Lattice Boltzmann aero-acoustics modelling of flow around obstacles

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In this paper, we suggest to present and discuss the aeroacoustics modelling of flow around different obstacles using LaBS software which is based on Lattice Boltzmann method. Within the framework of a consortium including industrial companies and academics institutes, LaBS was created around Lattice Boltzmann method (LBM). One of the advantages of LBM compared to classical CFD methods is its ability to determine aeroacoustic field by a direct computation of acoustic phenomena. To discuss LaBS performances, a jet flow is studied around a model composed of a cube which is mounted behind a fence. Various reports of scales and velocities are studied. This flow is characterized by the existence of different types of noise (detachment, impact, wake …). Computational results are compared with a complete list of experimental measurements (hot wire, PIV, acoustic source localization ...). From an aerodynamic point of view, the flow's global structure is found by computation and unsteady quantities are correctly simulated. From an acoustic point of view, computation and measurements converge on location of the main source and on dipole behavior of radiation.

1 Introduction

In the transport sector, identification of aerodynamic noise sources is a major issue for constructors. The identification of sources can be performed experimentally for example by array processing or numerically by simulation. Lattice Boltzmann Method (LBM) is one of the numerical methods used for aeroacoustic modeling. It's an innovative approach based on kinetic theory introduced in 1992 [8] to replace the Boolean nature of the lattice-gaz automata method (LGA) [1]. During last two decades, academic research devoted to the LBM enabled it to have a strong theoretical support and several applications including multi phase-flows [2], visco-elastics flows [3], chemical-reactive flows, etc. The LBM method has become a serious alternative to classical CFD methods based on solving the Navier-Stokes equations, particularly for aeroacoustic flow modeling [4]. It has also other advantages as the simplicity of parallelization, implementation and incorporating different physical models.

LaBS is a numerical tool based on the LBM method for modeling three-dimensional flows. It was developed through a collaborative project including industrial companies and academics institutes. The objective of this project is to offer to users a software with direct aeroacoustic simulation capabilities (simultaneous simulation of aerodynamic noise sources and their acoustic propagation) and optimized for massively parallel computing.

The paper is organized as follows. In section 2, a brief overview of the LBM formulation used in LaBS is given. For more details see [5, 9]. In section 3, a study performed to evaluate the performance of LaBS is presented. The studied configuration is a turbulent jet flow around a model composed by a cube which is mounted behind a fence transverse to the flow.

2 LBM formulation

In the following section, we denote $f(\vec{x},\vec{c},t)$ a distribution function that represents the density probability of finding a particle at position $\vec{x}$ at time t with velocity $\vec{c}$. Then, the macroscopic quantities as density, momentum and total energy which are the moments of f are calculated by :

$$\begin{cases} \rho = \int f\,dc \\ \rho\vec{u} = \int \vec{c}\,f\,dc \\ \rho e + \frac{1}{2}\rho u^2 = \frac{1}{2}\int c^2 f\,dc \end{cases} \quad (1)$$

By using the BGK collision operator, the evolution of the function f is governed by the Boltzmann equation as follow :

$$\frac{\partial f}{\partial t} + \vec{c}\nabla f = -\frac{1}{\tau}\left(f - f^{eq}\right) \quad (2)$$

Where τ is the relaxation time of the fluid and f^{eq} is the equilibrium distribution and can be computed by :

$$f^{eq} = \frac{\rho}{\left(2\pi RT\right)^{D/2}}\exp\left(-\frac{\left(\vec{c}-\vec{u}\right)^2}{2RT}\right) \quad (3)$$

Where R is the ideal gas constant, D is the dimension of the space and T is the temperature.

To calculate the function f, the velocity space is discretized into a set of N_α discrete velocities $\{c_{\alpha=1,\dots N_\alpha}\}$. The governing equation (2) then read :

$$\frac{\partial f_\alpha}{\partial t} + \vec{c}_\alpha\nabla f_\alpha = -\frac{1}{\tau}\left(f_\alpha - f_\alpha^{eq}\right) \quad (4)$$

Where f_α and f_α^{eq} are respectively the distribution function and the equilibrium function corresponding to the direction α.

