



Acoustic metamaterials based on polymer sheets: from material design to applications as sound insulators and vibration dampers

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Received: 31 May 2023 / Revised: 6 September 2023 / Accepted: 15 September 2023 / Published online: 11 October 2023
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Abstract

Flat and uniform plate-like materials made of rubber, glass, and metal can be utilized as sound insulators. The weights of these materials need to be increased to increase the sound insulation effects according to the mass law. In contrast, acoustic metamaterials with periodic structures composed of numerous resonators can break the mass law limit at certain frequencies. However, their feasible applications are still limited because of the time-consuming processes for assembling and integrating resonators. Recently, our group reported an acoustic metamaterial based on a polymer sheet that mutually connects spring-mass local resonators. The integrated structure enables high-throughput fabrication through a polymer molding method and single-step implementation on target objects. It is expected that acoustic metamaterial sheets and the customization of the sheet designs according to individual requirements will offer practical and innovative solutions for various problems related to noise and vibration. In this Focus Review, the polymer-based material design, functional control based on the physical properties of polymers, and applications to sound insulators and vibration dampers are described. Moreover, useful insights of new acoustic materials that are developed by combining polymers and metamaterials are provided.

Introduction

In general, plastics, glasses, and metals can prevent sound transmission by reflecting airborne sound, and the performance generally depends on the mass law, which states that the heavier the material weight per area is, the greater the sound insulation effects (Fig. 1) [1, 2]. The sound insulation performance is generally evaluated by measuring a sound transmission loss, which represents the reduction degree of a transmitted sound through a material relative to incident sound. According to the mass law, lighter materials are more likely to be vibrated by incident sound that excite the air on the opposite side, and they emit stronger transmitted sound. Therefore, their sound transmission losses can be improved by increasing the material densities and/or the thicknesses (Fig. 1a, b). By attaching a polymer material with a high loss factor, which is a ratio of the elastic loss modulus to the elastic storage modulus, the vibration energy

of materials can be absorbed, and the sound radiation can be suppressed [3–5]. However, in any approach, a weight increase inevitably occurs, and even if heavier weights are accepted to some extent, the performance may be insufficient in the low-frequency range because the mass law effect decreases as the sound frequency decreases.

In recent years, the automotive industry has been rapidly accelerating the shift to electric vehicles with low CO₂ emissions for a carbon neutral society. The electrification of vehicles has resulted in noise emergence from motors and inverters [6]. To make electric vehicles more silent, lightweight, and energy-efficient, innovative solutions that simultaneously achieve weight and noise reduction are needed.

Acoustic metamaterials (AMMs) are new attractive materials that can break the trade-off between sound insulation improvement and weight reduction at certain frequencies [7, 8]. Beyond the mass law, achieving a significant improvement in the sound insulation intensity while using materials that have similar weights to those of conventional materials, or a substantial reduction in weight while maintaining the same performance as those achieved by conventional materials is desired. In those artificially designed materials, resonance structures of smaller sizes than the target wavelength are periodically arranged and

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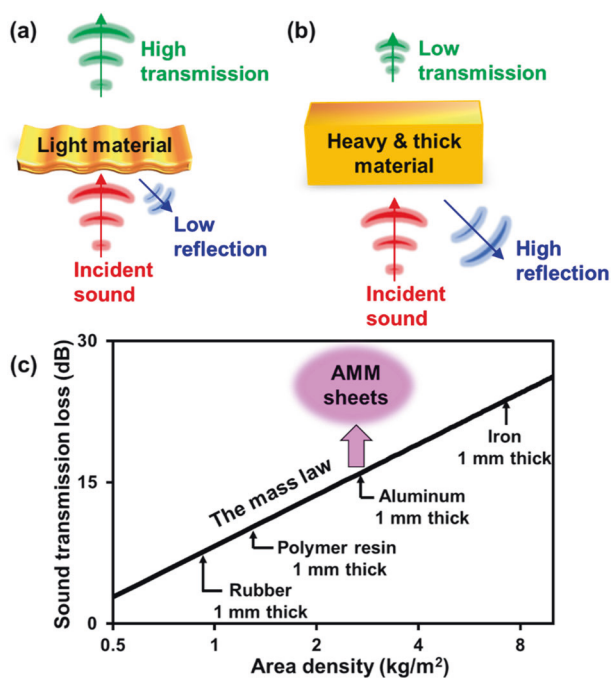


