THE DIFFERENCE FREQUENCY DOPPLER METHOD FOR DIAGNOSTICS OF BUBBLE STREAMS

PACS REFERENCE: 43.30.Pc, 43.30.Qd, 43.30.Lz, 43.25.Yw

Didenkulov, Igor[1]; Kustov, Leonid[2]; Martyanov, Alexander[2]; Pronchatov-Rubtsov, Nikolay[2]

[1]Institute of Applied Physics
46 Ulyanov str.
Nizhny Novgorod, 603950
Russia
Tel: +7-(8312)-38-4282
Fax: +7-(8312)-36-5976
E-mail: din@hydro.appl.sci-nnov.ru

[2]Nizhny Novgorod State University
23 Gagarin ave.
Nizhny Novgorod, 603950
Russia
Tel: +7-(8312)-65-6305
Fax: +7-(8312)-36-5976
E-mail: nikvas@rf.unn.runnet.ru

ABSTRACT

In the present paper a method of bubble diagnostics based on the difference frequency scattering is considered. It is described the specific Doppler effect for the difference frequency scattering. This allows one to detect bubbles and measure their velocities. For the bubble stream it is described the nonlinear acoustic Doppler tomography for measurement of the velocity distribution across the stream of liquid. Experimental measurements were done in a hydroacoustic tank with a submerged water jet. The results of the work demonstrate the possibility of remote nonlinear acoustic diagnostics of bubble streams.

INTRODUCTION

The subsurface ocean layer is saturated with air bubbles, which play a significant role in underwater acoustics and oceanography. The breaking of surface waves is one of the most likely generating mechanisms, producing bubble clouds in the upper layer. Such bubble clouds influence the gas flux between atmosphere and ocean [1,2] and also play significant roles in sound propagation as well as ambient noise generation [3-6]. Bubbles are also essential elements in many technological processes in industries and in medical diagnostics.

Many works have been devoted to different acoustic methods of bubble density measurement. They are based on the specific acoustic properties of bubbly liquids. Even the presence of a small number of bubbles can make an enormous change to the sound velocity, attenuation, and scattering, which allows one to realize linear methods of bubble diagnostics [2,7,8].

It is known that a bubble has prominent nonlinear properties. Nonlinear distortions in scattered fields from a bubble are easily observed at the second or higher harmonics of the incident frequency, as well as at the subharmonics of the fundamental frequency and at the sum and the difference frequencies of the primary waves [9,10]. Since a bubble is an oscillator, both linear and nonlinear sound scattering are resonant effects. The existence of such a nonlinear acoustic response opens up the possibility of using it for bubble sizing. The advantage of nonlinear acoustic techniques are their high selectivity. Their usage easily allows one to distinguish a bubble from the other scatterers, since nonlinear scattering from a bubble is much stronger than that from the other scatterers such as solid particles or any other inhomogeneities in fluid. Different nonlinear acoustical methods have been developed for bubble diagnostics: the second harmonic method [11,12], the difference frequency and the sum frequency method [13], the modulation method [14], the subharmonic method [15], the subharmonic-modulation method

[16]. A comparative analysis shows that the sensitivity of the second harmonic method is higher, but selectivity is less compared to the other methods, in particular, to the difference frequency method [12]. The use of the latter in measurements is relatively simple. Some modifications of the method for the case of many bubbles in a scattering have been recently developed [17]. For moving bubbles the specific Doppler frequency shift arises at the difference frequency, which can be used for bubble flow velocity measurement [18]. In the present paper we use the difference frequency method for reconstruction of the flow velocity distribution across the cavitation water jet.

EXPERIMENT

A scheme of the experiment is shown in Fig.1. Two plane piezoceramic transducers insonify the jet and the scattered acoustic wave at the difference frequency is received by the receiving system. The frequency of transducers 1 and 2 were around 1 MHz, and the difference frequencies varied from 100 to 200 kHz.

