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An investigation of the lattice Boltzmann equation-based hybrid approach for simulation of sound generated by isotropic turbulence

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A B S T R A C T

We study noise radiated by forced isotropic turbulence numerically using a hybrid approach, i.e. lattice Boltzmann equation-based DNS/acoustic analogy. In the present contribution, a deterministic force model is developed in direct LBM simulations and its characteristics is analyzed and compared to a recently proposed stochastic forcing scheme. The fluctuating acoustic pressure, acoustical spectrum and sound pressure level are first evaluated on the ground of the hybrid approach and compared with the results from various numerical and analytical solutions. In this paper, we also address the effects of local time delay based on different forcing schemes on prediction of the radiated noise when Lighthill's acoustic analogy and LBM are used for computation of the turbulent flow field and acoustic field.

1. Instruction

Flow-generated noise is a serious problem in many engineering applications. With the development of computer technology, computational fluid dynamics (CFD) and computational aero-acoustics (CAA) have become very effective tools to examine flow noise generation and propagation processes and to obtain a better understanding of the physics of the problems in many engineering areas, such as jet noise, fan noise, marine propeller noise and cavity noise [1]. The numerical studies of aeroacoustics are prompted by the need for quieter modern aircrafts, vehicles and submarines. The sound generated by turbulence, i.e. aerodynamic sound generated by a turbulent jet, is of major concern for aerodynamic sound source as well as for acoustical field, and is becoming more and more relevant. Thus, there has been a considerable effort in recent years to study turbulent noise, to understand the mechanisms that lead to its generation.

The study of flow-induced noise focus on two issues, the near-field aerodynamics (or hydrodynamics) and the far-field sound radiation which need to be predicted correctly to get the results concerned [2,3]. Two main computational methods, hybrid approaches and direct noise computations, can be categorized. The direct method which requires no assumption, computes the sound propagation and its source field as dynamically coupled phenomena, and provides multi-point information in the temporal (or frequency) domain. Therefore, all flow scales from dissipative micro-scales to the large wave-length scales of far-field noise, should be included within the computational domain simultaneously [4]. It also is required to across several orders of magnitude in scale of aerodynamic and acoustic quantities. Hence, a single numerical method may not be sufficient to capture all scales and a hybrid approach may be more effective.

Hybrid approaches are often employed in which the computation of flow field is decoupled from acoustic field. The near-field aerodynamic fluctuations are computed first by solving Navier–Stokes equations, and then the far-field radiated noise can be obtained by acoustic analogy based on the source field data [5]. As the first attempt to estimate the sound radiated from a finite region of turbulent flow, Lighthill's analogy based on the resolution of Lighthill's equation derived from the compressible Navier–Stokes equations [6,7]. For flows at relatively low Mach numbers, two-way coupling is neglected in acoustic analogies, i.e. the unsteady flow generates sound but the refraction effect on the flow is not taken into account, and the turbulent region as sound source is required to be compact. The acoustic analogies are numerous and have been used to study the sound generated by homogeneous isotropic turbulence, jet noise, or the sound radiation by other shear flows [8,9].

As part of a hybrid method, direct numerical simulation (DNS) [10], Reynolds averaged Navier–Stokes simulations (RANS) [11], or Large eddy simulation (LES) [12,13], can be used to compute the near field pressure data as noise source. One important consideration for hybrid approaches is how to determine the finite volume that the main sound source is covered inside the integral domain [14]. Simple truncation of the integration boundary may

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create spurious sound. Oberai and Hughes [15] and Wang et al. [16] tried to demonstrate this and make various corrections to remove the spurious noise. The general extension form of Lighthill's analogy is usually used for some engineering problems in which source region contains moving solid boundaries [17,18].

Homogeneous isotropic turbulence has been the most in-depth theoretical model in the study of turbulence, and its radiating noise has the character of quadrupole sources. Therefore, the far-field acoustic characteristics of isotropic turbulence has academic importance for study the mechanism of turbulence-induced sound [19,20]. Proudman [21] first analyzed acoustic spectrum induced by homogeneous isotropic turbulence and proposed the Proudman constant. Rubinstein and Zhou [22] proposed the sweeping velocity hypothesis theory for the modeling of sound radiation of isotropic turbulence. Sarkar and Hussaini [23] studied the noise radiated by isotropic turbulence using hybrid method based on pseudo-spectral method, their results was consistent with the Lighthill's and Proudman's theoretical results. Recently, a hybrid method of LES and Lighthill acoustic analog with different SGS models are developed to calculate the sound radiated by isotropic turbulence [24,25], where the new challenges are the effects of unresolved scales on time correlations [26,27] and the missing scales in turbulence sources (Lighthill tensors) [28,29].

