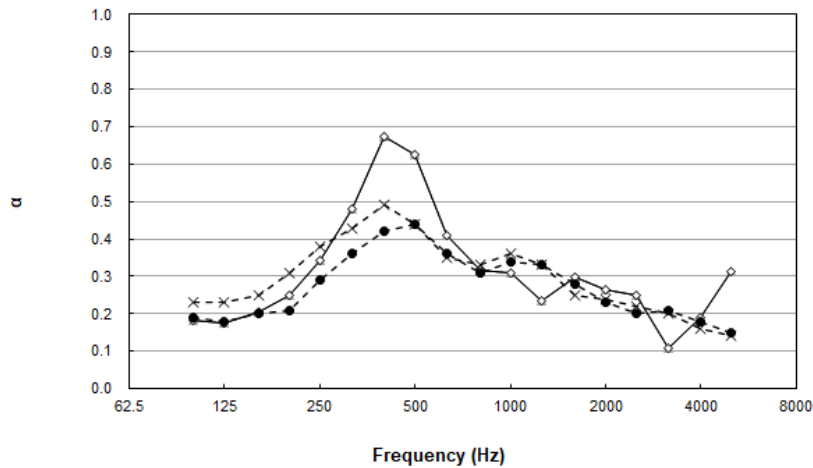


Figure 5. Measured diffuse-field equivalent sound absorption area for 1-m² surface area (i.e., equivalent to sound absorption coefficient). Crosses: CMSA; closed circles: RMSA; open circles: SMSA. As the characteristic dimensions of all specimens were almost the same, the peak frequency of the absorption due to the resonance was almost the same in the three types.

CMSA and RMSA show a broad and mild peak at a resonance frequency. The peak value is around 0.4–0.5, which is lower than conventional MPP absorbers with a rigid-back wall. These 3D-MPAs show low additional absorption at low and high frequencies, which is a unique feature of 3D-MPAs and is not observed in conventional-type absorbers. Although the peak absorption is not high, they can be of some use in spaces where original absorption is not enough. SMSA shows a rather sharp and high peak, with a value of 0.7 ca. This may be more effective than CMSA and RMSA in some situations, e.g., when a target frequency band is narrower, etc. (See also Article Note 2.)

Three-dimensional space sound absorbers with permeable membranes

Permeable membranes (PMs) are traditional materials which have long been studied [9,10]. They absorb the sound energy by their acoustic flow resistance; therefore, the absorption characteristics are similar to those of the porous/fibrous type. In traditional use, they are placed in front of a rigid back-wall with an air-layer between the wall and the absorber, which is quite similar to the application of porous/fibrous materials. In contrast to frequency-selective absorption characteristics of MPPs, PMs show rather broad absorptivity, though limited to mid and high frequencies. Using PM as a space sound absorber, a slight additional sound absorption is **observed** at low frequencies, which may be of some use in realistic cases as well [19]. A recent study of conventional PM absorbers with a rigid back-wall by Okuzono et al. [20] investigated the possibility of using various textiles (woven and non-woven) of different materials, which are recyclable. It was found that, as long as the flow resistance and areal mass are the same, acoustic properties of PMs are not dependent on the material.

The simplest three-dimensional space sound absorber with PM (3D-PMA) is the rectangle plane 3D-PMA [9] (Figure 6), which is quite simple, as a rectangular PM is suspended from a frame or other structure. This is similar to an 'acoustic curtain', traditionally used in an auditorium to control the reverberation. Through the use of PMs, which are typically made of woven or non-woven textiles with polypropylene, polyester or PET (polyethyleneterephthalate), easily washable and durable absorbers which are suitable for 'new style' daily life can be made. The typical absorption characteristics of this type of absorber are shown in Figure 8.

