



## The 33<sup>rd</sup> International Congress and Exposition on Noise Control Engineering

# Wind tunnel experiments for the validation of numerical models for outdoor sound propagation

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**Abstract [469]** Since regulations concerning traffic noise are becoming more and more demanding, meteorological effects (turbulence, temperature and wind speed gradients) can no more be neglected in noise propagation prediction at long ranges. To validate numerical models such as Parabolic Equation approach or Boundary Elements Methods with modified Green's functions, it is of high interest to collect experimental data obtained under controlled atmosphere. A measurement campaign has been performed in the wind tunnel of CSTB, Nantes (France). The objective of this experiment was to characterize the aerodynamic flow and the acoustic pressure during the sound propagation. A number of geometrical configurations (flat ground, embankment, with or without complex noise barrier, the ground surface being absorbing or not) and various wind profiles and turbulence intensities have been tested. A combination of traditional (hot wire probe) and recent (Particle Image Velocimetry, PIV) measurement techniques has been used in order to describe precisely the 2D wind speed field along the propagation as well as in the vicinity of the barrier where recirculation phenomenon occurs. For acousticians, experiments in wind tunnel are a good mean to improve their knowledge on outdoor sound propagation and to develop novel barrier shapes.

## 1 INTRODUCTION

A measurement campaign has been performed in the wind tunnel of CSTB, Nantes (France) during the first two weeks of March 2004. A number of geometrical configurations and various wind profiles and turbulence intensities have been tested in order to study the aerodynamic flow effect in sound propagation. The aim is to compare experimental measurements with numerical results including aerodynamical profiles from numerical simulations and Particle Image Velocimetry (PIV) measurements.

In this paper, the wind tunnel characteristics, the acoustic measurement method and the PIV technique are first presented. Then results obtained for a typical road configuration are given: PIV as well as acoustical experimental and numerical results. The goal is to validate acoustic computational code in the case of an evolving sound speed profile.

## 2 DESCRIPTION OF THE CAMPAIGN MEASUREMENTS

### 2.1 Wind tunnel

The measurements have been carried out in the wind tunnel of the Centre Scientifique et Technique du Bâtiment at Nantes, France (See Figure 1 for details). This wind tunnel works in closed circuit which gives the ability to control precisely the physical characteristics of the airflow. The large size of the test room allows a simulation of natural wind speeds from  $0 \text{ m.s}^{-1}$  to  $30 \text{ m.s}^{-1}$  ( $\pm 0.1 \text{ m.s}^{-1}$ ). Different types of roughness upstream on the floor of the tunnel allow to shape different wind profiles and flow turbulences. The wind tunnel can replicate real wind profiles between scales  $1/20^{\text{th}}$  and  $1/1000^{\text{th}}$ .

