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Technical note

A note on the viscous boundary layer in plate-type acoustic metamaterials with an internal tonraum resonator

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ABSTRACT

Plate-type acoustic metamaterials are typically constructed from a tensionless membrane. These acoustic metamaterials are characterized entirely based on the resonant behavior of the membrane. To enhance the acoustical performance, an additional feature such as a *tonraum* resonator can be incorporated into the design. Consequently, more design parameters can be tuned on top of the material properties and the geometries of the membrane. However, the resonator's effect could be damped (i.e., missing sound transmission loss peak and dip) because of (1) the poor cylindricity of the orifice produced by fused deposition modeling, and (2) the viscous losses caused by the acoustic boundary layer developed within the orifice. This study clarifies the influence of the two possible causes on the damping of the resonator's effect by investigating the specimen from a previous work in greater detail numerically and experimentally. To achieve this objective, the shape and the depth of the orifice were varied. The results show that the damping of the resonator's effect was not caused by the poor cylindricity of the printed orifice, but was attributed to the viscous losses induced by the acoustic boundary layer developed within the orifice. As a side note, the observations from a comparative study show that the printing time of the specimen can be reduced—up to 41%—without compromising on acoustical performance by having a lower infill percentage. Consequently, this study offers complementary insights into the design of plate-type, and even membrane-type, acoustic metamaterials with an internal *tonraum* resonator so that they can be tuned for low-frequency noise control applications—if required—and not be implicated by the viscous boundary layer developed within the orifice.

1. Introduction

Over the past years, the development of membrane-type acoustic metamaterials has been progressing rapidly. Recently, plate-type acoustic metamaterials have been studied because of their benefits over membrane-type acoustic metamaterials if considered for mass production in the industry [1–4]. The construction of plate-type acoustic metamaterials is similar to membrane-type acoustic metamaterials except for the use of a membrane with negligible pretension. Therefore, the former is advantageous over the latter because of less concerns over stress uniformity and relaxation in the membrane.

The acoustical performance of plate-type acoustic metamaterials is characterized entirely by the resonant behavior of the membrane. A highly dense platelet can be attached to the membrane surface for tuning the resonances to occur at low frequencies. However, if extended in scale, the spatial consistency of the platelet on the membrane surface could potentially be another manufacturing issue.

An alternative is to introduce additional feature(s) in the design of plate-type acoustic metamaterials that could provide more tuning parameters. For example, a recent work [1] showed that the acoustical performance of plate-type acoustic metamaterials could be improved at selected frequencies by an internal *tonraum* resonator, which is a type of Helmholtz resonator. The design involved two cavities enclosed by two membrane layers and a partition. At the center of the partition, a circular orifice was used to couple both cavities, forming the internal *tonraum* resonator. The numerical and the experimental results were consistent in showing the relationship between the orifice size and the occurrence of the resonator's effect in the frequency domain. However, when the orifice diameter was much smaller (3 mm), the resonator's effect was absent in the measured sound transmission loss (TL) curve albeit present in the simulation. It was claimed that the observation could be attributed to two possible reasons: (1) poor cylindricity of the orifice produced by fused deposition modeling; and (2) viscous losses caused by the acoustic boundary layer developed within the orifice.

The first reason could be possible because orifices with poor cylindricity are expected when fused deposition modeling is used [5,6]. The

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cylindricity of the orifices is determined by the nozzle diameter and the printing layer height. To print a curvature, the nozzle is programmed in a manner such that the curvature is realized as close to the ideal surface profile as possible. Consequently, the curvature is realized with a "staircase" effect. This effect is noticeable especially if both printing parameters are large and the feature size is small (i.e., small orifices). Recently, Sajan et al. [6] reported that other printing parameters—bed temperature and printing speed, for example—may also contribute to the cylindricity of the orifices produced by fused deposition modeling. To achieve orifices with good cylindricity, they suggested that the various printing parameters should be optimized. Instead, the cylindricity of the orifices can be improved by considering alternatives such as selective laser sintering, stereolithography, or even conventional machining processes.

As sound waves propagate in a narrow channel, acoustic boundary layer is developed along the interior boundaries of the channel [7]. The acoustic boundary layer includes the viscous and the thermal portions. The former and the latter are associated with the change in tangential velocity and temperature, respectively, from the mainstream flow to the channel boundaries. It can be mathematically shown that both boundary layer thicknesses are inversely proportional to the square root of frequency in which the thermal boundary layer is slightly thicker than the viscous boundary layer by about 13% at a given frequency. For simplicity, the effect of the thermal boundary layer may be neglected by assuming minimal temperature fluctuation between the mainstream flow and the channel boundaries. However, Ingard [7] emphasized on the importance of accounting for the influence of the viscous boundary layer if the study involves sound propagation through a narrow channel, consistent with the views of Maa [8]. This effect was not considered numerically in the previous work [1]. Therefore, the second reason could be possible because of the large ratio of the viscous boundary layer thickness to the orifice radius (1.5 mm). Consequently, the interaction between the viscous boundary layer and the mainstream flow could cause the damping of the resonator's effect.

