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Ultrasonic Measurements of Two-Phase Flow

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Abstract—The paper presents development of a complex method of ultrasonic measurement of two-phase flows. The method enables measurement of the dynamic and structural characteristics of ascending inhomogeneity. A software and hardware complex for realization of the proposed method has been developed and implemented and tested in water. Results of experimental studies show that the software and hardware complex enables detection of rising gas bubbles in a liquid medium, monitoring of their dynamics, and localization of them in a volume of 5 to 50 cm^3

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INTRODUCTION

The use of modern non-contact precision diagnostics tools significantly increases the efficiency and safety of technological processes in the energy sector and industry [1–4]. Modern technologies for studying the structural and dynamic parameters of three-dimensional multiphase optically nontransparent flows are very complex and insufficiently developed for industrial use. This is associated with the necessity of solving a set of complex multidisciplinary scientific and technical problems.

Various methods can be applied for non-contact measurement of structural and dynamic parameters of nontransparent multiphase media [6–10]. The potentiometric method is based on measuring the conductivity of "pipeline-heat carrier" system [11]. It has a low sensitivity (5–10% of the volumetric void fraction) and yields information only about the integral void fraction in the measured section.

The eddy current method [11] imposes structure requirements that cannot be met in all cases. The pipeline location should ensure passage of gas bubbles directly under the coils, and thus the pipeline must be horizontal or inclined. In addition, in this method, sensors have a very limited operating life and detect gas bubbles mainly in the volume of the heat carrier adjacent to the area where the coils are located.

X-ray methods [12] have a relatively low frequency of data collection, and thus the system cannot operate in real time. In addition, these meters are difficult to implement and very expensive.

Methods to reveal presence of gas by pulsations of the EMF value between electrodes [11] do not allow detecting small gas bubbles and cannot work with a large number of bubbles.

Ultrasonic methods are the most promising for non-contact measurement of structural and dynamic parameters of nontransparent multiphase media [13, 14]. A multifaceted configuration and complex data processing algorithms based on synchronous detection and correlation and time-frequency analysis allow creating a tool for three-dimensional measurement of geometrical parameters and velocity field of two-phase flows.

The aim of this work is to develop a method for ultrasonic measurement of two-phase flows. To achieve this goal, it is necessary to solve the following tasks.

1. Develop a method for measurement of dynamic and structural characteristics of liquid-gas medium.

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2. Perform a series of laboratory experiments for measurement of dynamic and structural characteristics of liquid-gas medium.

A huge number of different methods for ultrasonic diagnostics have been developed by now for a wide range of problems: from non-destructive testing of solid products to multiphase flow metering. In the context of the problem posed, these methods can be divided into two essentially different groups: integral diagnostics of medium and localization of phase inhomogeneities in a medium and their spatial diagnostics.

The methods of the first group underlie the operation of ultrasonic flow meters in [3, 4] (phase, frequency, pulse-time, Doppler, etc.), which solve related problems, performing integral diagnostics of different phases in motion, but cannot cope with the task of spatial local diagnostics of multiphase medium. Although such methods do not provide knowledge about local parameters of flow, they provide important experimental information for quantitative assessment of the motion of substance in the measurement volume.

The shadow (or amplitude-shadow) method is based on recording of decrease in the amplitude of transmitted wave (through signal) under the influence of phase inhomogeneity [15]. In the absence of phase inhomogeneities in the measurement volume, ultrasound is transmitted without losses between the source and the receiver. Part of the ultrasonic wave generated by the source is screened from the receiver by a gas bubble. As a result, a decrease in the amplitude of the received signal is observed, by which one can judge the presence and size of gas bubble in the measurement volume.

This method enables detection of phase inhomogeneity, as well as estimation of its position and size in the measurement volume at a certain moment in time. The method is practically inapplicable to inhomogeneity of extremely small volume, is very sensitive to the position of the receiver and transmitter, and does not allow one to accurately determine the velocity and position of inhomogeneity in the medium. The amplitude-shadow method has a number of modifications, and there are some diagnostic methods having similar operational principles: mirror-shadow, echo-shadow, and many others.

The time-of-flight method (echo method). In this method, the measurement volume is scanned with short pulses and the echo signals reflected from inhomogeneities are received. Based on the time of detection of echo signal and its shape, one can calculate the position and size of inhomogeneity [16]. A transducer probe emits short pulses of ultrasonic waves. The ultrasonic waves are reflected from a rising bubble and the back wall of the vessel and return back to the transducer probe, which operates in the receiver mode. As a result, a characteristic echogram is recorded. Detecting on the echogram the position at which the echo signal from the bubble reaches its maximum, one can measure the propagation time t_B during which the ultrasound reaches the bubble and returns back to the transducer probe. From the information about the time t_B, the position of the bubble X_B is calculated as follows:

$$X_B = c \cdot t_B/2, \tag{1}$$

where c is the ultrasound velocity in the liquid, which can be calculated using the time T_{BW1} of the signal propagation from the transducer to the back wall of the vessel and back. From the dependence $X_B(t)$, one can calculate the trajectory and velocity of the ascending bubble. This requires using several sensors installed in a certain way in a row in combination with non-trivial algorithms for signal interpretation. Furthermore, analyzing the echo signal from the rising bubble and using transducers installed opposite each other at the same height, one can obtain the dimensions of the bubble [17].

This method is extremely difficult to implement and requires time-consuming calibration and adjustment. It is not advisable to use this method for measuring the bubble velocity since many sensors are required and the hardware of the system will become much more complicated. As in the case of the amplitude-shadow method, the echo method allows different configurations of geometric arrangement of transducers.