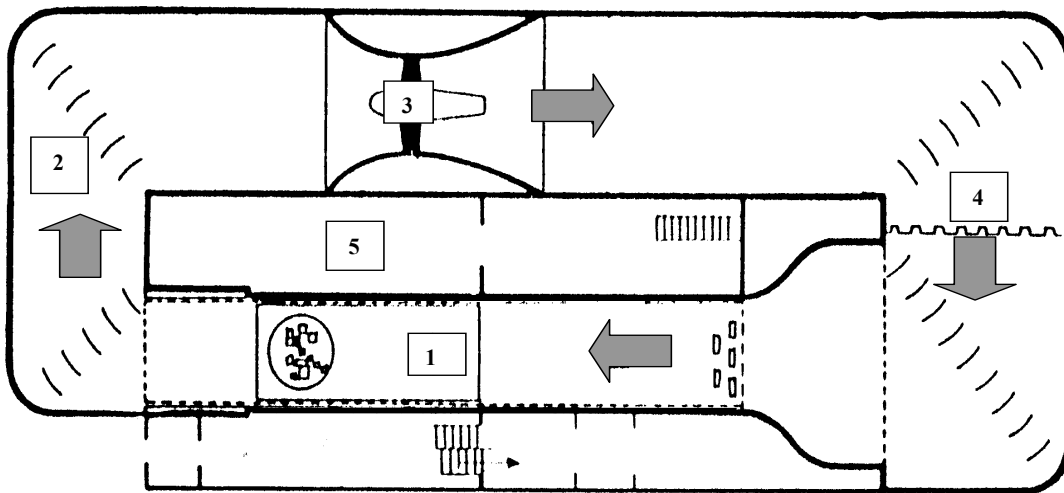


Figure 1: *Measurement wind Tunnel in CSTB, Nantes.*

(1) *main stream: length = 20 m, width = 4 m, height adjustable from 2 to 3 m, flow speed = 0-30 m.s<sup>-1</sup>, reduced scale reproduction of natural wind conditions, turntable and probe support controlled by microprocessor, laser visualisation chamber, measurement pit;* (2) *return flow;* (3) *variable pitch screw propeller (acoustics dampers integrated in walls);* (4) *hot and cold exchanger (temperature control);* (5) *measurement chamber: measurement and data processing instrumentation*

### 2.2 The logarithmic sine sweep technique for acoustics measurements

A scale of  $1/20^{\text{th}}$  has been chosen for the experiments. Acoustic measurements have been made in the frequency range 1000-20000 Hz which reproduces measurements in the frequency range 50-1000 Hz at full scale. In order to reject the signals reflected on the ceiling and walls and to obtain a good signal-to-noise ratio, the sine sweep measurements method described in [1, 2] is used. A sinusoidal signal swept logarithmically from low to high frequency is fed to a loudspeaker and recorded by the microphone. Then, after several calculations, the impulse response can be obtained. The logarithmic sine sweep technique presents many advantages. One of them is that the method is valid in windy and turbulent atmosphere conditions. Another one is the possibility to reject the unwanted reflection. Since the waves reflected from the ceiling and walls have different propagations delay relative to the direct and ground reflected waves, they can be cancelled by an adapted filter of the impulse response. The wanted frequency response is finely achieved by an FFT of the filtered impulse response.

## 2.3 Configuration

During the measurement campaign, a number of geometrical configurations (flat ground, embankment, with or without complex noise barrier, the ground surface being absorbing or not) and various wind profiles and turbulence intensities have been tested. In this paper, a typical road traffic configuration, described in Figure 2, has been studied with two sound speed profiles:

- The uniform case: wind speed  $10 \text{ m.s}^{-1}$  at 10 meter high and an intensity of turbulence of 1% measured at 4 meter high
- The turbulent case: wind speed  $10 \text{ m.s}^{-1}$  at 10 meter high and an intensity of turbulence of 10% measured at 4 meter high

A source is located at (0 m, 0.5 m) and sound pressures are calculated for six receivers placed at (15 m, 2 m), (15 m, 5 m), (30 m, 2 m), (30 m, 5 m), (60 m, 2 m), (60 m, 5 m). The ground is rigid and a 3 meter high rigid barrier is located at (10 m, 0 m).

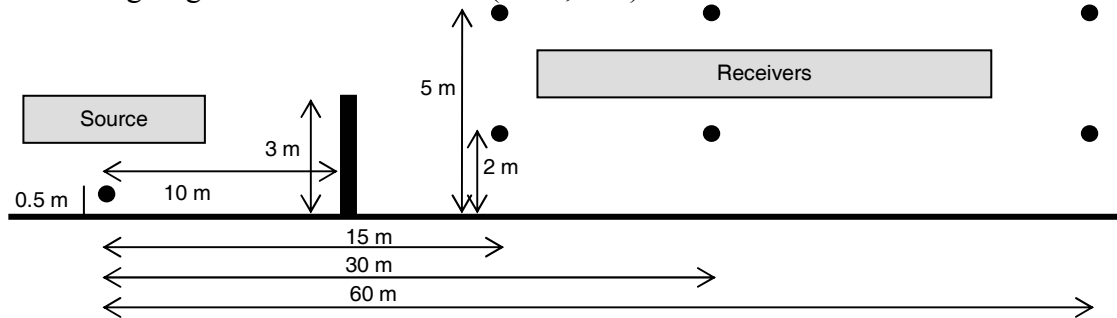


Figure 2: Studied configuration: thin barrier on a plane rigid surface.

