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A Brief Study on Noise Propagation of Airfoils from Wind Turbines Using the Lattice Boltzmann Method

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Summary

The Lattice Boltzmann Method (LBM) is a very promising Computationsl Fluid Dynamics (CFD) model, which attracts many researchers and engineers because it allows concurrent solving of many physical phenomena and it has the advantage to be highly parallelizable, i.e., simultaneous performance of multiple operations, in order to divide the domain into small parts and assign each one to a processor. The LBM resolves all scales, macro and micro, simultaneously and is gaining momentum for solving multiphysics and aeroacoustic problems. The LBM may solve in a simplicity of programming and moderate computational cost the Navier-Stokes equation, with a restriction that the Mach number must be low. This restriction does not hinder the application of the method to the simulation of the noise propagation of airfoils from wind turbines. Therefore, it is important to compare the LBM with other CFD methods to select the best way to predict the noise generated by wind turbines and its propagation to the far field. This article intends to make this investigation in the context of potentially improving the Pnoise module, which is a Poli-USP & TU-Berlin collaboration

project implemented in the QBlade software, available for download under a General Public License. The aim is to allow limited validation for high-Reynolds numbers self-noise and inflow noise models under development for full-size rotor noise prediction.

1. Introduction

Wind energy is one of the most important renewable energy sources today, and has been used increasingly in the world. The largest source of wind power generation comes from horizontal axis wind turbines (HAWT) both in onshore and offshore areas. However wind energy needs prerequisites for its implementation, because of technical dependency of strong winds places and in locations that are capable to support the installation of large turbines (100m high for example). Figure 1 shows the rapid increase of the wind energy in the last decades.

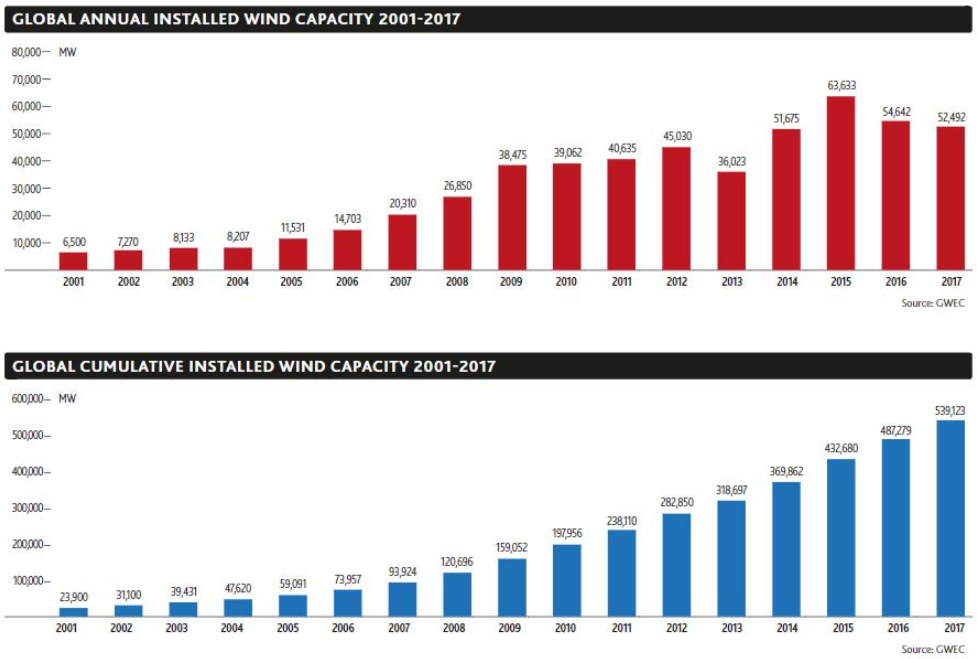


Fig. 1 Global annual installed and Global Cumulative Installed Wind Capacity [25].

Another important aspect is that the dimensions of wind turbines have grown over the years (see in Figure 2), specially the blades, this increase come with the multitude of benefits, in particular helping to drive down the cost of wind energy because wind speeds increase with altitude, thus the taller the turbine the faster it spins and the more energy it can generate. Furthermore, the wind is generally steadier higher up, easing power peaks and troughs and increasing reliability. The trend is to increase the size of the turbines and not the wind farms, reducing maintenance and operation costs.
One of the main obstacles to using wind turbines considering its large dimensions and the proximity in populated areas, increasingly recurrent situation, is the noise produced by them, which annoys residents and the local fauna nearby. Therefore, it is important predict properly the noise to define the best places for wind parks and enables the improve of the design of quieter turbine in order to avoid future problems.

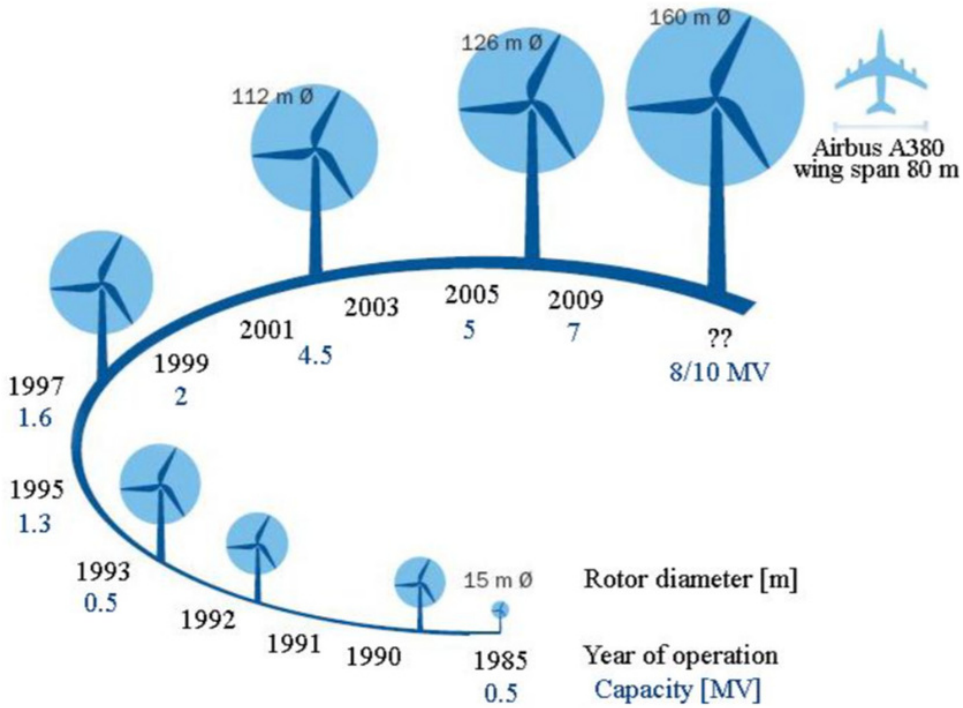


Fig. 2 Growth of wind turbines over time [8].

Other important fact is that an decrease of the sound pressure level by one decibel would increase the annual energy production by 20% [26] (see in figure 3).

