Experimental investigation of grid-generated turbulence using ultrasonic travel-time technique

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Abstract

This paper presents a summary of experimental work conducted by the authors in the area of acoustical wave propagation through turbulent media. The ultrasonic time-of-flight method, using dual transducers, is utilized to determine some characteristics of grid-generated turbulent flow produced in a low turbulence, low speed open circuit type wind tunnel. The experimental work utilizes the high speed Data Acquisition (DAQ) card, Labview Software connecting the experimental apparatus and computer, Low Speed Wind Channel with ultrasonic transducers placed in it and customary built grids, with heating elements inside.
Keywords: ultrasonic travel time technique, caustics.

1 Introduction

There has been an intensive research work focusing on ultrasonic flow meters and their capabilities for measuring non-ideal flows [3]. Evidence of ultrasonic technology's value to industry as effective flow diagnostic solutions can be taken from the fact that the Ultrasonic Flow Metering market size quoted in 2002 at nearly $406 Million dollars, is projected to expand to a $600 Million dollar industry by 2007. New applications for ultrasonic technology continue to emerge but its potential will depend on the innovations that take place in the future.

The classical theory of acoustic wave propagation through turbulence predicts linear increase of the first-order travel-time variance with the propagation distance. However, recent numerical and theoretical studies exhibit an almost quadratic growth of travel time variance with travel distance [4],[5],[6]. This

WIT Transactions on Engineering Sciences, Vol 52, © 2006 WIT Press
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/AFM06015

effect is believed to be closely related to the occurrence of caustics.[7]-[10] If a wave propagates in a random medium, then at some distance x from the source, caustics appear. The higher the turbulence intensity, the shorter the distance at which the first caustic occurs. The probability of the appearance of the caustics in a random field was explored theoretically [8],[9],[11] and numerically. [4],[5],[10]

The fact that an acoustic wave carries some structure information of the turbulent medium after interacting with a medium makes it possible to use some statistical characteristics of the acoustic wave as a diagnostic tool to obtain some statistical information about the medium[6],[5],[12],[13],[14]. The modern theory of sound propagation in a moving random medium has been developing intensively since mid-1980s and is systematically described in Ostashev [15]. In this part of the study the goal is to demonstrate quantitatively that effect of thermal fluctuations is as much important as effect of velocity fluctuations on acoustic wave propagation. In order to do that the ultrasonic flowmeter equation is reconsidered, where the effects of turbulent velocity and sound speed fluctuations are included. The result is an integral equation in terms of correlation functions for travel time, turbulent velocity and sound speed fluctuations. Experimentally measured travel time statistic data approximated by Gaussian function and used to solve integral equation analytically. Turbulence spectral models for sound propagation in turbulent media were addressed by different authors and a summary of recent works presented in [15].

2 Experimental arrangement

Figure 1 represents a schematic diagram of the experimental setup. We consider a locally isotropic, passive temperature field coupled with a locally isotropic velocity field, which is realized by introducing a grid in a uniform flow produced in a wind tunnel with $0.3m \times 0.3m \times 1.07m$ test section. [16] Travel time moments are studied versus mean flow velocity U and travel distance L. Turbulence was produced by a bi-planar grid consisting of a square mesh of aluminum round rods with diameter 0.635 cm positioned 2.54 cm between centers. Experimental conditions were chosen similar to the experiments by previous investigators. [17]-[19] In our experiment we used two transducers working at a frequency of 100 kHz, designed for air applications, located on the upper and lower sides of the tunnel, as shown in Fig.1. Transducer- transmitter is excited by the programmable signal generator and a power amplifier by means of burst of four 100 kHz square waves with 50mV amplitude. The function generator is initiated by National Instrument Data Acquisition Card (DAQ), which produces 5V amplitude square waves with a frequency of 500 cycles/s. The ultrasound beam, send by the first transducer was received by the second one. The analog data, then, from the second transducer was transported to a CompuScope 82G DAQ with large acquisition memory and wide analog bandwidth, that transformed analog data to digital data and transferred data from CompuScope 82G card to the PC memory with the resolution of $5 \cdot 10^{-9} s$. Both DAQ cards were installed inside the PC. The National Instrument DAQ allows one to detect the burst departure time extremely accurately and, finally, digital representation of the experimental data, provided by CompuScope 82G DAQ allowed determination of the travel time very precisely. Fig. 2 demonstrates a typical data representation obtained from CompuScope 82G DAQ, transferred to the PC and processed in Excel. The acquisition rate was $5 \cdot 10^7$ samples/s. The first signal e_1 corresponds to the burst of square waves produced by the function generated that initiate the transducer-transmitter. The second signal e_2 is the signal received by the second transducer. The measuring time for each single run was 45s (approximately 15Mb of measured data). For each measurement the travel time was averaged over more then 700 realizations.

