Bubbled Diameter Determination in Large Measurement Volume Using Phase Doppler Anemometry

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ABSTRACT

This paper presents an optical and mechanical design of an experimental stand for determination of bubble dimension distribution in a volume of pure or polluted water. The stand is fed with 20 liters tank of pure water which is delivered through a measurement cross section of 1 cm$^2$ with velocity 150 mm/s. It gives the sample measurement in about 20 minutes. In order to detect all bubbles in the sample volume, we decided to use Phase Doppler Anemometry system for bubble diameter determination with extended measurement volume to cross section 1 cm$^2$. Basic theoretical analysis and opto-mechanical design of this extended PDA system is included in this paper too.

INTRODUCTION

Cavitation processes rise as a result of pressure changes of bubbles contained in the liquid inside hydrodynamic systems. Cavitation effects lead to important mechanical damage of all parts submerged in the fluid. The intensity of the cavitation effect depends on many different factors, such as material, fluid velocity, bubble nuclei incidence angle and the number and dimension of bubbles contained in the fluid. The first three geometrical factors are well known in general. The last two factors, on the other hand, are not well known, and are dependent on the actual fluid properties and its history [1].

Bubbles can get into the liquid fluid in the liquid-gas phase boundary, but they can originate by local ebullience of liquid in the zones of large shear forces or negative pressures too. The bubble dimension is then unceasingly changed according to the thermodynamic state in the actual bubble position inside the hydrodynamic system. It leads to the conclusion that bubbles contained and their distribution may be very spatially and temporally varied.

There exist different experimental methods for evaluation of bubbles contained in liquid [2, 3]. These methods can be divided into global methods, which are able to measure large cross section areas like ultrasound methods, Interferometric Particle Imaging (IPI), holographic methods or Global Phase Doppler Anemometry (GPDA), and local methods like light scattering methods or Phase Doppler Anemometry (PDA). The main difference between these methods consists in the sampling rate capability. The global methods use 2D snaps of measured cross section for evaluation, and data acquisition frequency is limited by the snapshot repeatability of the used camera system.
Local methods evaluate light intensity or temporal shift of light signals taken with fast optoelectronic devices like photomultipliers or diodes and enable the measure of fast events up to MHz range. On the other hand, these techniques are limited to small cross section in order to eliminate interference of captured signals from more particles at once.

Our goal is to design an experimental stand for determination of dimensions and distribution of all detected bubbles in a volume of pure water. We decided to use Phase Doppler Anemometry technique modified for large cross section measurement of area 1 cm$^2$. The experimental stand is designed to be able to perform verification measurement of extended Phase Doppler Anemometry technique with Global Phase Doppler Anemometry and Interference Particle Imaging technique.

**PRINCIPLES OF MEASUREMENT METHODS**

Our measurement stand is designed for experimental determination of dimensions of all bubbles in a volume of pure water prepared by Watrex ULTRAPUR system for the next cavitation experiments. The same instrument will be used for all bubbles dimension distribution determination of pure water after cavitation process. Pure water is drained with an Aquatec pump CDP 6800 with flow rate of 16.6 ml/s. In order to attain laminar liquid flow inside the measurement volume, we decided to use square measurement cross section of 1 cm$^2$ that gives Reynolds number $Re = 1660$. In order to evaluate all bubbles we had to estimate the measurement rate of the sensors. Measurement depths of IPI or GPDA methods are limited with laser sheet depth, usually about 1 mm. It gives the necessary snapshot rate, at least approximately 200 Hz. In the case of observance of Nyquist sampling theorem, the snapshot rate should be greater then 400 Hz. This sampling frequency is possible to attain using high-speed camera systems only. Another complication arises with the scattered light intensity from the bubbles. Bubble scattered light intensity is highly angle dependent according to the Lorenz-Mie scattering theory, and it decreases exponentially with the bubble diameter in general. Consequently, some bubbles are too small to detect with this kind of technique. There exist other methods, which enable measurement of bubble diameter with another kind of sensor than a camera. Phase Doppler Anemometry technique uses photomultipliers as sensors, for example. That sensor is more sensitive to weak light intensities and it gives analog output, which can be sampled with a very high frequency. The evaluation of this technique, unfortunately, is very angular sensitive, which destines this technique for local measurement only. We, however, tried to modify our measurement set-up design in order to extend PDA technique evaluation across our large cross section 8x16 mm.

