Applied Acoustics 178 (2021) 108006

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Active acoustic absorption device using additive manufacturing technique for normal incident wave

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A R T I C L E I N F O

Article history:
Received 16 September 2020
Received in revised form 18 January 2021
Accepted 19 February 2021
Available online 22 March 2021

Keywords:
Additive manufacturing
Acoustic absorber
Anisotropic properties
Interference

A B S T R A C T

This research presents an application of the additive manufacturing (AM) technology for active acoustic absorption device. Fabrication of functional devices in acoustic system is one of the challenging goals of additive manufacturing technology. In order to achieve this objective, an important step is to test the acoustic performance and characteristics of AM device and make it active from an acoustics point of view. Numerous roadblocks that need to be overcome exist and research activities in this field are rare. Thus this research aims to experimentally observe and utilize the anisotropic absorption coefficients of AM device caused by its anisotropic stiffness characteristics. In addition, this research also proposes the concept of an active acoustic device. Some experiments are carried out to show the validity of the active acoustic device using AM technology.

1. Introduction

The present research develops an active acoustic absorption mechanism printed by the additive manufacturing (AM) technology that has been developed and recently used for a new promising fabrication technology with many challenges [1–9]. Many AM applications from kid toy to delicate medical device can be found and many attempts have been made to enlarge the application area [10–13]. To our best knowledge, the fabrication of functional device in acoustic system is rare and also one of the challenging goals of the state-of-the-art additive manufacturing technology. Thus, the present study applies the AM technology to make a part or a component and investigates its mechanical properties for the application of the active acoustic devices. The important steps in the present study are to test the acoustic performance and characteristics of acoustic device and to make the printed devices active from an acoustic point of view. To our best knowledge, research activities in the field of AM for acoustic components are rare. Several issues should be properly addressed with insights on the manufacturing technology and the inherited tolerance limit of the AM technology. This research aims to evaluate the anisotropic absorption coefficients of AM devices caused by the anisotropic stiffness characteristics of printed parts and the variations of the contact condition due to the tolerance. In addition, this research also presents the concept of an active acoustic device utilizing the acoustic and mechanical properties of AM product. Several experiments are carried out to achieve the active acoustic device using the AM technology.

Several relevant researches related to acoustics based on the additive manufacturing technology can be found [1–4,7–9,14,15]. The emit sounds while printing parts are investigated [16]. In their researches, it was claimed that the process information can be obtained by analyzing the emitted sounds during printing. The earmuffs are manufactured with acrylonitrile butadiene styrene (ABS)/clay nanocomposites [17]. Double cup and single cup pure ABS earmuffs are compared from an acoustic point of view. Small size acoustic metamaterial based on Helmholtz resonators is fabricated with the additive manufacturing technology [15]. The acoustic and mechanical characteristics of AM scaffolds are investigated using an ultrasound pulse echo technique for tissue engineering [1,18,19]. It reveals that the microstructures influence the acoustic and mechanical performances. The studies of the porous sound absorbing materials can be found using the additive manufacturing technology [1–3,6–8,18,20,21]. The absorber structure is printed with gypsum and its acoustic performance is tested[21]. The acoustical properties of fibrous absorbent material are presented [22]. The mathematical modeling of the Biot parameters is also studied [3]. The trend of porous sound absorbing materials is discussed [14]. 3D acoustic metamaterial sound absorbers are printed and tested[21]. Multiple material AM processes were researched [6]. The mechanical properties of AM products are tested and

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[1] Since 1880.

https://doi.org/10.1016/j.apacoust.2021.108006
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presented [5,23]. From the review of the relevant researches, the studies of acoustic and mechanical properties of AM technology can be found but it is rare to investigate the adaptive acoustic absorber using the AM technology. Therefore this research intends to investigate the acoustic properties of the AM technology and presents a new adaptive acoustic device utilizing the tolerance and the acoustic performance of the printed products.

In this research, the application of the additive manufacturing technology for active acoustic absorption plate is presented. Circular plates are manufactured by a 3D printer in Fig. 1 and due to the

Fig. 1. 3D printer and acoustic experiment setup. (a) 3D printer DREMEL DIGLAB and (b) an acoustic experiment for absorption coefficient (Two points measurement approach, the diameter: 0.1 m, and cutoff frequency: 1929 Hz ([3,20,22,25,26])).

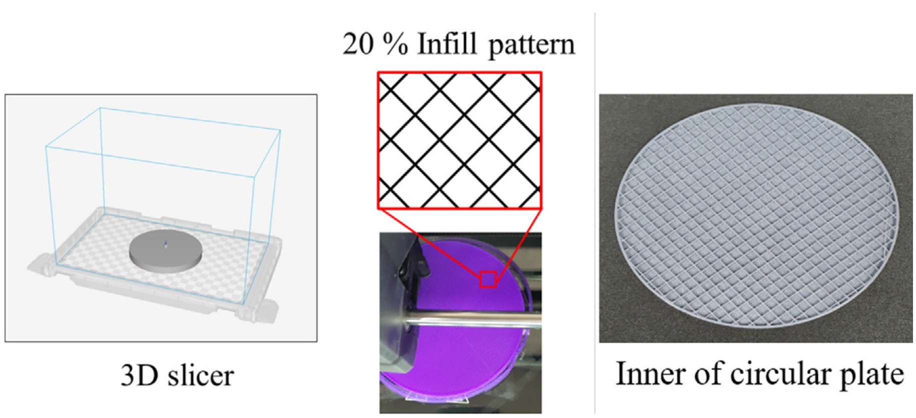


Fig. 2. Manufacturing of adaptive acoustic absorber. (A 3D slicer, 20% infill grid pattern and inner of circular plate).