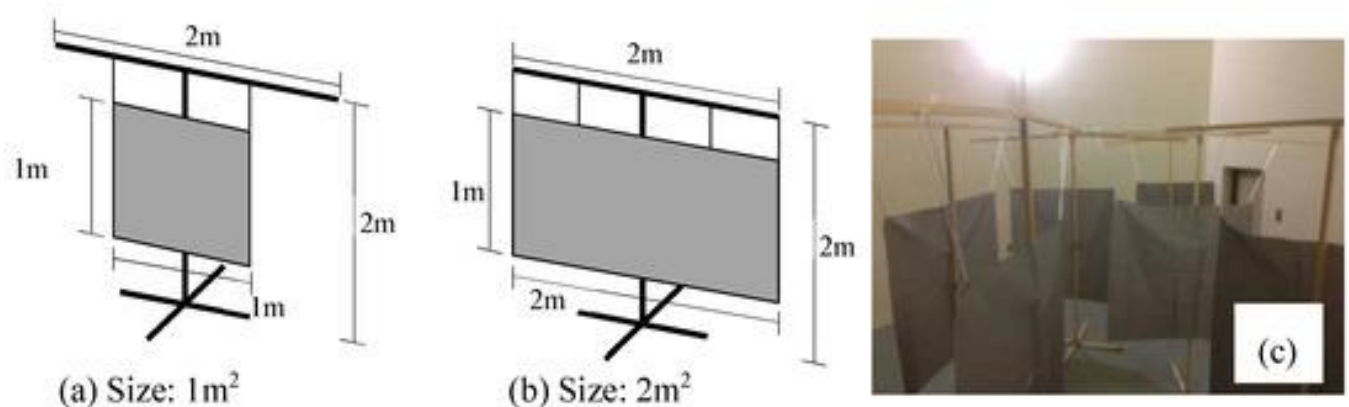


Figure 6. Overview of the studied specimens. (a) 1 m² and (b) 2 m² designs. (c) A photograph of specimens arranged in the reverberation chamber. The same configuration was applied to permeable membranes (PMs) of different flow resistance in the experiments.

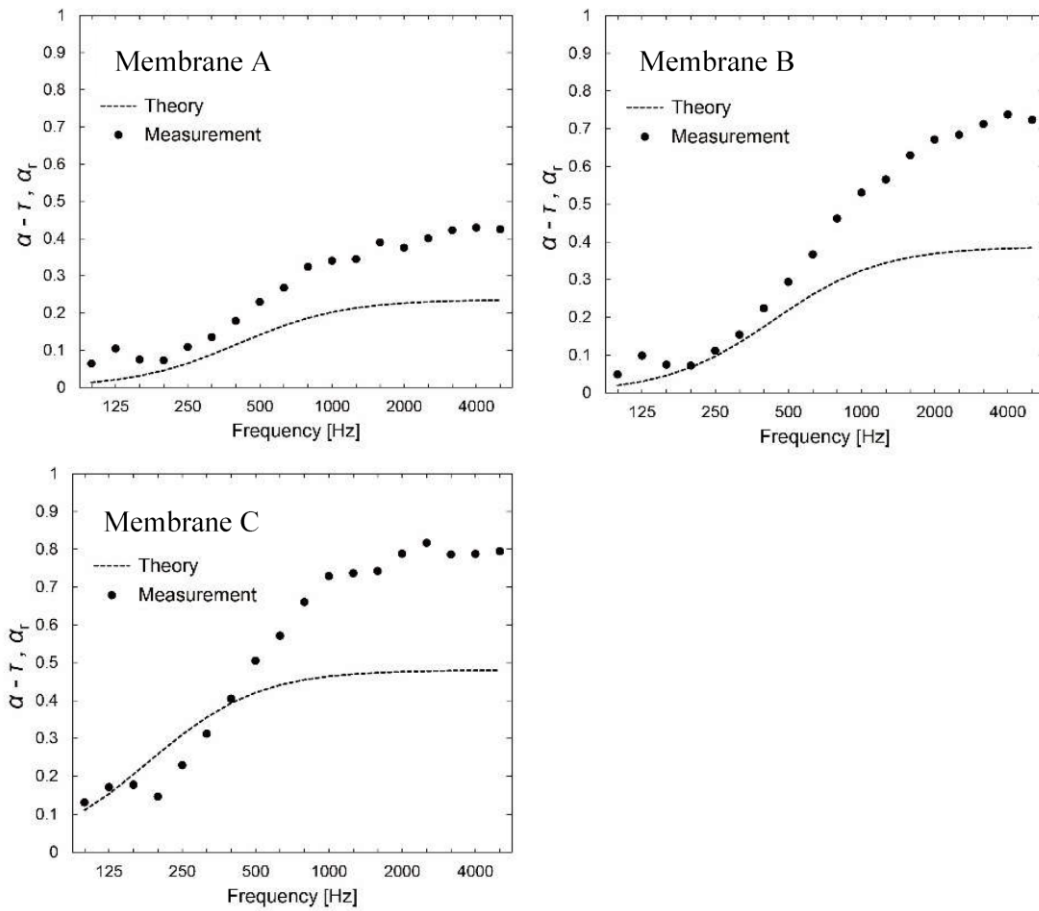


Figure 7. Measured diffuse-field absorptivity of rectangle shaped planar three-dimensional permeable membrane space sound absorbers (3D-PMAs). Membranes A, B and C showed a flow resistance of 196, 462 and 1087 Pa s/m. The curves in each figure show the theoretical values, as presented in [17].