The Doppler method is based on the effect of frequency shift of ultrasonic signal scattered on phase inhomogeneities relative to the reference frequency value. The difference $f_1 - f_2$ depends on the velocity V of the scattering particle (or inhomogeneity) and the speed of sound c in the medium. The following dependence holds:

$$f_1 - f_2 = 2 \cdot f_1 \cdot V \cdot \cos(\alpha)/c, \tag{2}$$

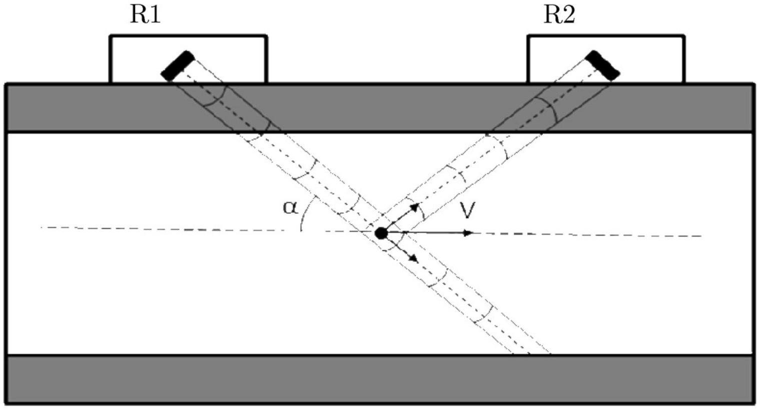


Fig. 1. Diagram of Doppler method.

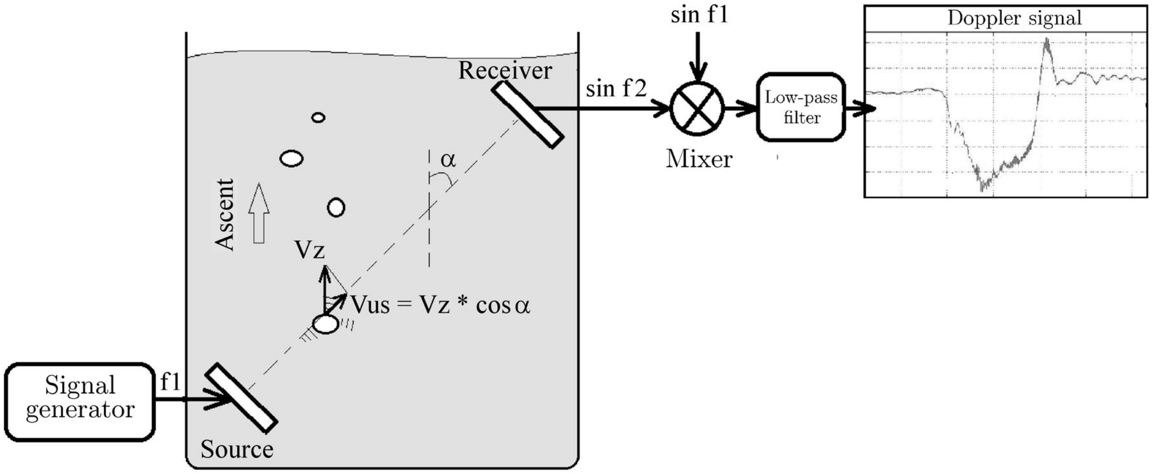


Fig. 2. Scheme of method proposed for ultrasonic diagnostics of medium.

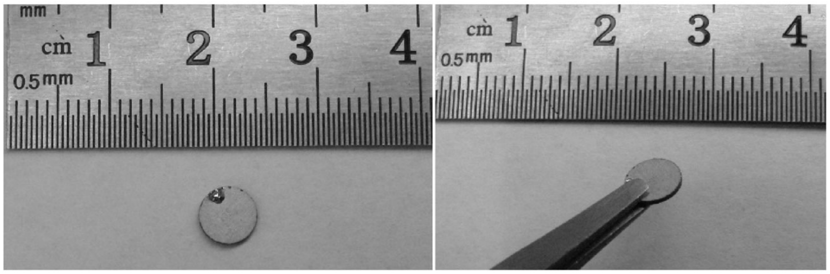
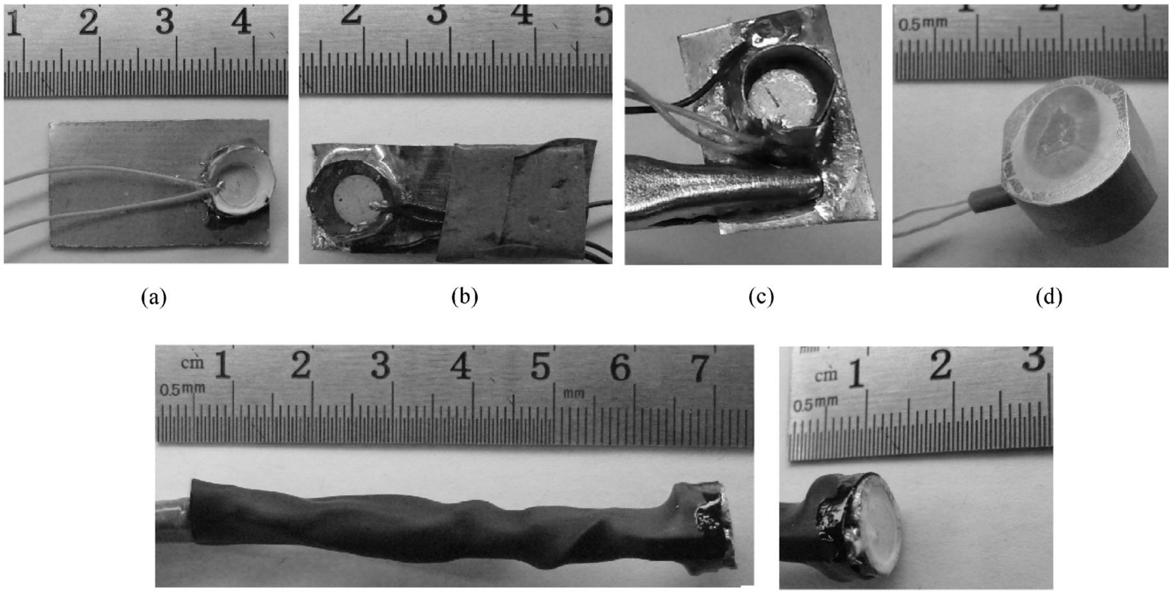


Fig. 3. Photo of piezoceramic transducers.

where f_1 and f_2 are the frequencies of the reference (generated by the source) and reflected (recorded by the receiver) acoustic wave, respectively; α is the angle between the direction of wave propagation and the vector of the scatterer velocity. The measured frequency difference can be used for determination of the velocity of phase inhomogeneity, in particular, a rising gas bubble [18]. Figure 1 shows the diagram of the method. P1 denotes the source transducer, and P2 stands for the receiver transducer.

