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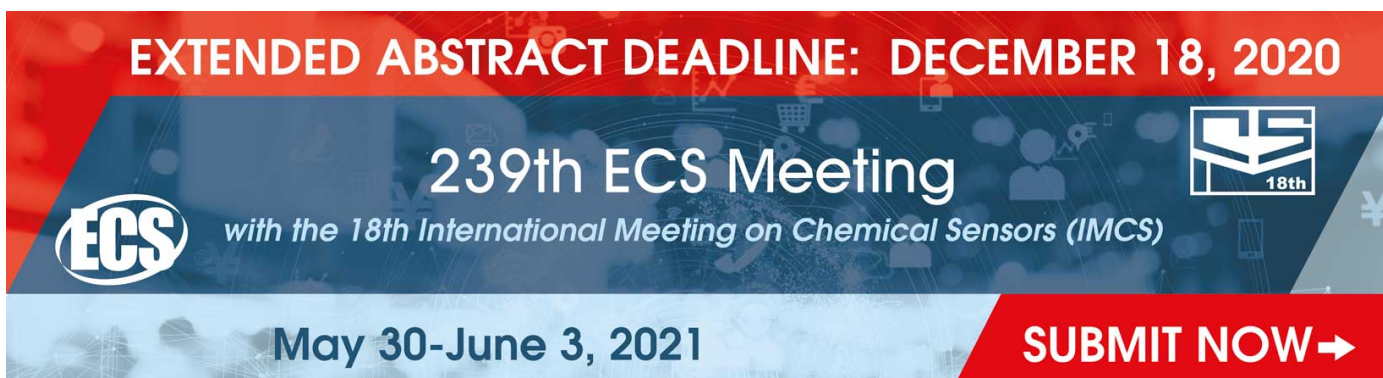Radiophysics for oceanology View project

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Ultrasonic multipath monitoring of turbulent gas flows: pulse signals correlation processing

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Abstract. The article proposes digital phase modulation and correlation processing of pulsed ultrasonic signals for the turbulent gas flows monitoring. Estimates of errors in measuring the relative time delay of ultrasonic pulses during multipath propagation and their interference in the receiver were made. The data obtained from the experiment show that the relative pulse delay measured in a turbulent gas flow has a resolution exceeding tenths of the carrier frequency period. As an example the possibilities of turbulence's quantitative control the air flow boundaries of a fan are shown. The perspectives to use the developed software and hardware in flow meters and other ultrasonic control and measuring devices are discussed.

1. Introduction

Ultrasonic (US) control methods are widely used in power engineering, in particular for flow measurement [1-4]. To improve the liquid and gas flows velocity measurement's accuracy, multipath ultrasonic measurement schemes are most often used [5-6]. A gas flows feature is a high level of turbulence, which leads to increased variability of the ultrasonic signals delay [7-11]. In these conditions, it is necessary to develop methods of digital shaping and processing of US signals to increase the resolution of the measuring equipment [12-14]. In this work, to control gas flows with a high turbulence, software and hardware based on digital phase modulation and correlation processing of ultrasonic signals are proposed.

2. Materials and methods

At multipath propagation, ultrasonic signals in the receiver are shaped as a result of the interference of pulses that arrive to the receiver along different paths. For two-rays control, as a particular case of multipath control, in the cross-correlation function (CCF) of the dual and reference signals two peaks appear, the time position difference of which corresponds to the pulses relative delay. To increase the resolution of the relative position of signals digital phase coding can be used according to the Barker sequence [15-17], which, in comparison with unmodulated signals use, increases the time resolution of US devices several times (figure 1).

　　Measurement of small relative delays ΔT_D between signals in the receiver (figure 2, *b*) in the work is proposed for the analysis of the CCF's power W asymmetry [12], i.e. by its weighted average time position (indicated by a vertical dashed line in figure 2).
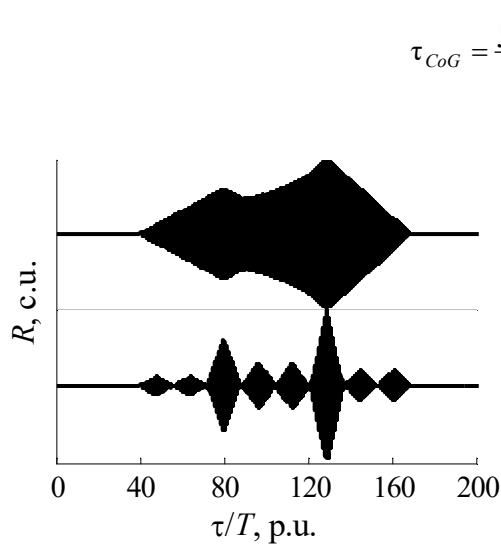
$$\tau_{CoG} = \frac{\int \tau W(\tau)\, d\tau}{\int W(\tau)\, d\tau}.$$

