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Discrete simulation of fluid dynamics

Lattice Boltzmann formulation for flows with acoustic porous media

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A B S T R A C T

Porous materials are commonly used in various industrial systems such as ducts, HVAC, hoods, mufflers, in order to introduce acoustic absorption and to reduce the radiated acoustics levels. For problems involving flow-induced noise mechanisms and explicit interactions between turbulent source regions, numerical approaches remain a challenging task involving, on the one hand, the coupling between unsteady flow calculations and acoustics simulations and, on the other hand, the development of advanced and sensitive numerical schemes. In this paper, acoustic materials are explicitly modeled in lattice Boltzmann simulations using equivalent fluid regions having arbitrary porosity and resistivity. Numerical simulations are compared to analytical derivations as well as experiments and semi-empirical models to validate the approach.

1. Introduction

Porous media are widely used as sound-absorbing materials in various industries to reduce noise emission. For example, in modern turbofan engines, the inlet wall is treated with acoustic liners. Highway and railway noise barriers often use acoustic treatments for solving community noise issues. At a microscopic scale, propagation of sound in porous media is difficult to characterize because of the topological complexity of materials. At a macroscopic scale, some porous materials can be treated as regions of fluid that have modified properties relative to air [1], in the rigid or limp frame approximation. Sound propagation in such media is theoretically well characterized and can be expressed in the terms of two intrinsic frequency-dependent properties of the material: the characteristic impedance and the complex acoustic wavenumber. Various models for these properties based on experimental studies are presented in the literature. Under certain assumptions, a given sound propagation model in an absorbing material can be put in the form of locally-reacting, frequency-dependent, complex impedance at the interface between two different media. Such surface impedance models appear in most traditional numerical acoustics solvers such as Boundary Element Methods (BEM), Finite Elements Methods (FEM), and Statistical Energy Analysis (SEA) methods, and are relatively easy to implement as boundary conditions in the frequency domain.

For problems involving flow-induced noise, suitable CFD (Computational Fluid Dynamics) and/or CAA (Computational Aero-Acoustics) numerical methods are non-linear and often time-explicit. For a time-explicit solver, time-domain surface impedance boundary conditions could likewise allow the modeling of acoustic absorption due to porous materials [2]. Ozyoruk et al. [3] proposed a curve fitting of the experimental impedance data in the form of fractional polynomials in

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the z-domain and derived an efficient implementation of the above impedance boundary condition in the time domain by using the z-transform. The simulations of the NASA Langley grazing flow tube case using this model [3–5] showed good agreement with experimental data. References [6,7] applied this scheme within a lattice Boltzmann method (LBM) flow solver and also showed similarly good correlations with the experiment. However, fitting the measurement data into this fractional polynomials might be challenging because causality, reality, and passivity listed by Rienstra [8] can not be always satisfied. Violation of these constrains could result in unphysical behavior or numerical instability.

Another possible approach is to model absorbing materials as equivalent fluid regions, such that sound waves travel through the materials. Analytical derivations show that the acoustic absorption is governed (or at least dominated) by the same physical mechanisms as the flow resistivity. As a consequence, the same equations used to achieve the correct flow resistivity for a particular porous material also achieve the correct acoustic impedance for that material. This approach was demonstrated valid for passive and homogeneous porous materials with high porosity near $\phi = 1.0$ [9].

In the present paper, in addition to the resistivity of porous materials, we account for the porosity as well in LBM, which greatly increases the applicability of the PM for solving acoustic and aero-acoustic problems.

The LBM has evolved over the last two decades as an alternative numerical method to traditional CFD [10–13]. The resulting compressible and unsteady solver is well suited for predicting a variety of complex flow physics [14,15] including aeroacoustics [16–20] and pure acoustics problems [21]. The present extension of porous media model with arbitrary porosity can be used to represent the flow resistivity of air filters, radiators, heat exchangers, evaporators, and other components that are encountered in simulating the flow through HVAC systems, vehicle engine compartments, and other applications.