The lattice Boltzmann method (LBM), based on microscopic models and mesoscopic kinetic equations, has been used widely in simulations of various fluid dynamics problems [30]. Furthermore, Navier–Stokes equations in the limit of low Mach numbers can be derived from the lattice Boltzmann equation (LBE) when Chapman–Enskog multiscale and small parameter expansion is used [31]. With advantages of simple code structure and kinematic properties, this method has been developed as a very powerful tool to compute flow field with complex boundaries and multiphase [32]. The LBM now also becomes a promising alternative to conventional numerical method on the study of aeroacoustic problems. Buick et al. [33] applied the lattice Boltzmann BGK model to simulate sound waves in situations such as a plane wave propagating in an unbound region and a wave in a tube, where the density variation is small compared to the mean density. Besides the standard collision-stream model, the lattice Boltzmann method based on finite difference technology provides a useful tool for simulating aerodynamic sound [34]. Li et al. [35] presented a lattice Boltzmann method with two relaxation times to carry out the direct acoustics simulations of a two-dimensional Gaussian sound pulse in a uniform flow.

Recently, the lattice Boltzmann method has enabled scholars to simulate turbulent flow as a potential computational tool [36–39]. However, hybrid approaches using LBM combined with acoustic analogy to study the far-field noise has not been conducted maturely. In this paper, we extend our previous work [38,40] to predict numerically near-field aerodynamic fluctuations and the far-field sound radiated by isotropic turbulence. It is the purpose of this study to develop a reliable and efficient numerical method, i.e. a hybrid lattice-Boltzmann-based DNS/Lighthill's analogy approach in predicting the near-field aerodynamic fluctuations and the far-field sound, to locate noise sources in the turbulence and to understand the mechanism of noise generation. Here, LBM-based DNS is used to solve the decaying and forced homogeneous isotropic turbulence, and Lighthill's equation is used to compute the radiated acoustic pressure.

The lattice Boltzmann method has been already applied to simulate decaying isotropic turbulence [38–40]. However, in these cases, kinetic energy is dissipated after several eddy-turns over time following a decay law, and lead to a vanishing acoustic pressure. It is important to keep the turbulence in a statistical equilibrium state, which is advantageous to obtain statistical characteristics of computed acoustic field. Hence, we also focus on the evaluation of two forcing schemes based on lattice-Boltzmann-based DNS in order to obtain forced turbulent field and its radiating noise. To our knowledge, few studies have meantime investigated the noise radiated by forced homogeneous turbulence used hybrid method with LBM and acoustic analogy theories.

The paper is organized as follows: In Sections 2.1 and 2.2, the mathematical formulations concerning the lattice Boltzmann method and Lighthill's equation are first reviewed. Section 2.3 we consider the forcing of the flow field as a source and describe the details of the forcing method. In Section 3, numerical calculation parameters and the initialization of the turbulence are addressed. Afterward, the general characteristics of an isotropic turbulence are analyzed and discussed. The characteristics of the forcing schemes, as well as the effect of local time delay on the accuracy of a prediction of the far-field noise are also evaluated. Finally, concluding remarks are summarized in Section 4.

2. Mathematical formulations

The noise radiated by a volume of isotropic turbulence is retained as a test case for the present study. The source term of acoustic field is assumed to be nonzero in a finite cube region with length 2π of each side. The forced isotropic turbulence with periodic boundary condition radiates acoustic waves into stationary media around the cube. Fig. 1 demonstrates the physical model of the present simulations. The origin is located at the center of the turbulent cube region.

For any observer defined by the vector $\boldsymbol{x}$, who locates on a shell. The radius of the shell is supposed as 36π, and the origin is located at the center of the turbulent cube region. For low turbulent Mach number, the pressure perturbations are assumed to be nearly isotropic. As detailed by Witkowska et al. [24] and Seror et al. [25], here, the ensemble average of acoustic signals is also performed by setting 50 different observing points located uniformly on the shell, at the same distance from the center of cube domain. These observing points distributed around the shell make ensemble average to the samples of acoustic signals to obtain acoustic characteristics more clearly.

2.1. Lighthill's acoustic analogy

We calculate the acoustic signal at far-field based on Lighthill's acoustic analogy. Assuming fluid has Newtonian property and the flow at the whole field follows Navier–Stokes equation:

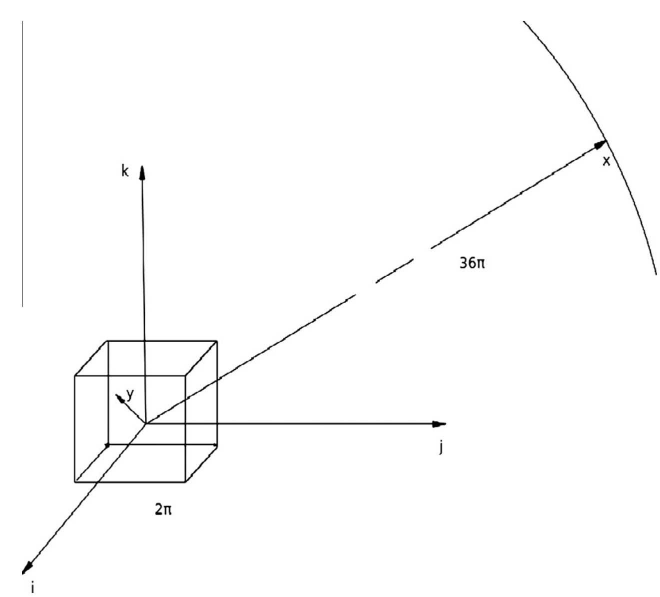

Fig. 1. Turbulent source region and observation points.