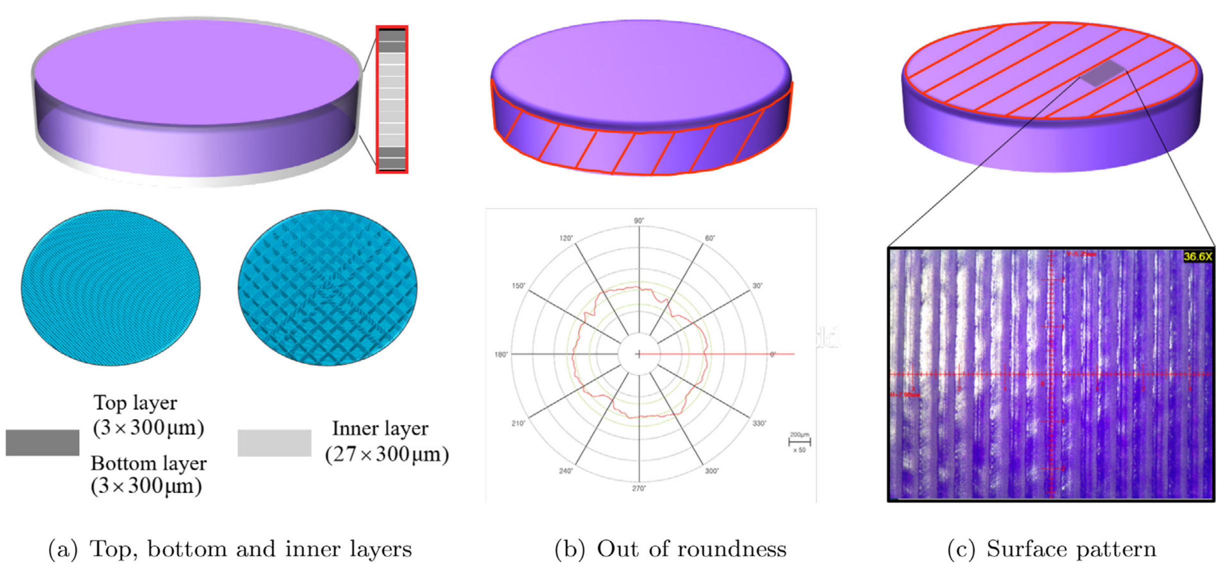


Fig. 3. Manufacturing of adaptive acoustic absorber. (a) A circular plate and the top layer, the bottom layer and the inner layer and (b) the measurement of the out of roundness (NITECH.CO.KR) and (c) surface pattern of circular plate.

nature of the 3D printing technology, layered structures are observed in Fig. 3(b). The layered structures become the sources of the anisotropic material properties of the structure (See [2,7,8,11,18,22,24] and references therein). On the other hand, the absorption coefficients of printed structures can be measured by the acoustic testing device in Fig. 1(b). The average absorption coefficient of printed structure was about 0.3 meaning that the reflected acoustic pressure is decreased by 30 percents; the average absorption coefficient can be varied depending on the porosity of the surface of circular plate. In addition, the operation factors such as environment temperature, layer thickness, printing direction, feeding ratio and etc influence the roundness of printed structure. Due to the rough roundness, the contact condition to the metal impedance tube is influenced and differentiated. This research witnessed that due to the anisotropic material property and the friction differentiation depending on the orientation of the printed plate, the resonance frequencies are differentiated and the associated acoustic absorption coefficients are also influenced. The roundness of the printed plates becomes a key factor in the boundary condition between the plate and the impedance tube. This implies that the boundary condition and the resonance frequencies become dependent on the orientation of the plate. In short, it is observed that the rotation of the plate determines the shift of the frequency value at the highest absorption coefficient. This research proposes to utilize the dependency of the frequency with respect to the rotation angle for the application of the adaptive acoustic absorption mechanism. To show this feature further, several experiments are carried out. With these experiment results, this research presents the engineering application of printed plate for the adaptive acoustic absorption mechanism.

The paper is organized as follows. Section 2 provides some backgrounds to the acoustic properties of printed parts. The experiment procedure is presented and the acoustic properties of the printed part are tested and compared with steel and cotton. In Section 3, the frequency shifts of the printed plate are presented and some potential applications are discussed. Section 4 provides the conclusions and suggestions for future research topics.

2. Printed anisotropic structure and active acoustic resonator

2.1. Anisotropic properties by additive manufacturing

One of the key aspects employed for the present adaptive acoustic device is the anisotropic material property of parts printed