Fig. 1 Sound insulation behaviors of conventional materials with (a) light and (b) heavy weights. **c** The typical mass law for conventional materials at 800 Hz in comparison with the sound insulation performance of acoustic metamaterial (AMM) sheets that break the mass law

integrated. Initially, electromagnetic waves have mainly been focused on in research, but the concept has expanded to the field of acoustics, where the acoustic wave equation is mathematically analogous to the electromagnetic equation. The mass density ρ and the bulk modulus κ are the key constitutive parameters that affect sound waves in AMMs, and they correspond to the dielectric constant ϵ and magnetic permeability μ in electromagnetic metamaterials, respectively. Through the implementation of AMMs for two decades, unique physical phenomena and functions, which cannot be achieved by only modifying material properties, have been demonstrated [9–16].

It is known that AMMs often show dynamic changes in the effective mass density and/or volume modulus, even leading to infinite or negative values, whereas normal materials take constant finite and positive values [17–19]. If either of them is negative or infinite, incident sound waves are strongly reflected, whereas sound transmission is likely to occur when either of these is close to zero. Such anomalous parameters can be obtained when metamaterial structures composed of many resonance components, such as spring-mass and Helmholtz resonators, are designed and manufactured with high accuracy over target scales and efficient resonance is induced upon sound incidence. Such structures can be created by using additive manufacturing technologies such as 3D printers, but the structural

complexity often makes high-throughput production and large-scale industrial applications highly challenging.

Polymers are lightweight, easy to process, and useful material components for forming AMMs [20]. For example, membrane-type AMMs consist of polyester films with steel weights that are attached to rigid frames and exhibit negative effective mass densities [21]. Plate-type AMMs have rubber pillars periodically deposited on metallic plates as spring-mass local resonators to exhibit negative effective mass densities [22, 23]. In these AMMs, polymer materials are used as not only structural but also functional components such as soft and elastic springs in spring-mass local resonance.

In this Focus Review, polymer-based AMM structures consisting of thin silicone rubber sheets that connect silicone rubber cylinders with embedded metallic weights, which are fabricated using polymer molding methods, are reported [24]. The introduction of polymer materials into AMM designs enables integral molding as sheet-like materials, which are easily mounted on target objects as sound insulators and vibration dampers with high functions exceeding the mass law (Fig. 1c).

Theoretical analysis of the dynamic effective mass of a spring-mass model

The dynamic change in the effective mass of AMM sheets is modeled using a spring-mass system consisting of one-dimensionally arranged spring-mass local resonators on a flat substrate (Fig. 2a). When an external harmonic excitation force $F(\omega)$ is applied to the spring-mass model, the motion equations can be expressed as follows [10]:

$$F(\omega) + nk(x_2 - x_1) = M\ddot{x}_1 \quad (1)$$

$$-k(x_2 - x_1) = m\ddot{x}_2 \quad (2)$$

where ω is the angular frequency of the external force, M and m denote the masses of the substrate and the weights, n is the number of resonators, k is the spring constant, x_1 and x_2 are the displacements of the substrate and the weights, respectively, and the double overdots indicate second-order time derivatives. Then, Eq. (3) is derived from Eqs. (1) and (2) as the motion equation of the entire system using the equation $\ddot{x} = -\omega^2 x$:

$$F(\omega) = \left(M + \frac{nm}{1 - \omega^2/\omega_0^2} \right) \ddot{x}_1 \quad (3)$$

where $\omega_0 = \sqrt{k/m}$ is the resonance angular frequency of the spring-mass resonators. Therefore, the effective mass of