Because the ultrasound wave is scattered in all directions from the scatterer, the Doppler method can be implemented in many ways with different positions of the receiver and source. Thus, different components of the scatterer velocity can be determined.



(a) (b) (c) (d)

(e) (f)

Fig. 4. Photos of ultrasonic sensors developed.

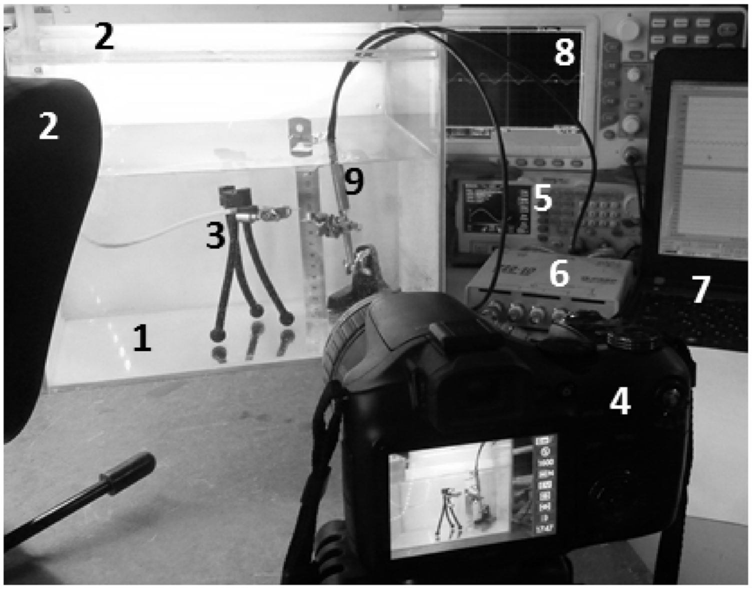


Fig. 5. Photo of experimental stand with software and hardware complex. 1-aquarium with water, 2—illuminators, 3—air supply system, 4—video camera, 5—generator, 6—ADC, 7—PC, 8—oscilloscope, 9—measuring part (source-receiver).

The Doppler method is the most efficient in measurement of the velocity of inhomogeneity in a medium; however, it is difficult to apply this method to localization of inhomogeneity and determination of its dimensions [14].

The method of ultrasonic diagnostics of two-phase flows. The developed ultrasonic diagnostics method is based on the amplitude-shadow, time-of-flight, and Doppler methods. The scheme of the method is shown in Fig. 2. The method is very flexible in its application. It does not regulate strictly the mutual position of the receiver and the source, i.e., different mutual arrangements of the source and receiver enable measurement of different parameters of inhomogeneity in the medium.

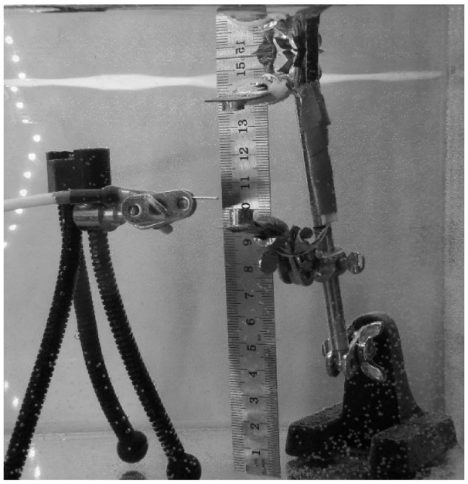


Fig. 6. Photo of experimental stand measurement area.

Fig. 7. Photo of rising bubble.

The generator sends a sinusoidal signal with the frequency f_1 to the piezoelectric element (source), which creates a sound wave with a frequency equal to the frequency of the sent electrical signal and to the resonant frequency of the piezoelectric crystal. The acoustic wave is emitted into the medium at the angle α, after which it is scattered by phase inhomogeneities occurring in the flow. In this case, a phase inhomogeneity means an air bubble, floating up in the measurement volume with a certain velocity V_z.

The scattered sound wave hits the receiving piezoelectric element and is converted back into a sinusoidal electrical signal with the frequency $f_2 = f_1 + \varepsilon$, where ε is the reference frequency shift caused by the Doppler effect due to the scattering on the moving phase inhomogeneities.