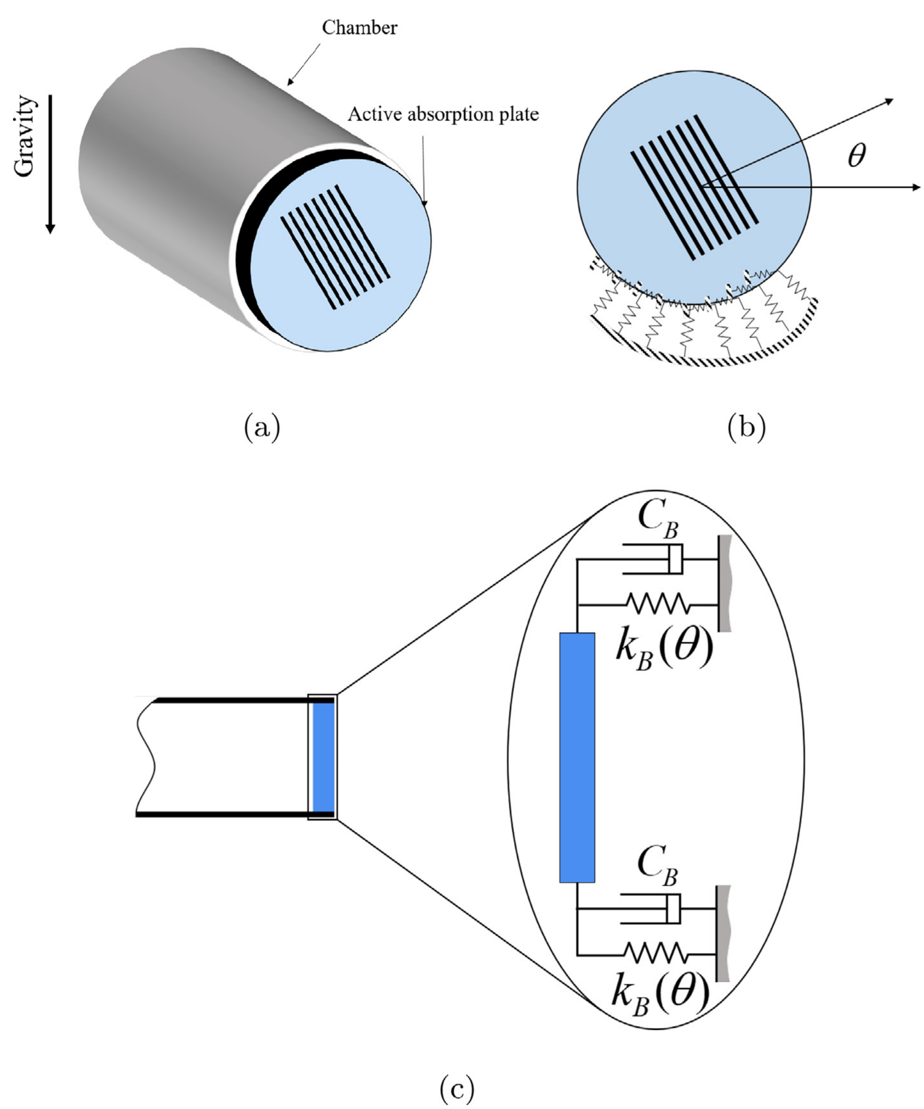


Fig. 4. The concept of the adaptive absorption mechanism. (a) An circular plate with anisotropic material properties, (b) the directional properties of the circular plate and the non-uniform contact and the uniformity of the printed circular plate and (c) the schematic diagram of the plate and the rotation dependent boundary condition.

by 3D printers. All specimens tested here are fabricated using an PLA material on DREMEL DIGILAB 3D45 with a density = 0.382 g/cm^2 as shown in Fig. 1(a). As illustrated in Fig. 2, the CAD software, (Dremel Diglab 3D slicer), is used to generate a G-code for 20% grid infill structure for the adaptive acoustic absorption device in Fig. 3. The present research fixes the infill structure as the first resonance frequency will be subject to be changed according to the stiffness of the plate and the infill structure. It is possible to increase the infill ratio or change the infill pattern to control the target frequency. Fig. 3(a) shows the detailed cross sectional structure manufactured in the present study. Fig. 3(b) shows the out of roundness and Fig. 3(c) shows the bottom surface with the layered structure.

In our experiments, the changes of the infill affect the resonant frequency range of the present adaptive acoustic absorber and the adaptive property becomes different. During the printing, the molecular orientation or chain orientation of polymers inevitably appear by rapid drawing of melted PLA. Thus this characteristic causes the change of the resonance frequency of the structure depending on the rotation of the structure and this feature is utilized in the present study. Circular plate is chosen as the basic shape of the adaptive acoustic device utilizing the anisotropic material properties.

The present studies utilizes the directional material properties to realize the acoustic adaptive absorption mechanism. As discussed above, the additive manufacturing technology or the 3D printing process constructs three dimensional objects by juxtaposing melted materials layer by layer. For example, Fig. 3(c) shows the example of printed circular plates whose material properties are dependent on the direction. Due to this manufacturing feature, printed parts inevitably show the directionality in material properties (Stiffness, roughness and etc.). The directional material properties are originated from the patters of the polymer components and the anisotropic material properties are observed. This study is not first to observe this feature. For example, depending on the magnitude of the raster angle, the feeding ratio and the layer thickness, the variations of strength have been observed and reported [2,7,8,11,18,22,24]. These studies reported that the variations more than 10% are inevitably observed due to the characteristics of the additive manufacturing process. The present active acoustic absorption mechanism utilizes these variations in stiffness. In other words, the anisotropic material properties influence the vibrations and resonance frequencies of circular structures printed by the additive manufacturing technology. Therefore it is possible to rotate the circular structure to change its resonance frequencies and the absorption coefficients at the resonance frequencies as shown in Fig. 4(a) and (b). One of the features we should consider is that the roughness of the surface of the printed parts becomes important too. In other words, the surface of the circular plate has some roughness affecting the contact conditions. The circular plate can be interpreted as the fixed mass with stiffness in Fig. 4(c). Our interpretation about the effect of the surface roughness is that the stiffness and the friction damping dependent on the rotational angle are attached at the rim of the circular plate. Indeed the variation of the rotational angle affects the overall stiffness of the plate and the absorption coefficient is affected by this rotation of the circular plate. For an example, Fig. 3(b) shows the roughness measurement of the printed circular plate (NITECH.CO.KR). It turns out that the maximum out of roundness is about 210.05 μm wihtout any polishing. As illustrated, some variations in the radial direction appear. These variations affect the linearity of the responses with respect to the rotational angle.

2.2. Active acoustic absorber system

First of all, the present study conducts the basic absorption experiment using the acoustic experiment setup in Fig. 1 in an arbitrary rotation and installation of the circular PLA structure in