To characterize the aerodynamic flow, two methods have been used: on the one hand, PIV measurements, and on the other hand, numerical simulations with a Computational Fluid Dynamics software Fluent.

## 3 PARTICLE IMAGE VELOCIMETRY

### 3.1 PIV principles

Particle Image Velocimetry (PIV) is a non-intrusive measurement technique used to determine simultaneously the velocities at many points in a fluid flow. The technique involves seeding the flow, illuminating the region under investigation and capturing two images of that region in rapid succession. From the displacement of the tracer particles, provided that the time interval between image captures is known, a velocity vector map can be calculated.

An iterative processing algorithm [3] is used to obtain the maps given in Figure 3. Its main characteristics are the use of direct cross-correlation calculation for complete flexibility in interrogation window size and shape, as well as the independent iterative interrogation window size reduction for each measurement location allowing to take into account local particle concentration characteristics in the image.

### 3.2 PIV results

For each camera position, 300 couples of images are captured in order to make accurate quantitative measures as well for the average velocity field as the instantaneous field.

Figure 3 presents averaged wind speed vectors measured for both uniform and turbulent cases. They are represented with different colors on maps in Figure 3. Streamlines have been added in black. It shows that recirculation phenomena occurred in the vicinity of the barrier. Those PIV

measurements point out that wind speed profiles become identical to the incident profile at shorter distances in the turbulent case, at distances starting from ten times the noise barrier height.