The numerical computation of macroscopic quantities is obtained by :

$$\begin{cases} \rho = \sum_{\alpha=1}^{N_\alpha} f_\alpha \\ \rho \vec{u} = \sum_{\alpha=1}^{N_\alpha} \vec{c}_\alpha f_\alpha \\ \rho e + \frac{1}{2}\rho u^2 = \frac{1}{2}\sum_{\alpha=1}^{N_\alpha} c_\alpha^2 f_\alpha \end{cases} \quad (5)$$

In order to treat flows with complex geometries, the modeling of boundaries in LaBS is performed by using immersed boundaries method [6]. With this method, a difficulty is encountered on nodes near to the boundaries. Indeed, the value of the distribution function on some of there neighbors is unknown. To overcome this difficulty, the reconstruction method is used. This method is based on the decomposition of the distribution function in an equilibrium part and a nonequilibrium part :

$$f_\alpha = f_\alpha^{eq} + f_\alpha^{neq} \quad (6)$$

The theory provides the following relation :

$$f_\alpha^{neq}(x, c_\alpha, t) = \tau_g \rho \frac{\omega_\alpha}{c_S^2} \sum_{i,j} \left(c_{\alpha,i} c_{\alpha,j} - c_S^2 \delta_{ij} \right) S_{ij} \quad (7)$$

Where $\tau_g = \tau + \frac{dt}{2}$, ω_α is a lattice weight, c_s is the sound speed, $c_{\alpha,i}$ are the components of the velocity $\vec{c}_\alpha$ and S_{ij} is the deformations tensor that can be computed by a simple finites differences method.

The turbulence modeling in LaBS is performed by the Large Eddy Simulation (LES). Subgrid stresses are described using the shear-improved Smagorinsky model developed by Leveque et al. [10].

3 Flow Past Fence-Cube geometry

3.1 Presentation

In this section, we present the study that is used to evaluate the performance of LaBS for a direct modeling of aeroacoustic flows. The configuration chosen is a three-dimensional flow of a jet around a geometry composed of a cube which is mounted behind a flow transverse fence. An experimental measurements campaign was conducted in the anechoic wind tunnel of Ecole Centrale de Lyon [7] to characterize the flow and to identify several structures and noise sources. That makes this flow an excellent candidate for evaluating LaBS.

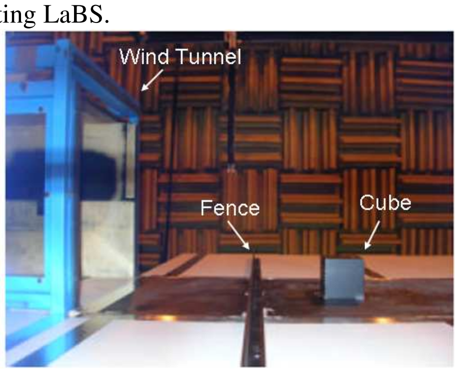

Figure 1 : experimental set-up

Figure 1 represents the experimental set-up for the study of the flow. It consists of a wind tunnel with a square section (50 cm side), a flow transverse fence (2 m length, h = 6 cm height, 5 mm thickness) and a cube (10 cm side). The fence is placed at a distance of 40 cm downstream of the wind tunnel output and the cube is placed at a downstream distance (fence upstream / cube center) of 4 h. At the output of the wind tunnel, the velocity is imposed at 45.6 m/s.

For the numerical results validation, experimental data of velocity field measured by PIV at y = 0 and measured hot wire in transverse plane "FC12h" at x = 12 h (Figure 2). For the acoustic validation, fluctuating wall pressure values are measured on some strategic points (Figure 3).