The acoustic study of wind turbines may be performed with QBlade, which is an open-source calculation software, distributed under the GNU General Public License, made by TU Berlin, its purpose is the design and aerodynamic simulation of wind turbine blades. The *Polytechnic School of the University of São Paulo* joined the group to improve the software to include the noise module, called PNoise. The noise prediction of this application is currently implemented in two dimensional (2D) and in the near future in three dimensional (3D).

The main motivation of this work is to contribute to the enlargement of the use of wind turbines, making them quieter and more efficient and enabling them to be used in more places with the multiscale fluid dynamic base with using the Lattice Boltzmann Method (LBM).

2. The Lattice Boltzmann Method (LBM)

The Lattice Boltzmann method [1, 2, 11, 28] is a modern approach in Computational Fluid Dynamics and it is often used to solve the incompressible, time-dependent Navier-Stokes equations numerically. This method is easily capable to represent complex physical phenomena, ranging from multiphase flows to chemical interactions between the fluid and the surroundings.

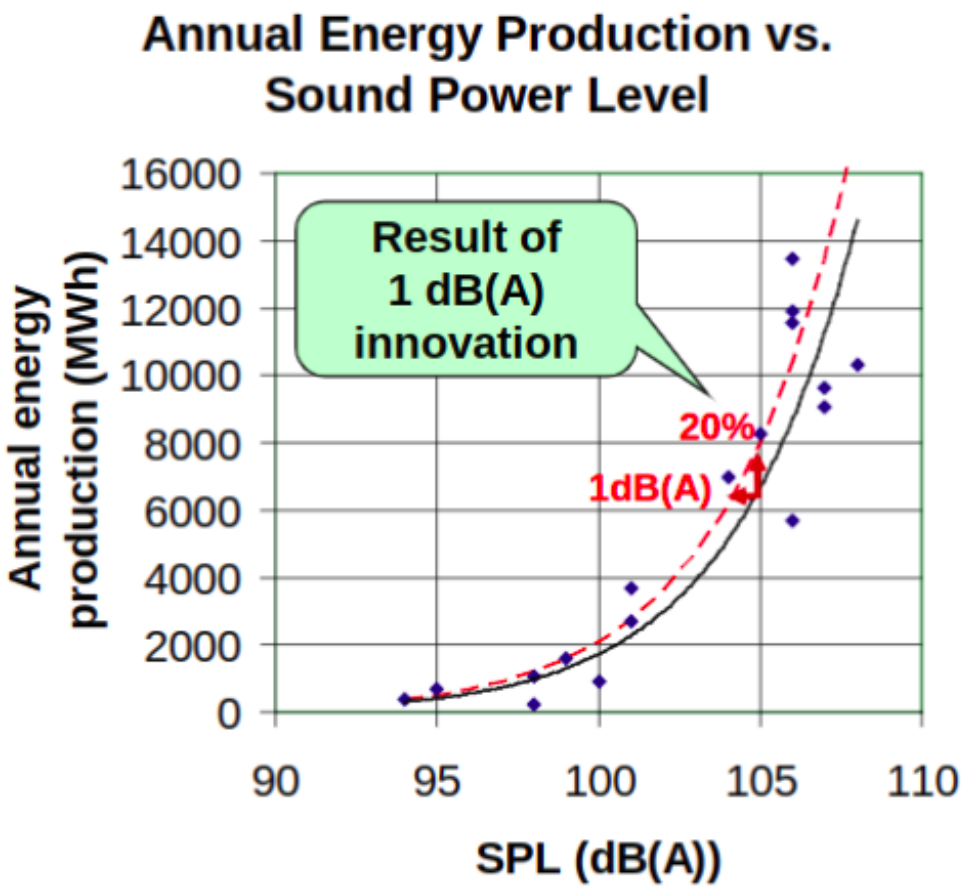


Fig. 3 Relation in increase in annual energy production by wind turbines and reduce the noise in 1dB(A) [26].

Based on a molecular description of a fluid, the LBM can directly incorporate physical terms stemming from a knowledge of the interaction between molecules. For this reason, it is an invaluable tool in fundamental research, as it keeps the cycle between the elaboration of a theory and the formulation of a simple corresponding numerical model.

Historically, LBM evolved from the Cellular Automata models, which is a computer model for the evolution of discrete states described by integer values, a different way of representation considering the lattice Boltzmann variables.

The Boltzmann equation is analogue of the Navier-Stokes equation at a molecular level and it describes the space-time dynamics of a statistical quantity called *probability distribution function*, which is defined in 6-dimensional phase space. The molecular level brings benefits comparing with the Navier-Stokes equation, because of no dependency of a separation of time scales and the ability to describe fluids in non-hydrodynamic regimes with large molecular mean free paths. Furthermore, the molecular model is able to capture transport phenomena such as friction, diffusion and temperature transport and derive the corresponding transport coefficients.

The LBM represents the position and velocity of interacting pseudo-molecular, ”mesoscopic” particles of a fluid and acts on real-valued quantities, but it describes some dynamics in a discrete phase space, which is displayed like a lattice. The lattice Boltzmann equation can be derived directly from the continuous Ludwig Boltzmann’s kinetic theory of gases equation, that considers gases/fluids like a large number of small particles with a randomly movement. The particle streaming and elastic particle collision are the base for calculation of exchange of momentum and energy. This process can be modelled by the Boltzmann transport equation, which is given by:

$$\frac{\partial f}{\partial t} + \vec{u} \cdot \nabla f = \Omega \tag{1}$$

where $f(\vec{x}, t)$ is the particle distribution function, $\vec{u}$ is the particle velocity, and Ω is the collision operator.

The LBM simplifies the Boltzmann’s original idea of gas dynamics, because reduces the number of particles and keeps them arranged in the nodes of a lattice, similar to simplification of a football game like a Foosball table. For a 2D model one particle can stream in 9 directions, that includes it stay at rest. The model is commonly known the denominated $D2Q9$ (see in Figure 4), because is 2D and has 9 velocity vector, the microscopic velocities are denoted by $\vec{e}_i$, for $i = 0, ..., 8$, defined by:

$$\vec{e}_i = \begin{cases} (0,0) & i = 0 \\ (1,0), (0,1), (-1,0), (0,-1) & i = 1,2,3,4 \\ (1,1), (-1,1), (-1,-1), (1,-1) & i = 5,6,7,8 \end{cases} \tag{2}$$

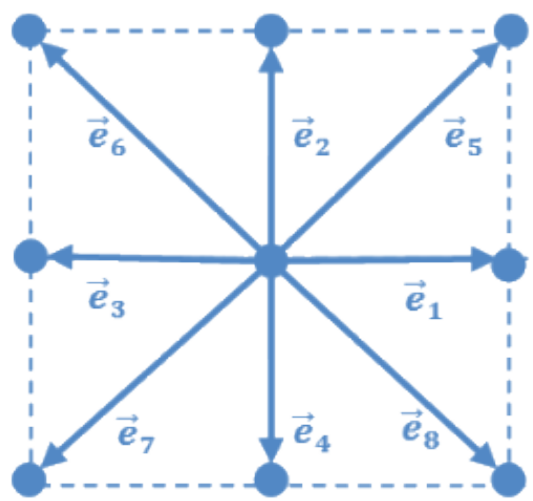


Fig. 4 Illustration of a lattice node of the $D2Q9$ model [1].