Currently, limited literature can be found considering the effect of the acoustic boundary layer in membrane-type and plate-type acoustic metamaterials. This trend is expected because most designs did not include any form of internal feature for enhanced acoustical performance. In other types of acoustic metamaterials in which the consideration of the acoustic boundary layer may be applicable, its effect was either neglected for simplicity [9,10] or included as a research focus [11]. For example, Li et al. [10] omitted the effect of the viscous boundary layer in the numerical model, which involved an array of Helmholtz resonators designed for wave steering. The reason for the omission was because of the small ratio of the viscous boundary layer thickness to the wavelength at 3430 Hz. Note that it would be more appropriate if the latter was the orifice radius (around 0.75 mm). Nonetheless, the large discrepancy between the measurement and the simulation could suggest the need to include the effect of the viscous boundary layer for better accuracy of the simulation.

This study aims to clarify the effect of the two possible causes on the damping of the resonator's effect for the case of a small orifice by investigating the specimen reported previously [1] in greater detail. As a side note, this study also aims to understand whether the printing time of the specimen could be reduced without compromising on acoustical performance by having a lower infill percentage. Consequently, the findings could offer complementary insights into the design of plate-type, and even membrane-type, acoustic metamaterials with an internal *tonraum* resonator so that they can be tuned for low-frequency noise control applications if needed. Section 2 presents the specimen details and the methods used to perform the experiment and the simulation. Section 3 discusses the results, which are divided into three segments. Section 4 concludes the study based on the findings.

2. Materials and methods

This section first presents the different specimen configurations considered before moving on to discuss the experimental set-up and the modeling approach of the simulation. Note that only the differences between this study and the previous work [1] are discussed.

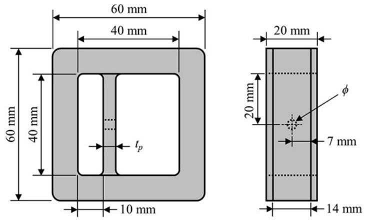

Fig. 1. Schematic representation of the specimen when viewed from the front (left) and the side (right). Dimensions are labeled by a value or a symbol to indicate a fixed or a varying dimension, respectively. t_p and ϕ denote the partition thickness and the orifice diameter, respectively. Cavities (white portions) are enclosed by sandwiching a Mylar film (127 μm thick) between the outer and the middle frames (both sides).

2.1. *Specimen details*

Fused deposition modeling (MOMENT Moment S) was used to print all specimen configurations (100% infill percentage) from polylactide filament based on the dimensions shown in Fig. 1. One specimen was fabricated exclusively from aluminum by machining. The partition thickness t_p and the orifice diameter ϕ were specified based on the values in the previous work [1] (t_p = 5 mm; ϕ = 3 mm). The purpose of the machined specimen was to achieve better cylindricity—and accuracy—of the orifice compared to that printed by fused deposition modeling. By comparing the results obtained between that produced by three-dimensional printing and that fabricated by machining, the first reason pertaining to geometrical inaccuracy could be investigated. Note that the partition was machined separately from the middle frame because of the inaccessibility of the drill bit. Slots were designed in the middle frame for the partition to be inserted.

To investigate if the resonator's effect was damped by the viscous boundary layer, t_p and ϕ were varied (t_p = 2, 3, and 5 mm; ϕ = 3, 5, and 7 mm). These dimensions were varied to verify the presence of the viscous boundary layer within the orifice and to understand the relationship between the influence of the viscous boundary layer on the resonator's effect and the orifice size. Keeping the same cross-sectional area as the circular orifice, a square orifice with edge lengths of 2.6 mm was also considered to further validate the experimental findings from the specimen when ϕ = 3 mm. In this case, only t_p was varied (t_p = 2, 3, and 5 mm).

2.2. *Experimental set-up*

Each specimen configuration was evaluated experimentally via an impedance tube according to ASTM E2611 [12]. A holder was designed to house the specimen in the circular tube. The holder was made from stainless steel to ensure that its natural frequency would not occur between 100 and 1600 Hz. Fig. 2 shows the overview of the holder and the specimen mounted in the impedance tube. Efforts were made to minimize sound leakages and experimental uncertainty. A detailed description of the experimental set-up is provided in the previous work [1].

2.3. *Numerical model*

The numerical model was developed in ABAQUS 2017 based on the modeling approach used in the previous work [1]. In the original model, the effect of the viscous losses was not considered. To include this effect, the volumetric drag coefficient of air was specified in addition to bulk modulus and density. The volumetric drag coefficient γ is