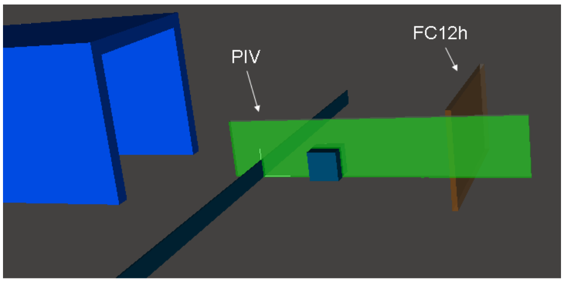

Figure 2 : Positions of measurement planes

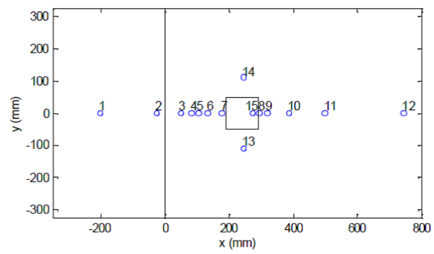

Figure 3 : Positions of wall pressure measurement points

3.2 Preprocessing

For simulating the flow with LaBS, the domain of computation has been discretized into 20 millions cubic cells. Near to the geometry and the wind tunnel walls which are strong gradient zones, the mesh has been refined (Figure 4).

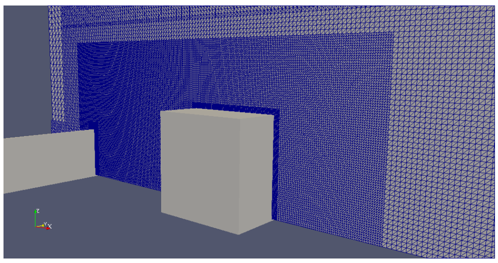

Figure 4 : mesh near to the geometry

Classical Dirichlet no-slip treatment is applied on the solid boundaries and constant pressure is imposed on non-solid boundaries. A velocity profile representative of experimental measurements is imposed at the inlet of the wind tunnel.

To allow an acoustic analysis of the flow, the physical time simulation was set at 0.78 s, which corresponds to 450000 iterations.

3.3 Results

To verify the convergence of the computation, we plot in Figure 5 the time signal of the calculated pressure at the top of the cube (point 15 in Figure 3). The signal has stabilized from time t = 0.1 s and therefore the convergence of the calculation is validated.

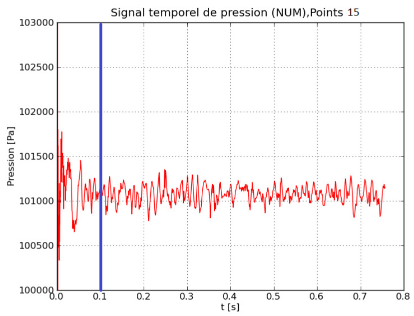

Figure 5 : simulation convergence

In Figure 6 we represent the mean longitudinal velocity in the PIV plane. The comparison with experimental measurements shows that LaBS gives consistent values of the mean velocity field and was able to capture the mean flow structures. However, the angle of separation at the top of the fence seems to be underestimated by the simulation. Therefore, the impact of the shear layer on the upstream edge of the cube is more pronounced.

The analysis of longitudinal fluctuating velocity field in the PIV plane given in Figure 7 shows that the turbulence level computed by LaBS between the fence and the cube is overestimated in comparison to measurements. On the contrary, the level of turbulence is underestimated in the wake of the cube. This last point is justified by the use of a too coarse mesh in this region.