The definition of the macroscopic fluid density is given by the sum of microscopic particle distribution:

$$\rho(\vec{x}, t) = \sum_{i=0}^{8} f_i(\vec{x}, t) \tag{3}$$

The macroscopic velocity $\vec{u}(\vec{x},t)$, consequently, is defined by an average of microscopic velocities $\vec{e}_i$ weighted by the distribution functions f_i:

$$\vec{u}(\vec{x},t) = \frac{1}{\rho}\sum_{i=0}^{8} c f_i \vec{e}_i \tag{4}$$

The streaming and collision processes, which consists the main phases in LBM are gives by:

$$\overbrace{f_i(\vec{x}+c\vec{e}_i\Delta t, t+\Delta t - f_i(\vec{x},t))}^{\text{Streaming}} = -\overbrace{\frac{|f_i(\vec{x},t) - f_i^{eq}(\vec{x},t)|}{\tau}}^{\text{Collision}} \tag{5}$$

where f_i^{eq} which is the equilibrium distribution, and τ is the relaxation time towards local equilibrium.

The model is implemented with the collision and streaming calculations performed separately, an special attention is given to the boundary nodes of the lattice. The Figure 5 presents the phases of the streaming progressively inside the lattice nodes.

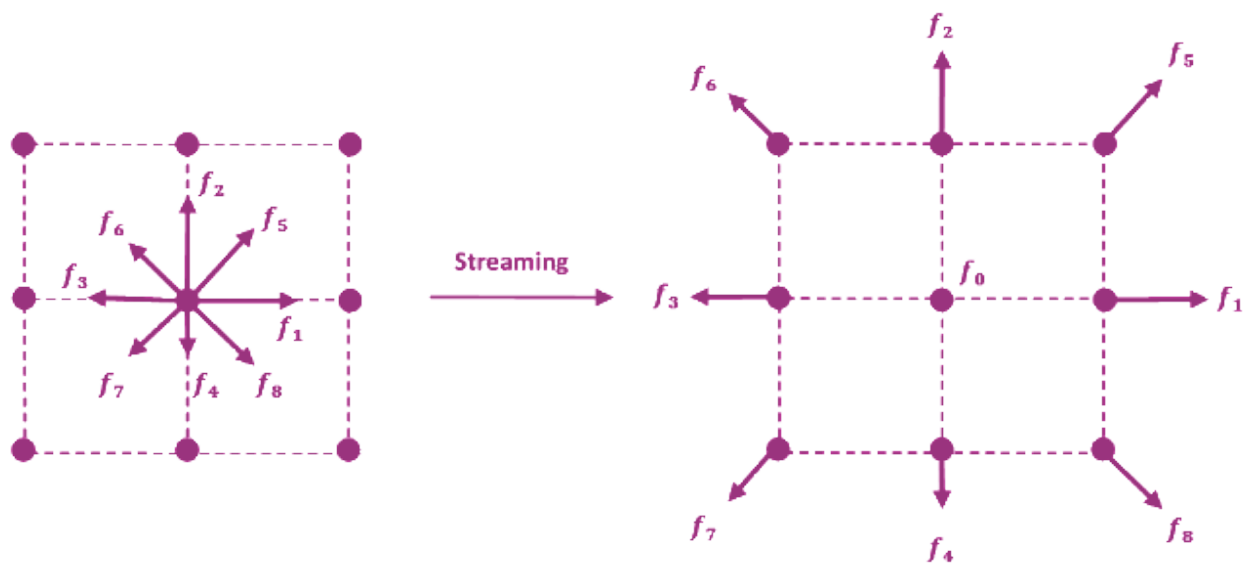


Fig. 5 LBM Streaming process [1].

For single-phase simulations is adequate use Bhatnagar-Gross-Krook (BGK) collision, where equilibrium distribution f_i^{eq} is defined by:

$$f_i^{eq}(\vec{x},t) = \omega_i\rho + \rho s_i(\vec{u}(\vec{x},t)) \tag{6}$$

and $s_i(\vec{u})$ is defined by:

$$s_i(\vec{u}) = \omega_i \left[3\frac{\vec{e_i} \cdot \vec{u}}{c} + \frac{9}{2}\frac{(\vec{e}_i \cdot \vec{u})^2}{c^2} - \frac{3}{2}\frac{\vec{u} \cdot \vec{u}}{c^2} \right] \tag{7}$$

where the weights designed by ω_i are:

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

and the lattice speed is given by $c = \frac{\Delta x}{\Delta t}$. The fluid kinematic viscosity ν is related to the relaxation time τ, it is used in the $D2Q9$ model and defined by:

$$\nu = \frac{2\tau - 1}{6}\frac{(\Delta x)^2}{\Delta t} \tag{9}$$

The LBM algorithm can be sketched by the following steps:
1) Definitions of ρ, $\vec{u}$, f_i, and f_i^{eq};
2) Stream phase, move $f_i \rightarrow f_i^*$ in the direction of $\vec{e}_i$;
3) Calculation of macroscopic ρ and $\vec{u}$ from f_i^* using Equation 3 and 4
4) Obtain f_i^{eq} using Equation 6;
5) Collision phase, compute the updated distribution function $f_i = f_i^* - \frac{1}{\tau}(f_i^* - f_i^{eq})$ using Equation 5
6) Repeat steps 2 to 5.

When $\tau \rightarrow 1/2$ numerical issues can occur, so, during the phase of streaming and collision are required special treatments to the boundary nodes on the distributions in order to satisfy the necessary macroscopic boundary conditions (BCs).

3. Boundary Conditions

One of the most important concerns of creating the correct flow with the LBM is to accurately impose the desired boundary conditions. Although specifying boundary conditions on the Navier-Stokes equation is straightforward, imposing boundary conditions within a Lattice Boltzmann simulation can be very hard, especially on the Graphics Processing Unit (GPU). The most common situations for BCs are:
- Bounce Back: No-Slip Boundary Conditions;
- Boundary Conditions with Known Velocity;
- Periodic Boundary Conditions;
- Imposed Pressure Difference Boundary Conditions.

The BCs are difficult to apply because macroscopic boundary conditions from the Navier Stokes equation must be translated to boundary conditions on f and f_{eq}. Therefore is necessary determine

appropriate equations for calculating these variables along boundaries given a macroscopic boundary condition and this is very important to the accuracy and stability of the LBM numerical solution.

Some of the popular BCs are the Bounce-back [27] and Zou-He [34].

In order to obtain a no-slip boundary condition for a specified boundary, we use the ”Bounce Back Method”. The most simple scheme for this method is to place a wall halfway between a wall and a fluid grid points and then ”bounce-back” particles that stream into the wall. The Figure 6 presents f_4, f_7, and f_8 stream into the wall, and are bounced back by setting $f_5 = f_7$, $f_2 = f_4$, and $f_6 = f_8$.

