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Two-dimensional lattice Boltzmann investigation of sound absorption of perforated orifices with different geometric shapes

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ABSTRACT

To gain insight into sound absorption mechanism and to evaluate its acoustic damping performance, two-dimensional numerical simulation of acoustically excited flow through perforated orifices with different geometric shapes is conducted by using lattice Boltzmann method. It is shown that vortex rings are formed when incident sound waves interact with and destabilize the shear layers formed at the orifice rims, and the sound energy is converted into kinetic energy being dissipated by the surrounding air. To quantify the orifice damping performance, sound absorption coefficient is used, which describes the fraction of incident acoustical energy being absorbed. Unlike frequency-domain simulations, the present study is conducted in time domain and the damping behavior of different shaped orifices is quantified over a broad frequency range at a time by forcing an oscillating flow with multiple tones. Comparing the numerical results with those obtained from the theoretical models and experimental measurements, good agreement is observed. And the square-shaped orifice is associated with larger damping effect than that of a rounded one. Finally, parametric study is conducted. It is found that the maximum sound absorption and the effective frequency bandwidth depend strongly on the combination of the bias flow Mach number and the orifice thickness. The successful demonstration reveals that the lattice Boltzmann method has great potential to be applied in aeroacoustics research field.

1. Introduction

Thermoacoustic instability occurs in many practical combustion systems, such as aero-engine afterburners, rocket motors, boiler, ramjets and gas turbines. Most often it arises due to the dynamic interaction between unsteady heat release and acoustic waves [21]. To mitigate such instabilities, the coupling between unsteady heat release and acoustic waves must somehow be interrupted [26]. Perforated liners are usually metal sheets, which have tiny orifices in them. They are placed and used along the bounding walls of a combustor as acoustic dampers to absorb acoustic waves [24,25,34,35,37,39]. In practice, a cooling air flow through the orifices (known as bias flow) is needed in combustion systems to prevent the liners from being damaged due to extremely high temperature. The need to improve acoustic liners designs with current low-emission engines [20,36,38,41] and 'quiet' HVAC (heating, ventilation and air conditioning) systems leads to a resurgence of liner [3] or porous foam focused research [9].

Over the last few decades, acoustic liners have been the subject of intense research activity, aiming to better understand and predict their damping performance. Theoretical, numerical and experimental investigations are conducted. However, experimental studies [7,14] focus on measuring the liners impedance or power absorption coefficient, which is easier to measure in comparison with the flow field near the tiny orifice, typically around 1 mm in diameter. Eldredge and Dowling [7] experimentally measured the power absorption of a double-layer liner in the presence of bias and grazing flow. It was shown that approximately 80% of sound energy can be absorbed with an 'optimum' bias flow Mach number. Jing and Sun's experiments [14] confirmed that the orifice thickness and the bias flow Mach number play dominant roles in affecting the liners' damping performance. Ingård and Labate [12] experimentally visualized that the incident sound amplitude, frequency, the orifice diameter and thickness affected the induced motion of the fluid near the orifice.

Theoretical studies have been mainly carried out in frequency domain and focus on the damping mechanism of single or multiple orifices. Howe [10] used Rayleigh conductivity to model the acoustic energy dissipated by the periodic shedding of vorticity for a single orifice at a high Reynolds-number. Hughes and Dowling [11] showed that the sound incident on a perforated liner with a bias flow might be completely absorbed, if the flow speed and the liner geometry were chosen properly. Eldredge and Dowling [7]

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developed a 1D duct model in frequency domain to simulate the absorption of axial plane waves by using a double-liner with a bias flow. The damping mechanism of vortex shedding was embodied using a homogeneous liner compliance adapted from Rayleigh conductivity.

Compared with frequency-domain theoretical modeling [7,40], time-domain numerical simulations [13,23,31,33,42] become more popular. This is most likely due to the availability of high performance computer and the development of more efficient computational algorithms. Zhang and Bodony [33] recently used DNS (direct numerical simulation) to investigate the acoustics behavior of a circular orifice backed by a hexagonal cavity. It was found that the orifice boundary layer played a critical role in affecting the nonlinearity. Mendez and Eldredge [23] conducted compressible large-eddy simulations (LES) in time domain to study the flow and acoustic characteristics through a single or multiple orifices. Tam et al. [31] numerically studied the sound damping effect of a single aperture using DNS. They showed that vortex shedding was the dominant damping mechanism for large-amplitude incident waves. The time-domain simulations described above attempt to solve the Navier–Stokes equations by using high-order FV (finite volume) or FD (finite difference) method.