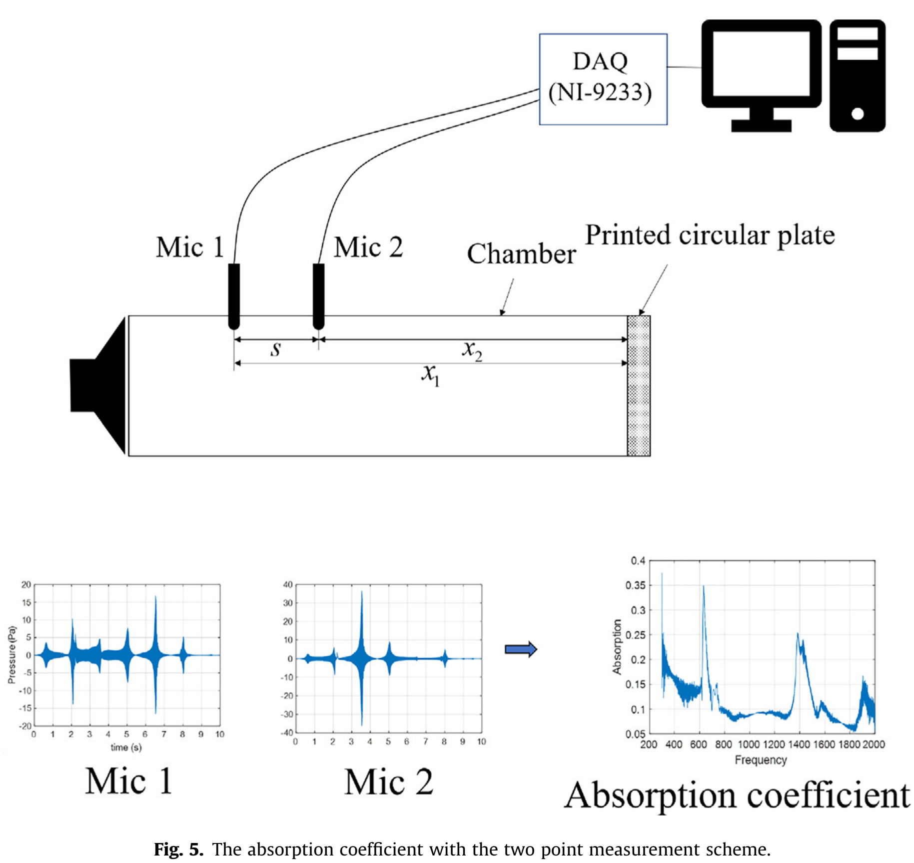


Fig. 5. The absorption coefficient with the two point measurement scheme.

Fig. 2, Fig. 3. The absorption coefficient is measured by the following Eq. (1).

$$\alpha = 1 - |R|^2 = 1 - \left|\frac{Z - Z_0}{Z + Z_0}\right|^2 \quad (1)$$

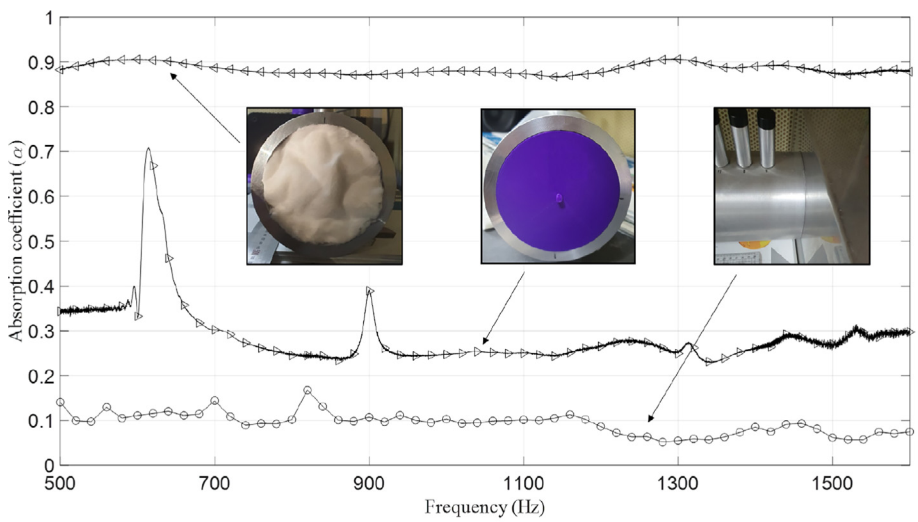
where the absorption coefficient is denoted by α. The reflection coefficient and the impedance of the printed structure are denoted by R and Z, respectively with Z_0 for the impedance of air. The reflection coefficient with the two point measurement system can be formulated by measuring the pressures (P_1 and P_2) at microphone 1 and microphone 2 as follows:

$$H_{12} = \frac{P_2}{P_1} = \frac{e^{jkx_2} + R(e^{-jkx_2})}{e^{jkx_1} + R(e^{-jkx_1})} \quad (2)$$

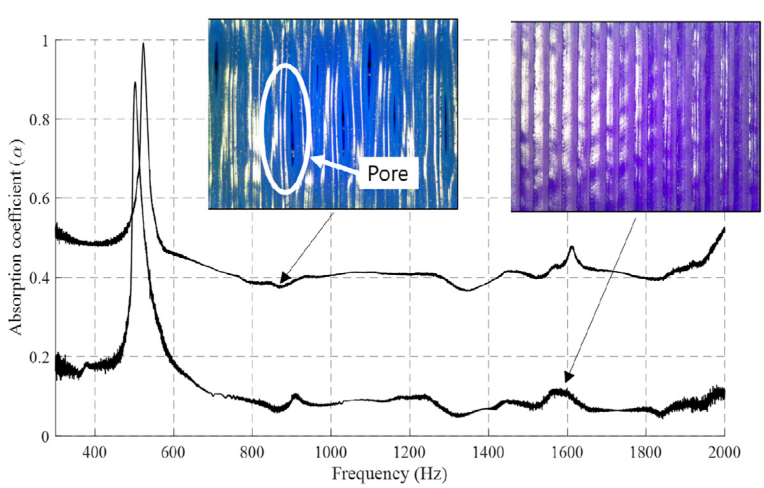
where x_1 and x_2 are the positions of the micro phones (see Fig. 5). The distance between the microphones is denoted by s and the wavevector is denoted by k. The frequency response functions are defined as follows:

$$H_I = \frac{P_{2I}}{P_{1I}} = e^{-jks}, \quad H_R = \frac{P_{2R}}{P_{1R}} = e^{jks}, \quad Z_0 = \rho_0 c_0 \quad (3)$$