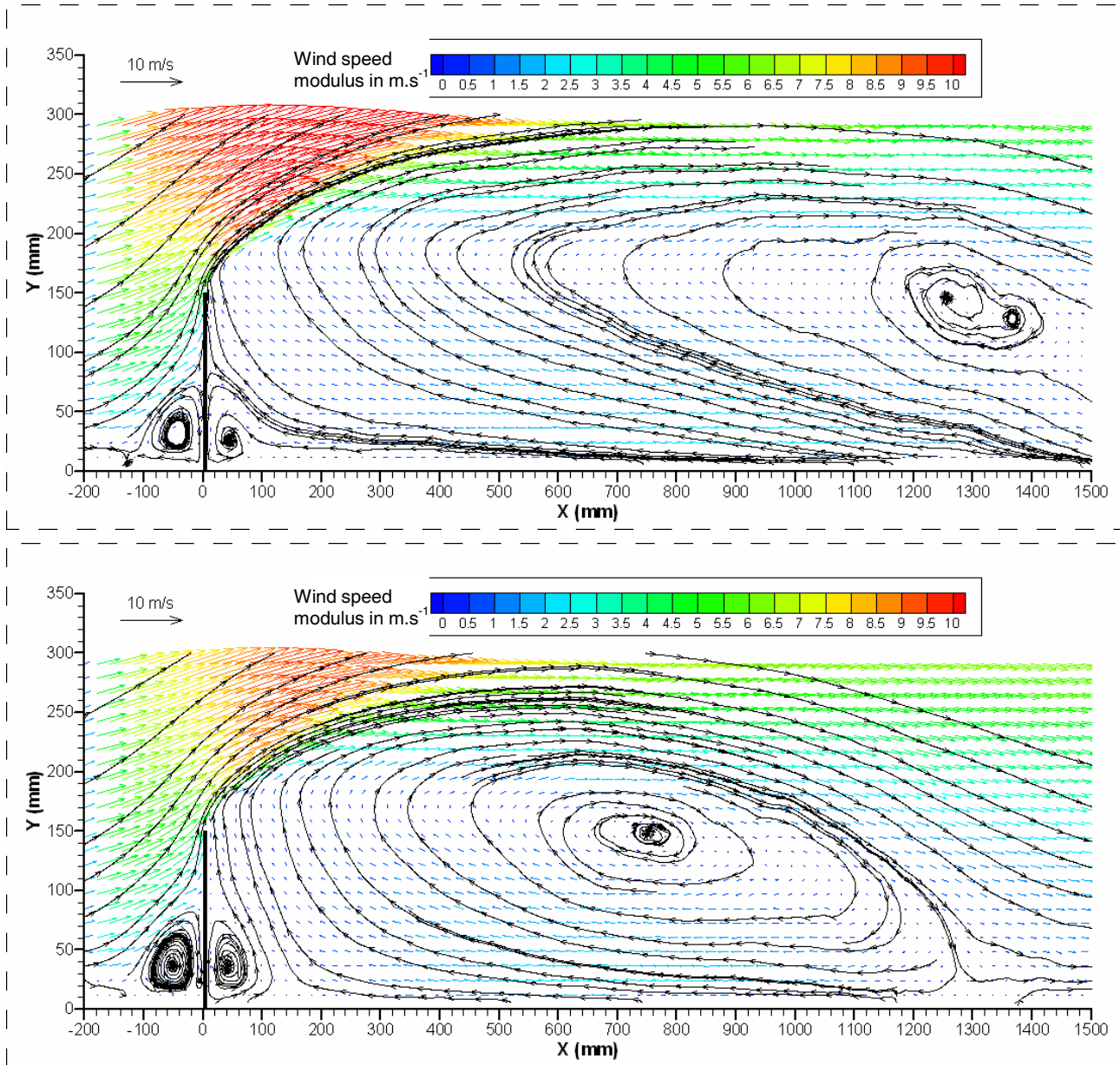


Figure 3: Wind speed vector field maps obtained for the studied configuration described in Figure 1.

Uniform case (up) and turbulent case (down)

PIV measurements have been carried out by Arnaud Susset from R&D Vision [2]

Distances are at scale  $1/20^{\text{th}}$ . They must be multiplied by 20 to be relevant to full scale distances given in Figure 2.

The velocity vector can be used as input data in an acoustic code in order to compute the sound propagation in a refracting atmosphere (see section 4.2). The effective sound speed profile used in acoustic code can be written as:  $c(z) = c_0 + \vec{V}_{wind} \cdot \vec{x}$ .

## 4 ACOUSTIC RESULTS

### 4.1 Results in homogeneous medium

Before making any simulation in inhomogeneous atmosphere, measurements and numerical results are compared in homogeneous conditions. In this section acoustical results obtained for the geometrical configuration described in Figure 2 are presented. These measurements have been carried out when the fan was off. Sound pressure levels relative to free field are presented in Figure 4. Experimental results are compared with numerical results carried out with two different models: MICADO [4] based on the Boundary Element Method (BEM) and ATMOS [5] based on the Green's Function Parabolic Equation (GFPE) [6].