(1)

Figure 1. Comparison of the CCF of the dual and reference signals without modulation and using phase-modulation according to a Barker code.
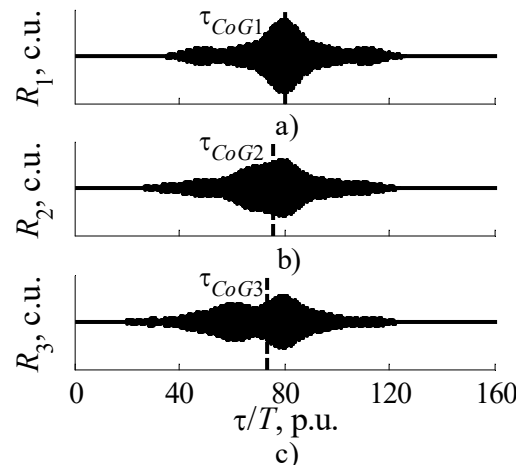

Figure 2. The changing of CCF's shape with relative pulse delay changing (T is an acoustic wave period).

At the same time, the symmetric CCF is assumed at a zero value of delay (figure 2, *a*). $\Delta T_D(\tau_{CoG})$ dependence changes linearly with the superposition of significant quasi-regular oscillations [12]. Such oscillations are smoothed out in real experimental measurements with long-term averaging due to phase fluctuations of the signals. The proposed approach does not impose any restrictions on the lower bound of the resolution of pulses relative time position. The theoretical resolution is about 15 ns at 40 kHz ultrasound carrier frequency and 1 ms pulse duration.

FPGA-based functional blocks of a pulsed ultrasonic device [12] are enclosed in a receiver–transmitter device (RTD) (figure 3). The shape of the pulse packet can be adjusted in the device (ordinary or phase-modulated according to a Barker code [15]). Ultrasonic transducers (UST) have a relatively wide radiation pattern (about 60°). In the general case, the signal at the receiver input is a superposition of two signals: direct and reflected. According to the radiation patterns, the radiation power of the side rays differs from the power of the direct ray by about 5 dB. To increase the system sensitivity to the signal reflected from the flow the USTs were turned about 45° in the experiment (figure 3). For the laboratory experiment, an industrial fan with a power of 170 W, an orifice diameter of 0.15 m, a rated velocity of 2430 rpm and an output of 1200 m³/h was used. Using the digital phototachometer (P) the fan velocity was calibrated. It provides contactless measurement with a resolution of 0.1 rpm and 1.0 rpm in the range of less than 1000 rpm and more than 1000 rpm, respectively.

By measurement of the spatial and temporal flow velocity changes using an X-Line AeroTemp anemometer (A) the structure of the air flow was experimentally controlled. Velocity values were monitored for 20 s with a periodicity of 0.25 s at different points of the flow: in 11 points along the flow and in 5 points across the flow. The fan velocity was varied with a controller (C) (figure 3).

The invariant embedding method for the theoretical estimates was used to solve the problem of acoustic wave scattering from a randomly inhomogeneous layer of the medium. This method allows to transform problem with boundary conditions into problem with initial conditions [18]. The process is described by a first order nonlinear differential equation. Its solution is the reflection coefficient of a harmonic wave with ω frequency [19]:
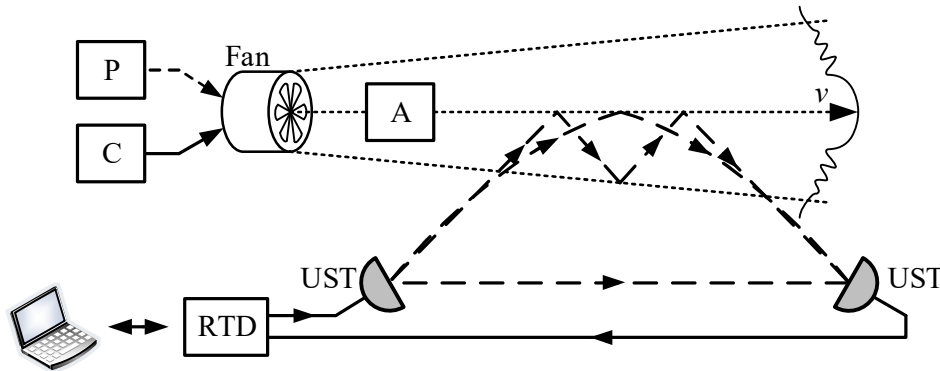
Figure 3. Functional scheme of the experiment.

$$\frac{dR_L}{dL} = 2ikR_L + i\frac{k}{2}\varepsilon(L)(1 + R_L)^2, \tag{2}$$

where $k = \omega/c$ – acoustic wave number in a homogeneous medium; c – sound speed; $\varepsilon(L)$ – random layer inhomogeneity function; L – layer thickness (integration parameter). The frequency response $R_L(\omega)$ of the reflection coefficient can be obtained by solving (2) for different frequencies. The shape of the reflected pulse finally can be get by $R_L(\omega)$ inverse Fourier transform.