Before presenting the active acoustic absorption system, the nominal absorption coefficient of PLA plate is measured between 500 Hz to 2000 Hz in Fig. 6. As the steel plate reflects all acoustic energy, the absorption coefficient is very low. On the other hand, the cotton structure absorbs the acoustic wave at the frequency ranges of interest and shows the higher absorption coefficient. The printed PLA structure absorbs about 30% of incoming acoustic wave which is between steel plate and cotton structure; importantly depending on the porosity setting in 3d printer, the absorption coefficients can vary. Note that some peaks in the absorption coefficient are observed in Fig. 6 due to the resonance of the printed circular structure. From the absorption coefficient point of view, not to mention, cotton structure is superior compared with



(a)



(b)

Fig. 6. Comparison of the absorption coefficients of cotton plate,printed plate and steel plate. (a) A comparison (Dremel DigiLab 3D Slicer setting: PLA infill ratio 20, printing temperature 220 degrees, build plate temperature 45 degrees, feeding diameter 1.75 mm, printing speed 60 mm/s, travel speed 120 mm/s) and (b) the curves of the absorption coefficients with the different surface structures.

the other materials. However, cotton or fibrous structure is inferior in terms of the stiffness and the durability. Thus this research presents to utilize the appearances of the peaks in the absorption coefficient and develops an engineering approach to change the resonance frequencies for the adaptive acoustic absorption mechanism.

The present adaptive absorption coefficient is realized by the rotation of the printed circular plate. As mentioned, the parts manufactured by 3D printer show the anisotropic material properties due to its manufacturing technique, i.e., in-fill patterns and raster angle. In addition, as melted PLA flows downward, the surfaces of printed parts are rough and have some tolerance issues. Due to these geometric properties of the printed parts, they show the directionality of the acoustic absorption coefficients. As a result, the response curves of the absorption coefficients can be varied depending on the installation configuration, i.e., the rotation of the circular plate in our research. This feature has been reported in some relevant researches [2,7,8,11,18,22,24] and this research uses these directional properties to realize the adaptive acoustic absorber in Fig. 4. First of all, the manufactured circular plates are installed in the experiment device. The surfaces of the circular plate are rough and the contact surfaces are influenced due to the gravity and the tolerance of the 3D printer. It is observed that due to the directionality of the material properties, i.e., the anisotropic material property and the contact condition, the frequency with high absorption coefficient varies depending on the install angle as shown in Fig. 4. As the circular plate with anisotropic material properties contacts at the bottom surface, the vibration of the plate shows the directionality.

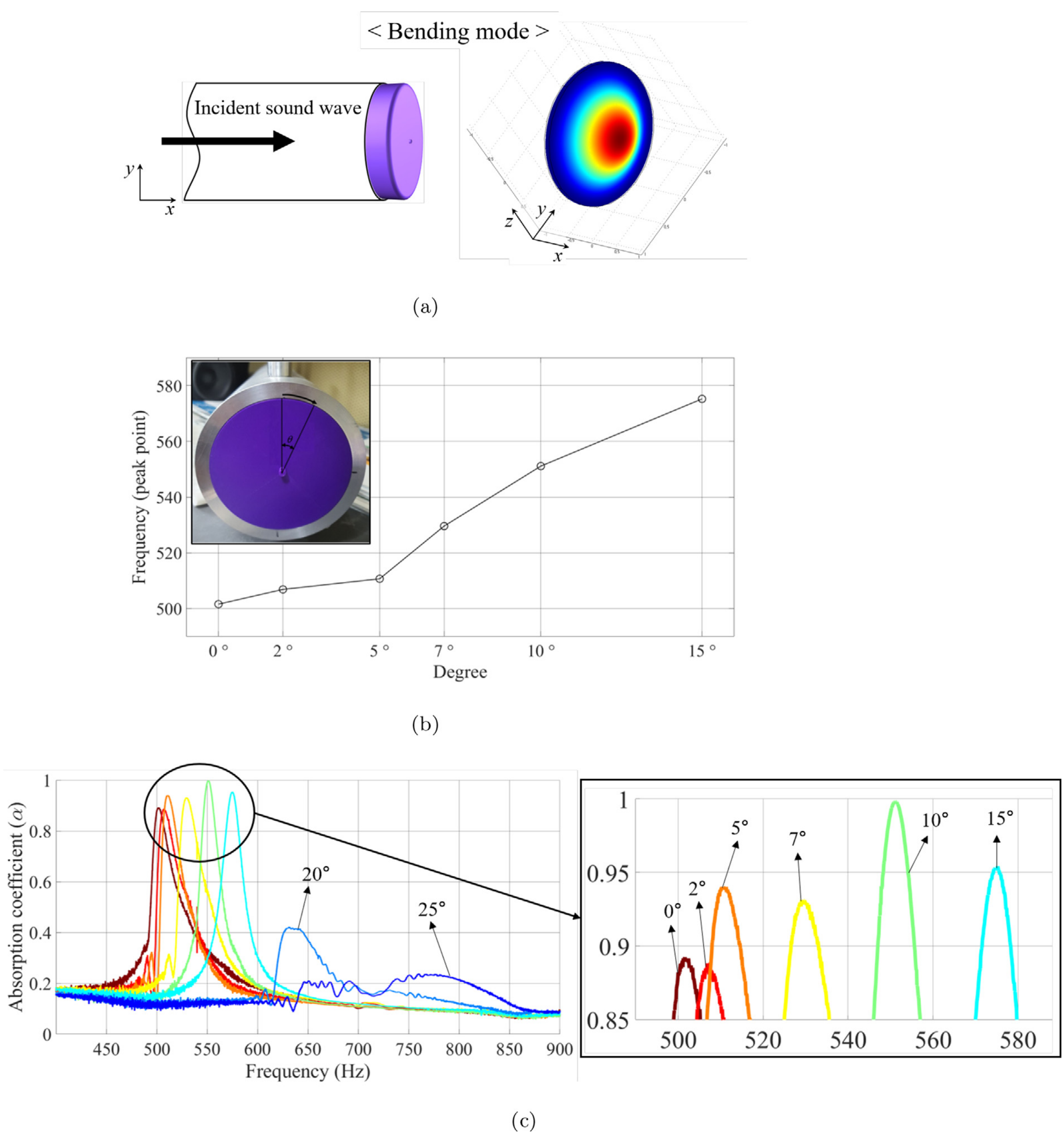


Fig. 7. The shift of the peak frequency. (a) Incident sound wave caused by banding mode in circulate plate (total mass: 30 g), (b) the shift of its peak frequency with respect to the rotational angle and (c) its absorption coefficients by rotating between 0 degrees and 25 degrees.