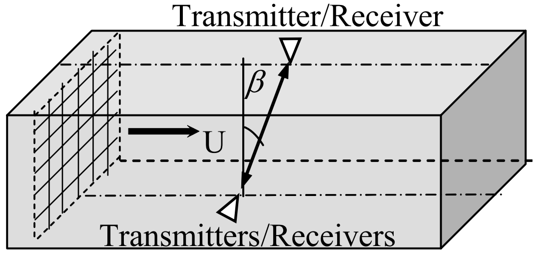

Figure 1: Wind-tunnel test section with flowmeter.

3 Experimental results and discussion

In the present work we demonstrate summary of the present work consisting of two parts: experimental demonstration of caustic effect and development of a semi-analytical model based on experimentally measured travel-time statistics for determination of statistical characteristics of grid-generated turbulence, such as correlation functions and spectral density of turbulent velocity and temperature fields.

3.1 Caustic effect

In this part two series of experiments, for heated and non-heated grids, were conducted. Experiment for a non-heated grid was devoted to a study of the travel time variance as a function of the travel path and turbulent intensity for long distances. The second set of experiments is conducted for the heated and non-heated grids at constant mean velocity for short travel distances to evaluate the effect of thermal fluctuations on travel time variances.

3.1.1 Non-heated grid experiment

Path length was changed from 0.0508m to 0.254m and the transducers were of 100 kHz working frequency. The first grid size, M_1, was $6.35 \cdot 10^{-3} m$. The measurements were collected at 0.63m downstream the grid. The mean flow velocity U was 0m/s, 10m/s, 15m/s, 18m/s, 20m/s. The corresponding Reynolds numbers Re_{M_1} based on M_1 was 4200, 6350, 7200, 8400. We compare the travel-time variance with Chernov [20] estimates and with theoretical estimations of second-order travel time variance by Iooss *et al.* [6]

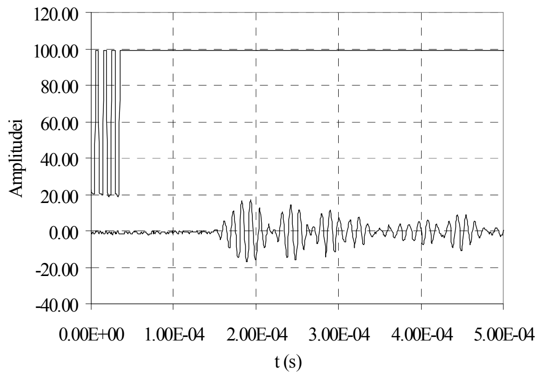

Figure 2: Transmitted (left) and received (right) waves.