It should be noted that the frequency shift is affected only by the projection of the bubble velocity on the direction of propagation of the sound wave.

$$f_1 - f_2 = 2f_1 \frac{V_{us}}{c}, \tag{3}$$

where

$$V_{us} = V_z \cos(\alpha). \tag{4}$$

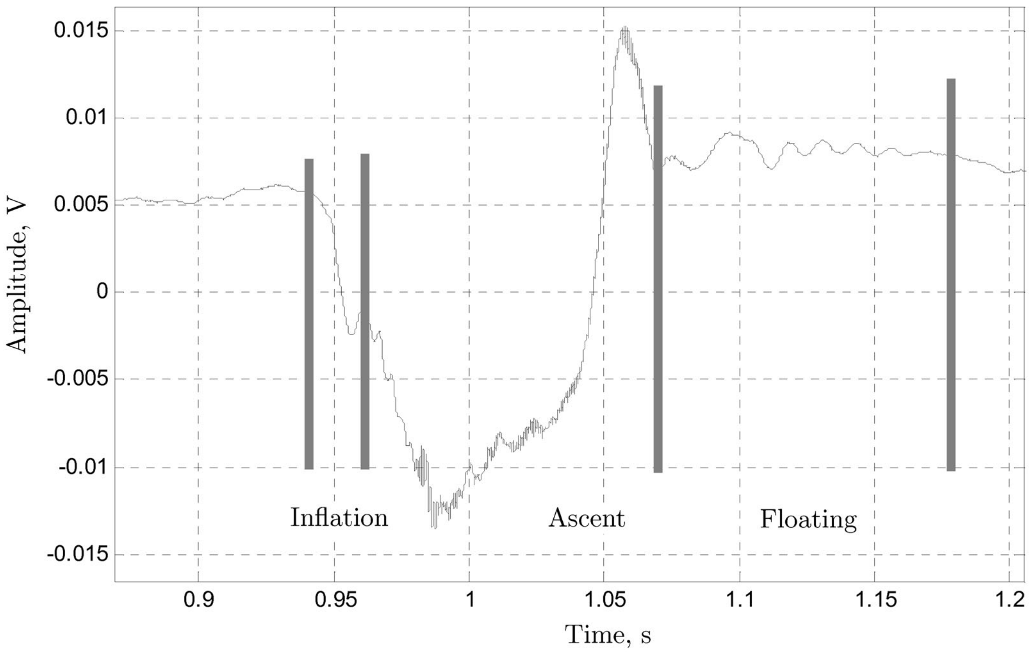


Fig. 8. Doppler signal.

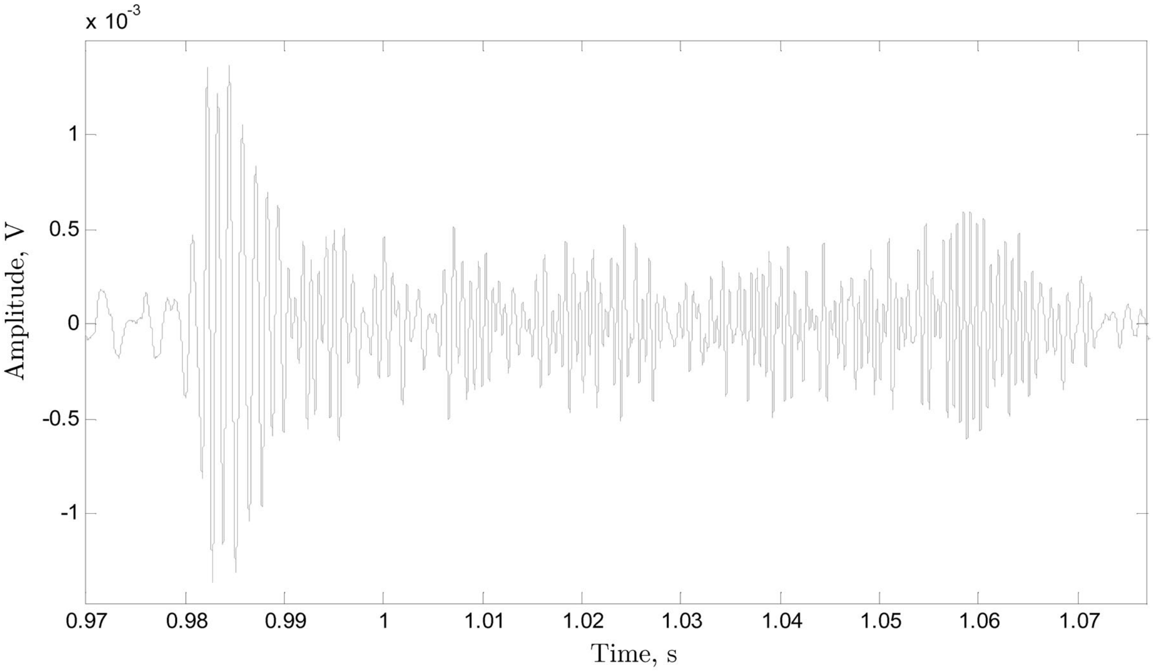


Fig. 9. Doppler signal without low frequency component.

This yields the projection of the velocity on the selected direction.

Next, the quadrature mixing operation is performed, i.e., multiplication of the recorded signal, containing the Doppler frequency shift, by the reference signal with the frequency f_1 and the orthogonal signal of the same frequency (shifted by $\pi/2$ relative to the reference one).

$$A\sin(f_1)\cdot B\sin(f_1+\varepsilon)=\frac{A\cdot B}{2}(\cos(f_1+\varepsilon-f_1)-\cos(f_1+\varepsilon+f_1))$$

