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INTENSITY FLUCTUATIONS OF AN ACOUSTIC WAVE PROPAGATING THROUGH THERMAL TURBULENT FIELDS

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ABSTRACT

The intensity fluctuations of an ultrasonic wave that propagates through a medium exhibiting temperature fluctuations are investigated. A heated array of conductors in air is utilized to generate a spatially-random thermal field typical of atmospheric or oceanic environments. Incident acoustic waves are emitted with spherical transducers.

Results are given for the normalized variance and for the probability distribution function of intensity fluctuations.

INTRODUCTION

The propagation of acoustic waves through temperature fluctuations has been investigated under laboratory conditions by several authors with a principal emphasis on the statistics of the wave amplitude fluctuations and the related dependence on turbulence characteristics. The thermal random field has usually been produced by a heater array mounted at the bottom of a water filled tank (Stone and Mintzer |1| ; Chotiros and Smith |2|). In this arrangement, minute air bubbles could be generated and presented an additional and not well controlled parameter. An installation has been adopted with a grid in air to eliminate this problem (Blanc-Benon, Chaize and Juvé |3|, Blanc-Benon and Juvé |4|, Blanc-Benon |5|). To simulate atmospheric or oceanic conditions of acoustic propagation, two relations have to be satisfied. The acoustic wave length λ must be small compared to the integral length scale L_T of the temperature field, which in turn has to be much smaller than the range of propagation x, i.e $\lambda \ll L_T \ll x$.

In our previous work (|3|, |4|, |5|) investigations were made for spatial-correlation functions and mean intensity repartitions that demonstrate the importance of a correct modelling of the turbulent thermal field using a von Karman spectrum and the role of the particular form of the incident wave (spherical or extended sources). Good agreement was obtained between the data and the predictions deduced from the parabolic approximation of the Helmholtz equation.

In this paper, we present experimental results for the intensity fluctuations with various conditions from weak turbulence to strong turbulence. There is no exact solution to predict either the variance or the probability distribution of the intensity fluctuations for arbitrary conditions and arbitrary incident waves. Of course, theories have been proposed which are valid under limiting conditions. For extremely "weak turbulence" the method of smooth perturbations (the Rytov approximation) is generally accepted. In this approximation, the normalized variance of the intensity σ_I^2, $\left(\langle (I-\langle I\rangle)^2\rangle / \langle I\rangle^2 \right)$, is related to the variance of the log-amplitude and the intensity fluctuations follow a log-normal distribution. For "strong turbulence" attempts have been made using an equation for the fourth-order coherence function

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(Tatarski |6|). No analytical solution exists for this equation and only asymptotic (7|, |8|, |9|) or numerical results (|10|, |11|, |12|) are available with limited range of validity. A useful approach has been made by Gracheva et al. |13| who suggest that σ_I depends on only one parameter x/ℓ, where ℓ appears as a longitudinal scale $(0.033\, C_c^2\, \pi\, k_0^{7/6})^{-6/11}$ related to the Rytov solution. We note that most published data on this problem concerned optical propagation phenomena in turbulent atmosphere.

EXPERIMENTAL ARRANGEMENT

The experiments were carried out in a large anechoic room (10 m x 7 m x8 m). The heated grid as well as the locations of acoustic transmitter and receiver are sketched in Fig. 1. Each grid consists of a plane arrangement of conductors with square mesh of 9 cm. The two grids are placed horizontally and the mixing of the free convection thermal plumes above them generates the turbulent field.

The overall dimensions of the system are 1.1 m x 2.2 m and the size of the heating cells is M= 9 cm with one heated grid and M= 4.5 cm with two heated grids. The acoustic propagation measurements were made at the height H = 1.75 m corresponding to 20 or 40 times the mesh size M. With one heated grid, the mean temperature rise above ambient was 27°C and the relative temperature fluctuation $T'/\overline{T}$ had a r.m.s. value of 1.7 10^{-2}. The integral scale L_T deduced by integration of the spatial correlation function was 7.6 cm. The changes which may be induced by velocity fluctuations in the x direction prove to be negligible ; an upper limit is $\sqrt{\overline{u_z'^2}}\ /\ c_0^2$ = 6.10^{-4} (u_z' is the fluctuating component in the upward direction). With two heated grids the mean temperature rise was 35°C, the r.m.s. value of $T'/\overline{T}$ reached 2.5 10^{-2} and the integral scale L_T was 5 cm. Additional details are reported in Blanc-Benon (|5|).