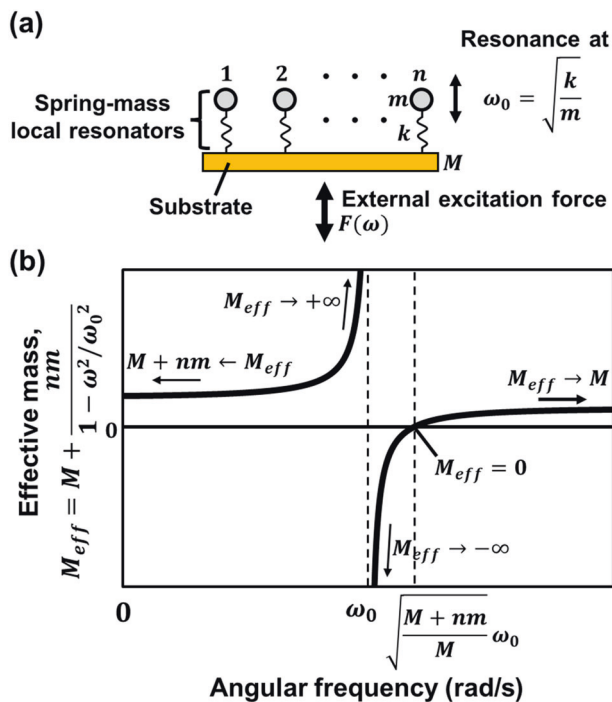


Fig. 2 **a** Schematic illustration of a spring–mass model with one-dimensionally arranged local resonators on the substrate under the external harmonic excitation force. **b** The dynamic effective mass of the spring–mass model as a function of angular frequency of the external force. Adapted with permission from ref. [24] Copyright 2021, The Authors

the entire system, M_{eff} , is expressed below.

$$M_{eff} = M + \frac{nm}{1 - \omega^2/\omega_0^2} \quad (4)$$

The effective mass, M_{eff} , dynamically changes with the incident sound frequency ω , as shown in Fig. 2b. The dynamic value is positively and negatively divergent at the resonance angular frequency of the resonators, ω_0 , which indicates the suppression of the substrate vibration and sound transmission. At the angular frequency of $\omega = \sqrt{(M + nm)/M} \omega_0$, the value of the effective mass is zero, which means that substantial vibration of the substrate and transmission of incident sound will occur. When the incident sound frequency is close to zero, the effective mass approaches $M + nm$, which corresponds to the static mass of the entire system. As the frequency increases, the effective mass again becomes a positive value greater than zero and asymptotically approaches the mass of the substrate M . Although the number of metallic weights and their total mass are considered in Eqs. (1–4), the two-dimensional arrangement of the resonators is not considered. However, the dynamic effective mass derived from Eqs. (1–4) can explain the properties of AMM sheets when they are dispersed at a constant distance less than the target wavelength

and uniformly interact with the target substrate. When the resonator geometry changes, the resonance angular frequency ω_0 can be shifted mainly due to the change in the spring constant k . However, the dynamic change in the effective mass at the resonance frequency occurs in the same way unless the vertical vibration mode of the resonators remains unchanged. This theoretical analysis based on simple modeling is available to qualitatively understand the acoustic properties of AMM sheets in relation to the dynamic effective mass, whereas numerical simulation based on the finite element method (FEM) is useful for the quantitative prediction of the performance.

Material design and fabrication method of AMM sheets

To realize the sound insulation mechanism based on the dynamic effective mass in practical use, numerous spring–mass local resonators should be uniformly dispersed and placed over target scales. Therefore, integrated sheet-like structures with sufficient sizes were designed to obtain practically available sound insulation materials. Figure 3a shows an AMM sheet consisting of a thin silicone rubber sheet that connects silicone rubber cylinders with embedded metallic weights. The AMM sheet is prepared by introducing metallic weights into the holes of a mold and then thermally cross-linking silicone resin (Fig. 3b). The sheet-like integrated metamaterial can be fabricated through the polymer molding method with high productivity and dimensional accuracy and easily mounted on target objects without needing to individually assemble those resonators. The cylindrical parts function as spring–mass resonators because the silicone rubber and the metallic weights work as a spring and mass, respectively (Fig. 3c). Since the metallic weights are embedded in the top parts of the cylinders, there is little risk of detachment during resonance. The thickness of the silicone rubber sheet connecting the resonators is sufficiently thinner in comparison with the height of the cylinders to maintain the inherent resonance mode and frequency.

In addition to the target frequency, some constraints regarding the weights and sizes of the AMM sheets that depend on the conditions of the implementation targets can also be important sheet design factors. By simply changing the metallic mold, it is possible to optimize the masses of the weights, shapes and numbers of resonators, and overall dimensions of the AMM sheets because silicone rubber has good moldability. AMM sheets that have different shapes of resonators can also be produced using metallic molds with different hole shapes. In contrast to using viscoelastic damping polymer materials to suppress vibration, AMM sheets need active resonance to interfere with the vibration of target objects. Silicone rubber has a low loss factor and a small

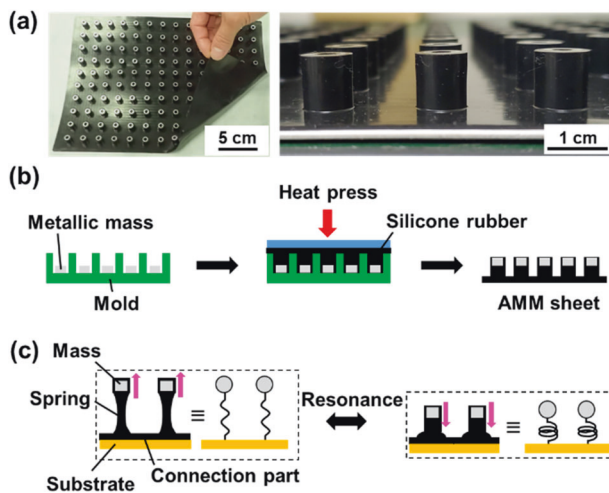


Fig. 3 **a** Photographs of (left) top and (right) side views of the AMM sheet. **b** Schematic illustration of the integral molding process of the AMM sheet. **c** Schematic illustration of resonance behaviors of the AMM sheet as a spring-mass system. Adapted with permission from ref. [24] Copyright 2021, The Authors

temperature dependence of the elastic moduli, which ensure high and stable sound insulation performance of AMM sheets.

Sound insulation properties and mechanisms of AMM sheets

The sound insulation properties of an AMM sheet with a size of $210 \times 297 \text{ mm}^2$ on a stainless steel substrate were evaluated by measuring the sound transmission loss. The substrate with the AMM sheet with a total area density of 7.8 kg/m^2 was placed at an aperture between the reverberation and anechoic rooms, and white noise was generated in the reverberation room. Then, the sound pressures of the incident and transmission sides were measured using a microphone placed in each of the reverberation and anechoic rooms. A stainless steel plate with the same area density of 7.8 kg/m^2 was also measured for the reference. At the target frequency of 771 Hz, the AMM sheet showed 15 dB higher sound insulation performance than that of the reference plate, which is equivalent to the performance of an 8 times heavier insulator with an area density of 60 kg/m^2 according to the mass law (Fig. 4a). On the other hand, at 971 Hz, which is in the higher frequency range than the sound insulation frequency, the sound insulation performance was lower than that of the reference. This behavior is consistent with the theoretical analysis for the dynamic effective mass (Fig. 2b). The experimental measurement was also in good agreement with the FEM-based numerical simulation of the sound transmission loss (Fig. 4b).

To analyze the sound insulation properties, the vibrational displacement field for one of the cylinders under sound

incidence was simulated (Fig. 4c, d). The cylinder showed successive stretching and compression motions vertical to the substrate at both sound insulation and transmission frequencies, whereas a clear difference was observed for the substrate motions. For a sound insulation frequency of 775 Hz, little displacement was generated on the substrate (Fig. 4c). The amplitude on the substrate surface was $1/360$ of that on the top surface of the cylinder, which will result in the suppression of the sound transmission. This suppressed displacement of the substrate is attributed to the divergence of the dynamic effective mass (Fig. 2b). In contrast, the vibration amplitude of the substrate was amplified by 2200 times at 950 Hz (Fig. 4d), which will cause sound radiation from the substrate. This amplified displacement of the substrate is attributed to the dynamic effective mass being near zero (Fig. 2b). Based on this mechanism, the spring-mass resonators of AMM sheets interfere with the vibration of the substrate and reflect incident air-borne sound waves. The sheets can insulate sound incident onto either the sheet surface or the substrate side. In addition, they can target a specific frequency of various sound types, such as narrow band noise, white noise including a broad range of frequencies and sound incident from random directions.