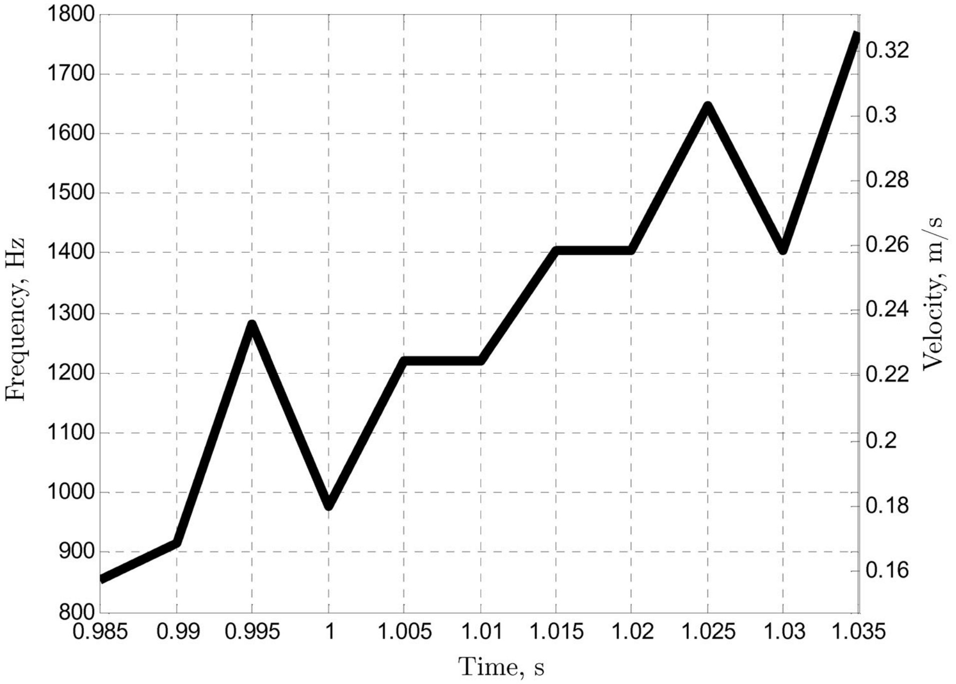


Fig. 10. Doppler frequency and velocity of floating up vs. time.

$$= \frac{A \cdot B}{2}(\cos(\varepsilon) - \cos(2f_1 + \varepsilon)), \tag{5}$$

$$A\cos(f_1) \cdot B\sin(f_1 + \varepsilon) = \frac{A \cdot B}{2}(\sin(f_1 + \varepsilon - f_1) - \sin(f_1 + \varepsilon + f_1))$$

$$= \frac{A \cdot B}{2}(\sin(\varepsilon) - \sin(2f_1 + \varepsilon), \tag{6}$$

where A is the amplitude of the reference signal, and B is the amplitude of the received signal after its scattering on the air bubble. The B value depends on the number and size of scatterers (bubbles) in the flow and will be used in implementation of the amplitude-shadow method.

This mixing operation allows obtaining the low-frequency signal that carries information about the Doppler frequency shift. Indeed, from the above trigonometric formulas, the multiplication results in a two-component signal, composed of a high-frequency $(2f_1 + \varepsilon)$ sinusoid and a low-frequency sinusoid ε. By applying a low-pass filter and thus weakening the high-frequency signal, one can isolate the low-frequency Doppler signal of interest. Further processing of this signal using the sliding Fourier transform yields the dependence of the Doppler frequency shift on time and, accordingly, the dependence of the bubble velocity on time:

$$V_{us}(t) = c \cdot (f_1 - f_2)/2f_1 = c \cdot \varepsilon(t)/2f_1. \tag{7}$$

Thus, the described method allows monitoring of the dynamics of the bubble ascent and breaking the ascent into stages. Using the amplitude-shadow method, one can estimate the bubble size and position.

DEVELOPMENT OF SENSORS BASED ON PIEZOELECTRIC TRANSDUCERS

The source and receiver of ultrasonic waves are the main working elements in the ultrasound diagnostics method. A number of sensors based on piezoceramic disk transducers (Fig. 3) made from barium titanate, of ≈ 6 mm in diameter and ≈ 0.6 mm thick, have been developed.

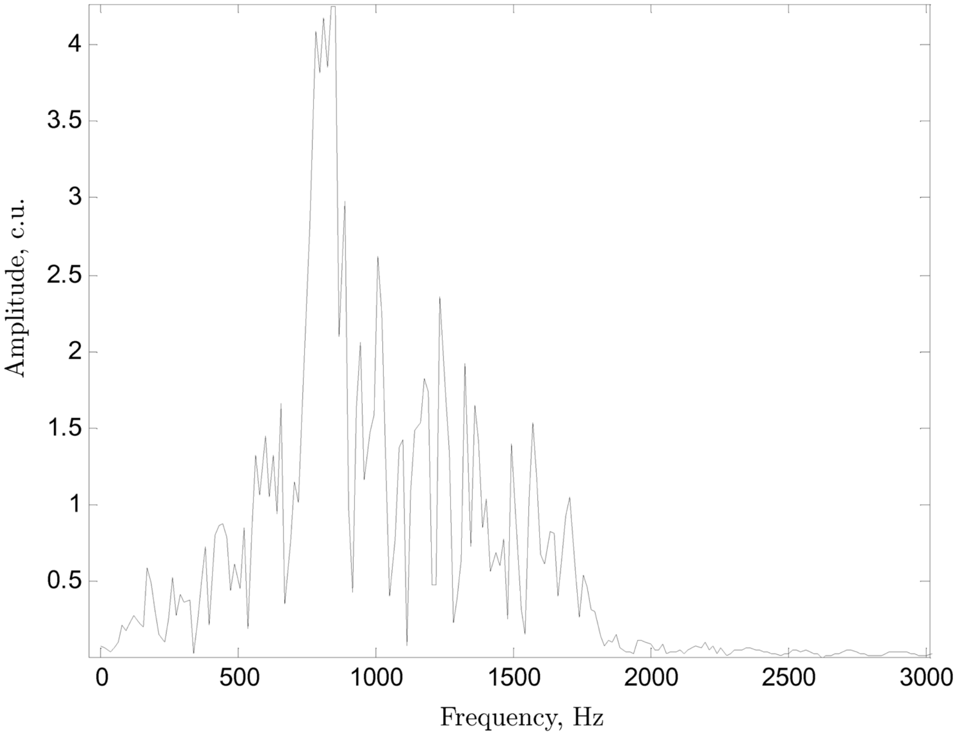


Fig. 11. Doppler signal spectrum.

