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EXPERIMENTAL STUDIES OF SOUND PROPAGATION THROUGH THERMAL TURBULENCE NEAR A BOUNDARY

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ABSTRACT
An experimental study of acoustic waves propagating through a thermal turbulence near a rigid boundary was achieved under laboratory conditions. A heated grid was placed in a large anechoic room; the mixing of free convection plumes above it generated a homogeneous isotropic random thermal field. The spectrum of refractive-index fluctuations is accurately described by a von Kármán model which takes into account the entire spectrum of turbulence. Experimental data were obtained by varying both the frequency and the distance of propagation. In this paper, we present experimental results for the mean relative sound-pressure level for different frequencies and a comparison with theoretical results deduced from the analytical solution developed by Ostashev et al. ([3]).

1 - EXPERIMENTAL ARRANGEMENT

Outdoor experiments [1] have established the influence of atmospheric turbulence on sound propagation. In particular it was shown that turbulence affects the interference pattern because of the existence of direct and reflected waves as well as changes the sound-pressure level. However, the uncertainties with regard to meteorological parameters, namely the velocity and temperature gradients, make it critical to assess their individual influences on sound-pressure level. We therefore decided to make a laboratory experiment in which the turbulence could be perfectly controlled. To simulate atmospheric conditions of forward acoustic propagation, it is assumed that the acoustic wavelength λ remains small compared with the integral scale of the turbulent field L_T, which is smaller than the range of propagation x, i.e. $x \gg L_T \gg \lambda$. We will consider that the fluctuations of the refraction index μ are only due to the fluctuations of temperature. All the experiments were done in the anechoic room (10m $\times$ 7m $\times$ 8m) of the Ecole Centrale de Lyon. In this facility, thermal turbulence is created using a heated grid (4.4 m $\times$ 1.1m) which consist of a plane of conductors with a square mesh of 9 cm and a maximum heating power of 64 kW. The mixing of the free convection plumes above it generates the thermal turbulence field. The mean ambient temperature increase is about 25°C and the temperature fluctuations have values between 2°C and 3°C. Then, if $\bar{T}$ is the mean temperature and T' is the temperature fluctuation, the rms value of the refraction-index fluctuation μ_{rms}, defined by $\mu_{rms}= \sqrt{\bar{T'^{\,2}}}/\left(2\bar{T}\right)$, is in the range 3 10^{-3} $-$ 4.5 10^{-3} . The acoustic propagation measurements were made at a height of z=190 cm from the grid. The boundary was made of perfectly rigid Plexiglas (12 cm thick, 120 cm high and 300 cm long). It was set vertically and inside the volume of turbulence so that the boundary could be heated on both sides.
To characterize the random thermal field we have measured the mean temperature $\bar{T}$ and the temperature fluctuation T' at many different points located in the z=190 cm plan. $\bar{T}$ was measured by moving a thermocouple above the grid with a resolution of 1°C. Using P5501 cold wire probes connected to a Dantec anemometric system, we have measured temperature fluctuation profiles and one-dimensional spectra of temperature fluctuations. These spectra were measured in the range of 0-400 Hz with a bandwidth of 0.25 Hz. Frequencies were converted into wavenumbers $K_1 = 2\pi f/\bar{U}_z$ by a Taylor hypothesis based on

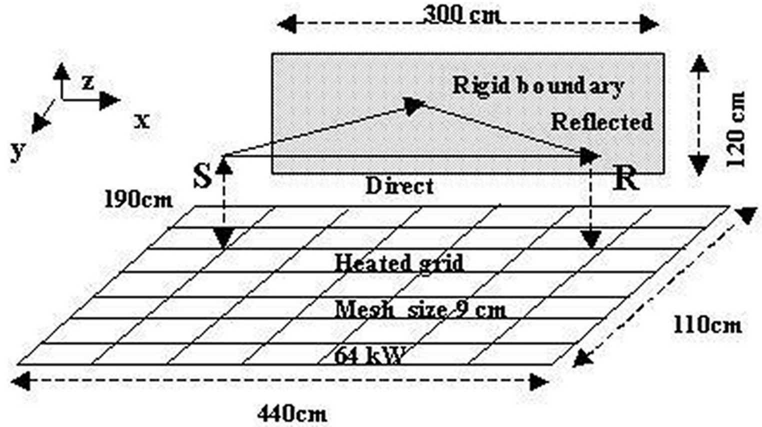

Figure 1: Experimental setup.