In Section 2, numerical details related to LBM, and implementation of the porous media model is proposed. In Section 3, some background on acoustic propagation in porous media is described and analytical and semi-empirical models are given. In Section 4, two numerical setups are used to validate the predictions of the complex acoustic impedance and pressure losses of PM by comparison to analytical results. In the last section, some more realistic materials are investigated and further comparisons to experiments and semi-analytical models discussed.

2. LBM model for porous media

To model porous media we need to consider the PM resistance and the interface constraint.

The flow resistance σ of a porous medium is described by Darcy's law, which states that the pressure drop Δp is proportional to the flow velocity u and the thickness L of the PM, i.e.:

$$\Delta p = -\sigma u L \tag{1}$$

It can be generalized in 3-D in term of the resistance tensor $\boldsymbol{\sigma}$ of order 2 and velocity vector $\mathbf{u}$:

$$\nabla p = -\boldsymbol{\sigma} \cdot \mathbf{u} \tag{2}$$

In order to simulate the acoustic behavior in the PM, it is essential that the density and the velocity solved represent the real fluid density and velocity in the pores, excluding the solid portion of the porous media because the objective is to model the sound wave propagation in fluid. Meanwhile, the mass flux conservation should be satisfied at the fluid–PM interface. For non moving infinitely rigid solid micro-structure of PM it is expressed as:

$$(\rho u_n)_{\mathrm{f}} = \phi(\rho u_n)_{\mathrm{PM}} \tag{3}$$

with $u_n = \mathbf{u} \cdot \mathbf{n}$, $\mathbf{n}$ the interface normal vector, and ϕ the porosity. The indices f and PM represent fluid side and PM side, respectively.

Another aspect of interface is the interface resistance due to the presence of the solid structure. This interface resistance depends on the porosity, flow velocity and microscopic structure of the PM.

In the current study these PM related properties are incorporated in the 3-D 19-speed LBM (D3Q19) [11]:

$$f_i(\mathbf{x} + \mathbf{c}_i, t + \Delta t) = f_i(\mathbf{x}, t) - \frac{1}{\tau}(f_i(\mathbf{x}, t) - f_i^{\mathrm{eq}}(\mathbf{x}, t)) \tag{4}$$

with $f_i(\mathbf{x}, t)$ the particle density distribution function, τ is the single relaxation time, $\mathbf{c}_i$ the discrete particle velocity, and Δt the time step. The equilibrium distribution function $f_i^{\mathrm{eq}}(\mathbf{x}, t)$ has the following 3rd order form [22]:

$$f_i^{\mathrm{eq}}(\mathbf{x}, t) = \rho\, w_i \left[1 + \frac{\mathbf{c}_i \cdot \mathbf{u}}{T_0} + \frac{(\mathbf{c}_i \cdot \mathbf{u})^2}{2T_0^2} - \frac{\mathbf{u}^2}{2T_0} + \frac{(\mathbf{c}_i \cdot \mathbf{u})^3}{6T_0^3} - \frac{(\mathbf{c}_i \cdot \mathbf{u})\mathbf{u}^2}{2T_0^2} \right] \tag{5}$$

with $w_0 = 1/3$ for stop state, $w_i = 1/18$ for states in Cartesian directions and $w_i = 1/36$ for states in bi-diagonal directions. Here $T_0 = 1/3$ is the constant lattice temperature. The hydrodynamic quantities ρ and $\rho\,\mathbf{u}$ are the zero-th and first-order moments of the distribution functions, respectively:

$$\rho(\mathbf{x}, t) = \sum_i f_i(\mathbf{x}, t), \quad \rho(\mathbf{x}, t)\mathbf{u}(\mathbf{x}, t) = \sum_i \mathbf{c}_i f_i(\mathbf{x}, t) \tag{6}$$