Functional control by tuning the physical properties of silicone rubber

For specific applications, it is important to precisely match the sound insulation frequencies of AMM sheets with target noise. The resonance frequencies of the cylindrical resonators are tunable by controlling the material properties (Fig. 5a), which indicates that AMM sheets are applicable to various target frequencies. To estimate the tunability, the resonant frequencies of the composite cylinders were simulated by changing the viscoelastic properties of silicone rubber. The resonance frequency was shifted to lower frequencies by decreasing the elastic storage modulus (Fig. 5a). The frequency modulation was also achieved by changing the structural parameters, including the cylinder diameter and height, the rubber sheet thickness, and the weight mass, which can be attributed to the changes in the spring constant and the mass of the spring-mass local resonators (Fig. 2a). As a result, the AMM sheets can target a specific frequency in a broad range from 60 to 8000 Hz, and compact sheets within a thickness of 5 mm can be applied to very low-frequency sound below 100 Hz by optimizing the structural and material parameters. It is also possible to design a sheet with multiple sound insulation frequencies by combining different resonators on one sheet. The insulation strength improves with decreasing loss factor of the rubber (Fig. 5b) because the cylinders can efficiently resonate when the springs are elastic. The sound transmission loss can also be increased by

Fig. 4 **a** Measured sound transmission losses of the AMM sheet with the stainless steel substrate and the thicker reference stainless steel plate with the same weight. **b** Simulated sound transmission loss of the AMM sheet with the stainless steel substrate and the corresponding mass law. Simulated vibrational modes of one of the cylinders at **(c)** a sound insulation frequency of 775 Hz and at **(d)** a sound transmission frequency of 950 Hz. Adapted with permission from ref. [24] Copyright 2021, The Authors

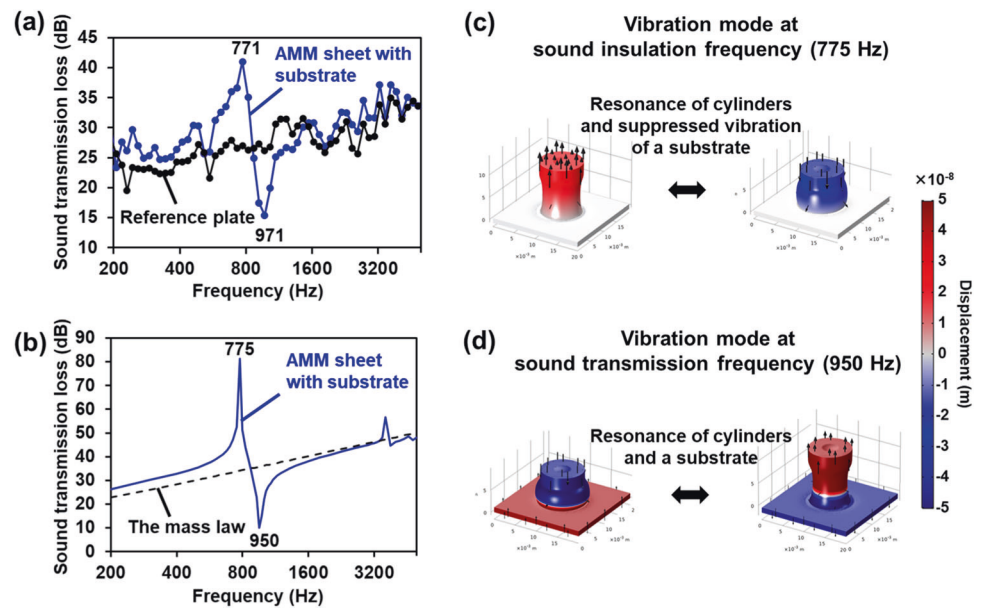
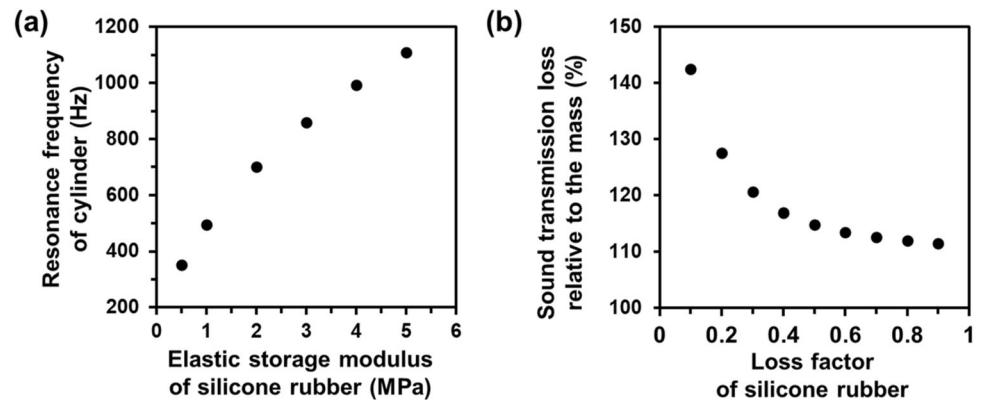