The spherical acoustic waves were generated by TDK ultrasonic sources (f = 23,5 kHz ; 31 kHz ; 39 kHz ; 75 kHz). The transmitted signals were received on 1/4" microphones (Bruël & Kjaer 4135) located along the x-axis.

THE NORMALIZED VARIANCE OF THE INTENSITY FLUCTUATIONS

If $I(x, \vec{\rho})$ is the intensity at a point located in a plan x perpendicular to the direction of propagation and at a distance $|\vec{\rho}|$ from the x-axis, the normalized variance of the intensity fluctuations is defined by :

$$\sigma_I^2 = \frac{\langle (I(x,0) - \langle I(x,0)\rangle)^2 \rangle}{\langle I(x,0)\rangle^2}$$

where <...> indicates an ensemble average. The data were obtained by a digital treatment of the acoustic pressure signal. In a first step the narrow-band received signal was heterodyned to a frequency of 5 kHz. Then using a digital acquisition DIFA TR 1030 (10 bit) interfaced to a PDP 11-23 processor with an array processor SKY, the pressure field was digitized with a sample period of 40 μs, and the data were stored on the system disk for later processing. The different moments of the intensity fluctuations $\langle (I - \langle I\rangle)^n \rangle$ (n is the order of the moment) have been computed with a signal length corresponding to 100 blocks of 8192 samples.

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In Fig. 2 the values of σ_I estimated from the data are plotted in terms of β_o, the Rytov solution for spherical waves :

$$\beta_o = \left(0.56\ C_\varepsilon^2\, k_o^{7/6}\, x^{11/6} \right)^{1/2}$$

$$C_\varepsilon^2 = 1.91 \left(\frac{\sqrt{\overline{T'^2}}}{2\,\overline{T}} \right)^2 L_o^{-2/3}$$

where C_ε^2 is the structure constant, L_o is the outer scale of turbulence related to the integral scale L_T ($L_o = 1.339\ L_T$) , and k_o is the acoustic wave number. Various frequencies have been used and the distance of propagation x in the turbulence has been changed in the range 0.7 m - 2.2 m. For weak fluctuations ($\beta_o < 1$) we observe a linear increase of σ_I as predicted by Rytov's solution (dotted curve). When the distance X or the r.m.s. of the relative temperature fluctuations $T'/\overline{T}$ increase, the normalized variance σ_I tends to saturate at a level slightly above 1. To test the similarity relationship $\sigma_I = f(\beta_o)$ predicted for spherical waves we have plotted the solution suggested by Gracheva et al. |12| for the large fluctuations $(\beta_o > 1)$ case :

$$\sigma_I^2 = 1 + 1.9\ (\beta_o^2)^{-2/5}$$

Our measurements of σ_I as a function of β_o are in agreement with this prediction.

THE PROBABILITY DENSITY FUNCTION OF THE INTENSITY FLUCTUATIONS

There is considerable theoretical and experimental interest in the probability distribution of the normalized intensity $I/\langle I \rangle$ (Strohbehn |14|, Furutsu |15|). For weak fluctuations the application of the central limit theorem leads to a log-normal distribution for the intensity I (Tatarski |16|). For strong fluctuations a Rayleigh distribution in amplitude is often proposed, it corresponds to an exponential distribution for the intensity. Some authors have suggested that the experimental results could be modelled by a generalized gamma distribution that varies smoothly from log-normal to exponential (Blanc-Benon |5|, Ewart and Percival |17|) :

$$W(I) = \left(b\mu^k / \Gamma(k) \right) I^{bk-1}\, e^{-\mu I^b}$$

$$\mu = \left(\Gamma(k+\tfrac{1}{b}) / \Gamma(k) \right)^b$$

Γ gamma function ; $I > 0$, $b > 0$, $k > 0$

The parameters b and k are deduced from the measurements of the moments $m_2 = \langle I^2 \rangle / \langle I \rangle^2$ and $m_3 = \langle I^3 \rangle / \langle I \rangle^3$. There are obtained by solving two non linear equations :

