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Laboratory-scale experiment for the propagation of N-waves in a turbulent and refracting medium with ground effects

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Sound propagation in a refracting atmosphere close to the ground leads to the formation of a geometrical shadow zone in which sound can be scattered by turbulence. Laboratory scale experiments allow to control and study separatly ground reflection, refraction and turbulence effects. Therefore, a new experiment which allows quantitative study of outdoor nonlinear propagation has been designed to compare measurements to theoretical models. An electrical spark source is used to generate short duration (20 μs) and high pressure (1500 Pa) N -waves. A convex surface models the effect of an upward refracting atmosphere, and a heating grid generates thermal turbulence (1% fluctuations of refraction index). Previous studies showed that the microphone directivity and limited frequency response have a great influence, leading to distorted measured waveforms and overestimation of the rise time. Without turbulence, the waveforms and pressure levels are measured, and scattering of sound into the shadow zone by turbulence is discussed.

1 Introduction

Propagation of high amplitude *N*-waves in various conditions, such as turbulent and refracting atmosphere, is relevant to the sonic boom problem. As can be seen in figure 1, a negative sound-speed gradient causes the acoustical rays to be refracted. Close to the ground, this refraction leads to the formation of a shadow zone which is geometrically delimited by the cut-off. Some authors did outdoors measurements to study the propagation of sound into a shadow zone in real atmospheric conditions [1, 2]. In order to control separatly the effects of ground reflections, refraction and atmosperic turbulence, laboratory scaled experiments have also been done. These experiments allow statistical study of turbulence random effects by doing a great number of realisations of the same measurement. Laboratory-scale experiments to study acoustical propagation in a shadow zone have been performed using a temperature gradient [3], or an inhomogeneous mixing of CO_2 and air [4]. In order to control precisely the sound-speed gradient, a curved boundary can also be used, as illustrated in figure 2, to study linear or non-linear propagation into an acoustical shadow zone [2, 5, 6]. The combined effects of non-linear propagation and turbulence was studied later [7, 8]. Laboratory scale experiments with turbulence and a curved boundary have already been performed in linear propagation regime [9] and non-linear propagation regime [10]. In this communication, we present the results of an experiment of *N*-waves propagation through thermal turbulence, in which a shadow zone is generated with a curved boundary. Two mechanisms of sound propagation into the shadow zone are discussed: diffraction on the ground, and turbulence scattering as shown in figure 1.

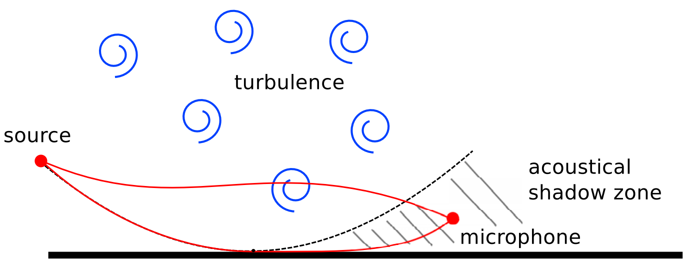

Figure 1: Two possible mechanisms of propagation into the shadow zone: diffraction on the ground, and scattering by turbulence.

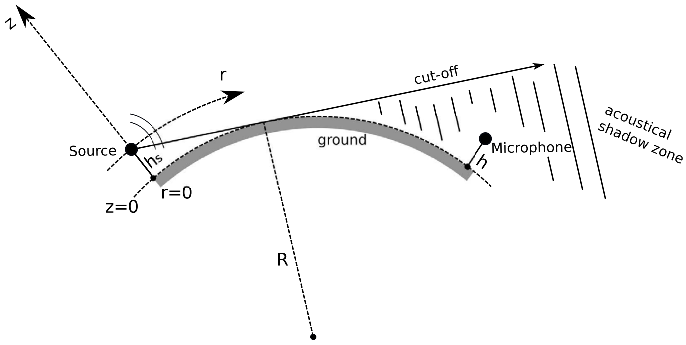

Figure 2: Formation of a shadow zone over a convex boundary.