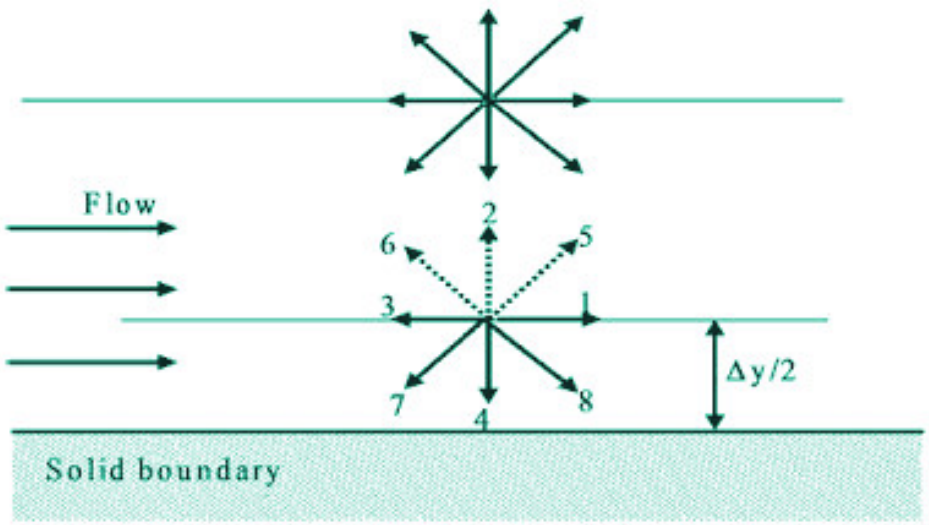


Fig. 6 Scheme of the Bounce Back Method [21].

Another common situation on simulations is to impose a constant velocity at an inlet and outlet. Considering the case presented by the Figure 7, in the west inlet there are particles f_6, f_3, f_7, f_2, and f_4 that will stream onto a point on the wall and the condition is to solve for f_5, f_1, and f_8 based on the constant velocity assumption. usually one should apply bounce back to the non equilibrium part of f on the boundaries, i.e. $f_5 - f_{5,eq} = f_7 - f_{7,eq}$ [34]. The f_{eq} depends on the aerodynamic variables, so the constant-velocity boundary condition will enter through f_eq.

The periodic boundary condition is more simple because one can directly relate the knows of one boundary to the unknowns of the other boundary. In the Figure 8 in (a) the unknowns are, after streaming, f_6, f_2, and f_5. However, along boundary (b) these three distributions are known. So it is possible to solve all of the unknowns by relating $f_{6,a} = f_{6,b}$, $f_{2,a} = f_{2,b}$, and $f_{5,a} = f_{5,b}$, and likewise for the other boundaries and for the unknowns of (b) relating them to the known variables of (a).

The pressure boundary condition is a particular case, because as pressure enters Lattice Boltzmann simulations in a subtle way, an example is relate the pressure to density by $\Delta P \propto \rho c_s^2$. To set f at each boundary one way is to follow a procedure similar to the BCs with known velocity but in the present case, setting ρ to a constant.

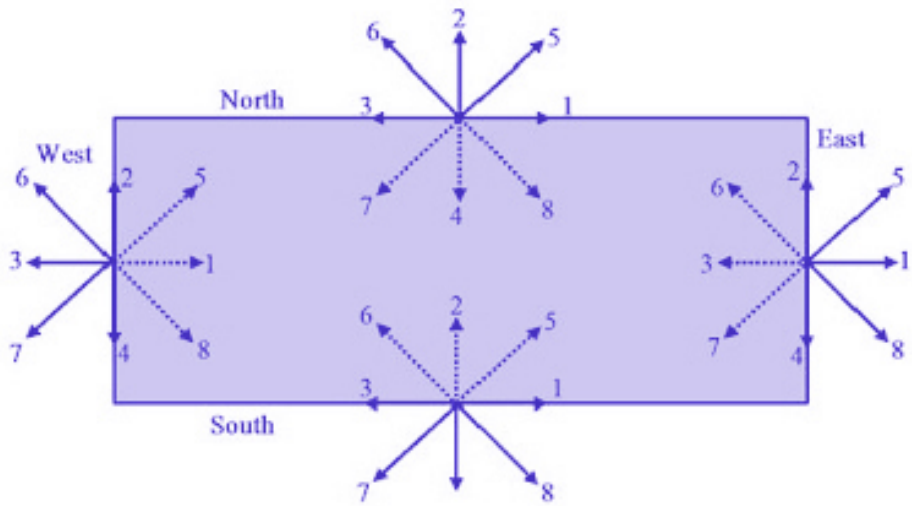


Fig. 7 Schematic showing the known and unknown distribution functions at respective boundaries of the domain [21].

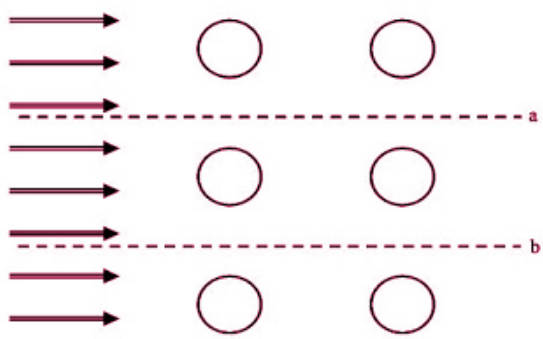


Fig. 8 Schematic illustrating the periodic boundary conditions and how they relate to each other and the flow [21].

The Lattice Boltzmann simulations become unstable when $\Delta\rho$ is large, so it must to adjust the resolution of the simulation until $\Delta\rho \sim 0.01$. For this method it is also important to make sure that the initial velocity and density matches that of the imposed flow.

4. Relations of the Lattice Boltzmann Method and Navier-Stokes Equations

The LBM is considered a special finite difference method [7] for solving the Boltzmann transport equation arranged like a lattice. Describing the Boltzmann transport equation in terms of the discrete distribution function:

$$\frac{\partial f_i}{\partial t} + \vec{e}_i \cdot \nabla f_i = \Omega_i \tag{10}$$

Discretizing the differential and collision operators:

$$\frac{f_i(\vec{x}, t+\Delta t) - f_i(\vec{x}, t)}{\Delta t} + \frac{f_i(\vec{x} + \vec{e}_i \Delta x, t+\Delta t) - f_i(\vec{x}, t+\Delta t)}{\Delta x} = -\frac{f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t)}{\tau} \tag{11}$$

Defining that $\Delta x = \Delta t = 1$, the Equation 5 is recovered.