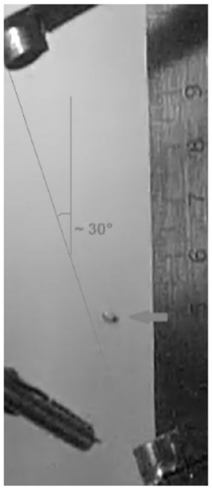


Fig. 12. Photo of ascending bubble.

During the development of the sensor, it was necessary to solve two main tasks: to ensure complete isolation of the sensor contacts since measurements are done in a conducting medium; to create a structure for shielding the sensor from electromagnetic waves, thereby excluding the influence of interference and other fields on measurements.

The first task was solved via multilayer varnishing of the transducer and contacts (Figs. 4a–4c). In one of its versions (Fig. 4d), the transducer in the sensor body was encapsulated with epoxy resin, but this approach negatively affected the amplitude of ultrasonic vibrations.

Several versions of copper body were created for shielding (Figs. 4a–4c). The body consists of two parts: the flat substrate and the cylindrical part, in which the piezoelectric element is fixed. As a damper

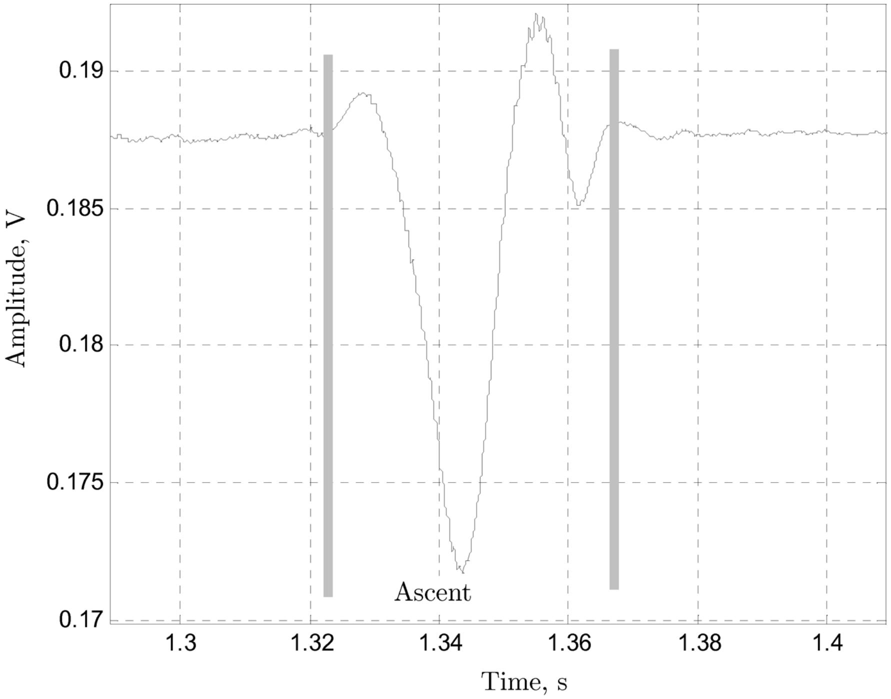


Fig. 13. Doppler signal.

between the substrate and the piezoelectric element, plasticine (Figs. 4b and 4c) and sealant (Fig. 4a) were used. The braid of the coaxial cable was soldered to the body, which ensured its grounding.

Special attention was paid to the development of the submersible sensor for experiments. Figure 4e shows the sensor. Its structure is similar to that of other sensors, except for the fixation and the presence of additional rubber insulation of the body.

The sensors were tested in various operating modes (continuous, pulsed, and mixed). The frequency response of the sensors was measured, and a resonance frequency of 4 MHz was determined. The direction of the radiation of the sensors was investigated experimentally, and the sensors were found to have an extremely small angle of divergence of the ultrasonic wave at a distance from 5 mm to 30 cm, i.e., they produced directional "narrow" radiation in the specified range of distances.

EXPERIMENTAL STAND

For experimental studies in water, a compact stand is required with the possibility of quick and convenient alignment of ultrasonic sensors, alternative control using optical methods, and variation of the configuration of the measurement part of the complex. The stand developed solves these tasks and includes the following elements: $30 \times 25 \times 20$ cm^3 glass aquarium filled with water; illuminators; high-speed (1200 frames per second) camera Casio EXILIM EX-F1; air supply system for creating small (0.01–0.05 cm^3) bubbles; oscilloscope Aktakom ADS-20131V (30 MHz bandwidth and sampling frequency of 250 MSa/s) for signal visualization and control of measurements.

Figure 5 shows a photo of the experimental stand with the software and hardware complex. The measurement zone is presented in Fig. 6.

The experimental stand together with the software and hardware complex enables conduction of measurements with any angle of transducer inclination α and any distance between the transducers in the range from 5 mm to 30 cm.

Below are given descriptions and results of experiments with various configurations of the measurement part of the complex: the vertical, inclined, and horizontal configurations, as well as the reverse configuration with reflection of ultrasonic waves from a bubble.