3. Experiment and validations

3.1. Adaptive acoustic absorption coefficient

To validate the concept of the adaptive acoustic absorption mechanism, some circular plates are printed by the 3D printer. The radius and thickness of the circular plates are initially set 5 cm and 1 cm with 20% infill. The wire thickness of plate which is the diameter of the nozzle of the printer is set to 300 μm. The sound absorption coefficient is also influenced by the reflection coefficient of the surface. In our study, the absorption coefficients under 1000 Hz are of interest or the wavelengths are larger than 30 cm. Thus, the effect of the printing thickness (300 μm fixed in the present study) can be neglected. The acoustic experiments

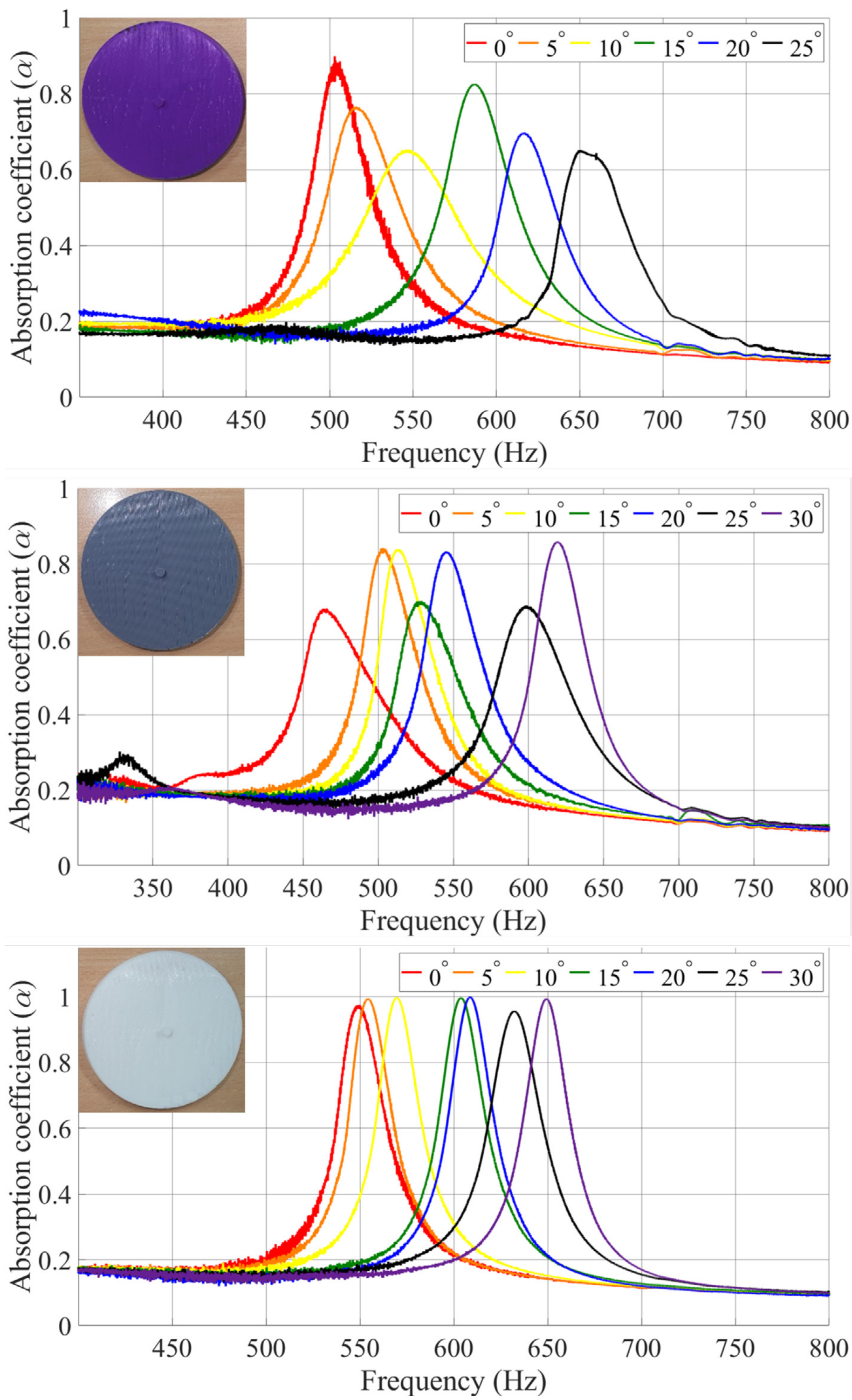


Fig. 8. The test of the variations of the responses.

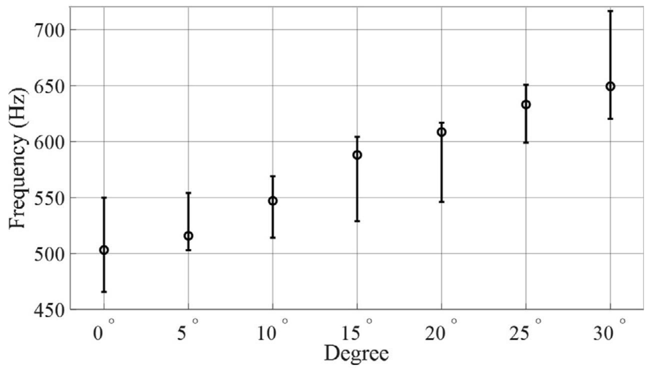


Fig. 9. Frequencies with the maximum absorption coefficients with respect to the rotational angle of the three samples in Fig. 8.

are carried out to measure the characteristics from an acoustic point of view. First of all, the standard two-point approach to measure the acoustic absorption coefficient of material is employed to compare the absorption coefficients of steel, cotton and printed PLA structure. The average absorption coefficients of the printed structure are about 0.3 and these values are between that of steel and that of cotton as illustrated in Fig. 6(a). Interestingly some higher absorption coefficients are observed around 600 Hz and 900 Hz due to the resonances of the printed plate. The resonances of the printed plate absorb the incoming acoustic energy and result in the higher acoustic absorption coefficients. The resonance frequencies can be varied by changing the ratio of the orthogonality of the in-plane stiffness and by changing the geometry.

