Independent component analysis of hydrodynamic bubbles’ properties

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Abstract. The paper considers the existing acoustic methods for determining the dispersion composition of the gaseous phase in liquid medium used in hydromechanical systems. The shortcomings of these methods were identified. A new method based on the analysis of independent components is proposed. The specialties of the use of the method based on the analysis of independent components are described. An experimental plant was assembled and a number of measurements were carried out.

1. Introduction

With an increase in the volume of hydromechanical systems including the substances in different phase states, there is a need of study the hydrodynamic processes occurring in them.

Special attention is paid to determining the dispersion composition of the gaseous phase in liquid medium, in particular to air bubbles in water [1–3].

At present, there are three types of methods for determining the dispersion composition of the gaseous phase in liquid medium: optical, photometric and acoustic. Optical and photometric methods are the most common [4–7], but they have one significant weakness — they are applicable only in optically transparent media.

Acoustic methods are based on the hydroacoustic properties of bubbles, such as radiation, absorption and reflection of sound waves by bubbles. The noise emitted by bubbles has been the subject of research for many decades. This question was paid attention by scientists such as: Leyton (1994), Shtrassberg (1956), Longet—Khiggins (1990), Din iStoks (2008) and many others. However, their works are mainly dedicated to the study of the acoustic of a single bubble or a small group of bubbles.

The most modern acoustic methods for determining the distribution of bubbles by size are based on measurements of the acoustic wave’s velocity attenuation waves passing through a layer of a bubble cloud. These methods are called “active”. Examples of the realizations of these methods are described in [8, 9]. However, we should take into account that the acoustic wave generated for the bubbles irradiation can influence on the bubbles. This phenomenon can be noted in the results of [10]. The authors of this work carried out a series of experiments, changing the emitted acoustic wave intensity and in each of the experiments obtained different results. Thus, in a number of hydromechanical systems, where the maintenance of working conditions with a certain bubble size is especially important, the use of active methods is inadmissible.
Another type of methods are passive methods. They all originate from the research of Minaert. He became the first to describe the sound waves generated by a bubble in 1933. According to his research, under adiabatic conditions, the frequency of the sound wave emitted by a bubble relates with its size as:

\[ f = \frac{1}{R} \left( \frac{3\gamma P}{(2\pi)^{2}\rho} \right)^{\frac{1}{2}}, \]  

where

- \( f \) – is the frequency of the sound wave emitted by the bubble;
- \( P \) – is the absolute liquid pressure;
- \( \gamma \) – is the coefficient of gas specific heat,
- \( \rho \) – is the density of the liquid;
- \( R \) – is the bubble radius.

The principle of passive methods is that the noise emitted by bubbles is measured, and the size of the bubbles is calculated from equation 1. Examples of the implementation of these methods are described in [11–14]. The disadvantage of these works is that under this approach, it is possible only to understand the size of bubbles, but impossible to get the size distribution.

In [12], the author associated the noise spectrum of bubbles, measured by a single hydrophone, with their size distribution. It is worth noting that the author did not take into account the properties of the acoustic field, where the measurements were carried out. Also, the geometry of the collocations of the hydrophone and the bubbles was not taken into account. In other words if we move the hydrophone or slightly change the acoustic field conditions, we will get a completely different spectrum, and, therefore, a different distribution.

At present, the growth of computing power and a variety of new algorithms of data processing allows to liquidate the disadvantages of the methods described above. In this article, to improve the passive methods for determining the size distribution of bubbles, it is proposed to use the algorithms of analysis of independent components. These algorithms are used in virtually all areas of contemporary science [15–19].

2. Formulation of the problem

There are \( n \) signals being recorded from hydrophones. Each of the signals is a mixture of acoustic waves emanating from a variety of sources (bubbles). In a first approximation, assume that the sources have a certain number \( n \), i.e. there are only \( n \) different sizes of bubbles. The goal of the task is to identify our initial signals from the incoming mixtures of signals. In matrix form, this can be written as:

\[ X = A \times S, \]  

where

- \( X \) – is the matrix of recorded signals;
- \( A \) – is the confusion matrix;
- \( S \) – is the matrix of the original signals.

In other word, the goal is to find the confusion matrix \( A \) to count initial signals:

\[ S = A^{-1} \times X. \]  

In this paper, the FastICA algorithm [20,21] was chosen as the basic algorithm for the analysis of independent components. It refers to standard algorithms and does not take into account the temporal structure of the input signals. But as a test of the feasibility of further works, FastICA algorithm is the optimal choice.
3. Experimental part
It was supposed that surfacing bubbles execute a harmonic vibration with frequencies determined by formula 1. The measurements were carried out in a hydroacoustic anechoic chamber at the academic chair «Ecology and Industrial Safety», Bauman Moscow State Technical University. Installation diagram is shown in figure 1.

Figure 1. Schematic diagram of experimental plant.

Figure 2. Diagrams of bubble size distribution.
Bubble noise was recorded using four Bruel&Kjaer type 8103 hydrophones with the Pulse LAN-XI multichannel analyzer. Next, the recorded signals were processed by an algorithm of analysis independent components and the bubble size distribution was calculated. At the same time, bubble cloud images were taken, and these images were processed in the Shadow sizing software of Dynamic studio by Dantec Dynamics [22]. Thus three experiments were carried out. The results are presented in figure 2.