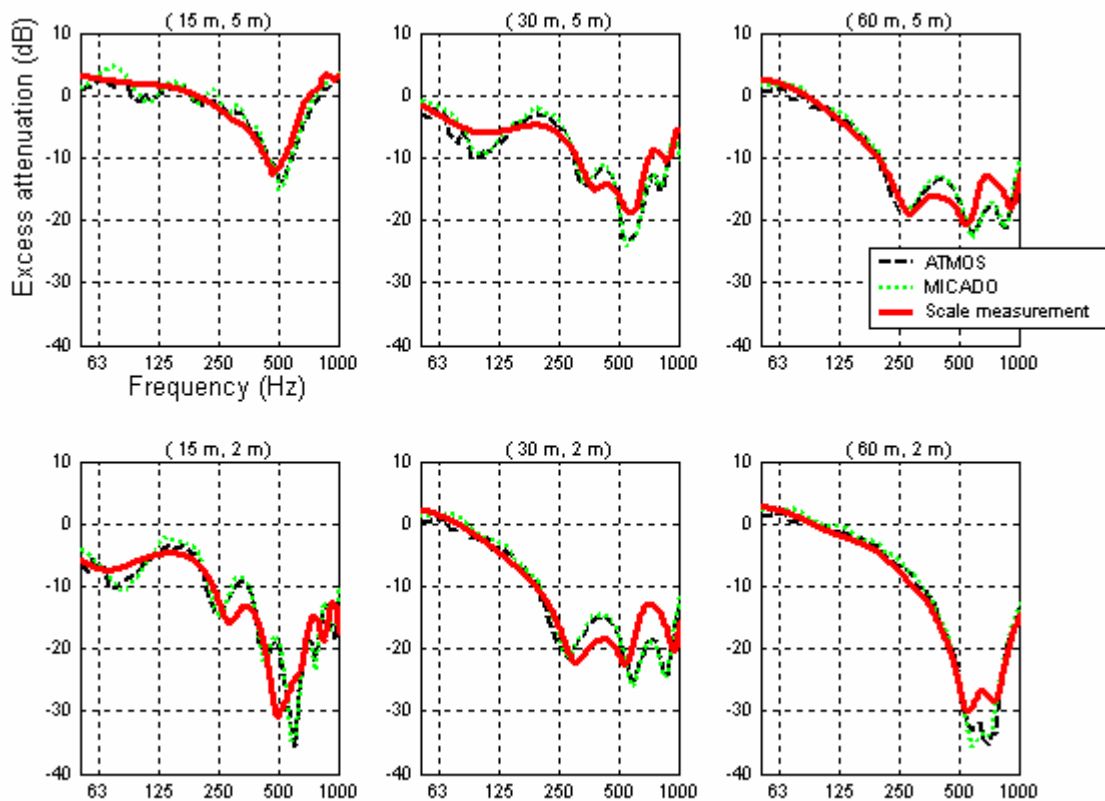


Figure 4: Acoustics measurements for the configuration described in Figure 2 in the homogenous case (solid line) and numerical acoustic results obtained with ATMOS (dashed line) and MICADO (dotted line).

For the all receivers, experimental data and numerical simulation good correlate. Indeed, the interference pattern is well described by both experimental and numerical results. This validation in homogeneous medium is important and makes us feel confident for investigations with wind speed profiles.

### 4.2 Results with meteorological effects

#### simulations with FLUENT

The calculation code FLUENT is used to calculate the wind flow along the propagation path and precisely in the neighborhood of the noise barrier.

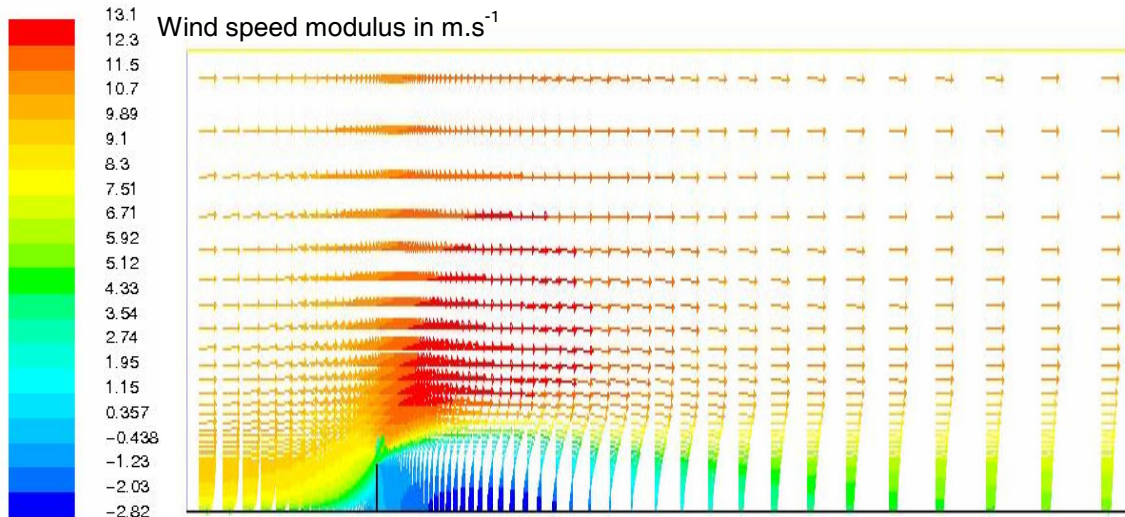


Figure 5: *Wind speed Vectors calculated with FLUENT*

The wind speed vectors calculated with FLUENT are taken into account in the numerical code ATMOS as input data. Sound pressure levels relative to free field obtained with the numerical code and experimental data are compared in Figure 6 for the uniform case.