The LBM may be used for fluid simulations because the Navier-Stokes equations can be recovered from the discrete equations through the Chapman-Enskog procedure using a multi-scaling expansion technique. The $ID2Q9$ model used for simulate Rayleigh-Bénard convection is able to recover the incompressible Navier-Stokes equations, using a multi-scaling expansion:

$$g_i = g_i^{(0)} + \epsilon g_i^{(1)} + \epsilon^2 g_i^{(2)} + \ldots \tag{12}$$

$$\frac{\partial}{\partial t} = \epsilon \frac{\partial}{\partial t_1} + \epsilon^2 \frac{\partial}{\partial t_2} + \ldots \tag{13}$$

$$\frac{\partial}{\partial x} = \epsilon \frac{\partial}{\partial x_1} \tag{14}$$

where $g_i^{(0)} = g_i^{eq}$ and $\epsilon = \Delta t$ is the expansion parameter. Is possible that up to $O(\epsilon)$ to derive the following continuity and momentum equations [11]:

$$\nabla \cdot \vec{u} = \epsilon \left(\tau - \frac{1}{2}\right) P + O(\epsilon^2) \tag{15}$$

$$\frac{\partial \vec{u}}{\partial t} + \nabla \cdot (\Pi^0) = \epsilon \left(\tau - \frac{1}{2}\right) Q + O(\epsilon^2) \tag{16}$$

$$\tag{17}$$

where $P \sim O(\epsilon)$ and $Q \sim O(\epsilon) + O(M^2) + \frac{c^2}{3}\nabla^2 \vec{u}$ and M is the Mach number.

With the results of P and Q to Equations 16 and 17, the continuity equation is derived accurate to $O(\epsilon^2)$ and the momentum equation is derived to $O(\epsilon^2 + \epsilon M^2)$.

$$\nabla \cdot \vec{u} = 0 + O(\epsilon^2) \tag{18}$$

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\nabla p + \nu \nabla^2 \vec{u} + O(\epsilon^2 + \epsilon M^2) \tag{19}$$

5. Lattice Boltzmann Method and Acoustics

The LBM is commonly used to predict some wave behavior using the D2Q9 system with a delta function to excite in a defined node, see Figure 9, but it is not useful to the acoustic study because

this solution vary with the system's viscosity and has no simple analytic solution.

The first studies of LBM acoustics [5, 6, 9, 12], the sound waves have been generated configuring an initial density and velocity distribution wave correspondent. These studies was focused in waves with a ”infinite” dimension letting the initial wave distribution propagates through a periodic boundary.

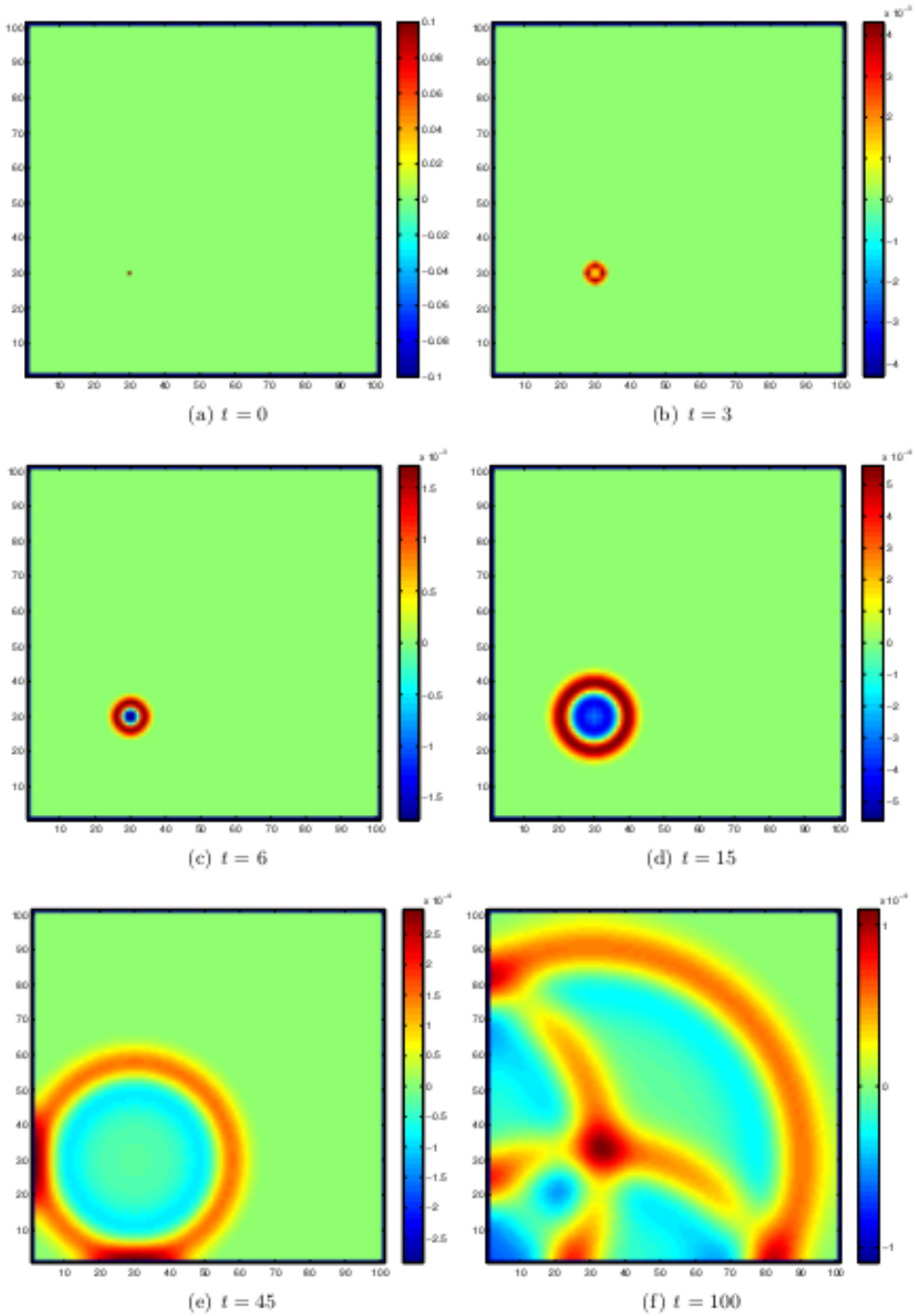


Fig. 9 Simulation of a walled system excited by a delta pulse [31].

For acoustic simulation of non-infinite waves the node of the acoustic source sends a sinusoidal signal. In the work of [31] is presented a simple way to define it, locking a node's density to a sine function around the equilibrium density:

$$\rho(\vec{x}, t) = \rho_0 + \rho_S \sin\left(\frac{2\pi}{T} t\right) \tag{20}$$

where ρ_S is the source amplitude point, and T the period of the oscillation in lattice units.

For wave propagation the Navier-Stokes equation assumes to be a linear phenomenon for small disturbances, so $\rho_S \ll \rho_0$ and the non-linear wave effects are avoided.

For macroscopic velocity $\vec{u}$ placed in a point source one may to lock it to a constant source velocity, like $\vec{u} = 0$ or to let the particles streams into the node decide the macroscopic velocity at the point of the source, that makes the source to emit particles compatible with the environment.

The equilibrium distribution is obtained setting the values of ρ and $\vec{u}$ with the point source node locked using the equation 20 to the node streams out the right number of particles, so the constraints of the equilibrium distribution are not valid $\left(\text{i.e. } \sum_i f_i^{(0)} = \sum_i f_i\right)$ as ρ changes.

So there is essential that the point source node is always set to equilibrium in the collision step to the correct number of particles will be always present in the point source before streaming.