the mean measured upward velocity $\bar{U}_z$=1.1 m/s ([2]). In Figure 2 we have plotted experimental spectra for different locations of the cold wire (x=40 cm, x=70 cm, x=100 cm) and we have compared them with the theoretical one-dimensional spectrum $F_\theta(K_1)$ deduced from the modified von Kármán spectrum $\Phi_n(K)$ by:

$$\begin{aligned} F_\theta(K_1) &= 16\pi\bar{T}^2 \int_{K_1}^{\infty} K\Phi_n(K)\,dK \\ \Phi_n(K) &= 0.033\ \ C_n^2\left(K^2+1/L_0^2\right)^{-11/6}\exp\left(-K^2/K_m^2\right) \\ C_n^2 &= 1.91L_0^{-2/3}\ \ \mu_{rms}^2\ \ ;\ \ K_m = 5.92/l_0 \end{aligned} \qquad (1)$$

where n is the refraction-index. The outer scale of turbulence L_0 is related to L_T by $L0$=1.339L_T. In our experiment, the temperature fluctuations are isotropic and L_T=11 cm. The inner scale l_0 is related to the high-frequency cutoff of the spectrum and was estimated to be 0.5 cm (for more details see [2]). Very good agreement was obtained between experimental and von Kármán spectra for any location of the cold wire probe.

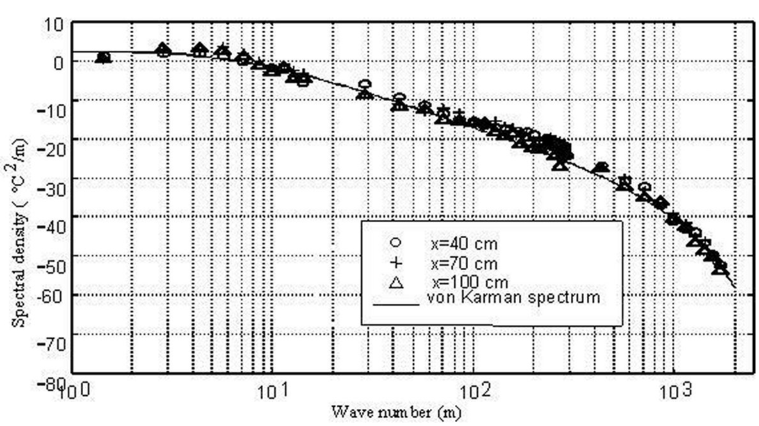

Figure 2: Comparison between the experimental one-dimensional spectrum of temperature fluctuations $F_\theta(K_1)$ and the theoretical spectrum deduced from the von Kármán model $\Phi_n(K)$.

The acoustic sources are small piezoelectric ultrasonic sources (20kHz $\ll f \ll$80kHz) which can be considered as point sources and which generate spherical acoustic waves. The distance between the source and the rigid boundary is h_s=10 cm. Note that the ratios λ/h_s and λ/x are of the same order as those obtained in outdoor sound propagation experiments [1]. Experimental data are obtained by varying the distance of propagation between 0 and 2.5 m and we can note that we the condition $x \gg L_T \gg \lambda$ is fulfilled. The transmitted signal was received on a 1/4" microphone (Bruël & Kjaer 4135) moved at fixed distances of the wall h_r=10 cm along the propagation axis x. The locations of the acoustic transmitter and receiver are shown in Figure 1. The acoustic pressure signal was first heterodyned to a frequency of 1kHz, then digitalized by an HP 3567 A analyzer (16 bit of resolution and 16 Mo memory). The signal was sampled with a period of 122 μs and the time average was twenty seconds. Finally, the signal was stored on the disc for later post-processing.