3.2. Shift of the resonance frequency by rotating plate

The idea of the present research is to rotate the printed plate in order to shift the resonance frequencies for an adaptive acoustic absorber. The shifted resonance frequencies naturally lead the shifts of the frequencies at higher absorption coefficients. Due to the anisotropic material properties of the plate, the shifts of the resonance frequencies are observed by rotating the printed plate. The rotation of the plate makes the contact boundary conditions different and consequently the resonance frequencies become different as well by rotating of the plate. Naturally the resonance peaks become dependent on the angle. To our best knowledge, the acoustic performance of parts printed by the additive manufacturing has not been measured and its application for the adaptive acoustic absorber has not been developed before this research.

To test the shift of the resonance frequency with respect to the rotational angle and the associated changes in the boundary condition, the arbitrary line of the surface of the circular plate is set to the reference line in Fig. 7(a). Due to the heterogeneous material properties, the shifts of the absorption curves are observed in Fig. 7. Basically, the absorption occurs due to the bending mode of the circular plate in Fig. 7(a). Depending on the rotational angle, the boundary condition of the circular plate is changed and the resonance frequency is subject to be changed as shown in Fig. 7(b) and (c). By changing the angle from 0° to 15° gradually in Fig. 7 (b), the resonance frequencies are shifted from 500 Hz to 580 Hz. Rotating the plate further about 25°, the resonance frequency is increased up to 800 Hz. However, due to the friction damping, it is observed that the absorption coefficient becomes lower at 25°.

Depending on the material properties and the printing configurations, i.e., in-fill, melting temperature, feeding ratio and etc, the magnitude of the frequency shift becomes different. Our interpretation is that due to the contact between the irregular bottom surface of the circular plate and the chamber, the direction or the alignment of the printed plate causes the directional properties in Fig. 7(b). Fig. 7(c) shows the curve between the rotation angle and the frequency at the highest absorption coefficient. Using this curve, it is possible to determine an optimized angle for a certain frequency with the highest absorption coefficient for an engineering application. It is possible to install the circular plate to attenuate the incoming acoustic wave while supporting hole. Depending on the frequency range of incoming acoustic noise, it is possible to choose a specific rotational angle and rotate it to efficiently attenuate acoustic pressure. To our best knowledge, the present study may be the first study to investigate the acoustic effect of the 3D printed parts.

As the present absorption mechanism is manufactured by the additive manufacturing, some variations of the responses of the maximum absorption coefficient are depending on the manufacturing conditions. To test this aspect, three samples with the same manufacturing conditions are manufactured. As the melted plastics are juxtaposed in the additive manufacturing scheme, some variations in the geometry and the tolerance are inevitably occurs and Fig. 8 shows the responses of the three circular plates. As illustrated, some variations occurs but the similar relationship between the frequency with the maximum absorption coefficient and the rotation angle can be obtained. This test shows the potential application and limitation of the present approach. In addition, the variations of frequencies with the maximum absorption coefficients with respect to the rotational angle of the three samples in Fig. 8 are shown in Fig. 9. This figure shows the dependency of the variation and proves that the present mechanism can be utilized from the acoustic engineering point of view.

3.3. Effect of the added mass

In order to modify the resonance frequency of the circular plate, it is also possible to add or remove mass at the center of the plate. To illustrate this idea, the masses, e.g., 43 gram, 49 gram and 56 gram, are added at the center of the printed plate in Fig. 10. As the fundamental resonance is the center vibrating mode, the additions of the masses at the center of the plate decrease the fundamental resonance frequency and the associated peak frequency are shifted accordingly. Fig. 11 shows the curves of the peak frequencies with respect to the rotational angle for the plates with the added masses. In our experiments, the frequencies at the peak acoustic absorption coefficients are decreased about 60 Hz by adding 6 gram mass. By adding more mass, it is possible to have lower frequencies. This experiment also illustrates the validity of the present adaptive absorption mechanism of the printed structures. In addition, this experiment suggests that it may be also possible to reinforce the plate in order to increase the fundamental frequency. In addition to the effect of the mass, the manufacturing properties such as the microstructure influencing the anisotropic properties, the tolerance between the plate and the cylinder, and the out of roundness influence the absorption coefficients. Therefore, the individual properties should be measured and tuned to obtain the adaptive curve for each plate.

4. Conclusions

The present study focuses on the application of the anisotropic material properties of the additive technology which is one of the promising manufacturing technologies. As the additive manufacturing technology uses the juxtaposing and stacking melted PLA material, inevitably the orthogonality from a material properties point of view is observed. This property leads some unsymmetrical vibrations of printed plates and shows the peculiar acoustic energy absorption phenomenon; the average absorption coefficient of