Probability densities for the occurrence of caustics were calculated theoretically [4],[8]-[10],[11],[22]. For our experimental data we estimate the probability density of occurrence of caustics using theory developed by Klyatskin [11] and explored by Blanc-Benon *et al.* [9] and Iooss *et al.* [6]. The probability density function $P(\tau)$ for a plane wave propagating through 3D isotropic turbulence is defined as [8],[11]

$$P(\tau) = \frac{\alpha}{\tau^4}\exp\left(-\beta/\tau^3\right); \alpha = 1.74, \beta = 0.66 \tag{1}$$

The normalized distance τ is defined as $\tau = D^{1/3}x$,where D is the diffusion coefficient introduced by Klyatskin and x is a variable travel distance. For a Gaussian correlation function the diffusion coefficient D in a moving random medium is defined in [9] as

$$D = \frac{\sqrt{\pi}}{2L_0^3}\sigma_\varepsilon^2; \sigma_\varepsilon = \sqrt{\left\langle \varepsilon^2 \right\rangle}; \varepsilon = 2n\ , \tag{2}$$

where σ_ε is a standard deviation of an index of refraction ε and n are fluctuations in the refractive index. In Figure 3 the probability density of the occurrence of caustics is plotted along with experimental data for the travel time variance, Chernov theory for the linear propagation and results of the theoretical model developed by Iooss *et al.* as functions of normalized distance of propagation, τ . The peak of the probability density function appears at approximately $\tau = 0.85$, which corresponds to $x \approx 8.5 \cdot 10^{-2}\,\mathrm{m}$, or in nondimensional units $x/M_1 \cong 13.2$. It is noted in [22],[23] that strong fluctuations are connected with random focusing of acoustic waves. The level of amplitude fluctuations is expressed through the wave amplitude as $\chi = \ln(A/A_0)$ and, the variance of the log amplitude variations is $\sigma_A^2 = \left\langle \left(\chi - \langle\chi\rangle\right)^2 \right\rangle$. In Fig. 4 experimental data for the standard deviation of log amplitude variations versus actual travel distance is plotted for undisturbed medium, $10 m/s$, $15 m/s$, $20 m/s$. Fig.4 exhibits substantial increase in standard deviation of log amplitude variations in the region, where probability density is different from zero, which has been predicted theoretically [22][23].

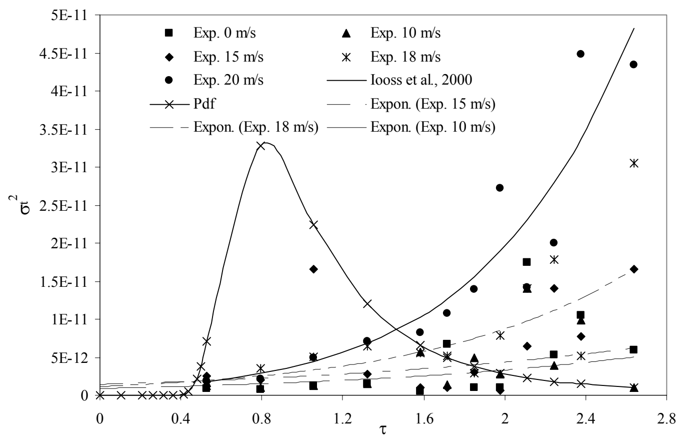

Figure 3: PDF of occurrence of caustic.

3.1.2 Heated grid experiment

Nine cases of different distances L for two different temperatures $\mathrm{T} = 59^\circ F$ and $\mathrm{T} = 159^\circ F$, were studied. The grid size was $M_3 = 2.54 \cdot 10^{-2} m$. To insure the high quality grid the heating elements were inserted in hollow aluminum rods with diameter $d = 6.35 \cdot 10^{-3} m$. The mean flow velocity was U = 3.5 m/s. The Reynolds number Re_M based on M and U was about $6 \cdot 10^3$ and the corresponding Péclet number $Pe_M = \mathrm{Pr}\,\mathrm{Re}_M \sim 4350$; $\mathrm{Pr} = 0.725$ for the working fluid air. The goal is to compare the dynamics of the travel-time variances for heated and non-heated grid experiments. Fig. 5 shows the travel-time variation as a function of scaled distance of propagation. It is obvious that temperature fluctuations lead to the appearance of nonlinearity in the dynamic of the travel time variance. The travel time variance at $59^\circ F$ is plotted for a comparison. The experimental data confirm theoretically and numerically established theory stating that the higher the turbulent intensity, the shorter the distance at which the first caustics occurs [4].