Is necessary to guarantee the real behaviour of the analytic solution of the simulated system, so in cases 2d the z coordinate is infinite and the results are independent of z, according the following equation:

$$\rho_0 = A H_0^{(2)}(kr) e^{jwt} \tag{21}$$

that represents an outgoing cylindrical wave with z being an infinite line, in cylindrical coordinates.

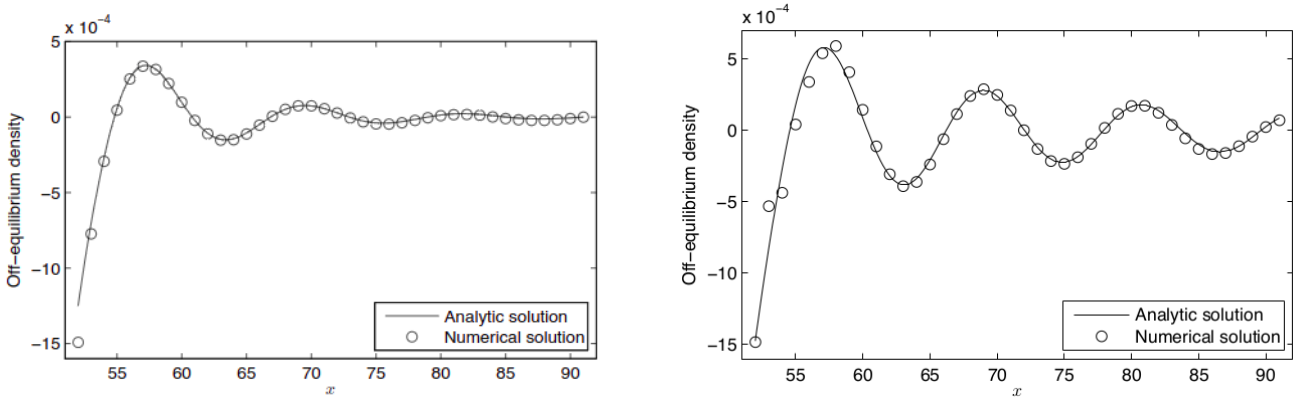
Considering a single point source (see Figure 11) the results are not precises when the interest points are measured next to the source node, and that is a limitation of the LBM for the acoustic case.

The results are impressive because the viscous absorption coefficient α_S in k is calculated using the sum $4\nu/3 + \nu'$, where this viscosities are calculated by:

$$\nu = c_s^2 \left(\tau - \frac{1}{2}\right) \tag{22}$$

$$\nu' = \frac{2}{3}\nu \tag{23}$$

the comparison between the attenuation of the analytic stationary and the numerical solutions are remarkable (see Figure 10), validated, thus, the expected results for the lattice viscosity as presented



(a) **(b)**

Fig. 10 Best comparison of transient numerical solution with the analytic stationary solution for t = 75 a) τ = 0.6 and b) τ = 1 [31].

in [31].

In the results obtained by [31] τ values were adjusted by the value of $|A|$, and an important observation is that for some values of τ the speed of sound measured are not correct and the wavelengths differ between the analytic and numerical methods, and this is an indication that the speed of sound depends on more than the viscosity.

Using a single source point to simulate an infinite line source in z direction results in a damped cylindrical wave, and simulating a continuous line of point sources along a given x in a periodic system results in a plate source that is infinite in y and z direction. The propagation are 2d and symmetrical in x and $-x$ directions of the plate, and this propagation is based by:

$$p_a = Ae^{-\alpha_s x} e^{j(\omega t - kx)} \tag{24}$$

and α_s is the *spatial absorption coefficient* and is given by:

$$\alpha_s = \frac{\omega}{c_s\sqrt{2}}\sqrt{\frac{\sqrt{1+(\omega\tau_s)^2}-1}{1+(\omega\tau_s)^2}} \tag{25}$$

The expected behavior is good but not adequate when the system approaches a steady state, see in Figure 12.

6. The Use of LBM Simulation of HAWT Noise

The LBM can predict far field noise according the studies [17, 33] and has also been used to simulate airfoil sections, like to investigate the TE noise [16, 29, 30].