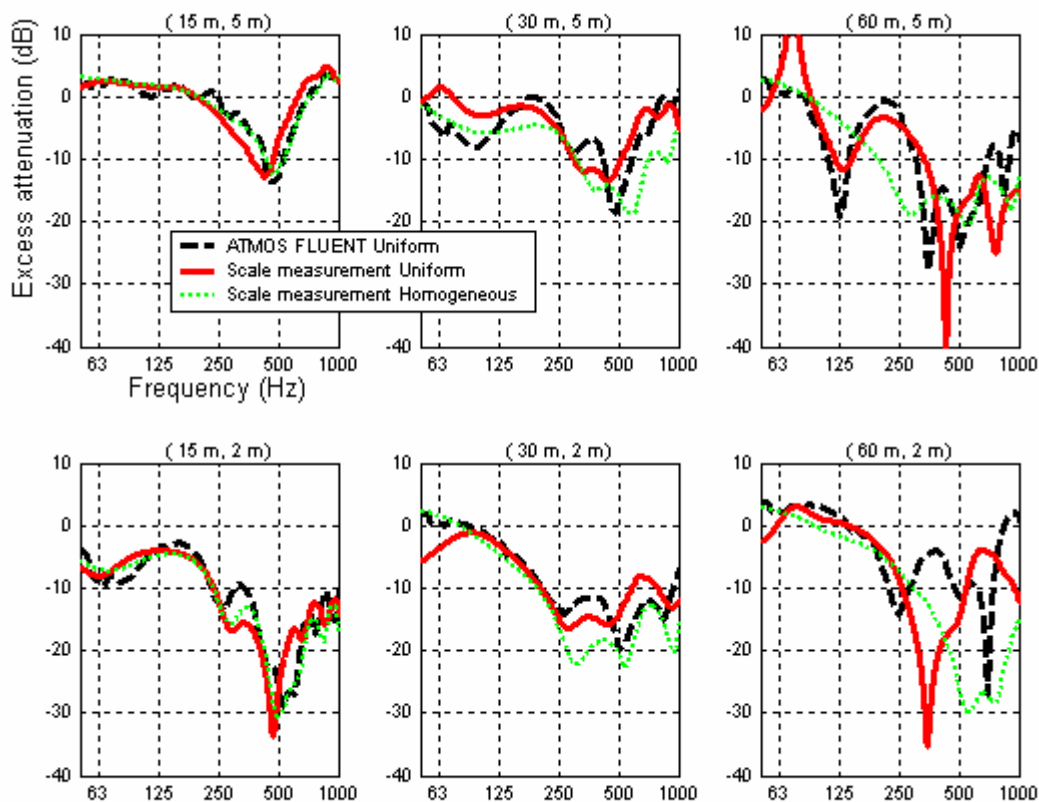


Figure 6: *Acoustics measurements (solid line) for the configuration described in figure 2 in the uniform case (wind speed  $10 \text{ m.s}^{-1}$  at 10 meter high and an intensity of turbulence of 1%) and numerical acoustic results (dashed line) obtained with ATMOS and with meteorological effects calculated with FLUENT. Scale measurement in the homogeneous case (dotted line).*

On the whole, experimental data are in accordance with numerical simulations. From these results, the following conclusions can be drawn:

- For receivers near the barrier, results for the uniform case or for the homogeneous case are almost the same.
- Meteorological effects are relevant for the receiver at (60 m, 2 m)

### Simulations with PIV results

Simulations with PIV results have been undertaken for the turbulent case. Sound pressure levels relative to free field obtained with the numerical code and experimental data are compared in Figure 7.