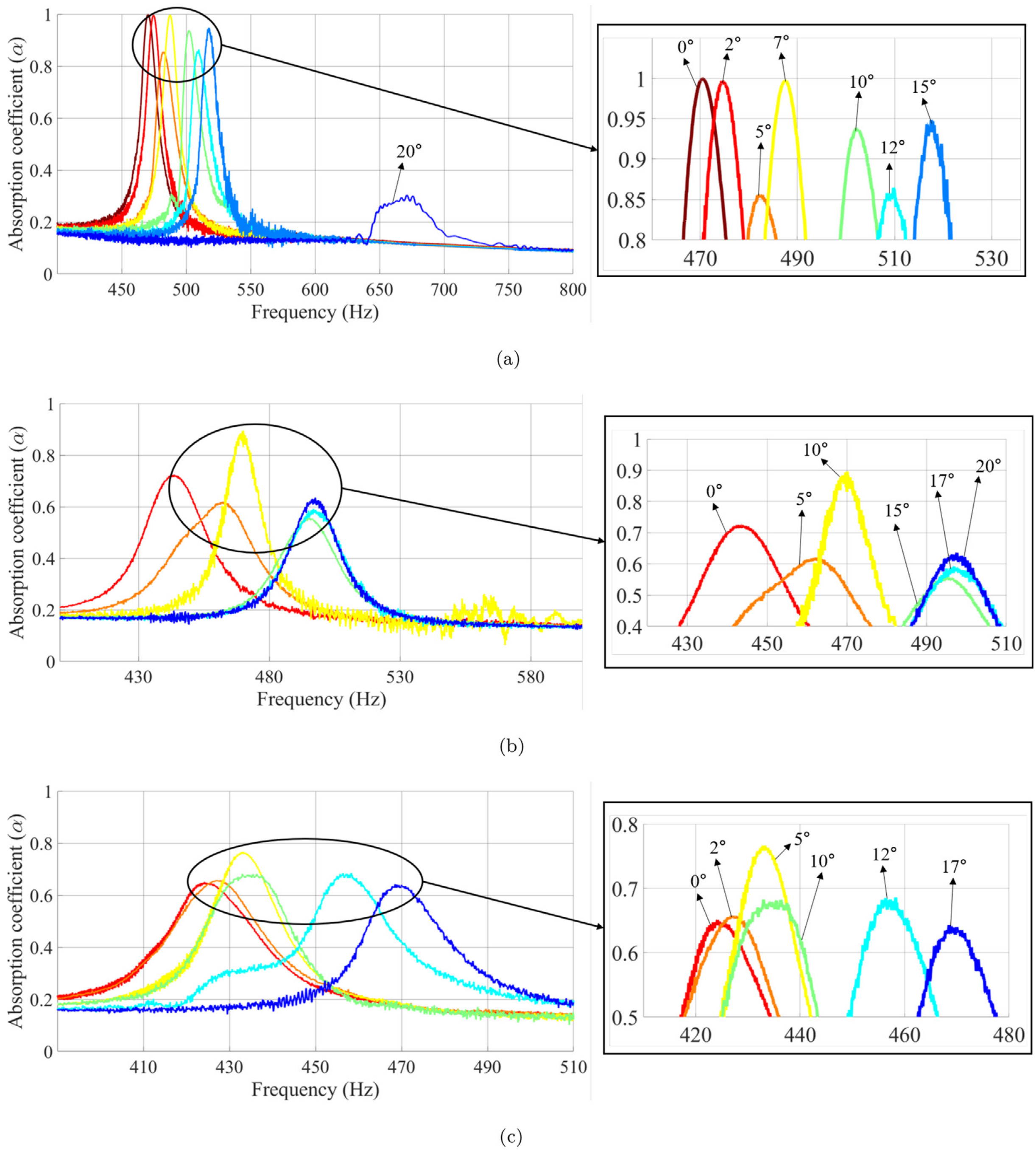


Fig. 10. The effects of the added masses for the absorption coefficient. (a) The absorption coefficient with 43 g mass, (b) the absorption coefficient with 49 g mass and (c) the absorption coefficient with 56 g mass.

flawless plate is about 0.3. This research utilizes this anisotropic property for the application of sound absorption. By rotating printed plates, the acoustic absorption coefficients become dependent on the rotational angle and the adaptive acoustic absorption device can be developed. To show this feature, several plates are printed and acoustic absorption experiments were carried out to prove the concept. One of the remaining issues may be the increase of the robustness of printed structures by controlling the tolerance and the surface microstructure. As melted plastics or similar materials are used, the solicitations of polymer or crystal are hard to be uniformly controlled and some variations inevitably are observed accordingly. For future research, the present study suggests the need of the advanced additive manufacturing technology to improve the acoustic characteristics and the reliability and it is also expected that the present application can be applied to adaptive acoustic metasurface.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

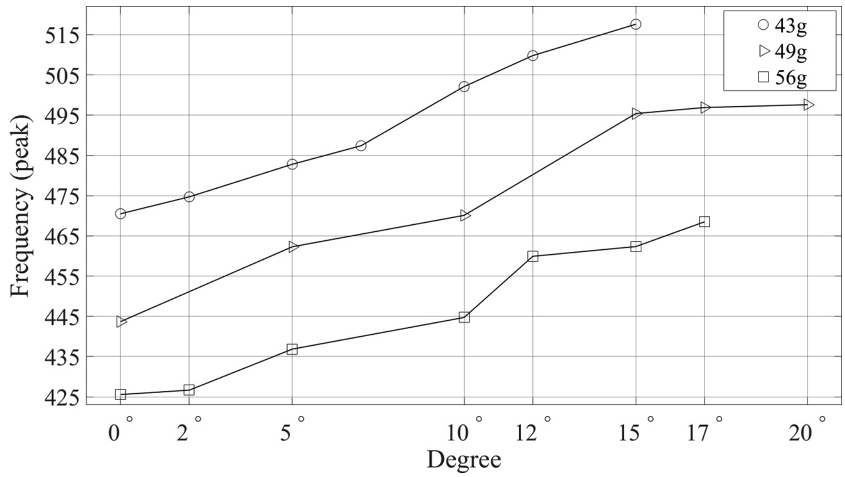


Fig. 11. The effect of the added mass for the absorption coefficient.

Acknowledgement

This work was supported by Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (20202020800030, Development of Smart Hybrid Envelope Systems for Zero Energy Buildings through Holistic Performance Test and Evaluation Methods and Fields Verifications).

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