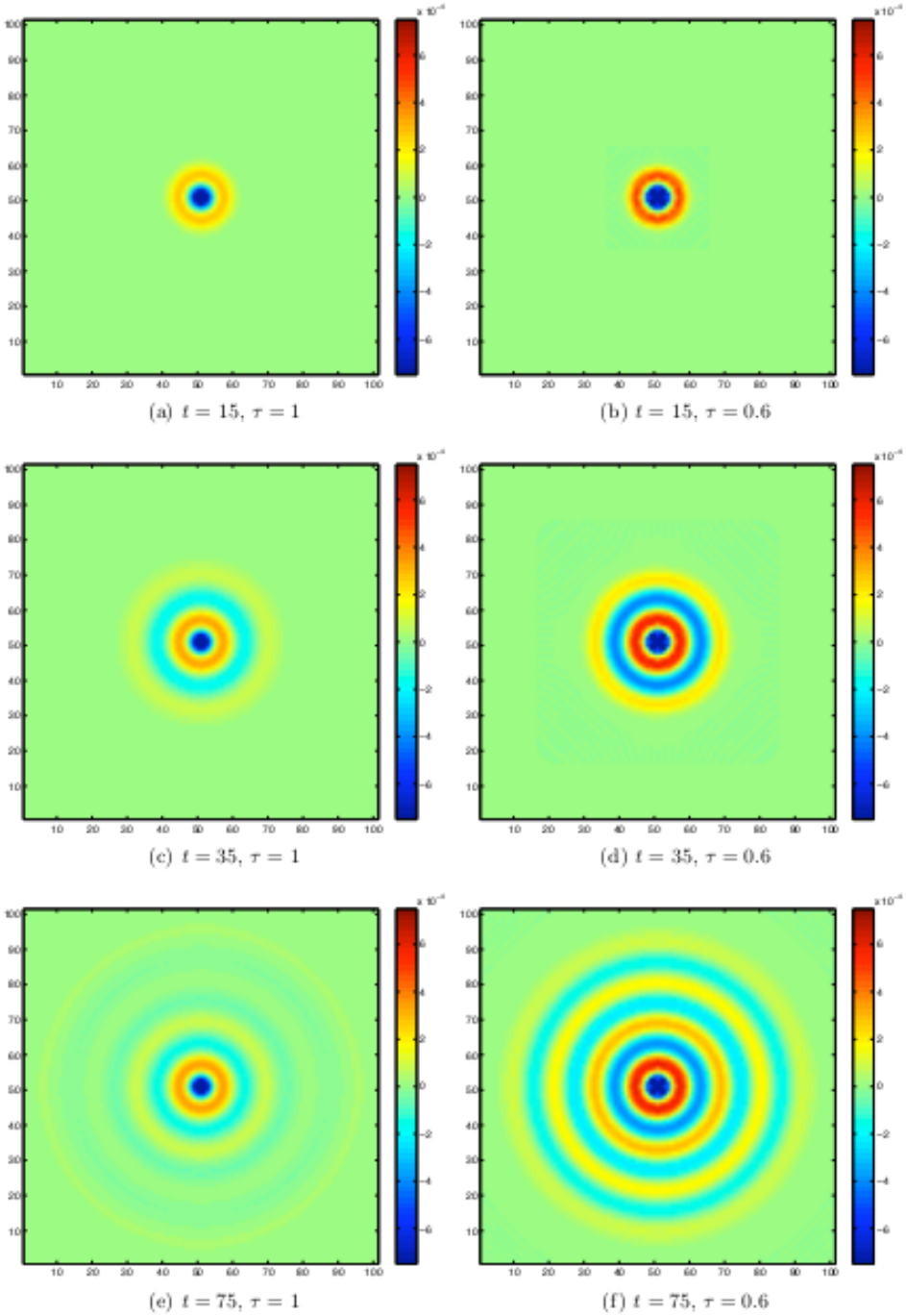
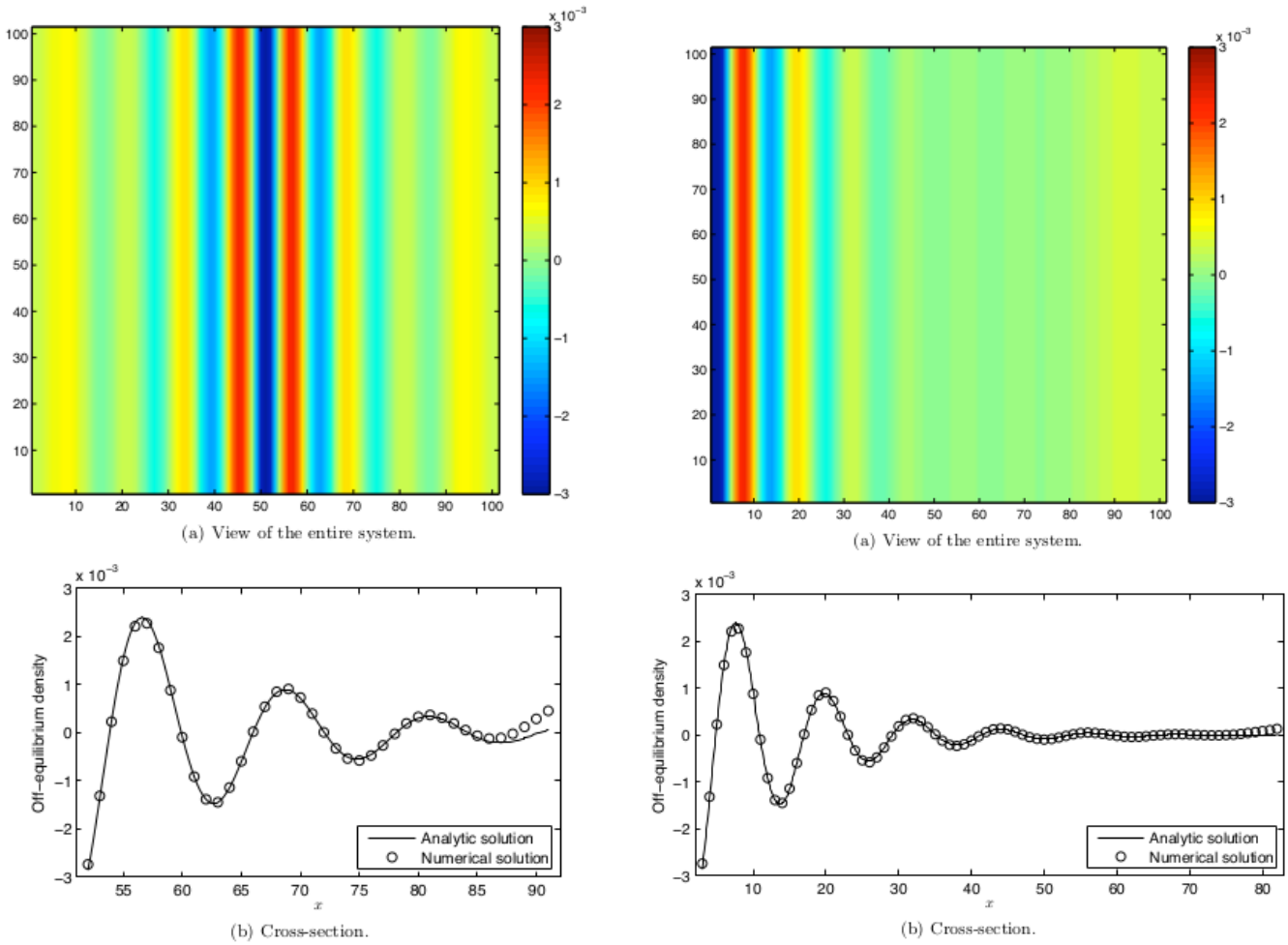


Fig. 11 Snapshots of off-equilibrium density in two different periodic systems by a point source, with for $\tau = 1$ and $\tau = 0.6$, considering the minimum pressure [31].

The main advantage of the LBM comparing with Computational Fluid Dynamics is that it can solve the compressible flow equations and obtain the hydrodynamic and acoustic pressure fluctuations.

The LBM segments the flow area in an unitary 3d elements called voxels and they may be grouped in variable resolution (VR) zones and this this implies in the refinement of the mesh. The open source



(a) **(b)**

Fig. 12 The state of a system at $\tau = 1$ and $N = 101$ of point sources along a) $t = 75$ and $y = 51$, b) $t = 155$ and $y = 2$ [31].

Palabos.

The Palabos application consider the mesh refinement according to [14], which is based on the off-equilibrium and equilibrium parts of the distribution function are based by the Knudsen number:

$$f^{\text{neq}} \sim f^{\text{eq}} Kn \tag{26}$$

and the refinement criterion is determined by the measured Knudsen number (see equation 27), and this implies in the quality of the solutions when compared with the ”theoretical” Knudsen number (see equation 28).

$$Kn = \frac{\lambda}{L} = \frac{\tau c_s}{L} \sim \frac{f_i^{(1)}}{f_i^{(0)}} \tag{27}$$

$$Kn = \frac{\lambda}{L} = \frac{\tau c_s}{L} = \frac{Ma}{Re} \tag{28}$$

To simulate an airfoil is important to set the boundary conditions, so the inlet is given a input velocity and in the outlet is defined by the atmospheric pressure.

The expected results for this simulation according [16] must be close to the obtained by other methods (f.e. LES) and the experimentally measured. It is also presumed that the far field will be more accurated then points measured next to the source nodes, because the microphones are placed in the simulation area, and it is possible to calculate a frequency dependent correction factor in 2d simulations:

$$\beta = 10 \log_{10} \left(\frac{f b^2}{cR} \right) \tag{29}$$

where b is the segmented span, c is the sound speed and R the observer distance.

The most significant source of noise is, according the literature [3, 29], located in the TE area from the airfoil, and it generates turbulent eddies from this site.

The most simple way to perform the simulation is with the *Exa PowerFLOW™*, and it gets a lot of computational cost (between two and three days). Using an open source software like *Palabos* the difficulty is greater given the need for great knowledge of computational programming.

Another use for the LBM is to obtain the acoustic directivity in complex shapes, like in [29] that investigated the fluid flow parameters in a clean and serrated wind turbine profile called DU95. The LBM also may simulate turbulent and transition structures and may help to predict the noise in the far field.