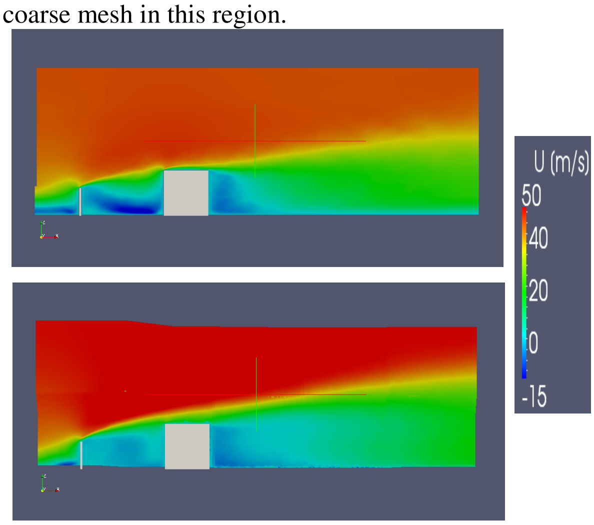

Figure 6 : mean longitudinal velocity in PIV plane, top LaBS, bottom measurement

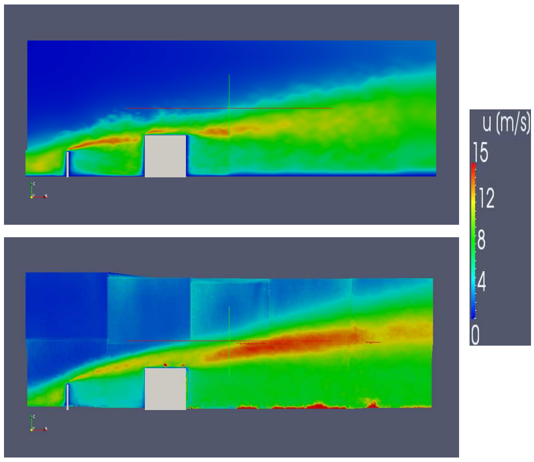

Figure 7 : fluctuating longitudinal velocity in PIV plane, top LaBS, bottom measurement

The mean longitudinal velocity field in FC12h plane is given in Figure 8. The agreement between simulation and measurement is still well found. However, the shear layers appear to be more diffused.

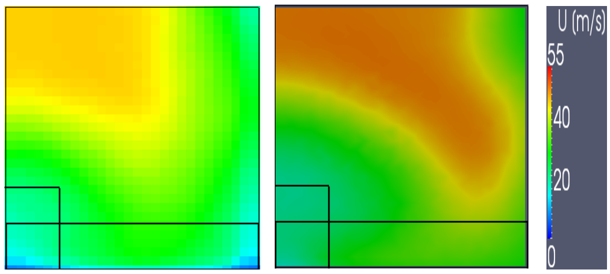

Figure 8 : mean longitudinal velocity in FC12h plane, left LaBS, right measurement

In Figure 9, we give the fluctuating longitudinal velocity in FC12h plane. We note that the turbulence level is underestimated by the computation, particularly near the ground, indicating that the low level of mesh refinement at this place.

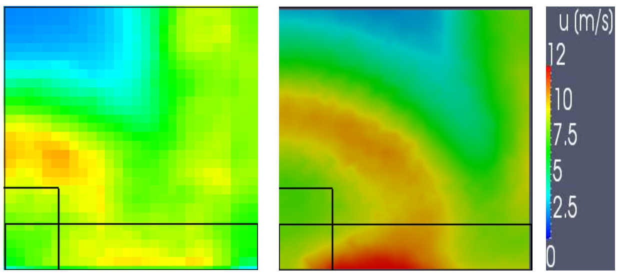

Figure 9 : fluctuating longitudinal velocity in FC12h plane, left LaBS, right measurement

The power spectral density (PSD) of the wall pressure at points 14 and 15 (see Figure 3) are shown in Figure 10. We see that the numerical and experimental results are consistent on low and medium frequencies. At high frequencies, a significant difference between the numerical curve and the experimental curve is observed. This difference shows that the mesh refinement in the near wall is not sufficient to correctly model all sizes of structures.

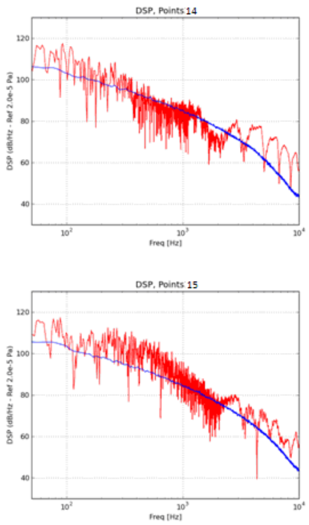

Figure 10 : PSD of wall pressure at points 14 and 15. Red LaBS, blue measurement

4 Conclusion and perspectives

In this paper, we presented the LaBS solver which is based on the Lattice Boltzmann method. We also presented the study to evaluate its performance for the direct modeling of aeroacoustic flows. The flow used is a jet around a geometry consisting of a transverse fence and a cube mounted in the fence downstream. The confrontation of numerical results with experimental measurements has shown that from an aerodynamic point of view, the results calculated by LaBS are quite satisfactory. From an aeroacoustic point of view, spectral analysis shows an agreement between the numerical results and the experimental measurements in low and medium frequencies. However, at high frequencies, the results of computation diverge from experiments. To correct this problem, other simulations for this flow will be performed by increasing refinement mesh near to solid boundaries.

5 Acknowledgements

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