2 Description of the experiment

A convex curved boundary, made out of polyvinyl chloride, with a radius of 1m, is used. The curved boundary is smooth and rigid. Thermal turbulence is generated by a 4.4m x 1m heating grid of electrical resistors, with a square mesh of 9 cm. Turbulence outer scale was found to be around 20 cm, and the experimental spectrum of temperature fluctuations can be fitted with an excellent agreement to a modified von Kármán theoretical spectrum. A mean temperature around 35°C, and root-mean square fluctuations of temperature about 5°C are measured, leading to about 0.8% fluctuations of refraction index. A 1/8" Brüel & Kjær type 4138 microphone is used to measure the *N*-waves. The microphone is flush-mounted in a baffle to postpone diffraction effects. The microphone is used with a Brüel & Kjær Nexus amplifier, whose frequency reponse has been extended (-3dB cut-off at 200 kHz). The amplifier output voltage is digitized at a sampling frequency of 10 MHz. The microphone directivity has a great influence on the measured waveforms [11], hence the microphone baffle is mounted on a turntable and both position and angle of the baffle are remote-controlled in order to keep the microphone at normal orientation with respect to the incident wave. An electrical spark source is used to generate short duration and high pressure *N*-waves. The spark source is made of two tungstene electrodes separated by a gap of 20 mm, connected to a 20 kV electrical supply. The characteristics of the emitted wave have been studied in details previously by the present authors [12, 13, 14]. As illustrated in figure 3, the parameters of the wave discussed hereafter are the positive peak pressure of the wave P_{max}, the "half duration" T, defined as the time interval between the middle of the front shock and the first zero-crossing of the waveform, and the rise time τ of the front shock. The rise time is defined here as the time interval during which the pressure rises from 10% to 90% of the positive peak pressure P_{max}. Typical values at 30 cm from the source are P_{max} = 700 Pa, T = 22 μs and τ = 0.4 μs [13]. In figure 3, the differences between the measured waveform (black line) and the simulated [12] waveform (red line) are caused by the filtering of the microphone. The limited frequency response of the microphone causes an overestimation of the rise time, and some oscillations appear on the measured waveform, as recent studies proved [11, 12, 13, 15].

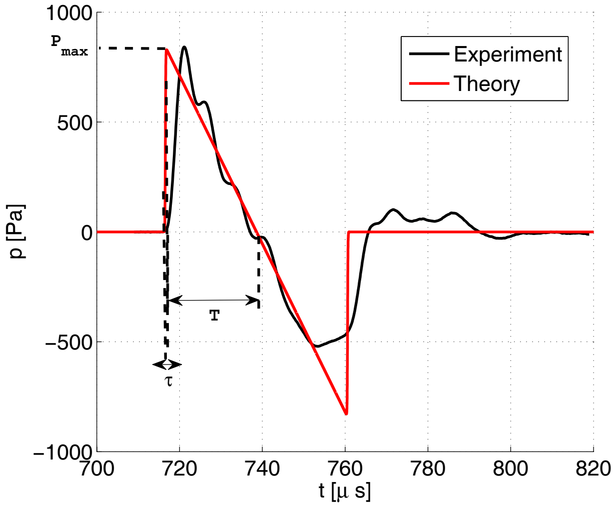

Figure 3: Theoretical waveform (red lines) at 30 cm from the spark source, and measured waveform at the same distance (black line). The positive peak pressure P_{max}, half-duration T and rise time τ are defined.

As can be seen in the plan view of the experiment in figure 4, a measurement with variable height h was performed. The positions of the microphone is shown in blue. Without turbulence, 60 waveforms are recorded at each position. With turbulence, 500 waveforms are recorded at each position to estimate accuratly the mean parameters of the pressure waves. Points A and B (red dots) are used to plot example waveforms. An additional measurement of 2000 waveforms was performed at point C (red dot) in order to estimate statistical parameters accuratly. The spark source is located in S.

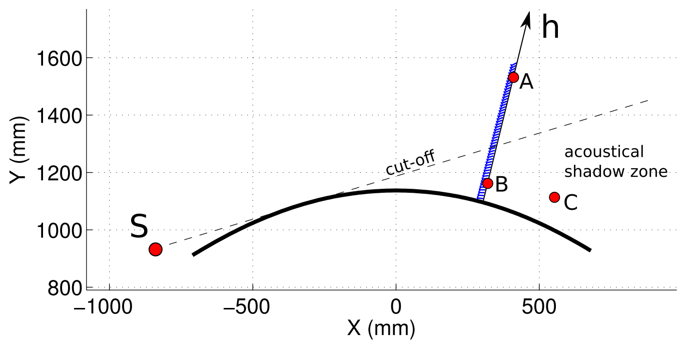

Figure 4: Plan view of the experiment, with the positions of the curved boundary, source and receivers.

3 Results

3.1 Waveforms and spectra without turbulence

Without turbulence, waveforms measured in the illuminated zone (point A) and in the acoustical shadow zone (point B) are plotted in figure 5. The origin of the time axis is set to t_0 for each waveform, t_0 being the zero-crossing of the waveform. In the illuminated zone (point A), the measured waveform (in black) presents a direct wave and a reflected wave, which leads to a wider half-duration T around 30 μs. The peak pressure P_{max} is about 100 Pa. The measured rise time τ is about 3 μs. In the shadow zone (point B), the peak pressure P_{max} is around 25 Pa, and the waveform no longer offers a shock and oscillations induced by the filtering of the microphone. The spectra plotted in figure 6 show that the waveform measured in the shadow zone has a lower high-frequency content than in the illuminated zone.