$$m_2 = \Gamma(k).\Gamma(k+\tfrac{2}{b}) \,/\, \Gamma^2(k+\tfrac{1}{b})$$

$$m_3 = \Gamma^2(k).\Gamma(k+\tfrac{3}{b}) \,/\, \Gamma^3(k+\tfrac{1}{b})$$

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In Fig. 3 and Fig. 4 experimental histograms of the normalized intensity $I/\langle I \rangle$ are plotted for a spherical wave at a frequency of 23.5 kHz and for different regimes of fluctuations. The data are compared with the exponential distribution, the log-normal distribution and the generalized gamma distribution calculated with the parameters b and k obtained by solving the equations giving m_2 and m_3. For weak fluctuations $(\sigma_I \leq 0.5)$ we note that the intensity distribution is nearly log-normal but the exponential distribution does not fit closely the data even for high levels of fluctuations $(\sigma_I \simeq 2\text{-}3)$. The agreement with the generalized gamma distribution is good for all the range of intensity fluctuations. It is interesting to indicate that similar conclusions have been obtained for acoustic wave propagation through a turbulent velocity field (Blanc-Benon |18|).

CONCLUSIONS

The effect of temperature fluctuations on the intensity fluctuations of a spherical acoustic wave has been investigated in laboratory conditions. For the normalized variance of the intensity our investigations confirm the existence of a "saturation" region, and that its variation can be expressed as a function of the Rytov solution for the small fluctuation case.

For the probability density function of the intensity fluctuations we have shown that the experimental data are well fitted by a generalized gamma distribution, for weak fluctuations as well as for moderate to high fluctuations. Work is currently in progress to extend our results. Higher fluctuation levels are considered as well as other types of acoustic sources.

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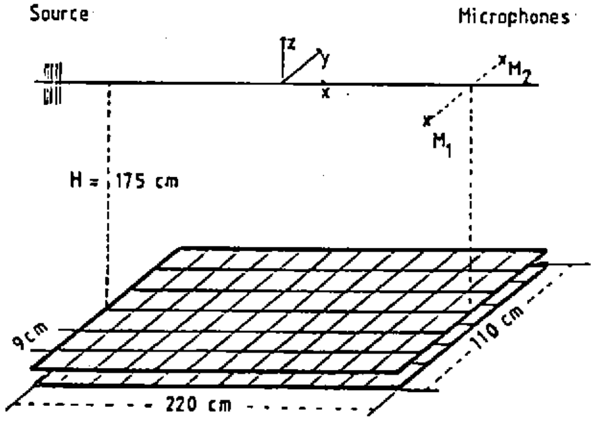

Fig. 1 : Experimental set-up.

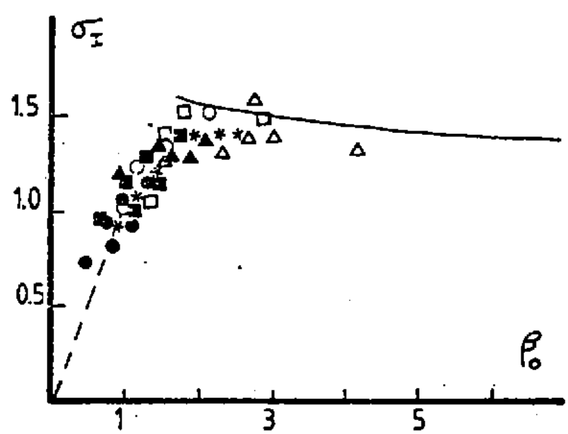

Fig. 2 : Normalized variance σ_I versus Rytov's solution β_o
a/ L_T = 7.6 cm ; $T'/\bar{T}$ = 0.017
● f = 23.5 kHz ; ▲ f = 75 kHz ; ■ f = 39 kHz.

b/ L_T = 5 cm ; $T'/\bar{T}$ = 0.025
○ f = 23.5 kHz ; * f = 31 kHz
□ f = 39 kHz ; △ f = 75 kHz

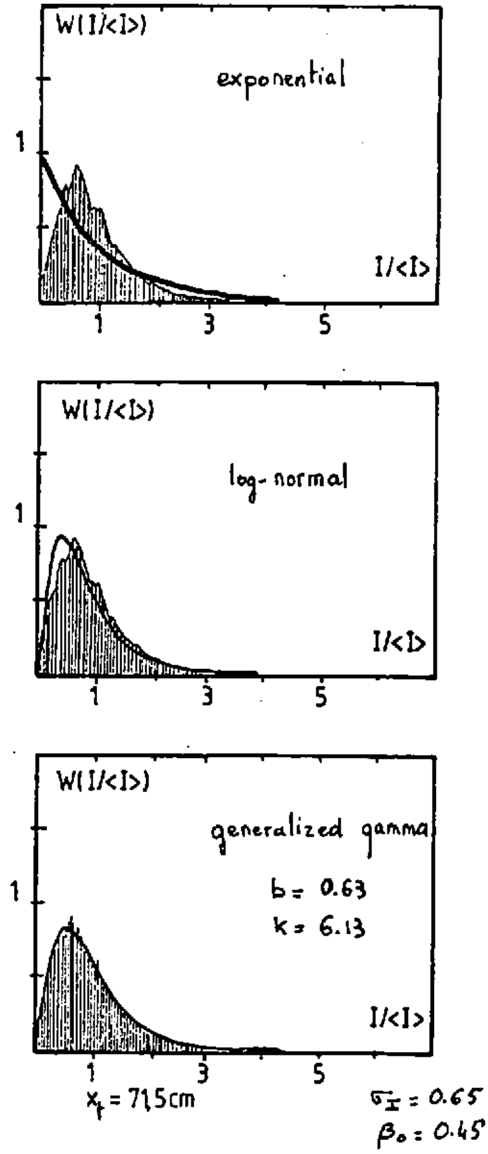

Fig. 3 : Probability distribution of the normalized intensity
$x = 71.5$ cm ; $f = 23.5$ kHz ; $L_T = 7.6$ cm ; $T'/\bar{T} = 0.017$

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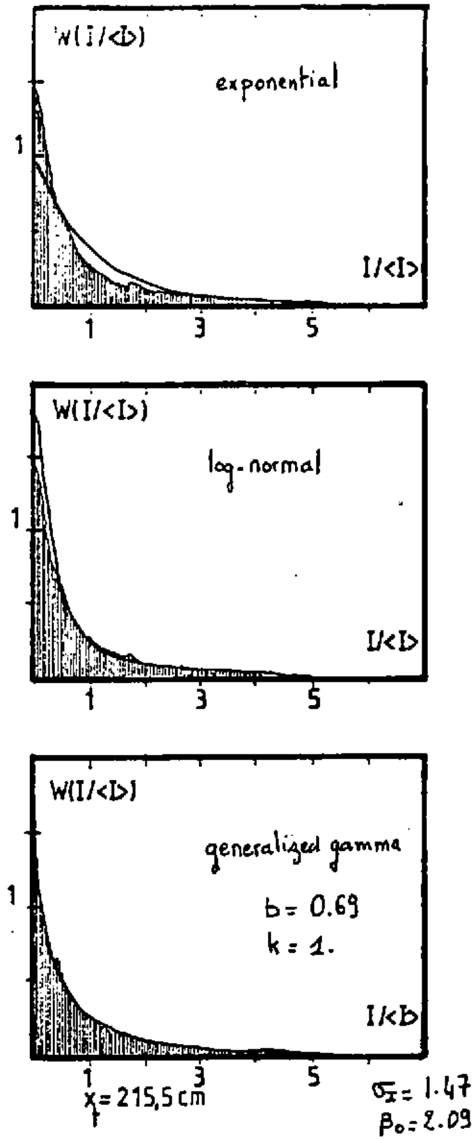

Fig. 4 : Probability distribution of the normalized intensity
$x = 215.5$ cm ; $f = 23.5$ kHz ; $L_T = 5$ cm ; $T'/\widetilde{T} = 0.025$