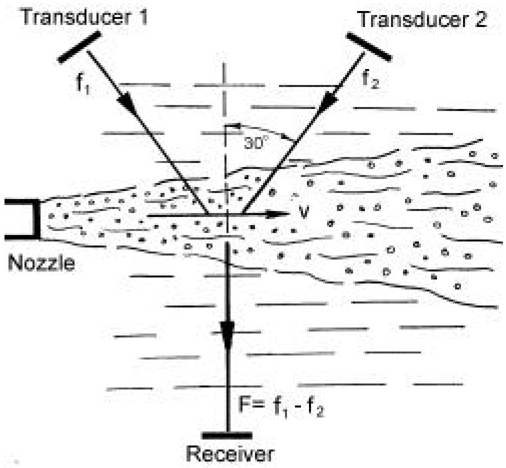

Figure 1. A scheme of the experiment.

In the experiment water flow was created by the centrifugal pump. The nozzle of 1 cm diameter ejected the jet with velocity of 25 m/s. Down the stream the jet diverges and the velocity decreases. The insonified part of the jet was at 60 cm distance from the nozzle. The mean diameter of the jet in the insonified zone was about 11 cm. Diameters of primary acoustic beams in the insonified zone are larger than the jet diameter. The nozzle, two transducers and the receiver were put at the depth of 41 cm from the water surface.

The receiving system represents a spherical hydrophone with the spherical reflector. The reflector of about 30 cm diameter has the focal distance 27.5 cm. The use of the reflector allows one to increase signal to noise ratio in the receiving acoustic signal. Heteronizing were used to transfer the receiving signal into low-frequency range for processing.

THE DIFFERENCE FREQUENCY DOPPLER TOMOGRAPHY

The experimentally measured spectra of acoustic signals at the difference frequency were compared to the numerical model for reconstruction of water flow parameters. The theoretical model was based on the approximation of the axially symmetric bubble distribution in the cross section of the jet. In numerical simulation it was supposed that bubbles move with the stream with the mean local flow velocity. It is taken into account the attenuation of primary acoustic waves inside the jet by resonance bubbles as well as the attenuation of the difference frequency scattered wave. Geometry of numerical and physical experiments is shown in figure 2. Since diameters of primary acoustic beams in the insonified zone are larger than the jet diameter, the primary waves can be considered as plane, and consequently intensities of rays incoming into different parts of the jet are equal to each other.

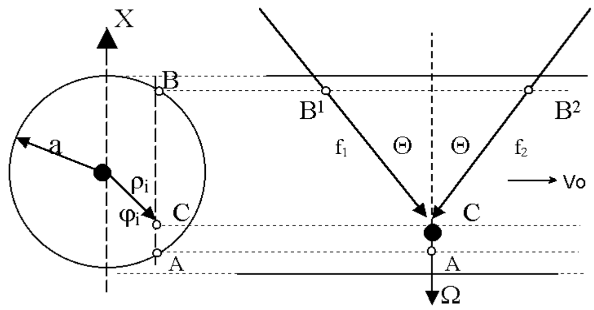

Figure 2. Geometry of the problem. Cross (left) and longitudinal (right) sections of the jet.

Elementary scattering volume in point C radiates the difference-frequency wave, which intensity is proportional to the squared multiplication of primary wave amplitudes and bubble concentrations in the scattering volume. In calculation of primary wave amplitudes insonifying the scattering volume the attenuation of high-frequency primary waves of frequencies f_2 and f_1 along geometry-acoustic rays Â$_1$Ñ and Â$_2$Ñ is accounted. Insonified part of the jet is considered as cylindrical volume filled in with microbubbles moving with the flow. The intensity of the difference-frequency-scattered signal generated from an elementary volume around the point C and the amplitude of the received signal are calculated.

Supposing that signals of combination scattering from elementary volumes are incoherent and taking into account the attenuation of primary waves and the difference-frequency wave inside the jet along the path CA, one can write the intensity of the difference-frequency signal at the receiver as follows:

$$\Delta W(r_i) \sim \exp(-b r_i)\cdot \int_0^{2p} \exp\left[-2s_f \int_B^C n(x)dx - s_\Omega \int_C^A n(x)dx\right] dj \,,$$

where s_f , s_Ω - bubble extinction cross sections at the primary frequencies and the difference frequency, respectively, $n(x)$, $n(x)$ - distribution of bubble concentrations along the primary wave paths and the difference-frequency wave path. This expression allows one to calculate the intensity of spectral component of the difference-frequency signal in any frequency range. This intensity is the sum of intensities of nonlinear scattered signals from elementary volumes, which are at the same distance from the jet axis. Considering the flow velocity distribution across the jet dependent from the radial distance as