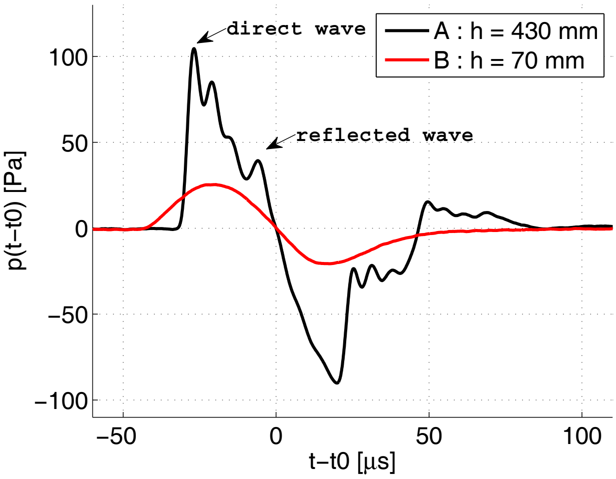

Figure 5: Examples of waveforms measured without turbulence. Black line : h = 43 cm (point A). Red line : h = 7 cm (point B).

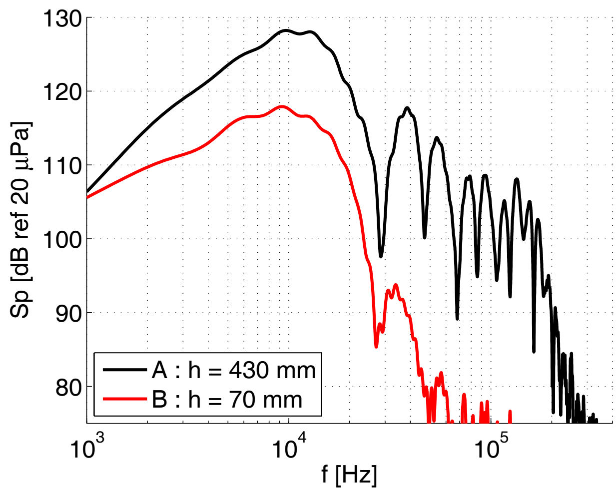

Figure 6: Spectra calculated from the measured waveforms (see figure 5), measured without turbulence. Black line : h = 43 cm (point A). Red line : h = 7 cm (point B).

3.2 Peak pressure P_{max} as a function of height h, with and without turbulence

The waveforms have been measured for variable height h (see figure 4). The mean value of the positive peak pressure $<P_{max}>$ is plotted in figure 7 as a function of h, without turbulence (black lines) and with turbulence (red lines). The position of the waveforms plotted in figure 5 are indicated with arrows and the letters A and B. If $h > 350$ mm, the measured pressure level corresponds to the one that has been measured in free field during a previous experiment, in both homogeneous and turbulent cases [16]. When h is decreased, an amplification region appears for $h = 270$ mm, due to the existence of a reflected wave. Then, if $h < 200$ mm, the microphone is in the shadow zone, and the measured pressure level is very low. In the experiment, turbulence has two major effects. First, in the illuminated region, the mean pressure level is decreased. This effect has been observed before by other authors [7, 8, 16]. In the shadow zone, the opposite effect can be found : the mean peak pressure $<P_{max}>$ is increased. For instance, the mean peak pressure is nearly doubled for h around 30 mm, compared to the mean peak pressure measured without turbulence. This is a clear evidence of the scattering of sound from the illuminated region to the shadow zone by the atmospheric turbulence.

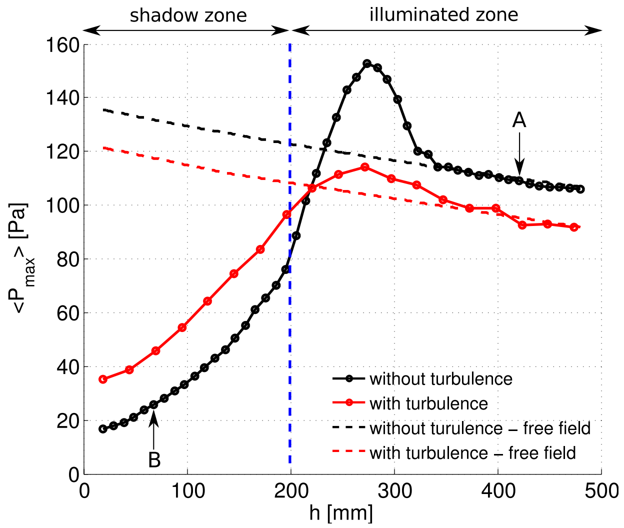

Figure 7: Measured positive peak pressure $<P_{max}>$ as a function of height h. Black solid line : homogeneous medium with the curved boundary. Black dashed line : homogeneous medium in free field. Red solid line : turbulent medium with the curved boundary. Red dashed line : turbulent medium in free field. The blue vertical dash line represents the geometrical limit of the shadow zone.