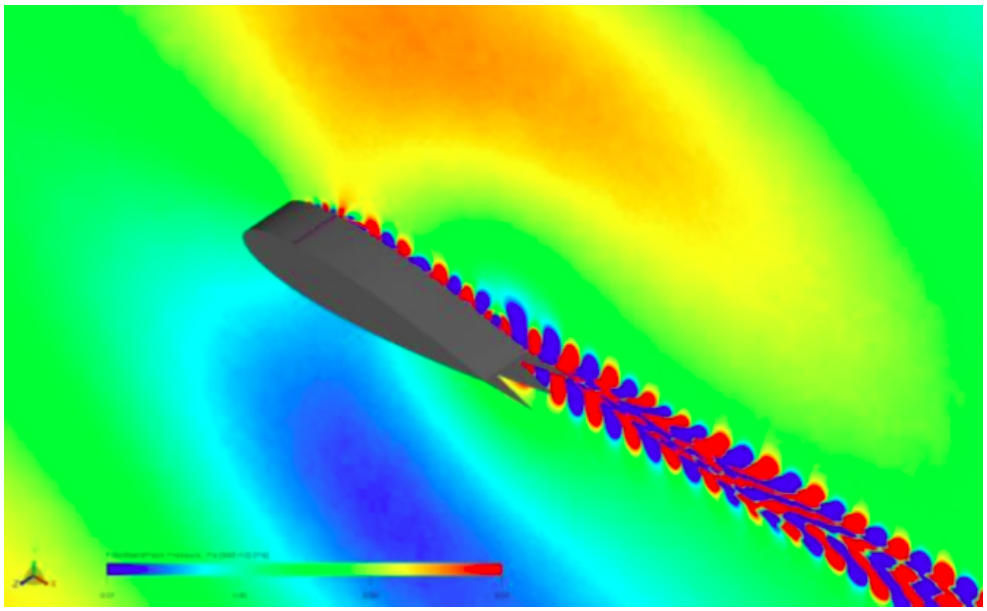


Fig. 13 Simulation of a WT airfoil in *Exa PowerFLOW™* [32]

7. QBlade and the PNoise Module

The QBlade is an open source made by the *Technische Universität Berlin* (T.U. Berlin) wind turbine calculation software, distributed under the General Public License (GPL).

This application allows users to rapidly design custom airfoils mainly for research purposes in a easy and intuitive way.

The noise module, called *Pnoise* was made and is still being performed in collaboration by the *Poli Wind* group, from the Poli-USP. Some of the works published by the group are [23] and [24].

This module has incorporated the trailing edge (TE) noise, that is is based on a modified Brooks-Pope-Marcolini (BPM) TE noise model [4] with turbulent boundary layer data provided by the analysis tool for airfoils nominated XFLR5 [10]. These two models were integrated inside the project of one wind turbine in the software QBlade [18–20, 22].

Some improvements are planned in the *PNoise* module with the inclusion of other self-noise sources, currently is being made the study of the leading edge (LE) noise for future implementation.

The ”quasi-3D rotor” prediction tool is being made too and a challenge for this project is to project the calculated noise at the far-field position from the noise source, for this was considered the use of the LBM.

The LBM is able to gain in refinement and quality of simulation results and also to compare with other predictive methods, like using a parabolic equation [15] and statistical predictions [13].

Even if it is defined that all the particles are arranged at a point source, this positioning is updated

according to their densities, as presented by equation 20, so, to create a one-sided plate source is made by setting the point sources next to a wall, and locking $\vec{u}$ to 0 the effects of the reflected particles are unconsidered. The behaviour would be similar in the D1Q3 lattice comparing with the D2Q9 lattice when the system is one-dimensional projected.

8. PNoise and LBM

The *PNoise* module in *QBlade* software is gradually increasing its noise analysis spectrum, like to include more noise sources as the leading edge noise and to implement the quasi-3d analysis.

The LBM is also being increasingly improved and it has brought us a new approach in the WTN area, mainly because of its great capacity to solve problems and to not depend on the Navier Stokes solutions, in effect almost all the studies in this area were performed using the commercial software called *Exa PowerFLOW™* and very little developed in open source applications, such as *Palabos*.

For the time the LBM may become another alternative for comparing the results from *PNoise* in order to validate the data obtained, however, to implement the LBM within *PNoise* there are certain difficulties. The parallelization (the ability to process in parallel a certain computational code to reduce simulation time) must be selected using the processor capacity from the computer that runs the software, the increase in simulation time, which would be a tremendous disadvantage in this implementation and the difficult to insert the LBM inside the *PNoise* code, among others.

The best way to introduce a LBM for WTN in the *PNoise* is using an existent open source software, created in the same computational language (like C based, the PNoise is created in ”qt”) and creating a specific model to be adjusted for each airfoil profile, and the best way to do this is using a geometry in ”stl” file format what turns the simulation in LBM in 3d considering the *Palabos* software. If the geometry is included as a 2d, each node will need to have boundary conditions, that is hard to do.

Therefore, the LBM was demonstrated in the literature to be useful and may be used to enhance the results of the simulation of *PNoise* for validation, mainly in the far field noise but not integrated inside the *PNoise* because it requires great computational capacity and this is not the scope of *QBlade* software.

9. Conclusion

This work presented the LBM, its characteristics, their use for the WTN propagation study considering the literature data and its application considering the results obtained with the module *PNoise* from *QBlade* software.

The LBM has been increasingly used in the WTN literature because of the several advantages for fluid simulations over traditional CFD methods in the following cases:

- To deal with Complex boundaries using on-grid bounce-back;
- LBM may be applied to simulate flows with complex geometries such as porous media flows;

- LBM can be easily parallelized and thus can be applied to the Large eddy simulation (LES).

One fault expected is come from the derivation of the Navier-Stokes equations from LBM, because the compressible effects can produce a source of errors when solving the incompressible Navier-Stokes equation, but this is not a problem for the WTN due to consider an incompressible flow.

Some of the main characteristics of the LBM are the efficiency and flexibility, it was designed to solve complex physics and sophisticated algorithms, and run in high performance hardware. With the LBM some problems that requires great accuracy could finally be solved. The LBM is based on particle mesh and allows the creation of hybrid systems that may be coupled in particle phenomena.

Compared to classical CFDs, the LBM is the largest resource consumer because the discrete probability distribution functions used in this model requires more storage memory than the Navier-Stokes equation variables, it may be compensated by the computational efficiency and the use of modern computers that suit parallel architecture or using General Purpose Graphics Processing Units (GPGPUs) and this is a disvantage for simulation WTN.

The *PNoise* is a module that calculates WTN from the trailing edge, has been increasingly improved like it is planned to include the leading edge noise source and the quasi 3d modelling. One thinked point in this study is how to use the LBM with *PNoise*.

Therefore, the LBM was demonstrated in the literature to be useful and may enhance the results of the simulation of *PNoise* but it requires great computational capacity and requires much simulation time, and the simulation speed is one of the main advantages of the *Qblade* software.

The use to validate the results from *PNoise* are interesting, mainly to comparison in the far field region.

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