3. Results

Based on model calculations figure 4 shows an example of the layer inhomogeneity function expressed in terms of the sound speed. It consists of two components: random and regular $\varepsilon(x) = \varepsilon_0(x) + \widetilde{\varepsilon}(x)$. The random component was specified as a function with a Gauss distribution and variance corresponding to the characteristic in homogeneities of the medium. The value of random inhomogeneity is comparable to the acoustic wavelength. Figure 5 shows as the example pulse waveform of an ultrasonic resonant transducer and form of distorted pulse after reflection.
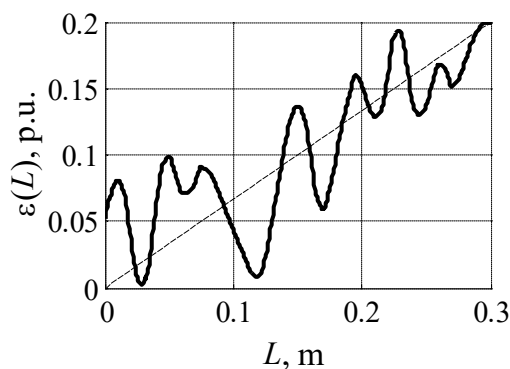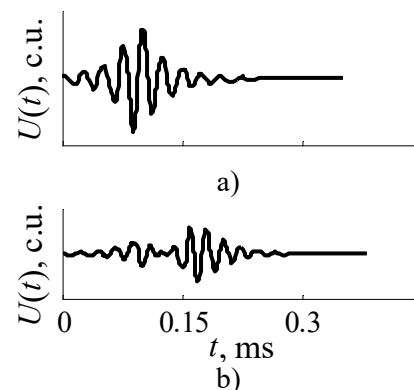

Figure 4. Sound speed profile.

Figure 5. Input and output pulses.

According to the simulation results, we can say that an increase in the amplitude of the random component $\widetilde{\varepsilon}(x)$ changes not only the amplitude and phase of the reflected signal, but also its duration. As a whole this affects the time delay of the signal.

A comparison of modeling results of the measured delay's error using the proposed algorithm based on estimating CCF's asymmetry and the trigger method with a cutoff level of 0.5 is carried out. From the histograms of the delay's statistical distributions plotted by 1000 pulses (figure 6, *a*), the

dependences of the average, standard deviation and asymmetry on the noise level σ_N in the range $1 - 9\%$ of pulses amplitude were obtained (at $\sigma_N > 10\%$ when measured by the trigger method, abnormal spikes appear in the delay histogram) (figure 6, *b*).

When calculating the delay based on the weighted average position of the CCF, statistical distribution's width (by about an order of magnitude) and asymmetry decrease. So in comparison with the traditional measurement method, the proposed algorithm makes it possible to reduce random and regular errors, thereby increasing the time resolution of pulsed ultrasonic devices.
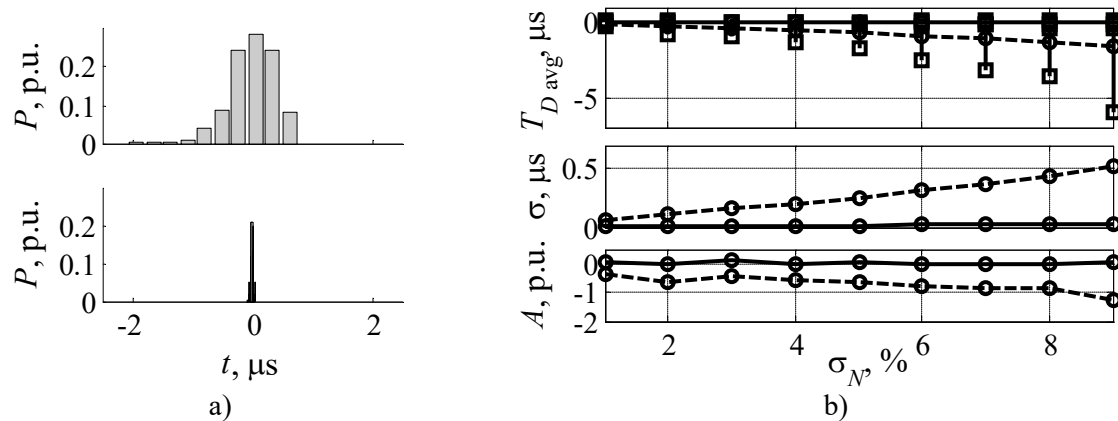

Figure 6. Analysis of statistical error
a) histograms of the delay distribution by triggering (top) and by the weighted average position of the CCF's power (bottom) with noise variance $\sigma_N = 7\%$;
b) characteristics of distributions depending on σ_N (average $T_{D\,avg}$, standard deviation σ and asymmetry A) when measuring the delay by triggering (dashed line) and by integral estimate of the CCF's shape (solid line).