**Phase Doppler Anemometry**

Phase Doppler Anemometry [4, 5] is a well-known experimental technique for simultaneous measurement of particle velocity, size, flux and concentration of multiphase fluid flows. This technique has been developed since the 70's of the last century. It is based on measurement of interference events of scattered light by particles crossing a field of interference fringes. As particles pass through an interference fringes field there are observed interference bursts corresponging to the Doppler frequency. This frequency is proportional to the particle velocity vector $u$ perpendicular to interference fringes plane and it can be expressed by equation 1:
where symbols meaning corresponds to the Figure 1.

\[ f' = f_1 - f_2 = f + \frac{\bar{u}_1(f - \bar{f}_1)}{\lambda} - f - \frac{\bar{u}_2(f - \bar{f}_2)}{\lambda} = \frac{2u \sin \phi}{\lambda}, \]  

(1)

Figure 1: Optical scheme of Laser Doppler Velocimetry.

The burst frequency depends on particle velocity and it has the same value in all directions. Burst arrival time, however, depends on receiver direction. Durst et al. [5] computed equations for determination of phase shift of burst detection between two receivers for measurement configuration as it is shown in the Figure 2:

Figure 2: Optical scheme of Phase Doppler Anemometry.

There are two vertically polarized laser beams in xz plane crossed in the measurement point. Burst signal is measured with two receivers R₁ and R₂, which directions are given by angle \( \phi \) laying in yz plane and angles \( \psi \). Particles cross the interference fringes along x axis with velocity vector \( u \). The phase shift between signals captured by receivers can be expressed by equations [6]:
for reflected rays and

\[ \Phi_{12} = C_2 d = \frac{2\pi d}{\lambda} \left[ \frac{\sin \phi \sin \psi}{\sqrt{2(1 + \cos \phi \cos \psi \cos \theta)}} \right] \]

for refracted rays respectively, where \( d \) is particle diameter, \( \lambda \) is illuminated laser beam wavelength, \( n \) is relative refractive index, and \( \phi, \theta, \psi \) are angles as it was established in the Figure 2. Equations show received beats phase shift is linearly proportional to particle diameter in the case of small angles \( \phi \) and \( \psi \). But, beat phase shifts, unfortunately, have different value and opposite slope for refractive and reflected rays. It causes signals interference, because spherical particles scatter as reflected and refracted rays of different intensity in all directions. There exists, fortunately, scattering angle \( \theta \) value, where the beat phase shifts \( \Phi \) are the same for both kinds of rays. This angle can be expressed by equation [7]:

\[ \theta = \arccos \left( \frac{1}{\cos\left(\frac{\phi}{2}\right)\cos\psi} \left(2n^2 - 1\right) \right) \]

for \( n < 1 \).

Equations (2) and (3) show different sensitivity of phase shift \( \Phi \) to each angles \( \partial \phi \) and \( \partial \psi \) too, where \( \partial \psi \gg \partial \theta \). This disproportional sensitivity has a large influence on technical solution of Phase Doppler Anemometry measurement systems.

**Global Phase Doppler Anemometry**

Global Phase Doppler anemometry technique was introduced by Damaschke et al. in 2000 [8]. This measurement technique is based on a similar principle as Interferometric Particle Imaging technique introduced by König et al. in 1986 [9], but it employs crossing laser beams, as is usual in PDA technique. This kind of measurement technique is based on evaluation of interference pattern of reflected and refracted rays' spots in defocused image of particles passing through a laser sheet. The principle of interference pattern generation within IPI method is shown in the Figure 3. Evaluated particle diameter can be easily computed from defocused image interference fringes spacing by equations:

\[ d = \frac{2\lambda N}{n\alpha} \left( \frac{1}{\cos^2 \frac{\theta}{2} - \frac{\sin \theta}{2}} \right) \]