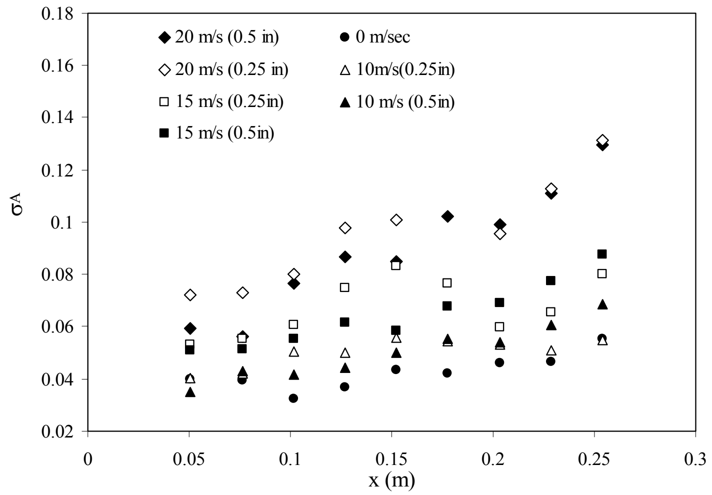

Figure 4: Standard deviation of log amplitude variations.

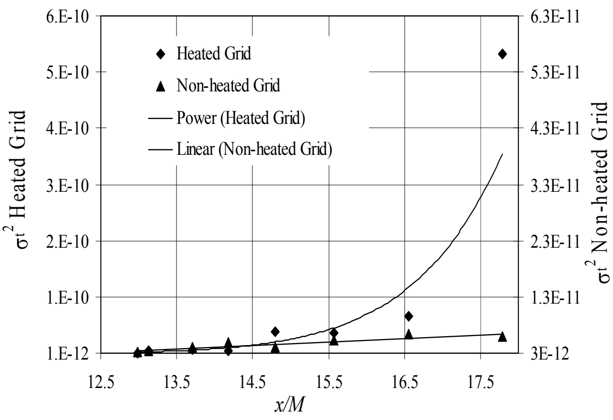

Figure 5: Experimental data for the travel time variance.

3.2 Correlation function of velocity fluctuations

The sound propagates across a grid-generated turbulence from a transmitter to a receiver separated by a distance s as shown in Fig. 1.

The angle β is changed from 0 to 40 degrees with 5-degree step. The measurements were collected at $x/M = 25$ x/M=35, where radiation effects are negligible. The mean flow velocity U was 3.5 m/s. The Reynolds number R_M based on M and U was about 10000 and the corresponding Péclet number $Pe_M = \Pr \mathrm{Re}_M$ ~4350; $\Pr = 0.725$ for the working fluid air. . A more detailed description of the experimental particulars may be found in [24]. Basic flowmeter equation may be used to derive an expression for a travel time t of a wave traveling from the speaker to microphone.

$$t = \int_s \frac{dy}{c-u} \approx t_0 + \frac{1}{c^2}\int_s u'dy; u = U\sin\beta + u' \tag{3}$$

where t_0 is a travel time in the undisturbed media, U is a mean velocity, c is a sound speed, u' are fluctuations of the mean flow velocity. In Equation (3) we neglected the terms of order $U/c, U^2/c^2$. Introducing a new variable $t_0 = t - <t>$ and neglecting correlation between fluctuations of velocity and sound speed one gets:

$$K_{t_0}(s,s') = \frac{1}{c^4}\left[\int_s\int_{s'}\left(K_{u'}(x,x') + K_{c'}(x,x')\right)dxdx'\right] \tag{4}$$

For the case of room temperature, $T = 59^0 F$, equation (4) reduces to [24]:

$$K_{t_0}(s,s') = \frac{1}{c^4}\left[\int_s\int_{s'}\left(K_{u'}(x,x')\right)dxdx'\right] \tag{5}$$