In the case of PMs, other three-dimensional shapes have been proposed, namely, cylindrical and rectangular [20] (Figure 8). The difference between these and the 3D-MPA is that the 3D-PMA shows higher sound absorptivity in general if the flow resistance of the PM is properly selected, and wide-band sound absorptivity from mid to high frequencies. Therefore, if the absorption treatment is needed in a certain space, and it requires high sound absorptivity for one piece of absorber, the 3D-PMA may be a better choice. Furthermore, the flexibility of the 3D-PMA may also be advantageous in some cases. Due to the nature of the membrane, transparency cannot be realised by the PM, whereas it can be easily obtained in the case of MPPs.



Figure 8. Prototype of 3D-PMA (left: cylindrical; right: rectangular) used in the experiment.

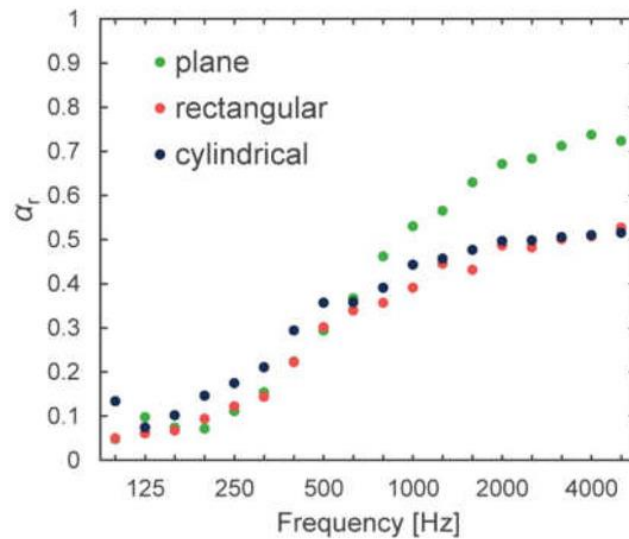


Figure 9. Comparison of the diffuse-field absorptivity of three types of 3D-PMA (planar rectangle, rectangular and cylindrical). The flow resistance of the membrane is 1087 Pa s/m and the surface area is 1 m² in all cases. As observed, the planar rectangle 3D-PMA is the most efficient at high frequencies (>1000 Hz). At low frequencies, there is no significant difference, although the cylindrical type showed the highest values.

Considering the shape of the 3D-PMA, as Figure 9 clearly shows, the planar rectangle 3D-PMA is the most efficient at high frequencies. This is because of the area effect taking place along the edge of the membrane. If the mid to high frequencies are targeted, the planar rectangle type can be effectively used. This type is also the simplest and the most easy to prepare and apply to various situations. It would be a good choice for conditioning room acoustics without the need of for extra construction or refurbishing.

Regarding the advantage of other shapes, for example, the cylindrical type can be arranged with surface roughness by means of the paper-folding technique, which may be appreciated for lighting purposes (details are provided in [21]). This type of absorber has an additional value as lighting equipment, as well as being a sound absorption tool (Figure 10).



Figure 10. Prototypes of cylindrical 3D-PMA without surface unevenness (left) and with surface unevenness by means of the paper folding technique (right).

Recent developments in the study of three-dimensional space sound absorbers include the theoretical study of the arbitrarily shaped three-dimensional space sound absorbers [22]. With such developments, more variations of the shape of absorbers will possibly become available, which will give sound absorption technology the additional value of aesthetic designability.

