We represent results of experiments on sounding of turbulent water stream inside a pipe by the method of interferometry. Technique of signal reception and conversation, used at radio interferometry, distinguishes fluctuating phase difference, originated by turbulent medium at different paths. Spectral analysis of interferometer signal allowed to perform the diagnostics of propagation media. Particularly, it was demonstrated, that interferometer power spectrum carries information about spatial spectrum of medium parameters fluctuations and velocity of irregularities movement.

This work devoted to experimental research of turbulent water by the method of sounding, which is used for remote investigation of hydrodynamic jets, the earth's atmosphere and other natural media. Conventional probing method, that consists in passage of reference signal through medium and analysis of disturbances, caused by propagation medium heterogeneities, is added by the method of interferometry. Under interferometric reception sounding signal, passed through disturbed media, is received in several spatially separated points. Technique of signal reception and conversation, used in interferometry [1-3], allows to distinguish fluctuating phase difference, originated by turbulent medium at different paths. The analysis of interferometer's response lets us to get information about propagation media. Having an aim to adjust procedure of this method and to use it in natural media, a special system was developed and several series of experiments on perturbed water media probing were carried out at Nizhnij Novgorod State University [3]. This work demonstrated results of past experiments.

Figure 1 shows the scheme of the system. The pool with sizes 4.7 × 3.8 × 5 m is filled by water. Water pump produces turbulent stream in the pipe with square section (5 × 5 cm) made from sound-transmitting material. Ultrasonic signal with frequency \( f_0 = 235 \text{ kHz} \) was propagated along axis \( Z \) perpendicular to the stream from transmitter to two interferometer receivers. The baseline of interferometer \( b \) (distance between detectors) was directed in the line of pipe; it changed its size from 10 cm till 45 cm. Velocity of the water rejection from the nozzle \( V \), air bubbles density and sonic speed were fitted by selection of nozzle and changing of stream pressure. The first measurement cycle examines the fluctuations of cavity bubbles density inside the pipe, generated by the cavity nozzle. The second cycle studies the fluctuations produced by installed propeller, which added disturbances and garble the character of medium irregularities distribution. The passive propeller was put inside pipe across the stream.

The water pump nozzle, transmitter and detectors were situated in the same plane at 50 cm depth from the water surface. The transmitter, made from several plane rectangular disks, generated the plane ultrasonic wave. The sound detector with sizes 7×55 mm were placed vertically. Such construction and orientation of receivers allowed to decrease the influence of reverberation interference from water surface. The probing is realized in pulse mode with frequency of sampling 60 Hz and impulse duration 500 \( \mu \text{s} \).

The signals, pasted through the medium by different paths and received in interferometer points, were multiplied. The result of this multiplication was put into computer memory by means analog-digital converter and it proved to be discrete sample. This procedure is common for interferometer receiving and it has some advantages in comparison with traditional one point receiving as it allows to investigate the field fluctuations caused by turbulent medium.
only on two different propagation paths. In this case the influence of source self-radiation is excluded and it allows us to sound the medium not only by monochromatic but also wideband source signal. Fourier-analysis of the signal sample with preliminary subtraction of simple average value was used. Field power spectrum of output signal is main result of signal processing.

Observed data were compared with the results of early theoretical analysis [1,2]. Calculations were made in the approximation of geometrical optics. Supposed, that temporary variations medium parameters fulfill conditions of freezing-in hypothesis – heterogeneities are not changed with time and moved with velocity of stream. Spatial spectrum of the cavity bubbles density was given by power law with index $p/2$ in certain interval of wave numbers $[\kappa_0, \kappa_m]$ ($\kappa_0=2\pi/L$, $\kappa_m=2\pi l_0$; $L$, $l_0$ – outer and inner scales of irregularities respectively):

$$F \sim \left(\frac{\kappa_0^2 + \kappa^2}{2}\right)^{-\frac{p}{2}}$$

(1)

Our calculations demonstrated that measurements proved to be more informative at weak phase perturbation. At weak phase fluctuations interferometer power spectrum must be drop-down power law function. When stream velocity is directed along baseline, dependence spectrum from frequency $\Omega$, baseline $b$ and stream velocity $V$ with accuracy of a constant factor at frequency interval $V\kappa_0 << \Omega << V\kappa_m$ is described approximately by the expression [2]:

$$Y(\Omega) = \frac{1}{V} \left(1 - \cos \left(\frac{\Omega b}{V}\right)\right) \left(\frac{\Omega}{V}\right)^2 + \kappa_0^2 \approx \left(\frac{1}{2}\right)^{p+1}$$

(2)

On the basis of (2) there must be oscillations on spectrum wings determined by factor $[1 - \cos(\Omega b/V)]$. They depend only on relation of stream velocity and interferometer baseline. It means, when $b$ is known the location of minimum on the frequency axes makes it possible to determine velocity stream along the propagation paths.