3.3 Analysis of the 2000 recorded waveforms at point C with turbulence

Figure 8 is a scatter plot obtained from 2000 waveforms measured at point C (see figure 4). For each waveform, the amplification factor of the peak pressure $P_{max}/<P_{max}^{homo}>$ is plotted as a function of the relative arrival time of the wave $t_{arr}-<t_{arr}^{homo}>$ for each measured waveform. $<P_{max}^{homo}>$ is the mean positive peak pressure, measured without turbulence at the same position, and $<t_{arr}^{homo}>$ is the mean arrival time of the waves, without turbulence at the same position. It can be seen that the dispersion of the measurement points is greater in turbulent medium than in homogeneous medium. Moreover, the arrival times of the waves measured in turbulent medium are smaller than the ones measured in homogeneous medium. This is due to heating, which highers the mean temperature and consequently increases the mean sound-speed. This figure highlights the amplification of the sound level in the shadow zone, due to turbulence. The mean value of amplification factor $P_{max}/<P_{max}^{homo}>$ is 2.06, with a standard deviation of 0.59. The effect of thermal turbulence is therefore to double the mean pressure level in the shadow zone. The maximum value of the amplification factor $P_{max}/<P_{max}^{homo}>$ is 7.06. The waveform with a pressure level amplified by 7.06 is presented in figure 9. It can be seen that the waveform is very close in shape to a so-called U-wave, which arises in the focusing of N-waves [17, 18, 19]. The minimum value of the amplification factor is 0.85. Except for a few cases (5 over 2000 measurements), we observe no attenuation of the pressure level, contrary to free field measurements, where both amplification and attenuation of the pressure level can occur randomly [16, 20].

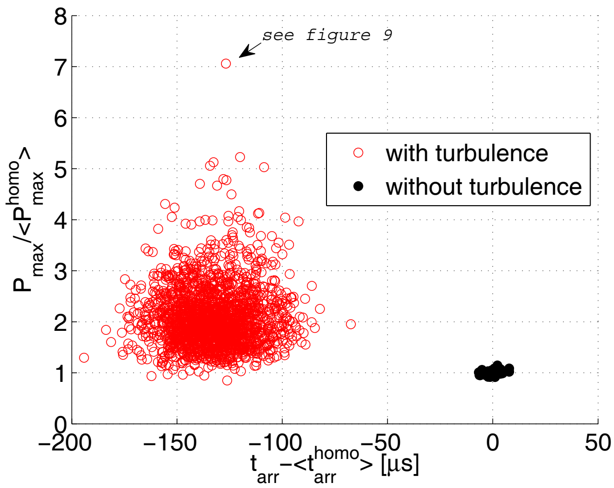

Figure 8: Scatter plot of P_{max} amplification factor $P_{max}/<P_{max}^{homo}>$ as a function of relative arrival time $t_{arr}-<t_{arr}^{homo}>$, for every 2000 waveforms measured in point C with turbulence (red circles) in the shadow zone. $<P_{max}^{homo}>$ is the mean positive peak pressure without turbulence, and $<t_{arr}^{homo}>$ is the mean arrival time of the waves without turbulence, at the same position.

4 Conclusion

A laboratory-scale experiment has been designed to study the non-linear propagation of N-waves in a turbulent and refracting atmosphere. The experiment gives the opportunity to control separatly the effects of nonlinear propagation, propagation through turbulence, and the effect of a sound-speed gradient near the ground. Thermal turbulence is found to decrease the pressure level in the illuminated region, as is the case in free-field. In the shadow zone, thermal turbulence is found to increase the pressure level by a mean factor of 2, because of turbulent scattering. The experiment showed that random focusing can occur by factors of up to 7, whereas no

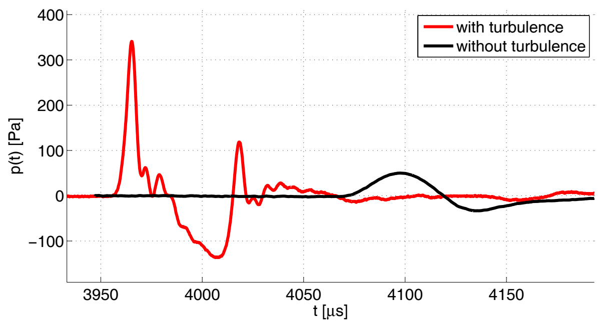

Figure 9: Example of measured waveform in point C, with a pressure level amplified by a factor 7. Red line : example of waveform in turbulent medium. Black line : reference waveform, measured at the same position without turbulence.

attenuation of the pressure level was observed in the shadow zone.

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