for \( n < 1 \) and

\[ \cos^2 \frac{\theta}{2} - \frac{\sin \theta}{2} = \sqrt{n^2 - 2n \cos \frac{\theta}{2} + 1} \]
\[
d = \frac{2\lambda N}{\alpha} \frac{1}{\cos \theta + \frac{n \sin \frac{\theta}{2}}{\sqrt{n^2 - 2n \cos \frac{\theta}{2} + 1}}}
\]

for \( n > 1 \), \( \lambda \) is illuminated laser beam wavelength, \( n \) is relative refractive index, \( \alpha \) is aperture angle value and \( \theta \) is angle of observation.

where \( N \) is number of observed interference fringes, \( \lambda \) is illuminated laser beam wavelength, \( n \) is relative refractive index, \( \alpha \) is aperture angle value and \( \theta \) is angle of observation.

Figure 3: Principle of interference fringes origin using image defocusation in IPI [10].

The disadvantage of IPI method used for particle diameter measurement is the few numbers of observation angles \( \theta \) with good interference fringes visibility. It is caused by different values of reflectivity and refractivity of interfering rays. The Global Phase Doppler technique overcomes this complication with the use of two spatially coincident laser sheets tilted from each other with angle \( 2\Phi \) as it is shown in the Figure 4:

Figure 4: Scheme of GPDA technique and defocused interference fringes pattern [10].

The defocused image contains four rays’ spots now, but, because there are two reflected and two refracted rays of the same intensity, the whole interference pattern is usually reduced to only two interference fringes systems.
Design of Phase Doppler Anemometer for large cross section measurement

Classical conception of Phase Doppler Anemometry measurement system design is shown in the Figure 5:

![An example of optical layout of Phase Doppler Anemometry system](image)

Figure 5: An example of optical layout of Phase Doppler Anemometry system [7].

It consists of two focused laser beams crossing in small measurement volume. Receiving optics consists of collimating lens with focal point coinciding at focused laser beams crossing, aperture diaphragms of each receiver and field of view stop placed in collimated beam focus. This kind of optical layout minimizes two main features affecting the ability of measured data evaluation. It is a high sensitivity of signal phase shift with receivers’ inclination angles and the probability of signal mixing from more particles inhered in measured volume simultaneously. The disadvantage of this arrangement is an inhomogeneous laser light distribution in the measurement volume given by laser beam gaussian profile that leads to the significant variation of measured signals with particle position in measured volume for large particles especially [11] and slit effect on measurement data [12].

We had had to ensure both upper spoken measurement complications minimization in the case of our measured volume of the PDA system. Minimization of the number of particles in the measured volume was performed on the base of known cavitation bubble nuclei distribution measurement shown in the Figure 6:

![Typical histogram of nuclei population on size](image)

Figure 6: Typical histogram of nuclei population on size [2].
Figure shows the number of cavitation bubble nuclei should be less then 2 per cm$^3$ for bubble diameters greater then 3 µm. We decided to use the measurement volume of 0.1 cm$^3$ approximately, which assures rather small probability for more particles at once there. Minimizing of received signal angle deviation was performed with an opposite optical setup than is commonly used. Aperture stop is mounted in front of the frontal lens of PDA system placed as close as possible to the measurement volume. Field of view stops of rectangular shape were placed in the image focal plane of the frontal lens. Stops dimensions, computed for the received burst signal phase change caused by angle deviation in each measured direction, was less then 3%. It demonstrates that stops dimensions 15x0.8 mm for lens focal distance 250 mm, 632.8 nm HeNe laser beam make an interference field with crossing angle $\phi = 3^\circ$ and out of plane angle $\psi = 4^\circ$. The optimal scattering observation angle for eliminating phase shifts of reflected and refracted rays was computed according to equation (4) to $\theta = 82,47^\circ$ for the bubbles in water. The scheme of the whole optical setup of designed PDA system is shown in the Figure 7:

Figure 7: Optical setup of designed PDA system for large volume measurement.

