Journal of Solid and Fluid Mechanics (JSFM), 15(3): 21-24, 2025

Shahrood University of Technology

Journal of Solid and Fluid Mechanics (JSFM)

DOI: 10.22044/jsfm.2025.15629.3932

Manufacturing Engineering of Iran

Numerical Investigation of Grazing Flow on a Micro Perforated Plate Liner

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Received: 01/23/2025 Revised: 04/21/2025 Accepted: 06/07/2025

Abstract

This study investigates the background flow field of a micro-perforated plate (MPP) liner for acoustic analysis under grazing airflow conditions. A segment of the MPP liner is modeled, and the three-dimensional Navier-Stokes equations are numerically solved using a carefully designed computational mesh. A turbulence model is employed to capture flow disturbances, and a fully developed flow boundary condition is applied at the channel entrance to reduce computational cost. The numerical results are validated against experimental data from previous studies. The impact of flow Mach number on two key mechanisms influencing the acoustic behavior of the liner is examined: (1) the vertical velocity component at the hole openings, and (2) vortex generation at and downstream of the holes. As the Mach number at the inlet of the duct increases, the rotation of the vertical component of velocity along the hole also increases, which leads to changes in the acoustic properties of the liner, including its impedance. In other words, vortex generation downstream of the holes intensifies as Mach number increases. The findings reveal that increasing Mach number results in higher acoustic impedance, highlighting the complex interplay between flow dynamics and acoustic performance.

Keywords: Micro Perforated Plate; aeroacoustic; grazing flow; Navier- Stocks equations; vortex.

1. Introduction

Acoustic vibrations, besides their negative impact on human physical and mental health [1, 2] can significantly affect aerospace structures by causing fatigue, increased stress, and damage to components.

Understanding flow-acoustic interactions is crucial for reducing vibration and enhancing the safety of aerial and space vehicles. Micro-perforated panel (MPP) liners are widely used for this purpose in areas with grazing flow, such as engine inlets and ducts. This study investigates the acoustic response of micro-perforated panel (MPP) liners under grazing flow, relevant to applications such as engine inlets and ventilation ducts.

Kirby et al. [3] conducted experimental measurements to evaluate the effect of grazing flow at different velocities on the acoustic impedance of micro-perforated liners. Similarly, Malmari et al. [4] studied the impact of grazing flow up to Mach 0.7 on the acoustic impedance of these liners. In contrast, Zhao et al. [5, 6] investigated the acoustic response of MPPs exposed to normal flow, focusing on the influence of Mach number, perforation diameter, and porosity, using both experimental and numerical methods. A more detailed parametric numerical investigation was conducted by Zhenlin Ji et al. [7], who examined the effect of flow Mach number in the range of 0.05–0.2, perforation diameters from 2 mm to 6 mm, and various geometric factors on the impedance characteristics of MPPs. In the absence of flow, Bahman-Jahromi et al. [8] studied a perforated liner configuration similar to MPPs to characterize their baseline acoustic performance. The role of backing cavity geometry under grazing flow conditions was further explored by Dastourani [9], who demonstrated its significant impact on both absorption frequency and intensity. Ou et al. [10] examined the performance of existing semi-empirical models for impedance prediction in circular and rectangular ducts, validating them against numerical solutions of the Navier–Stokes equations. Wen et al. [11] numerically analyzed grazing flow over MPPs, focusing on how the perforation angle and diameter-to-length ratio affect the impedance for subsonic Mach numbers below 0.2. Several studies have further suggested that, when the porosity is approximately 1%, a single-hole model can effectively represent the acoustic behavior of the entire liner [3,12]. Moreover, it is generally accepted that the sound emitted by the liner itself is negligible compared to the sound it absorbs [13].

This study presents a detailed numerical analysis of micro-perforated panel liners under grazing flow, employing a fully developed inlet velocity profile. The key novelty lies in this boundary condition, which notably reduces computational effort without sacrificing accuracy, enabling more efficient and realistic aeroacoustic modeling.

2. MPP Liner Geometry

This study numerically analyzes grazing flow over an MPP liner, extending previous work by applying a fully developed inlet velocity profile. The geometric configuration investigated herein is based on the experimental setup of Malmari et al. [4]. Given that the porosity in their study is approximately 1%, the interaction between adjacent perforations can be considered negligible [3,12], allowing the hole arrangement pattern to be disregarded. As suggested by the results of [12], when the perforation ratio is low and hole interactions are negligible, the acoustic impedance of the liner can be approximated by that of a single hole divided by the porosity. The geometry of the liner adopted in this study is illustrated in Figure 1, where all dimensions are provided in millimeters.

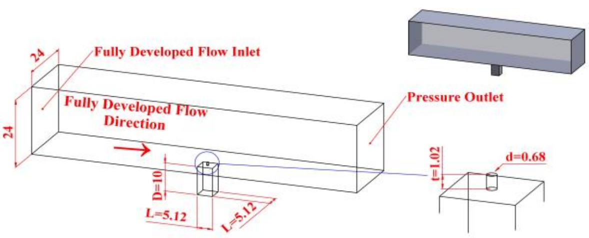

Figure 1. Schematic overview of the computational domain and applied boundary conditions

3. Governing Equations and Assumptions

To investigate the velocity and pressure fields inside the duct and around the liner, the flow is modeled as compressible, in accordance with the physical characteristics of the problem and the requirement for the results to be applicable in subsequent acoustic analyses. The turbulent flow regime is simulated using the single-phase fluid solver with the $k-\varepsilon$ turbulence model. The governing equations in this study are the continuity equation (1) and the momentum conservation equations (2) [14].