4. Results
As it can be seen from the figure 2, the results of the acoustic and photometric method are quantitatively different. It is worth noting that both methods give approximately the same picture of the distribution.

One of the factors limiting the precision of the acoustic method is that only four hydrophones were used. In other words, increasing the number of hydrophones in future, and thus the matrix size of the recorded signals X, a more precise distribution can be obtained. It is also worth noting that as an algorithm of analysis independent components was used the FastICA algorithm, which refers to the basic algorithms and does not take into account the time component of the input signals. In the future, it is expected to use another family of algorithms, using the temporal structure of input signals, such as: AMUSE, TDSEP, SOBI [23–25].

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References
[1] Bakhtin B I, Ivashov A I, Kuznetsov A V and Skorokhodov A S 2014 Experimental investigation of the specific features of formation of cavitation zones in intense ultrasound fields J. Eng. Phys. Thermophys. 87 672–85
[2] Kichatov B V, Polyaev V M and Runkovskii S V2001 Gas bubble dynamics with instability in the operation of a system of transpiration cooling Heat Transf. Res. 32 273–80
[3] Ganchev B G and Peresad’ko V G 1985 Processes of hydrodynamics and heat exchange in descending bubble flows J. Eng. Phys. 49 879–85
[4] Mazahermasab R and Ahmadi R 2016 Determination of bubble size distribution in a laboratory mechanical flotation cell by a laser diffraction technique Physicochem. Probl. Miner. Process. 52 690–702
[5] Baroni D B, Filho J S C, Lamy C A, Bittencourt M S Q, Pereira C M N A and Motta M S 2011 Determination of Size Distribution of Bubbles in a Bubbly Column Two-Phase Flows By Ultrasound and Neural Networks
[6] Zhang Y and Sun H 2012 Measurement of bubble size distribution in liquids by optical and acoustical methods Proc. Int. Conf. Commun. Syst. Netw. Technol. CSNT 2012 671–4
[7] Gaillard T, Honorez C, Jumeau M, Elias F and Drenckhan W 2015 A simple technique for the automation of bubble size measurements Colloids Surfaces A Physicochem. Eng. Asp. 473 68–74
[8] Wu X J and Chahine G L 2010 Development of an acoustic instrument for bubble size distribution measurement J. Hydrodyn. 22 325–31
[9] Xue J 2004 Bubble Velocity, Size and Interfacial Area Measurements in Bubble Columns 1–210
[10] Al-Masry W A, Ali E M and Aqeel Y M 2005 Determination of Bubble Characteristics in Bubble Columns Using Statistical Analysis of Acoustic Sound Measurements Chem. Eng. Res. Des. 83 1196–207
[11] Greene C A and Wilson P S 2012 Laboratory investigation of a passive acoustic method for measurement of underwater gas seep ebullition J. Acoust. Soc. Am. 131 EL61-EL66
[12] Manasseh R, LaFontaine R F, Davy J, Shepherd I and Zhu Y-G 2001 Passive acoustic bubble sizing in sparged systems Exp. Fluids 30 672–82
[13] Chen L, Wood S, Moore S and Nguyen B 2012 Acoustic Emission of Bubbly Flow and Its Size Distribution Spectrum Proc. Acoust. 1–6
[14] Husin S and Mba D 2010 Correlation between Acoustic Emission (AE) and Bubble Dynamics II 0–5
[15] Anishchenko L N 2016 Independent component analysis in bioradar data processing 2016 Prog. Electromagn. Res. Symp. PIERS 2016 - Proc. 2206–10
[16] Anishchenko L, Razevig V and Chizh M 2018 Blind separation of several biological objects respiration patterns by means of a step-frequency continuous-wave bioradar 2017 IEEE Int. Conf. Microwaves, Antennas, Commun. Electron. Syst. COMCAS 20172017–Novem 1–4
[17] Hyvärinen A, Karhunen J and Oja E 2001 Independent Component Analysis Appl. Comput. Harmon. Anal. 21 135–44
[18] Knyazev B, Barth E and Martinetz T 2017 Recursive autoconvolution for unsupervised learning of convolutional neural networks Proc. Int. Jt. Conf. Neural Networks 2017–May 2486–93
[19] Chernomyrdin N V., Zaytsev K I, Lesnichaya A D, Kudrin K G, Cherkasova O P, Kurlov V N, Shikunova I A, Perchik A V., Yurchenko S O and Reshetov I V. 2016 Principle component analysis and linear discriminant analysis of multi-spectral autofluorescence imaging data for differentiating basal cell carcinoma and healthy skin 99760B
[20] Heaton C and Ripley B D 2017 Package ‘ fastICA ’
[21] Langlois D, Chartier S and Gosselin D 2010 An Introduction to Independent Component Analysis: InfoMax and FastICA algorithms Tutor. Quant. Methods Psychol.
[22] S. R, H. H, W.Y. S, E. S-P, R.C. C, W. B, M. D, E. D and S.L. T 2010 Optimizing outcomes of IVM treatment cycles-results of a new and improved protocol Hum. Reprod.
[23] Liu W and Chi C-Y Research In AMUSE : A Blind Identification Algorithm Electr. Eng. 0
[24] Frølich L and Dowding I 2018 Removal of muscular artifacts in EEG signals: a comparison of linear decomposition methods Brain Informatics
[25] De Lathauwer L and Castaing J 2008 Blind identification of underdetermined mixtures by simultaneous matrix diagonalization IEEE Trans. Signal Process.