Some simple examples

The effectiveness of sound absorbers depends on different conditions, e.g., existing absorption, room volume, number of audience members, etc. Therefore, it is not simple to discuss the efficiency of those sound absorbers introduced above. The sound absorption performance can be evaluated by the sound absorption coefficient or the equivalent sound absorption area, or criteria derived therefrom. Therefore, some simple examples are presented here to demonstrate how the additional absorption may work. **In the following example, we consider rather smaller room with typical existing equivalent absorption area, however, it should be noted that the effect of additional absorption depends on the room size, existing absorption area, room shape and other factors. The purpose of the example is to show how additional absorption work in a simple way.**

Considering that a typical value for the equivalent absorption area of an audience member is 0.37 per person (in the average from 125 to 4kHz), and NRC (Noise Reduction Coefficient) is 0.39 [4], the absence of one person in the space may be compensated with a 3D-MPA with the equivalent sound absorption area of 0.4 ca. Therefore, by using 3D-MPAs effectively, the lack of absorption can be improved by introducing them by a proper number in the case of a smaller space. However, when the space is large and absence of a large

number of audience members must be compensated for, this becomes more difficult, as many absorbers are required. In such cases, a 3D-PMA can be more efficient, as its equivalent sound absorption areas are higher than standard systems with comparable volume.

Another example can be given, considering the change in the reverberation time and adjusting it by additional absorptions through a simple calculation. Suppose that there is a multipurpose room of $10 \times 15 \times 3 \text{ m}^3$ (volume: 450 m^3 , surface area: 600 m^2 and audience seating area 100 m^2). Assuming that the reverberation time of this room is 1.5 s, and that one person requires 1 m^2 in the seating area. It is also assumed that the usual capacity of this room is 100 persons. The equivalent absorption area of the seating area can be supposed to be around 40 m^2 . If the number of audience members is reduced to half of the usual capacity, i.e., 50 persons, the reverberation time can be 2.57 s. To adjust this to the original value, an additional absorption of 20 m^2 is required. This may be relatively difficult, requiring nearly 30 space absorbers, each with an equivalent absorption area of 0.7 m^2 . However, by introducing this additional sound absorption, the acoustics of the room can be somewhat improved, even though some elaboration will be needed: For example, when these absorbers are used among the users of a room, they should be designed not to disturb the users. Such a consideration will need some more design consideration, such as a shape and colour, etc, based on ergonomics. Some elaboration will be needed also in adding additional function: e.g., the sound-absorbing lampshade proposed in Ref [21] has been improved to provide better luminescence distribution, however, may need some more design consideration to optimise it as a lighting equipment according to rooms of different purposes.

Concluding remarks

In this study, acoustical problems, which are likely or already taking place, namely, a lack of sound absorption, were discussed. This problem has existed before, but it is likely to increase in the post-pandemic period, as reduced numbers of audience members or users of a room become 'standard' in order to maintain social distance in enclosed spaces. Therefore, the lack of sound absorption in the rooms should be compensated for, by introducing additional sound absorbents.

Additional absorption treatments are in many cases quite difficult to apply because they require considerable construction efforts and changes in architectural design. Therefore, to avoid this, one of the promising alternatives is the introduction of space sound absorbers.

Furthermore, in the 'new lifestyle' of the post-pandemic era, we must consider everything from the point of view of hygiene. Thus, the materials used should be washable and easily cleaned and sanitised. Considering these points, porous and fibrous materials such as wools or foams are not suitable. Therefore, sheets and panels such as microperforated panels and permeable membranes are good choices.

In this study, we introduced and summarised the nature of three-dimensional microperforated and permeable membrane space sound absorbers of various types, which

resulted from our on-going project for these several years. We presented their typical absorptive characteristics out of the published results from our projects. As these absorbers have displayed not only practical absorption performance, but also a wide applicability and the potential value of aesthetic designability. By adding some considerations about ergonomics, lighting, and other purpose-oriented design considerations, we believe that these absorbers can offer an alternative solution to the acoustic challenges of the "new style" built environment.

As pointed above, the sound absorbers are movable, so they can be rearranged as needed. In addition, it can be easily removed when it is no longer needed. Given the difficulty of predicting how long the 'new style' will last, it is considered that a method of controlling the sound field without major modifications to existing buildings will be needed. This can be a concept that will be required in some form for newly designed buildings as well. In any case, such a flexible and reversible design can be considered of some use, even if the 'new style' may only last short and the life style be back in pre-pandemic style.

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Article note:

1. The Guidelines for operation in performing art event in 'new style' in Japan was revised in September 2020, and now it is allowed to accommodate audience up to 100 % of the capacity for some types of performing arts. However, performers and performing spaces often reduce the number of audience members according to the former guidelines.
2. A detailed report of 3D-MPA project is available in: Kusaka M, Sakagami K, Okuzono T, et al. Three-dimensional MPP space absorbers: An overview of the project and recent development, *Proc. Inter-Noise 2020*, Seoul, Korea (e-conference), 23-26 Aug. 2020.

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Data availability: Dataset used in this work is available upon a reasonable request.