In many practical problems, the form of the correlation function is not known. However, its general shape is often approximated by a Gaussian function.[15] We represent the correlation function in Equation (5) by

$$K_t^{59F}(s,s') = \sigma_t^2\Big|_{F59}\exp\left(-(s-s')^2/l^2\right) = \sigma_t^2\Big|_{F59}\exp\left(-\tau^2/l^2\right) \tag{6}$$

Here σ_t^2 is a variance of travel time fluctuations. Choice of l made on the basis of the integral length scale of the turbulence [15]. Figure 6 demonstrates correlation function of travel time obtained using experimental data as a function of separation distance x compared with Gaussian curve providing the best fit. Experimental data allows us to determine unknown coefficients, $\sigma_t^2 = 9.85e-15$ and $l^2 = 0.0036$. Integration of Equation (5) with known leads to the following form of correlation function of turbulent velocity

$$K_{u'}^{F59^\circ}(\tau) = c^4\left[2\frac{\sigma_t^2\big|_{F59^\circ}}{l^2}\exp\left(-\tau^2/l^2\right)\right] - c^4\left[4\frac{\sigma_t^2\big|_{F59^\circ}}{l^4}\tau^2\exp\left(-\tau^2/l^2\right)\right] \tag{7}$$

Figure 7 shows the correlation function of turbulent velocity for our particular experimental data. Variance of velocity fluctuations is $\sigma_{u'}^2 = 2c^4\frac{\sigma_t^2}{l^2} = 0.0801$. At the same time we know, that $\sigma_{u'} = \left\langle u'^2 \right\rangle^{0.5}$, meaning that for our experimental conditions we have very small values of $u'^2/c^2 \sim 6.9 \cdot 10^{-7}$, which is in a very good correspondence with data [24]. The ratio of a turbulent velocity to the mean velocity is $\alpha = u'/U \cdot 100\% \sim 6\%$, which is typical for experiments performed in grid turbulence [19].

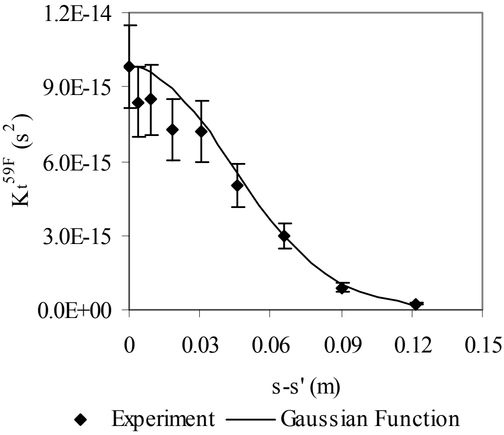

Figure 6: Correlation function of travel time.

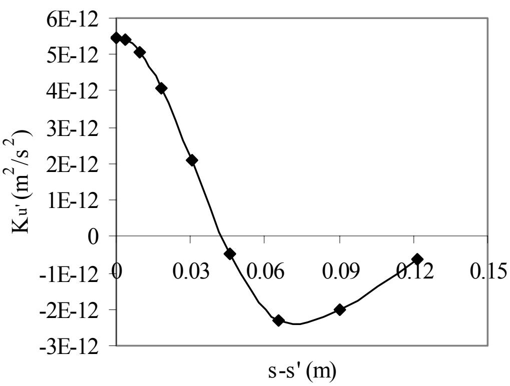

Figure 7: Experimentally obtained correlation function.

4 Conclusions

Analysis performed in laboratory conditions permit accounting for effect of temperature and velocity fluctuations resulting in occurrence of caustics, i.e., allows examining possible upgrades to travel-time meters and processing arrangements before expenditures. Semi-analytical Acoustical Model based on travel-time measurements allows assessing the statistical properties of the flow-testing environment, while requires the knowledge of only one parameter, which is measured experimentally – travel time.

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