$$V = V_0 \exp(-br^2) \,,$$

one can obtain an expression for the frequency of the difference-frequency-scattered signal by the elementary volume as follows [18]:

$$\Omega_i = 2f \cdot Sin\Theta \cdot \frac{V_0}{C_0} \cdot \exp(-br_i^2) \,.$$

Here V_0 – flow velocity at the jet axis, r_i - radial distance from the jet axis to the elementary volume of scattering, b - scaled coefficient describing the effective jet radius, $Ñ_0$ – sound velocity.

In paper [19] it was shown that the forms of experimental and theoretical spectra of linearly scattered acoustic waves at the submerged jet are in satisfactory agreement if the bubble distribution across the jet is described by the function:

$$n = n_0 \exp(-2br^2) \sim V^2(r)$$

In the present work the form of spectral line was calculated numerically with the use of the same model in the approximation of single-nonlinear-scattering. The model does not take into account turbulence flow pulsation, which results in mainly in the low-frequency part of the scattered spectrum. The latter is formed by the peripheral parts of the jet, where the mean flow velocities can be of the same value or even larger compared to the turbulent pulsation velocities. The relatively large amplitude of turbulent pulsation velocities results in arising “negative” spectral components, which do not exist in the theoretical model. Free adjusting parameters of the model are the exponent power b of the flow velocity distribution (and bubble distribution) across the jet and the velocity V_0 at the jet axis. Besides, values of the jet axis velocity and the bubble concentration were also varied in numerical simulations. Since the primary wave frequencies are closed to each other it was supposed that the primary waves have the same attenuation when propagate inside the jet.

In figure 3 it is shown normalized experimental spectrum of the difference frequency scattering (solid bold line) and theoretical spectra.

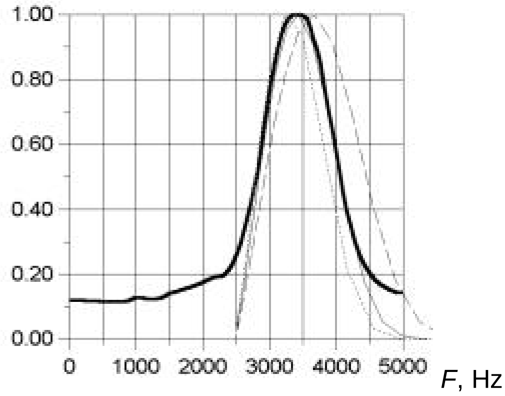

Figure 3. Experimental (solid bold line) and theoretically calculated spectra of the difference-frequency-scattered from the cavitation jet acoustic signal.

Solid thin line in the figure 3 is the theoretical spectrum for the jet flow velocity V_0 = 3.2 m/s and for the coefficient b = 0,2 cm^{-2}. Dashed line is the theoretical spectra for the jet flow velocity of 4ì /ñ and for the same value of b as in previous case. Dotted line represents theoretical spectrum for b=0,3 cm^{-2} and V_0 =3.2 m/s. In the given example the primary frequencies f_1 and f_2 were 1000 kHz and 1100 kHz, respectively. The heterodyne frequency was 97.5 kHz. As a result, the difference frequency W=100 kHz corresponds to the frequency 2.5 kHz in the figure 3. It is seen good agreement between experimental data and theoretical curve for V_0 = 3.2 m/s, b = 0,2 cm^{-2}.

The given examples of experimental and theoretical spectra demonstrate the possibility of the nonlinear acoustic tomography. Numerical simulation shows that even minimum a priory information on flow structure is enough for satisfactory accuracy measurements of the spatial distribution of scatterers and velocity across the stream.

CONCLUSION

The conducted experiments demonstrate feasibility of the difference-frequency technique for diagnostics of lquid streams with bubbles. It was shown theoretically and experimentally that the use of the difference-frequency scattering for diagnostics of moving scatterers is more effective compared to the linear scattering due to less reverberation and due to higher sensitivity of the nonlinear scattered wave spectrum to the variation of diagnostic parameters. The results of the work show the possibility of the nonlinear Doppler acoustic tomography of bubble streams, which can find applications in industrial and medical diagnostics.