Fig. 5 **a** Simulated resonance frequencies of the cylinders with different elastic storage moduli of silicone rubber. **b** Simulated sound transmission losses relative to the mass law at the sound insulation frequencies of AMM sheets with stainless steel substrates having different loss factors of silicone rubber. Adapted with permission from ref. [24] Copyright 2021, The Authors



increasing the number of cylinders on a sheet without changing target frequencies.

Sound insulation application of AMM sheets

The sound insulation effect of AMM sheets was demonstrated audibly using a speaker and handmade transparent acrylic boxes. Transparent silicon rubber was selected for the employed AMM sheets to be able to see the inside of the box. The box with AMM sheets and the reference box without AMM sheets were prepared. The wall thicknesses were controlled so that these boxes had almost the same area density. The inner speaker generated 630–1250 Hz band noise inside the boxes. The sound pressure levels of the speaker were compared under three conditions in the absence of any box cover (Fig. 6a), in the presence of a reference box cover without AMM sheets (Fig. 6b), and in the presence of a box cover with AMM sheets (Fig. 6c). The box with the AMM sheets prevented noise transmission by approximately 15 dB at

the target insulation frequency of approximately 800 Hz in comparison with the reference box (Fig. 6d). This demonstration shows that AMM sheets can be used for sound insulation applications, such as reducing sound intrusion or leakage through walls and improving the performance of existing sound insulation materials without increasing weights.

Vibration damping application of AMM sheets

For the demonstration of the vibration damping effects, an AMM sheet with a weight of 13 g was mounted on a 206 g polycarbonate (PC) plate with an eigenmode mode frequency of 340 Hz. External vibration at 340 Hz was applied to the PC plate in the absence and presence of the AMM sheet using a vibration excitor (Fig. 7a, b). The vibration acceleration level of the PC plate was reduced in the presence of the AMM sheet by 10 dB at the target frequency compared to that in the absence of the AMM sheet (Fig. 7c).

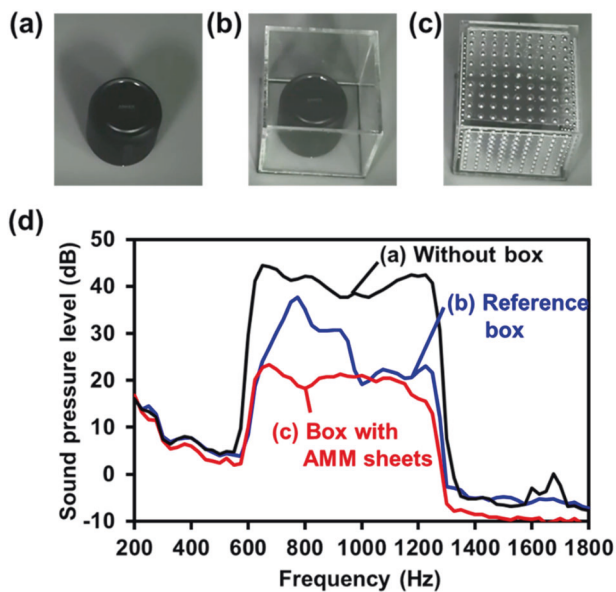


Fig. 6 Photographs of (a) the speaker without the box cover, (b) covered with the reference box and (c) covered with the box with AMM sheets. **d** Sound pressure levels of (a) the speaker without the box cover, (b) covered with the reference box and (c) covered with the box with AMM sheets measured at a position 10 cm apart from the top corner of the boxes diagonally upward at an angle of 45°. Adapted with permission from ref. [24] Copyright 2021, The Authors