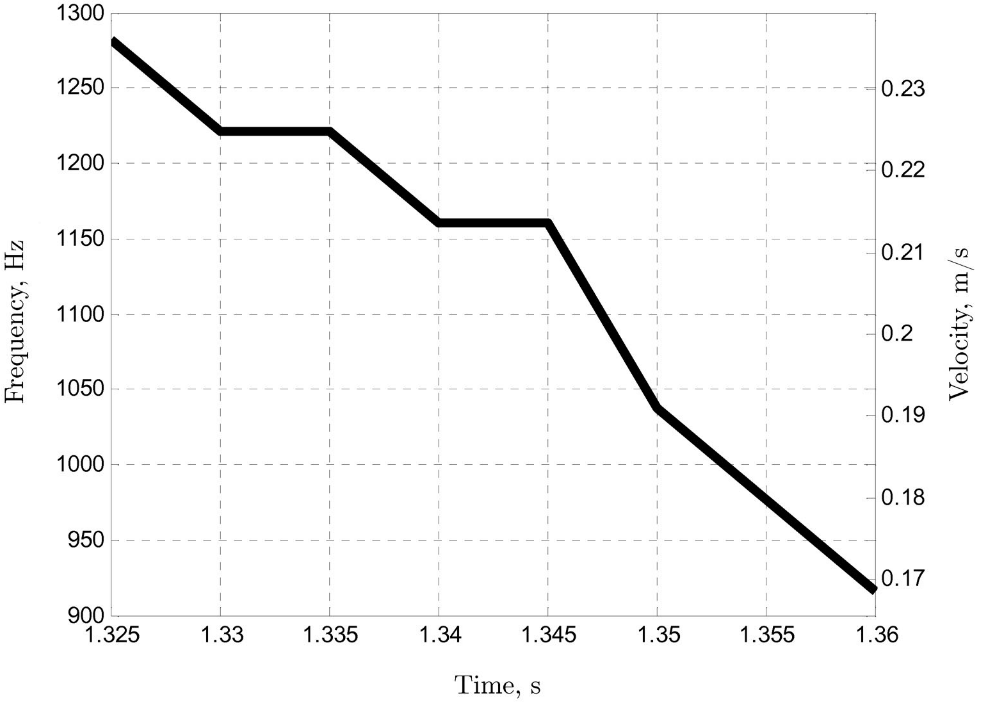


Fig. 14. Time dependence of Doppler frequency shift and velocity.

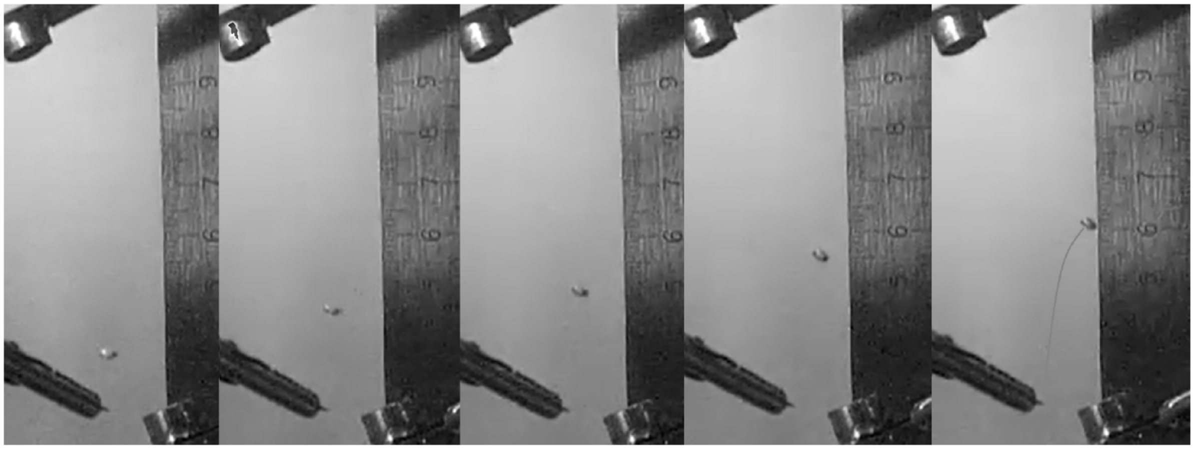


Fig. 15. Series of snapshots of high-speed camera record.

Vertical Configuration

In this configuration, $\alpha = 0°$. Figure 7 shows a snapshot of a rising bubble, made with the high-speed camera.

As a result, a Doppler signal (Fig. 8) was obtained, in which different stages of bubble floating up can be distinguished clearly: inflation, separation, ascent, and floating over the surface of the liquid.

After filtering to remove the low frequency component (Fig. 9) and the sliding Fourier transform, the dependence of the Doppler frequency shift on time was obtained (Fig. 10, left Y axis) and, accordingly, the dependence of the bubble velocity on time (Fig. 10, right Y axis).

So, with the use of the hardware and software complex, the dynamics of bubble ascent in a vertical configuration was established. The average velocity of bubble ascent was 0.24 m/s, which is confirmed by analysis of video recording from the high speed camera.

Fig. 16. Photo of ascent of bubbles in horizontal configuration.

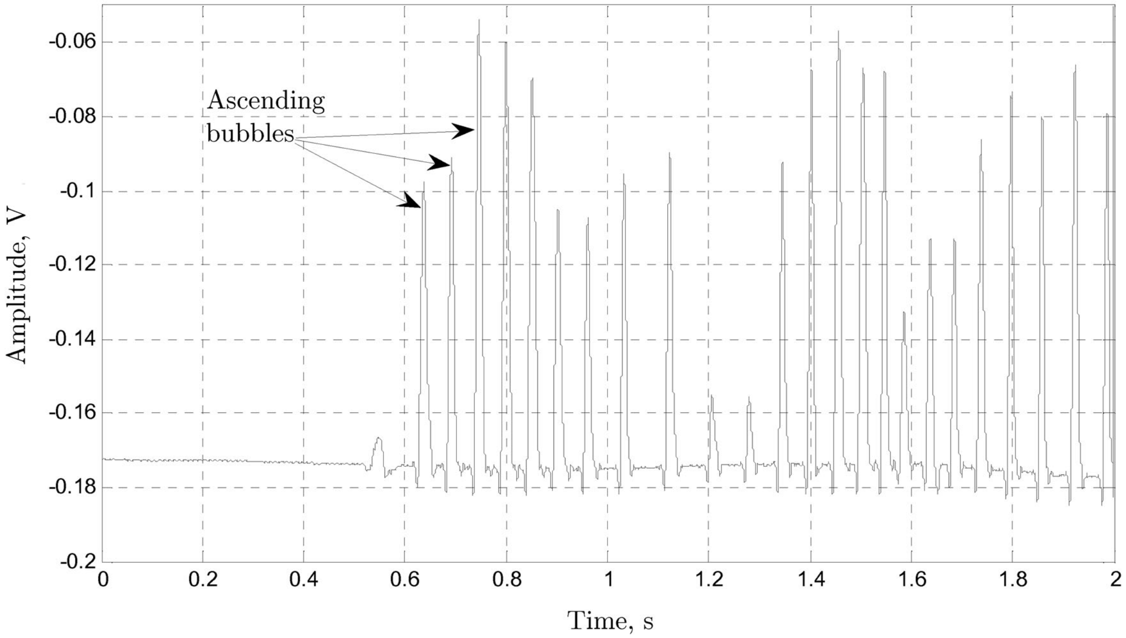


Fig. 17. Ascent of bubbles. Doppler signal.