In order to model and simulate complex physics in fluids [30], lattice Boltzmann method (LBM) could be used as an alternative computational tool. It simulates the space–temporal evolution of fluid field based on a time–space discretization of the Boltzmann equation, known as the lattice Boltzmann equation (LBE). The LBE controls the particles associated with collision and propagation over a discrete lattice mesh. The flow variables such as density, momentum and internal energy are obtained by performing a local integration of the particle distribution. Thus LBM is thought to be one of the particle techniques, which is different from conventional numerical schemes. Compared with FD or FV solvers, LBM is easier to implement and code, has the potential for parallelization, and more successful in dealing with complex boundaries [30]. It has been successfully applied to study aeroacoustics, such as jet [19], cavity [27] and airfoil [28] noise. Marié et al. [22] showed that LBM is faster and less dissipative (for a given dispersion error) in comparison with the conventional high-order FD models. For example, for a tolerated dispersion error of 0.1%, the LBM is about 37% less expensive in computation than the classical 2nd order NS schemes. However, in comparison with optimized 3rd order scheme, it is approximately 9% less expensive. Similar finding on reduced CPU-time is reported by Geller et al. [8]. The previous works [8,22,28] have confirmed that LBM possesses the required accuracy to capture the weak acoustic fluctuations.

In this work, two-dimensional lattice Boltzmann investigation is conducted to simulate vorticity-involved acoustic damping mechanism of perforated orifices with different geometric shapes, and to quantify/characterize their sound absorption performances. The numerical simulations are conducted in time domain, as described in Section 2. The 2D numerical scheme and configuration of interest are presented. To evaluate the sound absorption performance of the perforated orifices, Rayleigh conductivity and power absorption coefficient are defined and used. This is described in Section 3. In Section 4, time evolution of vortex shedding at the orifice rims is simulated. In addition, its sound absorption effect is estimated. Comparison is then made between the present numerical results, experimental and theoretical ones, which consider the orifice thickness. In Section 5, parametric study is performed to gain insight on the effects of the bias flow and the orifice thickness on its acoustic damping performance. Finally, in Section 6, the main findings of the present work are summarized.

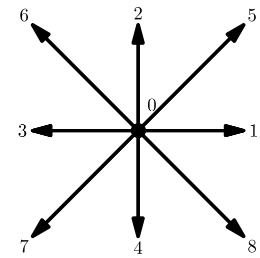

Fig. 1. Two-dimension, nine-velocity (D2Q9) lattice model.

2. Numerical method and configuration of interest

LBM originated from lattice gas automata [30], is based on mesoscopic models and kinetic equations. Simplified kinetic models are developed, which assume the fluid flow composes of a collection of pseudo-particles. They can be represented by a set of density distribution functions. These particles are associated with collision and propagation over a discrete lattice mesh. In order to perform particles motions, the fluid domain is discretized into a specific group by series of nodes and lattices, depending on the different models. Fig. 1 illustrates the D2Q9 lattice model used in the present work. It shows that a particle has nine feasible discrete propagation directions in each node and the motion in two dimensional space.

The discrete velocity vectors $\boldsymbol{e}_i$ of the particles are defined as:

$$\boldsymbol{e}_i = \begin{cases} 0, & i=0, \\ c_l(\cos(\frac{i-1}{4}\pi), \quad \sin(\frac{i-1}{4}\pi)), & i=1,3,5,7, \\ \sqrt{2}c_l(\cos(\frac{i-1}{4}\pi), \quad \sin(\frac{i-1}{4}\pi)), & i=2,4,6,8, \end{cases} \tag{1}$$

where $c_l = \Delta x/\Delta t$ (lattice space/time step) is the particle propagation speed on the lattice. And it is assumed that $c_l = 1$. The fundamental propagation and the collision of the fluid particles over the lattice are governed by a space–temporal discretization of the Boltzmann equation (known as lattice Boltzmann equation) as

$$f_i(\boldsymbol{x}+\boldsymbol{e}_i\Delta t, t+\Delta t) - f_i(\boldsymbol{x},t) = -\frac{1}{\tau}\big(f_i(\boldsymbol{x},t) - f_i^{eq}(\boldsymbol{x},t)\big), \tag{2}$$

where f_i is the distribution function associated with the propagation direction i at the spatial coordinate $\boldsymbol{x}$ and time t. The relaxation parameter τ defines particle collision and acts to control the kinematic viscosity of the fluid: $\nu = (2\tau-1)/6$. f_i^{eq} is the equilibrium distribution function, which is the second order truncated expansion of the Maxwell–Boltzmann equilibrium function as given as:

$$f_i^{eq} = \rho w_i\left(1 + \frac{3}{c_l^2}\boldsymbol{e}_i\cdot\boldsymbol{u} + \frac{9}{2c_l^4}(\boldsymbol{e}_i\cdot\boldsymbol{u})^2 - \frac{3}{2c_l^2}\boldsymbol{u}\cdot\boldsymbol{u}\right), \tag{3}$$

where w_i is the weighting factor and given as:

$$w_i = \begin{cases} \frac{4}{9}, & i=0, \\ \frac{1}{9}, & i=1,2,3,4, \\ \frac{1}{36}, & i=5,6,7,8. \end{cases} \tag{4}$$

The terms on the left hand side of Eq. (2) describes the propagation operator and determines the diffusion of the distribution functions over the lattice. The terms on the right hand side of Eq. (2), known as Bhatnagar–Gross–Krook (BGK) [2] collision operator, is a simplification of the collision function based on the use of the relaxation time τ in ith direction. The local macroscopic variables ρ and $\boldsymbol{u}$ on each lattice site are obtained in terms of the local distribution function f_i by: