Developing the software and hardware complex to diagnose the ascent of gas bubbles in a liquid metal by the Doppler anemometry method

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Abstract. The complex method of ultrasonic diagnostics of two-phase flows in a liquid metal medium is developed. It allows measuring the dynamic and structural characteristics of the floating inhomogeneity. A software and hardware complex that implements the proposed method is developed and tested for ultrasonic diagnostics of two-phase flows in water and liquid metal medium.

1. Introduction

The use of modern non-contact precision diagnostic tools significantly increases the efficiency and safety of technological processes in the energy sector and industry [1].

At present, the development of the nuclear power industry of the future is associated with the use of fast nuclear reactors [2].

Nevertheless, it is important to obtain experimental data on the structural parameters of the flow [3–6]. The problem of diagnosing the structural and dynamic parameters of the flow is especially acute in the presence of a gas component, caused by emergency or local overheating. The complex diagnostic tools will serve to determine the nature and cause of the emergency and to perform the minimum necessary actions to prevent the reactor from failing [7]. For non-contact diagnostics of structural and dynamic parameters of opaque multiphase media, it is promising to use ultrasonic methods [8, 9]. Complex configuration and sophisticated data processing algorithms based on synchronous detection, correlation and time-frequency analysis will allow creating a tool for three-dimensional diagnostics of geometric parameters and the velocity field of the investigated two-phase flow.

The specificity and difficulty of the task require a comprehensive research in this area. The purpose of this work is to develop a software and hardware complex for ultrasonic diagnostics of two-phase flows in a liquid metal medium.

2. Method of ultrasonic diagnostics of two-phase flows in a liquid metal medium

The developed method of ultrasonic diagnostics of two-phase flows in a liquid metal medium is based on amplitude-shadow, time-of-flight and Doppler methods. The scheme of the method is shown in Figure 1. The method is very flexible in terms of application. It does not regulate the strict
interposition of the receiver and the source, that is, different configurations of the positions of the
source and receiver allow measuring different parameters of inhomogeneity in the medium.

**Figure 1.** Scheme of the proposed method of ultrasonic diagnostics of the medium.

The signal generator sends a sinusoidal signal with a frequency \( f_1 \) to a piezoelectric element
(source), which creates a sound wave with a frequency equal to that of the applied electrical signal and
the resonant frequency of the piezoelectric crystal. An acoustic wave is emitted into the medium at an
angle \( \alpha \), after which it is scattered by phase inhomogeneities contained in the flow. In this case, the
phase inhomogeneity means a bubble with air floating up in the measuring 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 of frequency \( f_2 = f_1 + \epsilon \), where \( \epsilon \) is the shift of the reference frequency
caused by the Doppler effect due to scattering on moving phase inhomogeneities.

It should be noted that only the projection of the bubble velocity on the direction of propagation of
the sound wave influences the frequency shift:

\[
f_1 - f_2 = 2 f_1 \frac{V_{us}}{c},
\]

where \( V_{us} = V_z \cos(\alpha) \). The projection of the speed to the selected direction is measured. The
operations of multiplying the recorded signal containing the Doppler frequency shift by a reference
signal with a frequency \( f_1 \) and an orthogonal signal of the same frequency (shifted relative to the
reference by \( \pi/2 \)) are presented below.

\[
\begin{align*}
Asin(f_1) \ast Bsine(f_1 + \epsilon) &= \frac{A \cdot B}{2} \left( \cos(f_1 + \epsilon - f_1) - \cos(f_1 + \epsilon + f_1) \right), \\
Acos(f_1) \ast Bsine(f_1 + \epsilon) &= \frac{A \cdot B}{2} \left( \sin(f_1 + \epsilon - f_1) - \sin(f_1 + \epsilon + f_1) \right),
\end{align*}
\]

where \( A \) is the amplitude of the reference signal, and \( B \) is the amplitude of the receiving signal after
scattering by an air bubble. The value of \( B \) depends on the number and size of scatterers (bubbles) in
the flow and will be used to implement the amplitude-shadow method.

This mixing operation is performed to obtain a low-frequency signal that carries information about
the Doppler frequency shift. In fact, a two-component signal, consisting of a high-frequency (\( 2 f_1 + \epsilon \))
and a low-frequency (\( \epsilon \)) sinusoid, is formed from the above trigonometric formulas after
multiplication. By applying a low-pass filter, that is, by attenuating the high-frequency signal, we can
isolate the needed low-frequency Doppler signal. Further processing of this signal using the sliding
Fourier transform will serve to obtain the dependence of the Doppler frequency shift on time and,
accordingly, the dependence of the bubble velocity on time:

\[
V_{us}(t) = c \cdot (f_1 - f_2)/2f_1 = c \cdot \epsilon(t)/2f_1
\]
Thus, the described method will serve to track the dynamics of the bubble ascent, to distinguish the stages of its ascent and, using the principle of the amplitude-shadow method, to estimate the size of the bubble and its position.

3. Hardware and software complex
At the first stage of the work, the mixing and filtering operations were implemented in hardware on analog signals, and the Doppler signal was already digitized. This approach has several disadvantages: hardware-fixed frequency of the generated signal and filtering parameters, incompleteness of the extracted data from the receiver, etc. Therefore, to add to the complex flexibility and expandability, as well as for obtaining more information about the receiving signal, it was decided to digitize the receiving high-frequency signal and carry out mixing operations and filtering programmatically.

As part of this work, a laboratory sample of a software and hardware complex (HSC) was created to implement the method described in the previous chapter. The scheme of the complex is shown in Figure 2. Figure 3 contains a photo of the complex.

![Figure 2](image1.png)  
**Figure 2.** Scheme of the implemented software and hardware complex.

![Figure 3](image2.png)  
**Figure 3.** Photo of the implemented software and hardware complex.

The following functional elements of the complex may be distinguished: hardware, software, piezoelectric transducers (source and receiver).

4. Hardware part of the complex
The hardware part of the complex consists of the following elements: signal generator, ADC, personal computer, and connecting wires.

To excite the oscillations of the piezoelectric element (source), a high-frequency generator with high frequency stability is required. The requirement for high frequency stability is due to the following factors: a stable signal allows more accurately determining the Doppler frequency shift and, consequently, the bubble velocity; signal processing is greatly simplified; signal stability allows obtaining the experimental statistics.

The generator of brand Rigol DG1062Z was used. Using a coaxial cable, the piezoelectric element (source) and the signal output of the generator were connected. The receiving piezoelectric element was connected by a coaxial cable to a 14-bit L-Card E20-10-D-1 ADC with a typical signal-to-noise ratio of 73 dB. This ADC did not have input filters, which is essential for digitizing high-frequency signals. The used sampling rate used was 1 MHz and the oscillator signal frequency was 4.02 MHz. An explanation of this choice of frequencies is given below.

In this work, it is proposed to digitize a signal at a frequency of 1 MHz using the effect described above. The Doppler frequency shift in the proposed method is no more than 0.01 MHz. The spectrum of “useful” frequencies of the receiving signal lies in the range of 4.01–4.03 MHz, and after digitization, considering the aliasing effect, in the range of 0.01–0.03 MHz. Experimental research with a sampling rate of 10 MHz gives the same results (as with a frequency of 1 MHz) and confirms...
the operability and correctness of the above-described digitization technique at a frequency of 1 MHz. This technique is called bandpass sampling and has several practical applications. Data from the ADC is transmitted via a USB cable to a personal computer (Intel Core i5, Windows OS).

5. The software part of the complex
The processing of the data coming from the ADC is carried out using a program developed in the MATLAB package. The block diagram of the main elements of the program is shown in Figure 4.

![Figure 4. Software part of the complex.](image)

The input data to the program is an array of \( t \cdot 10^6 \) \( (f_{ADC} \cdot t = 1 \text{ [MHz]} \cdot t \text{ [c]} = t \cdot 10^6) \) values of the oscillation amplitude of the receiving piezoelectric transducer, where \( t \) is the recording time (data collection).

First, the program draws a graph of the signal from the receiving piezoelectric element (Figure 9). This signal allows fixing the moment of bubble rise and estimating its size (amplitude-shadow method). Next, mixing and low-pass filtering is performed. Filtering is implemented using a moving average algorithm with an averaging window of 300 points. The filtering procedure is applied to the data array two times sequentially.

As a result, a so-called Doppler signal is obtained (Figure 5). The Doppler signal takes on a nonzero value only when there is movement in the measuring volume, which confirms the physical picture of the method. Based on this signal, it is possible to distinguish the stages of bubble ascent (Figure 6). Inflation (growth) occurs rather slowly and does not introduce significant disturbances into the medium, but changes the amplitude of the receiving acoustic wave. During the ascent, the Doppler effect is well manifested. When the bubble drifts, the velocity of disturbances in the medium is small and the Doppler frequency shift is correspondingly small, and a low-frequency component is visible in the signal.
The Doppler signal contains a low-frequency component due to the amplitude changes in the receiving signal. By isolating this component from the signal using a high-pass filter, we obtain the following signal (Figure 7).

The high-pass filter is also implemented using a moving average algorithm with an averaging window of 1500 points. The resulting smoothed signal is subtracted from the original signal, and as a result, the low-frequency component is isolated (Figure 8).

Next, a sliding Fourier transform is applied with a window size of 10,000 points and a shift value of 5,000 points. As a result, the dependence of the Doppler frequency shift on time is found (Figure 9, left Y-axis). Applying the Doppler formula, we also obtain the dependence of the bubble velocity on time (Figure 9, right Y-axis).
Figure 9. Doppler frequency shift over time.

An increase in the Doppler frequency shift and bubble velocity with time is found to be natural for a bubble floating in a liquid. Thus, the software part of the described complex above allows tracking the dynamics of the bubble ascent.

Conclusions
A complex method for ultrasonic diagnostics of two-phase flows in a liquid metal medium has been proposed. The method allows measuring the dynamic and structural characteristics of a floating inhomogeneity (gas bubble). A laboratory sample of a software and hardware complex that implements the proposed method has been created. The complex is simple and flexible in use, that is, it sustains measurements in different configurations. Based on piezoelectric transducers, a series of ultrasonic submersible sensors has been developed and implemented to work in two-phase liquid metal.

The developed complex has been tested in a liquid metal environment and its efficiency has been demonstrated. The results of experimental studies show that the proposed method and the developed software and hardware colmpex are applicable for detecting the floating gas bubbles in a two-phase liquid medium and tracking their dynamics.

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