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Short Communication

Wind tunnel investigation of sound attenuation in turbulent flow

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ABSTRACT

Wind tunnel investigation of the sound wave attenuation by grid-generated turbulence is performed. The most influential parameters, such as the propagation distance, intensity of turbulent fluctuations and integral scale of the fluctuations are studied using an ultrasonic technique. The results are compared to the theoretical predictions available on the wave statistics. Theoretical predictions are well confirmed and partly extended. It is demonstrated that the ultrasonic technique provides the possibility of reproducing the main effects of atmospheric turbulence on sound propagation while benefiting from isolating the role of various parameters therefore sets of experimental data can be generated under laboratory conditions to benchmark further extensions of theoretical models and numerical simulations.

1. Introduction

Propagation of acoustic waves in the atmosphere is affected by numerous factors: mean temperature gradients, wind velocity, ground and topography, as well as random temperature and velocity fluctuations. Estimation of the acoustical wave intensity is still an open question from both, theoretical and experimental points of view. Theoretical problems result from the interactions of acoustic waves with the wide spectrum of atmospheric inhomogeneities and insufficient knowledge of their coherent structures [9]. Experimental problems arise from variety of factors, for example, the wave characteristics and atmospheric fluctuations cannot be measured simultaneously along the propagation path. The other environmental effects, such as a ground reflection and atmospheric stratification also must be considered that make the results hard to interpret [18] and references therein, [19]. It must be emphasized that characterization of the mentioned environmental effects including characterization of outdoor wind speed regimes requires very comprehensive instrumentation to obtain meaningful data ([15] and references therein).

In that perspective, a numerical simulation is a convenient alternative for analyzing sound propagation through turbulence. Many approaches have been used to simulate the propagation of acoustic waves through random media [21] and references therein. Quite exhaustive review on the numerical modeling of outdoor sound propagation and scattering effects induced by atmospheric turbulence can be found in Cheinet et al. [5] and Ehrhardt et al. [7]. Despite extensive numerical research the applicability of the results in real environment remains questionable. Assumptions required to obtain a sensible numerical or analytical solution in each setting are numerous and restrictive. As a result, comparison of analytical results with numerical still raises some questions [20].

While laboratory settings do not provide complete similarity with outdoor conditions, similar effects can be obtained in small-scale facilities by using ultrasonic waves and adjusting the intensity of random fluctuations. Moreover, laboratory conditions allow studying separately each effect in well-controlled and reproducible physical conditions [2] and references therein, [1].

The classical theory of wave propagation through turbulence dates back to Blokhintzev [3], Krasilnikov [10], Rytov et al. [26], and Tatarskii [22,23]. Current state of the isotropic turbulence sound scattering theory is presented in fundamental monograph by [17]. Present views concerning the future of the theory of turbulence have been outlined in the multi-author volume edited by [12], the paper of [9]. Krasnenko [11] completed extensive survey on modern advances in the remote sensing of the atmosphere with the use of electromagnetic and sound waves including so called “sodars” – ultrasonic radar analog used for monitoring of the atmospheric state. Providing comprehensive review of different techniques for measuring meteorological and ecological parameters in the atmosphere, he focused on the potential and further

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applications of the systems of acoustic sounding of the atmospheric boundary layer.

In the present paper we employ the travel time ultrasonic technique [13] together with a model of ideal grid turbulence to reproduce the main effects of atmospheric turbulence on sound propagation, specifically, sound wave attenuation in the field. The main advantage of the ultrasonic technique in its current state [14] combined with grid generated turbulence is the possibility of isolating the role of various parameters, such as temperature fluctuations, velocity fluctuations, intensity of turbulent fluctuations, the integral length scale of these fluctuations, a distance of wave propagation, and sound wave frequency.

The goal of the present investigation is to obtain experimental data for analysis of the effect of different factors of atmospheric turbulence on sound wave attenuation (turbulent attenuation), validate the experimental results by the available theoretical analysis, and, thus, demonstrate that sets of experimental data can be generated under laboratory conditions to benchmark further extensions of theoretical models and numerical simulations on the subject.

Sound propagation outdoors is strongly affected by atmospheric turbulence. Earlier experimental studies revealed that in the case of the short-range propagation the sound attenuation irregularities in the wind structure exceeded substantially classical absorption (through shear viscosity, heat conduction and radiation, diffusion) and molecular absorption (both that due to oxygen and nitrogen) [4]. Detailed review of experimental works related to so-called excess attenuation (beyond that due to classical and molecular absorption) presented in [21]. It has been established that sound was more influenced by wind fluctuations than by temperature fluctuations [18], Cheinet et al. [5].

The turbulent attenuation of sound waves is governed by the following parameters of the flow field and the sound field:

(1) The turbulent Mach number.
(2) The properties of the turbulence with respect to homogeneity and isotropy.
(3) A characteristic length of the turbulence, represented, for example, by turbulent eddies.
(4) The frequency of the incident sound waves.
(5) The length of the sound path in the turbulent medium.