Besides that, for integral analysis of the floating up, the spectrum of the “ascent” section of the Doppler signal was built (Fig. 11).

The relatively wide range of frequencies in the spectrum is due to the following factors: the ascending bubble is accelerating; the projection of the bubble velocity on the direction of propagation of the ultrasonic wave is changing with time; in addition to the main motion of the bubble, there are oscillations of the bubble walls and the medium.

Inclined Configuration

In the inclined configuration, the angle $\alpha \approx 30^\circ$ (Fig. 12). The Doppler signal for this case is presented in Fig. 13.

As with the vertical configuration, the time dependence of the Doppler frequency shift (velocity of floating up) was obtained (Fig. 14).

Fig. 18. Photo of bubbles floating up in reverse configuration.

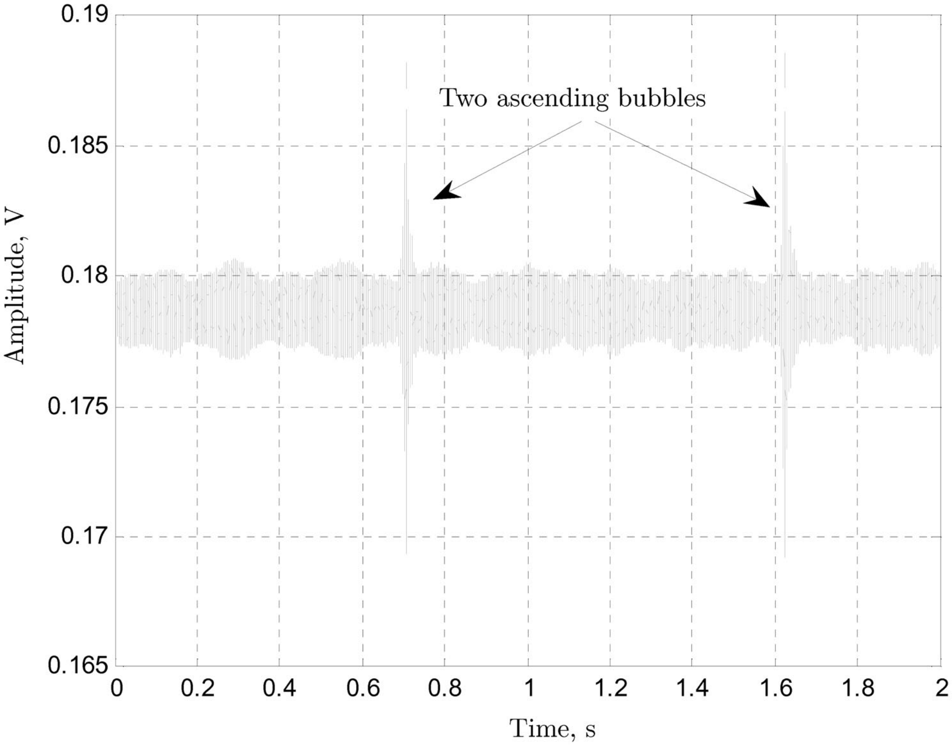


Fig. 19. Signal from receiver. Reverse configuration of hardware complex.

The observed decrease in the velocity is explained as follows. While floating up, the bubble moves along a non-linear trajectory. As a result, during its flight through the measurement zone, the projection of the velocity onto the direction of ultrasound propagation can change, which is observed in Fig. 14. Figure 15 presents a series of snapshots from the high-speed camera recording, which explains the bubble ascent data obtained with the use of the hardware and software complex.

Horizontal Configuration

In this configuration, $\alpha \approx 90°$. Figure 16 shows the ascent of bubbles in the horizontal configuration.

This configuration does not enable full use of the Doppler method because the projection of the bubble velocity on the direction of ultrasound propagation is small. But the amplitude-shadow method is quite applicable. The case with ascent of bubbles for horizontal configuration is presented in Fig. 17. This dependence enables detection of bubbles, as well as estimation of their size and even their velocity from the duration of one amplitude burst and the width of the measurement zone in the medium.

Reverse Configuration

This configuration is based on the reflection of the ultrasonic wave from the bubble walls. The source was positioned so that the wave reflected from the rising bubble and hit the receiver. Figure 18 shows the bubble rising in the reverse configuration.

The signal coming from the receiver has amplitude bursts, caused by the reflection of the ultrasonic wave from the bubbles. Figure 19 shows the graph of signal from the receiver with bursts from two bubbles ascending in succession.

Basing on this signal, one can judge the presence of bubbles in the measurement zone and their size. The Doppler method is also applicable in this configuration.

CONCLUSION

A comprehensive method for ultrasonic diagnostics of two-phase flows is proposed. The method enables measurement of the dynamic and structural characteristics of floating up inhomogeneity.

The results of the experimental studies show that the hardware and software complex, which implements the proposed method of ultrasound diagnostics, enables detection of ascending gas bubbles in a liquid medium, monitoring of their dynamics, and their localization in a volume of 5 to 50 cm^3. The results obtained confirm the efficiency and prospects of further development of the proposed methods of ultrasound diagnostics of two-phase flows.

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