Figure 7 shows the distribution of the flow velocity's fluctuations Δv (the degree of turbulence in the nominal fan operation) relative to its average value v_{avg}

$$e = \left(\frac{|\Delta v|}{v_{avg}} \right) \cdot 100\% . \tag{3}$$

As can be seen from the figure, at the edges of the flow, the degree of turbulence reaches 10-15 %.

The US pulses relative delay was measured at different values of the flow velocity by processing and averaging two hundred pulses. The averaging time can vary depending on the measurement conditions and the required accuracy. Figure 8 shows the dependence of the CCF's weighted average time position on the fan velocity. Thus, with flow velocity growth the relative time delay between the direct and the reflected from the flow signals monotonically increases. According to the results of experimental studies, the most important is the fact that when the transmitter and the receiver positions are swapped corresponding dependences of the delay on the flow velocity differ very little. In other words, the delay increases with the propagation of ultrasound both along and against the flow.
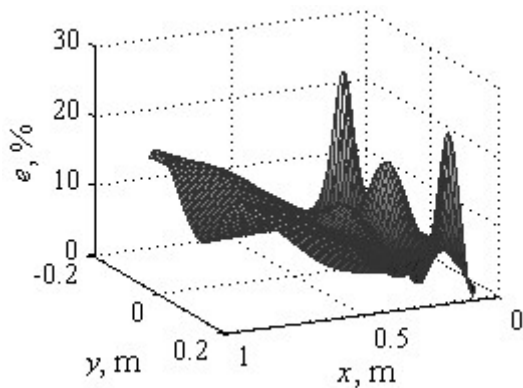
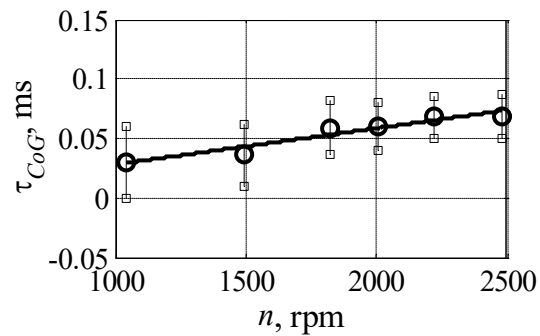**Figure 7.** Distribution of relative fluctuations of flow velocity.

Figure 8. Experimental dependence τ_{CoG} on the fan velocity. Circles – average value, vertical lines – value of standard deviation.

4. Discussion

Under re-reflections of the acoustic wave between random inhomogeneities of the layer the additional temporal delay according to the experimental results is appeared . The wave is "captured" by random stratification and propagates in a randomly inhomogeneous layer like in waveguide. This phenomenon is called the "localization effect" [19]. At a flow velocity of about 5 m/s on the fan's longitudinal axis the relative time delay between the direct and the reflected signals differs about 3-5 μs for forward (downstream) and backward (upstream) ultrasonic wave propagation. With flow velocity's increase the change range of the delay is about 25-30 μs. (figure 8). When calculating refraction using ray approximation, the delay is about few microseconds. In other words, the ultrasonic wave's propagation in a flow is associated not only with refraction, but also with the scattering, the occurrence of effects typical of waveguide propagation and localization effects when reflected from turbulent inhomogeneities [20]. Thus, experimental measurements based on the correlation processing of phase-modulated signals allow, due to the high temporal resolution in multipath propagation of ultrasound, to evaluate the mechanisms of acoustic wave scattering in a turbulent air flow. Besides the ray approximation the small-angle approximation (parabolic equation) can't be used too at modeling due to the scattering angles of ultrasound are at least 15-20 degrees according to the theoretical estimates and experimental results.

5. Conclusion

The measurement scheme presented in the article is an example of using the proposed technique for the digital forming and processing of acoustic signals. The technique makes it possible to quantify the parameters of the turbulent layer at the gas flow boundary. The approach can be applied even in the classical scheme of an ultrasonic flow meter based on measuring the relative delay of pulses that have passed along and against the flow direction. Similar signal processing can be used to increase resolution for a wide range of pulsed ultrasonic control and measuring equipment.

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