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VENTILATED ACOUSTIC METAMATERIAL FOR NOISE REDUCTION IN A DUCT WITH NON-UNIFORM CROSS SECTIONS

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ABSTRACT

The mitigation of noise propagated along flow path while allowing airflow is crucial in mechanical systems including fluid-guiding structures. While metamaterials are being actively researched to overcome the limitations of conventional materials used for duct noise reduction, most studies have only focused on ducts with uniform cross-sections, limiting their range of application. In this study, we propose a ventilated acoustic metamaterial, called a metaliner, for noise reduction in a duct with non-uniform cross-sectional areas. The design considers the effects of variations in duct cross-sectional areas on noise reduction performance and the influence of locally varying velocity profiles along the direction of flow. In order to achieve this, our impedance model for effective impedance of the metaliner is established to incorporate locally different friction velocities. Using this theoretical model, we design metaliners that achieve high insertion loss and experimentally demonstrate their effectiveness at reducing noise in ducts with non-uniform cross-sections under the presence of flow.

Keywords: *acoustic metaliner, duct noise reduction, non-uniform cross section, friction velocity*

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1. INTRODUCTION

Noise mitigation within ducts is crucial in many mechanical systems, including vehicle ventilation systems, building HVAC systems, and power plants. Conventional solutions, such as acoustic louvers [1] and mufflers [2], face limitations due to their bulky structures. Recently, acoustic metamaterials [3-6] have attracted significant attention due to their potential in noise control applications. However, existing studies mainly focused on ducts with constant cross sections, limiting their practical applicability. To address this, we propose an acoustic metaliner, a type of ventilated acoustic metamaterial, specifically designed to achieve high noise attenuation performance in ducts with non-uniform cross sections and validate its performance through experimental investigations.

2. THEORETICAL DEVELOPMENT AND EXPERIMENTAL VALIDATION

2.1 Theoretical development

The acoustic metaliner presented in this study features a thin structure relative to the target acoustic wavelength and is installed underneath the duct wall without obstructing the airflow as shown in Fig. 1. The primary challenge was accommodating the variation of cross-sectional area and associated locally varying flow velocity profiles along the duct length. To this end, a friction velocity-based analytical approach was formulated, enabling precise prediction of the metaliner's effective acoustic impedance under flow conditions in ducts with non-uniform cross-sections.

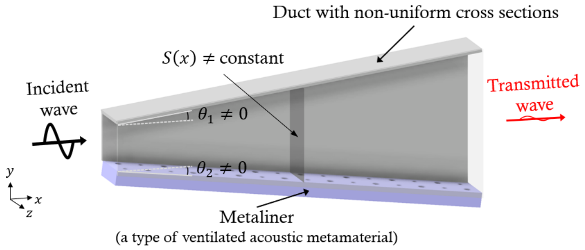

Figure 1. Schematic of an acoustic metaliner and a duct with non-uniform cross sections.

Using the developed impedance model, the metaliner was designed for a target frequency of 900 Hz. The designed metaliner exhibited an insertion loss of 45 dB at the target frequency for an inlet flow velocity (U_0) of 34 m/s, with a length of 408 mm and a thickness of λ/19. This result demonstrates a significant enhancement, exhibiting a 31 dB higher insertion loss compared to the metaliner designed using the methodology proposed in [6], which is suitable for ducts with constant cross sections.

2.2 Experimental validation

An experimental device, the Flow Grazing Incidence Tube (FGIT), was constructed to evaluate the metaliner's noise reduction performance under flow conditions in ducts with non-uniform cross sections. The designed metaliner was fabricated using 3D printing. Experimental measurement result is shown in Fig. 2. The measured insertion loss aligned with theoretical predictions, demonstrating the metaliner's effectiveness in reducing noise in ducts with non-uniform cross sections.

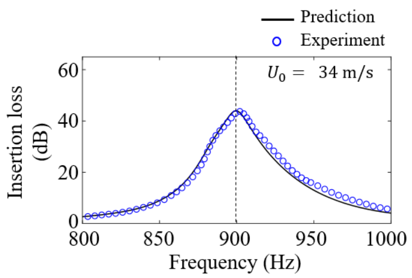

Figure 2. Insertion loss spectrum the designed metaliner. The blue circle indicates the measured results. For comparison, the predicted results are shown as the black solid line.

3. CONCLUSIONS

In summary, we demonstrated that the metaliner effectively reduces noise in ducts with non-uniform cross-sectional areas. To account for the effects of cross section's variation and locally varying flow velocity profiles, a theoretical model for the metaliner's impedance was established in terms of friction velocity. This model was employed to design the metaliner, which was subsequently fabricated using 3D printing. Experimental evaluations validated the impedance model's accuracy and showed the metaliner's effectiveness for noise reduction in ducts characterized by non-uniform cross sections.

4. REFERENCES

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