2 - COMPARISON BETWEEN THEORY AND EXPERIMENTS

On each of the following figures, we have plotted the evolution of the mean relative sound-pressure level $10\,\log_{10}\left(\bar{p^2}/p^2_{ref}\right)$ with the distance of propagation for different frequencies, and for each one we have plotted the deterministic case and the turbulent one. The reference level p^2_{ref} was measured in front of the source and at a distance of 2 cm. The main effect of the turbulence is to blur the pattern produced by the interference between the direct and reflected waves. This effect is illustrated in Figure 3. For a nonturbulent medium, the interference pattern is clearly marked with a reduction of sound-pressure levels of 30 dB or more in the region of destructive interference. For a turbulent medium, the characteristic interference pattern disappears. The influence of the turbulence increases with the distance of propagation, and for a distance greater than 2 m the acoustic field depends only slightly on distances.

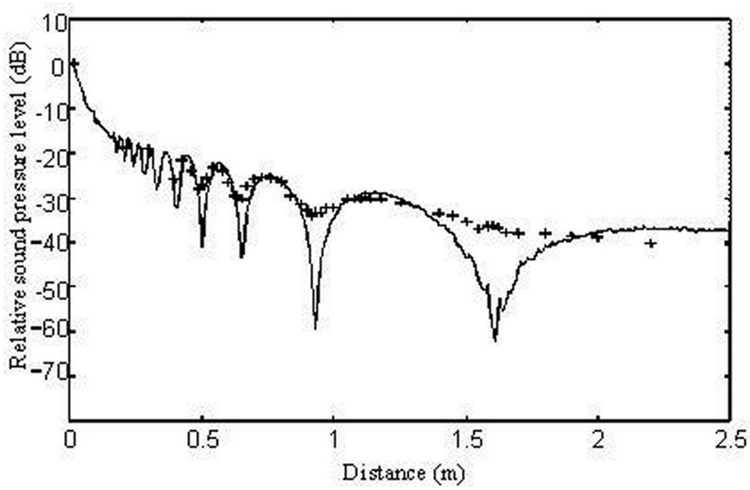

Figure 3: Relative sound-pressure level versus the distance of propagation; experimental data are obtained for f=40kHz, h_s=h_r=10 cm; the data without turbulence are indicated by a solid line; the data in the presence of turbulence are indicated by symbols (+).

For a rigid boundary, the mean square sound pressure derived by Ostashev et al. [3] is:

$$\bar{p^2} = \frac{1}{r_d^2} + \frac{1}{r_r^2} + 2\frac{C}{r_r r_d}\cos\left(k\left(r_r - r_d\right)\right) \tag{2}$$

where k is the sound wavenumber, and $r_d = \sqrt{x^2 + \left(h_s - h_r\right)^2}$ and $r_r = \sqrt{x^2 + \left(h_s + h_r\right)^2}$ are the direct and the reflected path lengths. The coherence factor C is given by:

$$C = \exp\left(-\frac{2xL_0}{h}\int_0^{h/L_0}\gamma\left(1 - \frac{2^{1/6}t^{5/6}}{\Gamma\left(5/6\right)}K_{5/6}\left(t\right)\right)dt\right) \tag{3}$$

where $\gamma = 3\pi^2 Ak^2 K_0^{-5/3} C_n^{2/}/\left(10\bar{T}^2\right)$, $A = 0.033$, $h = 2h_s h_r/\left(h_s + h_r\right)$ and $K_{5/6}$ is the modified Bessel function.

For the case without turbulence we verify that there is a very good agreement between theory and experiments (see Figure 4). This allowed us to establish the validity of our experimental arrangement.

In the turbulent case (see Figure 5), the agreement is very good in the first meter of propagation but small discrepancies appears at greater distances. Note that we probably should take into account the directivity of the sources in the analytical expression (Eq. 2) and compare with our experiments at large distances. Additional experimental data obtained with various frequencies of the acoustic source are detailed in [2].