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \qquad (1)$$

$$\rho \frac{\partial u}{\partial t} + \rho (u.\nabla) u = -\nabla p + \frac{\partial}{\partial x_j}\left[2\mu \epsilon_{ij} + \delta_{ij} \lambda div u\right] + F \qquad (2)$$

$$\epsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right) \qquad (3)$$

Here, ρ is the density, **u** the velocity vector (u, v, w), p the pressure, and **F** the body force vector. δ_{ij} is the Kronecker delta and λ the bulk viscosity. Air is considered as the working fluid under standard ambient conditions. Gravity and other body forces are neglected. The flow is assumed steady, adiabatic, fully developed, and subsonic (Mach < 0.3) with constant thermophysical properties.

4. Grid Specifications

To ensure reliable flow predictions, a grid independence study was conducted using three meshes ranging from 582,000 to 1,497,000 cells. All meshes had a hybrid structure: structured hexahedral elements in the main duct and unstructured cells near perforations and cavities. Results indicated that solutions were grid-independent beyond 887,000 cells, which was chosen for further simulations. The final mesh used 2 mm maximum element size in the duct, with 30 inflation layers along walls and 15 near perforations. The cavity was discretized with unstructured tetrahedra and boundary refinement near walls.

5. Numerical Simulation Results and Validation

The flow field was solved in COMSOL Multiphysics using the Single-Phase Flow, Turbulent Flow interface with the compressible steady-state k–ε model, as outlined in Fig. 1. No-slip conditions were applied at solid walls. A fully developed velocity inlet (Mach 0.1–0.3) and ambient pressure outlet were used. Initial conditions were ramped via continuation from lower Mach solutions. Validation against the experimental friction velocity data of Malmari et al. [4] (Figure 2) shows good agreement, with deviations mainly attributed to RANS wall stress modeling. Results are also consistent with studies [15][16] lacking fully developed inlet profiles.

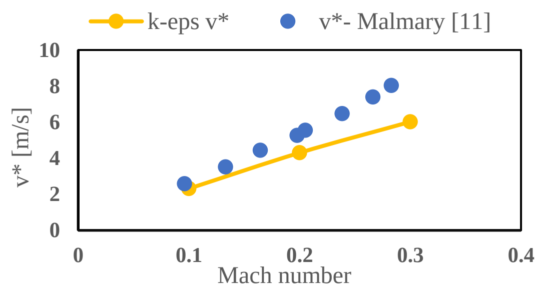

Figure 2. Validation via Friction Velocity: Comparison Between Experimental Data [4] and Present Simulation

As shown in Figure 3, z velocity component was extracted along the whole diameter in the x-direction. With increasing Mach number, upstream–downstream asymmetry intensifies, enhancing vortex shedding at the hole entrance. This mechanism significantly affects liner acoustics at SPLs above 125 dB [17, 18].

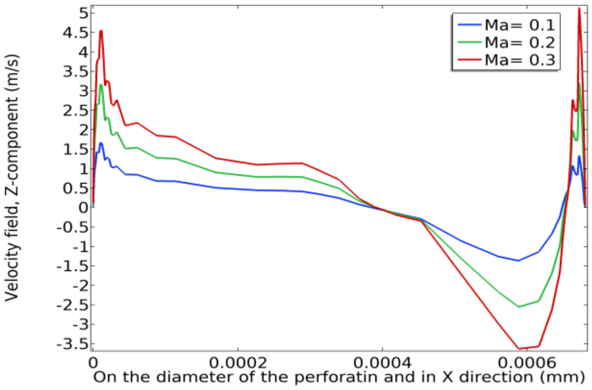

Figure 3. Z velocity component along the hole diameter in the x-direction

Figure 4 presents the vorticity contours at Mach 0.3, illustrating the growth and downstream convection of vortices from the hole entrance. This vortex shedding influences the liner's absorption coefficient and acoustic impedance.

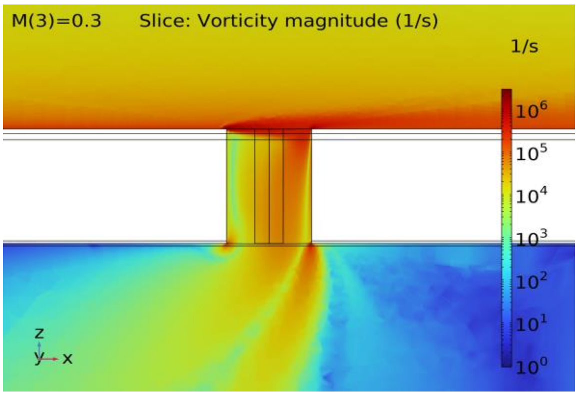

Figure 4. Vorticity contours at Mach 0.3 in the symmetry plane

6. Conclusions

This study numerically investigated fluid flow over an acoustic liner using a mesh of approximately 887,000 computational cells, confirmed by a grid independence study. Simulations in COMSOL Multiphysics employed a fully developed velocity inlet, reducing domain length and computational cost without loss of accuracy. Mach numbers from 0.1 to 0.3 were examined, and friction velocity results validated against experiments. Increasing Mach number intensified vertical velocity swirling through the perforation, enhancing vortex shedding. This altered the liner's acoustic properties, notably increasing acoustic impedance, with downstream vortex generation further affecting acoustic absorption.

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