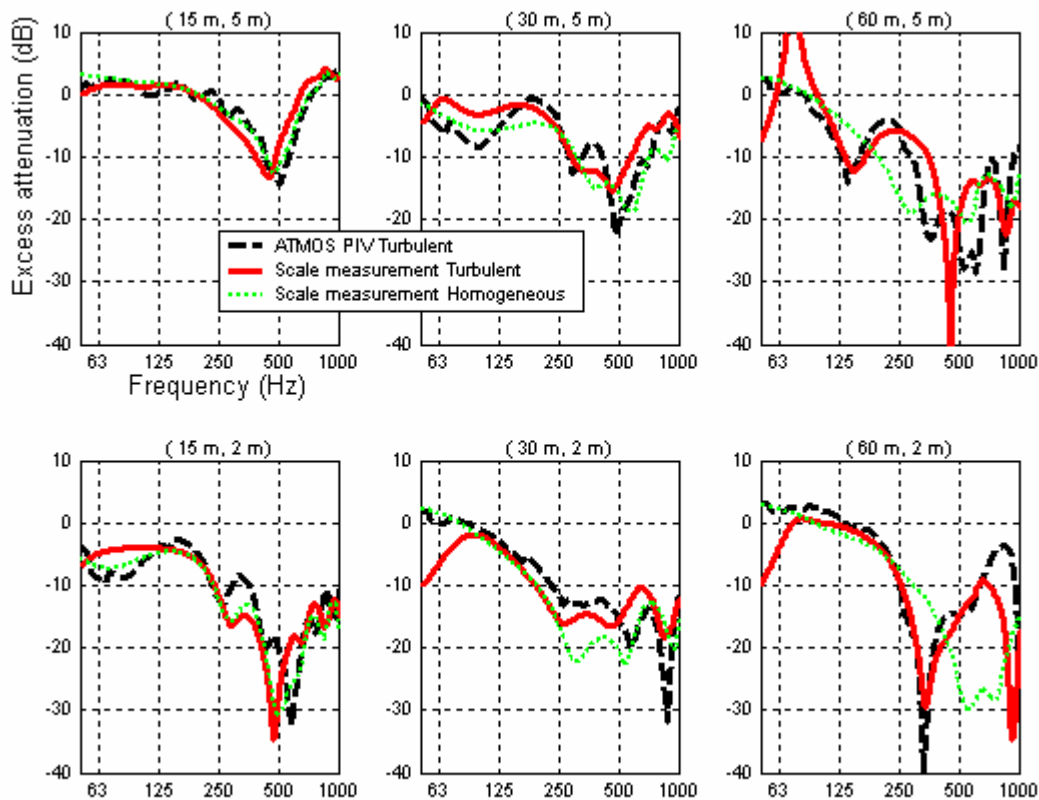


Figure 7: Acoustics measurements (solid line) for the configuration described in figure 2 in the turbulent case (wind speed  $10 \text{ m}\cdot\text{s}^{-1}$  at 10 meter high and an intensity of turbulence of 10%) and numerical acoustic results (dashed line) obtained with ATMOS and with meteorological effects from PIV measurements. Scale measurement in the homogeneous case (dotted line).

Some conclusions can be made on those results:

- At distances lower than 30 meter of the source, results in homogeneous medium are close to results obtained for the turbulent case.
- For the 2 receivers at 60 meter of the source, a remarkable difference between results in homogeneous medium and turbulent atmosphere is pointed out.
- For all the receivers, there is a good agreement between experimental measures and numerical results obtained with PIV data.



## 5 CONCLUSION

A measurement campaign in the wind tunnel of CSTB, Nantes has been presented. The road configuration studied was a rigid plane ground with a straight barrier. The results show a good concordance between experimental measurements and numerical results in both homogeneous and inhomogeneous atmosphere. The results also show the importance of meteorological effects on the outdoor sound propagation. Measurements bring to the fore the difference between homogeneous and inhomogeneous acoustical propagation.

Many geometrical and meteorological configurations have been studied during the campaign measurements. Work is still in progress to compare experimental results and numerical results for all of them (with aerodynamical results coming from Fluent calculations and PIV measurements). Comparisons aim at characterizing the link between the aerodynamic flow and the acoustic pressure during the sound propagation.

## ACKNOWLEDGEMENTS

The authors thank Eric Premat and Philippe Blanc-Benon for the helpful scientific discussions on that topic. The authors are grateful to Jocelyne Berthaud, Marc Dufresne de Virel for their help, kindness and availability during the campaign measurement.

The authors are also grateful to Frédéric Danbon for the Fluent calculations.

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