The paper is organized as follows: In Section 2 the experimental arrangement is described and parameters of the flow and grid are defined. The discussion of experimental results and comparison with the corresponding analytical results are provided. Concluding remarks are given in Section 3.

2. Experimental arrangement

The measurements reported in the paper were performed in a wind tunnel of 107 cm length with a 29.8 cm × 29.5 cm rectangular test section. Turbulent velocity fluctuations were generated by two bi-planar grids with different mesh sizes $M_1 = 1.27$ cm and $M_1 = 0.635$ cm, placed at the entrance of the test section. Path length was changed from 0.0508 m to 0.254 m. The measurements were collected at 0.53 m downstream of the grid. The mean flow velocity U was 0 m/s, 10 m/s, 15 m/s, 18 m/s, 20 m/s. The corresponding Reynolds numbers Re_{M_a} were 4200, 6350, 7200 and 8400.

In the experiments the amplitudes of ultrasonic waves propagating from a transmitter to a receiver, were measured using two low frequency narrowband transducers (Panametrics, Olympus X1020) with working frequency 100 kHz, and the element diameter 0.0254 m producing beam waves, designed for air applications and located on the upper and lower sides of the tunnel, as shown in Fig. 1. The transmitter was excited by a programmable signal generator and a power amplifier by means of a tone burst of four cycles of 100 kHz square waves with 100 mV pick to pick amplitudes. The mechanical design of the transducer resulted in a low-pass filtering such that the received sound pulse was sinusoidal. To compensate for the deflection of the sound beam due to the main flow in the tunnel, the receiving transducer is shifted in the downstream direction against the transmitter. The shift is the product of the length of the sound path and the Mach number of the main flow. Experimentally, it is found by adjusting the receiving transducer so that maximum sound intensity is received.

The function generator was triggered by the National Instrument (NI) Data Acquisition Card (PCI/PXI-6711/6713 DAQ), which produced 5 V amplitude square waves with a frequency of 500 Hz. The analog data from the second transducer were captured by the CompuScope 82G DAQ that transformed the analog to digital data and transferred those data from the CompuScope 82G card to the PC memory. The acquisition rate was $5 \cdot 10^7$ samples/s. The block diagram of analog and digital processing is shown in Fig. 1. For each measurement the travel time was averaged over more than 700 runs.

Isotropy and homogeneity of the turbulent flow was ensured by the location of the experimental setup, namely, $25 < x/M_1 < 45$, where x is the distance from the grid downstream the wind tunnel [16]. In this experimental setup the decay of the turbulence behind the grid and turbulent properties of the flow are well described in [25] and [24]. It has been stated above that the experimental data were taken at 0.53 m downstream of the grid. The streamwise integral length scale l of the streamwise velocity fluctuations can be estimated using the decay law [24]:

$$\frac{l}{M_1} = 0.13\left(\frac{x}{M_1} - 3\right)^{0.4} \tag{1}$$

According to Eq. (1) the streamwise integral scale corresponding to the location of the transducers is $l \cong 7 \cdot 10^{-3}$ m. For the maximum sound path propagation $s = 0.25$ m the first Frensel's zone is $\sqrt{\lambda s} = 2.7 \cdot 10^{-2}\,\mathrm{m}$, where λ is the wavelength.

All parameters of the turbulence, which have been stated in Section 1 to be important for the attenuation of sound waves, could be varied independently over a broad range by varying the size of the mesh M, the length of the measuring sound path s ($s = 0.05$ m÷0.26 m), the degree of turbulence (intensity of the turbulence) by varying mean flow velocity U ($U = 5$–20 m/s) only, since it has been shown [18] that the velocity inhomogeneities are the main factor in sound wave attenuation caused by turbulence.

As it has been stated in Section 1 the purpose of the current measurements is to determine ultrasound wave attenuation due to the turbulence present between the transmitter and the receiver. Viscosity and heat conduction contribute roughly equally to acoustic absorption in air however, the majority of the power losses due to viscosity and thermal conduction happen within the boundary layer. Morse and Ingard [17]. Since the boundary layer is so thin – for our experimental conditions the displacement thickness varies from $\delta^* \sim 0.9 \cdot 10^{-3}$ m to $\delta^* \sim 1.2 \cdot 10^{-3}$ m – the absorption takes place at the boundary. In the rest of the flow the turbulent scattering will have the predominant role in the sound wave attenuation. The level of amplitude fluctuations is expressed as $\chi = \ln(A/A_0)$, where A_0 is some constant with the same dimensions as A. The variance of the log amplitude fluctuations $\langle\chi^2\rangle$ for our experimental setup ($s^2 \gg l^2/\lambda$) according to Tatarskii [23] is:

$$\langle\chi^2\rangle = N\frac{C_v^2}{c_0^2}k^{7/6}s^{11/6}, \tag{2}$$