3 - CONCLUSION

An experimental study of an acoustic wave propagating through thermal turbulence near a hard boundary has been investigated under well-controlled laboratory conditions. We have presented the results for the

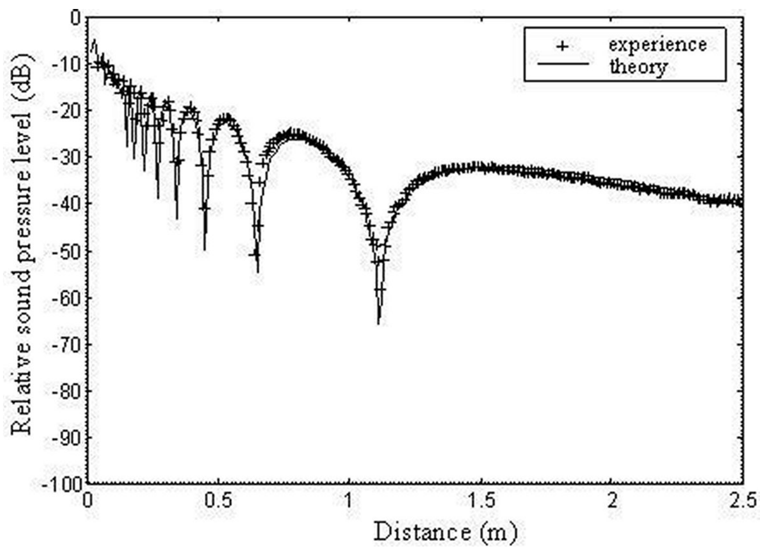

Figure 4: Relative sound-pressure level versus the distance of propagation in the absence of thermal turbulence; data are obtained for f=40kHz, h_s=10 cm, h_r=7 cm; the predicted values are indicated by a solid line and the measured data by symbols (+).

relative sound-pressure level in both the case of a turbulent and a nonturbulent medium. It has been revealed that temperature fluctuations result in dramatic increase of the mean sound-pressure level at the interference minima. The measurements were compared with a new theoretical model developed by Ostashev et al ([3]). There is good agreement between theory and measurements obtained over a wide range of propagation distances. It would be worthwhile to measure the relative sound-pressure level in the presence of a partially reflecting boundary. We are currently planning to do such experiments.

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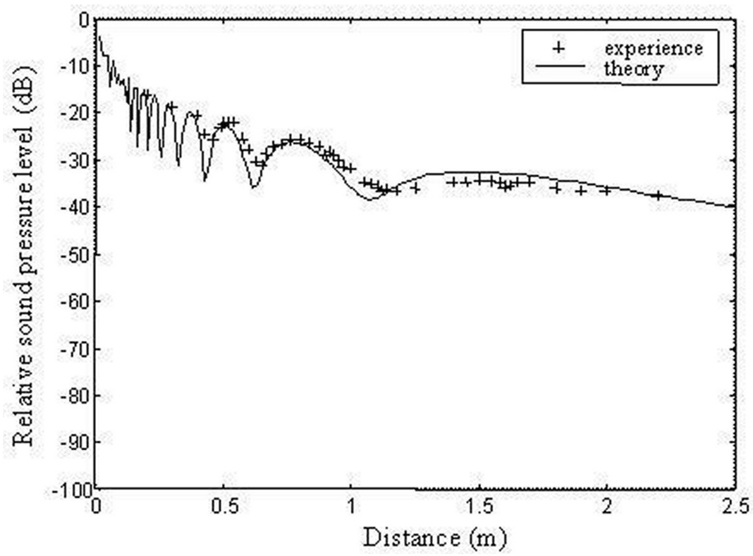

Figure 5: Relative sound-pressure level versus the distance of propagation in the presence of thermal turbulence; data are obtained for f=40kHz, h_s=10 cm, h_r=7 cm; the predicted values are indicated by a solid line and the measured data by symbols (+).