ACKNOWLEDGEMENTS

This work was supported by the Russian Foundation for Basic Research (01-02-17653, 01-02-16938) and in part by the International Science and Technology Center (project 1369).

REFERENCES

1. S. Thorpe: On the clouds of bubbles formed by breaking waves in deep water and

their role in air-sea gas transfer, Phil. Trans. R. Soc. London, **A304** (1982), pp. 155-210.

2. D. Woolf, S. Thorpe: Bubbles and the air-sea exchange of gases in near saturation conditions, J. Mar. Res., **49** (1991), pp. 435-466.
3. C. Clay, H. Medwin: Acoustical oceanography: principles and applications, John Wiley & Sons, New York, 1977.
4. D. Farmer, S. Vagle: Waveguide propagation of ambient sound the ocean-surface bubble layer, J. Acoust. Soc. Am., **86** (1989), pp. 1897-1908.
5. N.Q. Lu, A. Prosperetti, S.W. Yoon: Underwater noise emission from bubble clouds, IEEE J. Ocean. Eng., **15** (1990), pp. 275-281.
6. S.W. Yoon, L. Crum, A. Prosperetti, N.Q. Lu: An investigation of the collective oscillations of a bubble cloud, J. Acoust. Soc. Am., **89** (1991), pp. 700-706.
7. H. Medwin: Counting bubbles acoustically. Review, Ultrasonics, **15** (1977), pp. 7-13.
8. V.N. Glotov, P.A. Kolobaev, G.G. Neiumin: Investigation of sound scattering by bubbles, produced by artificial wind in sea water, and statistic distribution of bubble sizes, Sov. Phys. Acoust., **7** (1961), pp. 421-427.
9. E. Neppiras: Subharmonic and other low-frequency emission from bubbles in sound-irradiated liquids, J. Acoust. Soc. Am., **46** (1969), pp. 587-601.
10. E. Zabolotskaya, S. Soluyan: Emission of harmonic and combination frequency waves by air bubbles, Sov. Phys. Acoust., **18** (1972), pp. 396-398.
11. F. Fenlon, J. Wohn: On the Amplification of Modulated Acoustic Waves in Gas-Liquid Mixtures, in Cavitation and Inhomogeneities in Underwater Acoustics (Ed. W.Lauterborn), Springer-Verlag, Heidelberg, 141-150, 1980.
12. L. Ostrovsky, A. Sutin, Nonlinear acoustic diagnostics of discrete inhomogeneities in liquids and solids, Proc. 11th Int. Congr. Acoust. Paris, Vol.2, 137-140, 1983.
13. V. Zverev, Yu. Kobelev, D. Selivanovsky, A. Sokolov: On a method of detection of gas bubbles in a liquid, Sov. Tech. Phys. **50** (1980), 1544-1545.
14. V. Newhouse, P. Shankar: Bubble size measurement using the nonlinear mixing of two frequencies, J. Acoust. Soc. Am., **75** (1984), pp. 1473-1477.
15. A. Eller, H. Flynn: Generation of subharmonics of order one-half by bubbles in a sound field, J.Acoust.Soc.Am., **46** (1969), pp. 722-727.
16. T. Leighton, A. Walton, J. Field: Acoustic bubble sizing by combination of subharmonic emission with imaging frequency, Ultrasonics, **29** (1991), pp. 319-323.
17. A.M.Sutin, S.W.Yoon, E.J.Kim, I.N.Didenkulov: Nonlinear acoustic method for bubble density measurements, J. Acoust. Soc. Am., **103** (1998), pp. 2377-2384.
18. I.N.Didenkulov, S.W.Yoon, A.M.Sutin, E.J.Kim: Nonlinear acoustic Doppler effect and its use for bubble flow velocity measurement, J. Acoust. Soc. Am., **106** (1999), pp. 2431-2435.
19. A.N.Barkhatov, V.G.Gavrilenko, A.I.Martyanov: On form of spectrum of signal scattered by the sound absorbing turbulent jet, Acoust. Phys. **25** (1979) pp. 32-35.