To visually check the difference in the vibration states, two pieces of folded paper placed on the PC plate were also observed (Fig. 7a, b). In the absence of the AMM sheet, the folded-paper objects moved violently and fell to the floor shortly, whereas they moved less in the presence of the AMM sheet and stayed on the plate for a longer time. Adhesion between the substrate and the resonators is important for vibration transmission from the substrate to the resonators and induction of the resonance. In the transmission loss measurement (Fig. 4a) and the sound insulation demonstration (Fig. 6), the AMM sheet was fixed to the target substrate using a bonding adhesive. Although no adhesive material was used in the vibration damping demonstration (Fig. 7), the designed performance was achieved because the sheet was well adhered to the substrate. Based on these results, the AMM sheet is expected to be used for vibration damping applications to reduce vibration from excitation sources, suppress the resonance of components, and prevent vibration propagation.

Conclusions and outlook

Practical AMMs were developed based on polymer sheets that mutually connect spring-mass local resonators. AMM sheets were fabricated through integral polymer molding and easily mounted on target objects in a single step without needing to assemble numerous resonators one by one. The

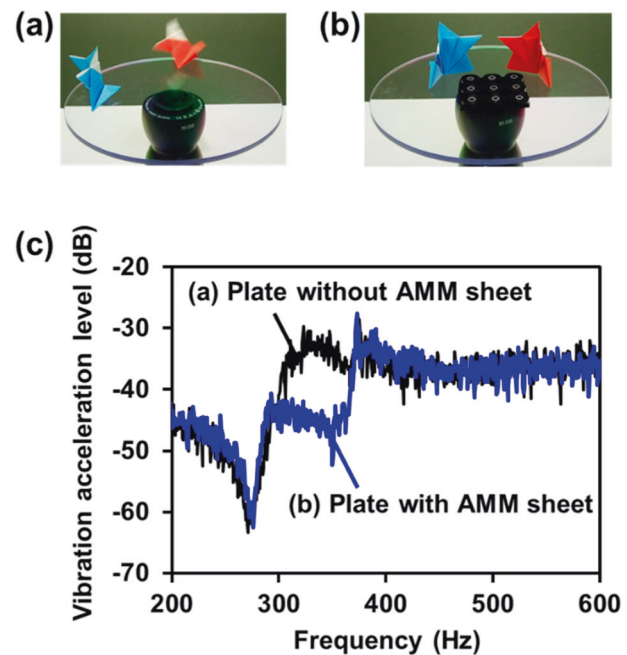


Fig. 7 Snapshots in the demonstration experiments for the comparison of vibration damping effects in the (a) absence and (b) presence of the AMM sheet, in which two pieces of folded paper were placed on the PC plate excited by the vibrator at 340 Hz for the visual clarity of the different vibrational states. **c** Vibrational acceleration levels of the PC plate excited by the vibrator at 340 Hz in the (a) absence and (b) presence of the AMM sheet

polymer-based sheets are flexible so that they can be applied not only to flat planes but also to curved surfaces. The AMM sheets demonstrate sound insulation and vibration damping performance that exceeds the mass law at target frequencies and potential for applications in various fields through customization of the sound insulation frequency, insulation strength, weight and thickness according to individual requirements. For example, low-frequency noise below 500 Hz from machines used in construction sites and factories can be a target for AMM sheets because ordinary sound insulators and absorbers are less effective in the low-frequency range. We showed that mechanical vibration is also suppressed by AMM sheets. By analyzing vibrating objects with AMM sheets mounted on appropriate positions through experiments and simulations, it is possible to effectively reduce the vibration and radiated sound with smaller sheet sizes, which can result in a more lightweight approach instead of attaching conventional vibration dampers in large areas or adding ribbed components for increasing structural rigidity. The combination of polymer materials with metamaterial structures may lead to innovative solutions for challenging noise and vibration issues. Further structural designs and functions can be explored by taking advantage of polymer properties such as flexibility, phase-segregated structures, viscoelasticity and stimuli responsiveness.

Acknowledgements The author is grateful to the collaborators at Mitsubishi Chemical Corporation who contributed to the achievements: Dr. Takeshi Matsuoka, Mr. Yuya Saito, Mr. Naoyuki Uchida, Mr. Kazuma Inoue, Mr. Hiroshi Mitani, Dr. Shuichi Akasaka, and Dr. Shogo Koga.

Compliance with ethical standards

Conflict of interest The author declares no competing interests.

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