Spectrum envelope in the frequency region $\Omega >> V\pi/b$ may be described by [2]:

$$Y(\Omega) \approx \Theta^{-p+1}.$$  

(3)

According the slope of spectrum it’s possible to calculate $p$ – index of spatial spectrum of fluctuations of cavitation bubbles concentration.

The case of weak phase fluctuations was examine experimentally at probing of water stream in the pipe by noise and monochromatic ultrasonic emission. Density of cavity bubbles in the medium produced, so as phase difference, accumulating at different paths, did not exceed $10^6$. This circumstance was checked by phase detectors. It was presumed, average stream velocity $V$ is constant along the whole length of pipe.

Power spectrum of interferometer signal in linear scale and in logarithmic scale are displayed at figures 2 and 3 correspondingly. Frequency resolution is $df=0.45$ Hz. The measurements were performed by interferometer with baseline $b=35$ cm. Experimental spectrum is marked by thick line. The spectrum, obtained in result of computational modeling, is marked by thin line. In course of calculation the parameters of stream (velocity $V$, outer scale of turbulence $L$, spectral index of spatial spectrum $p$) were selected so as experimental curve was agreed with theoretical. It was found, the outer turbulence scale $L$ possessed the high values ($L \sim 100$ cm), which exceed the pipe sizes and doesn’t correspond to processes with developed turbulence. So, more accurate definition of model was made, as a result the spectrum didn’t change its form. Certain effective scale $L_{ef}=V/\omega_0$ was brought and it works as outer scale. This value is determined by effective frequency of pulses, which generated by water pump nozzle and transferred by stream; effective scale depends on the cavity nozzle characteristics.

Oscillations are clearly seen on experimental spectral “wings”, its’ periodicity is determined by relative stream velocity to interferometer baseline and corresponds to the accepted model. Nevertheless,
values of experimental spectrum in its’ minimums don’t equal to zero. It is may be explained by the fact that velocity fluctuations were essential and leaded to the smoothing of minimums and to the disappearance of zero values. The stream velocity, measured by the location of local maximums spectrum at frequency axis equals to \( V=0.9 \text{ m/s} \pm 0.07 \text{ m/s} \). According to the slope of the spectrum the index of spatial spectrum of cavity bubbles density fluctuations takes on a value \( p=3.5 \).

In results of 12 measurements at interferometer with baselines \( b=15 \text{ cm}, 20 \text{ cm}, 25 \text{ cm} \) the next parameters were evaluated: the average stream velocity \( V=0.90 \text{ m/s} \pm 0.08 \text{ m/s} \) and spectral index \( p=2.9 \pm 0.2 \).

The passive propeller was fixed in the pipe for investigation of turbulence processes in the stream at alteration of influence nature (fig.1). Construction of system allows to change the distance between nozzle and sounding path (by simultaneous displacement of transmitter and interferometer along axis X), that allowed to study turbulent medium in different conditions. Figure 4, 5, 6 demonstrate the samples of spectrums, obtained at the position \( x_1, x_2, x_3 \) of sounding lines correspondingly (see fig.1).

The measurement showed, when sounding paths passes between nozzle and propeller (position \( x_1 \) at fig.1), the form of power spectrums coincide with results of previous experiments. Spectral index takes on a value \( p=2.7 \pm 0.4 \), the stream velocity equals to \( V=0.90 \text{ m/s} \pm 0.05 \text{ m/s} \) (fig.4).

When the stream in pipe is sounded at the flow segment after propeller (position \( x_2 \)), the character of turbulence is strong changing: the spectrums is more sloping (spectral index \( p=1.7 \pm 0.1 \)). The stream velocity is constant along the whole length of pipe \( V=0.90 \text{ m/s} \pm 0.05 \text{ m/s} \) (fig.5).

When line of probing goes on some distance from pipe (position \( x_3 \)) and stream is propagated in outer space of pool, data of experiment are in concordance with results of experiment on sounding of free-stream [3]. The spectral index takes a value \( p=3.1 \pm 0.1 \). The stream velocity is diminished at increasing the distance from the pipe and it equals to \( V=0.40 \text{ m/s} \pm 0.02 \text{ m/s} \) in position \( x_3 \). In this case the effective scale is decreased ten times, that may be evidence of completely developed turbulent process.

Thus the results of performed interferometer experiments on raying of the water turbulent medium by ultrasonic emission are in a good agreement with conclusions of theoretical analysis. We demonstrated the possibility of experimental measurement of index of spatial spectrum of cavity bubbles density fluctuations. The method of non-contact estimation of stream velocity in the pipe was proposed and approved.

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REFERENCES