We designed special trapezoid shape measurement cell, as it is seen in the figure, in order that the PDA system can measure the whole cross section of the measurement volume at computed scattering angle $\theta$. This cell shape enables us to observe the whole cell volume in scattering angles 90° - 60° without vignetting. Furthermore, rays passing through the cell do not change direction if the cell is filled with water. It will be used for small bubble measurement with use of its scattering pattern [13] or caustics [14] evaluation in the future. Measured volume is limited with intersection of illuminated laser beams marked with blue and green lines in the Figure 7 left. This cell is possible to use for GPDA or IPI systems measurement too, if the illumination laser sheet passes crossways the cell as it is marked with red line in the Figure 7 left. The whole illuminated cell cross section can be measured up to scattering angle 45°. GPDA or IPI will be performed with Casio Exilim Pro EX-F1 camera as a receiver. It enables us to take snaps
with frequencies 300, 600 and 1200 fr/s with resolution 512x384, 432x192 and 336x96, respectively.

We have used three photomultipliers Hamamatsu R 4632 as receivers of our PDA system because of its good sensitivity at this wavelength and rectangular photocathode shape. Three receivers were used to improve the system sensitivity for small as for larger nuclei bubbles because two out of plane angles can be evaluated $\psi_{12} = \psi_{13} = 4^\circ$ and $\psi_{23} = 8^\circ$. In order to eliminate interference of scattered and reflected lights among the receivers, we separate the beams just behind the field of view diaphragms with mirrors into three lightproof branches. Diffused stray light is suppressed with a series of vignetting diaphragms in the optical path.

The next step was to assure temporal stable and fixed position among measurement cell, illumination laser beams and measurement optics of PDA system. We fixed position between optical measurement system and measurement cell with a rigid lightproof box, where both parts were screwed down. We designed special spacers for measurement cell fixing, used as a piping reducer at once. Because of the very complicated shape of piping reducer duct profile we decided to use a rapid prototyping technology for its manufacturing. We had used stereolithography (STL) technology by EDEN 250 3-dimensional printing system [15] and materials FullCure®720 and VeroBlack™. Manufactured parts were tested in details and its geometrical congruency to the original CAD model had average deviation about 0,15 mm. We had to improve the surface roughness of critical faces of manufactured parts to assure smooth walls inside duct and waterproof of seating face. We polished these surfaces using CaO$_2$ polishing powder to achieve final surface quality. Demonstration of manufactured spacer is shown in the Figure 8 right:

![Figure 8: Snap of designed system parts experimentally manufactured using rapid prototyping technology.](image)

Because mutual position of measurement cell and PDA system is maintained fixed, all the necessary system aligning had to be performed with set of right position of illuminating laser beams. It was done with mirror alignment system used for interference fringes generation in the measurement cell and a movable slit placed just in front of the cell. The mirrors alignment system was designed to enable us to set mirrors position in four degrees of freedom. In order to verify its functionality, we made a model of this part
using rapid prototyping technology again. Two manufactured parts for mirror alignment are shown in the Figure 8 left. Experimental tests show good alignment capability of the designed solution. Finally, we will use a mirrors alignment part manufactured with traditional material and technology, because tested materials show insufficient long-term stability of aligned position. Final design of the whole experimental apparatus for nuclei bubble diameter distribution measurement with PDA system modified for a large cross section measurement is depicted in the Figure 9.

![Figure 9: A CAD model of the whole designed experimental system.](image)

**Conclusion**

This paper shows the theoretical possibility to perform bubble diameter measurement using Phase Doppler Anemometry technique modified for large cross section measurement. This technique can be used if the number of measured object in the measurement volume is one. We designed an optical setup of PDA system that assures the maximal deviation of received bursts phase shift less than 3%. That value has small enough influence on the right data processing and evaluation. Our design of the experimental setup enables us to perform bubble diameter measurement using Global Phase Doppler Anemometry or Interference Particle Imagining technique with PDA measurement simultaneously, in order that the comparison of all methods can be done together. The whole experimental system is not completed at all now, but the critical parts necessary for its functionality were tested in detail and optimized for this application. The presented system is manufactured now and we suppose the first experimental measurement will be performed till the end of this year.

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REFERENCES


