Particle characterization system for industrial and naval applications

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Abstract—**The Interferometric Particle Imaging (IPI) technique was modified and adapted to provide particle size and particle concentration measurements in harsh environments. The development was forced by the challenge of nuclei concentration measurement in cavitation tunnels and full scale measurements in the wake flow of a vessel. Because only bubbles act as cavitation nuclei, discrimination between bubbles and other solid particles in the multi-phase flow is necessary. The size measurement and classification and can be realized by defocussed imaging and analysis of the scattered light from particles. A few measurement results demonstrate the feasibility of the new developed Nuclei Concentration Measurement (HDNC) technique and there advantages in terms of robustness, moderate hardware effort and reduced measurement time.**

***Keywords-** particle charaterization; particle classification; interferometry; industrial measurement; naval measurement*

I. Introduction

The in-situ characterization of small particles, like droplets bubbles or small solids, is important for a number of industrial and naval applications. Often a robust measurement technique with low calibration effort and only few hardware components is required. One application example is the characterization of cavitation nuclei, which are bubbles in the size range of 20µm to several hundred micrometers. For this measurement problem the hydrodynamic nuclei concentration (HDNC) technique for particle characterization was developed in the framework of the KonKav project, funded by the German Ministry of Economics and Technology (BMWI). The joint research project KonKav stands for correlation of cavitation and erosion considering water quality and wake flow.

Cavitation on propellers and rudders influences the efficiency of vessels and causes vibrations, erosion and damage. Cavitation models should predict cavitation processes, but require input and validation data in terms of flow field and nuclei concentration. Usually the cavitation models are validated by cavitation observations in ship model basins. Nevertheless, the results of current models differ between model scale experiments and cavitation characteristics of full scale vessels. An improved prediction of cavitation in model scale and full scale is the goal of the KonKav project. The numerical models and calculations were performed by the Institute of Fluid Dynamics and Ship Theory at the Hamburg University of Technology and the industrial partners are Hamburg Ship Model Basin (HSVA), Potsdam Model Basin (SVA) and Flensburger Schiffbau-Gesellschaft (FSG).

Nuclei in the propeller inflow induce cavitation phenomena. In general bubbles are trapped by vortexes and expanded in low pressure regions of the fluid flow. Whereas the nuclei behavior of bubbles are approved, the influence of other particles (solids or organic components) on cavitation inception the still under discussion. The institute of General Electrical adapted the Interferometric Particle Imaging (IPI) technique (e.g. [1], [2]) for nuclei size and nuclei concentration measurements [3], [4], [5]. Measurements were performed in the three different cavitation tunnels of the project partners and in the Irish see behind a vessel. Because of the specific goals, the hardware adaptions and the improved signal- and data processing for nuclei measurements, all hard- and software changes are covered by the developed Hydrodynamic Nuclei Concentration (HDNC) technique.

II. LAYOUT FOR PARTICLE MEASUREMENTS

The IPI technique and the HDNC technique are based on the light scattering characteristics of particles, which are illuminated by coherent light. Different other particle measurement techniques like Phase-Doppler technique and time shift technique are also based on similar optical effects but have a more complex and expensive setup [6]. The scattered light from a particle contains information about particle size and particle structure. A homogenous spherical particle, like a small bubble, illuminated by one laser beam has separated glare points. The emanate light interfere in the far field and generates complex scattering function. For particular observation/scattering angels only two glare points contribute to the scattering characteristics (e.g. Fig. 1a). The two scattered waves of the glare points generate an interference pattern. The structure of this interference can be imaged on an array sensor by defocusing an imaging system in the far field. As an example fringe pattern in Fig. 1b shows the calculated interference fringes in the image plane depending on the degree of defocussing. In the center the sharp image of the glare points can be vaguely seen. The interference fringes are located left and right from the focus in the center. The major advantage of the IPI and HDNC technique is, that the spatial resolution of the imaging optics can be much less than the resolution for direct glare point imaging in the focal plane.

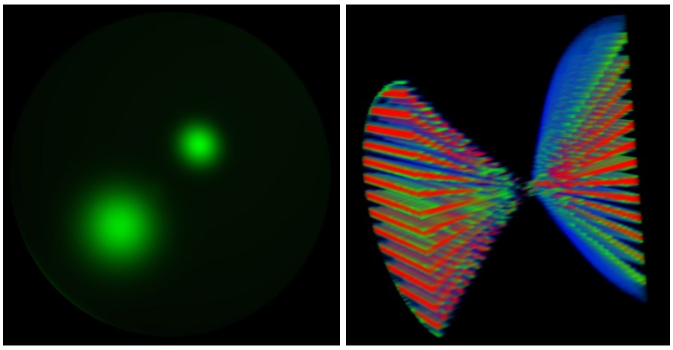

Figure 1. a) Example of two glare points from a homogenous spherical bubble, b) Example calculated focal series of the imaged interference pattern (Colored for better visibility)

By illuminating several particles and imaging a larger volume more than one particle can be imaged in the same frame. A sample recording of 3 spherical bubbles recoded with an EOS7D Camera and a 532nm DPSS laser are depicted in (Fig. 2).

For two glare point, the fringes distance and therefore fringe count in each defocussed image is proportional to the bubble size. Fig 3 shows this linear relation for a sample optical setup. The calculations were done by the Fourier Lorenz Mie Theory described in [7].

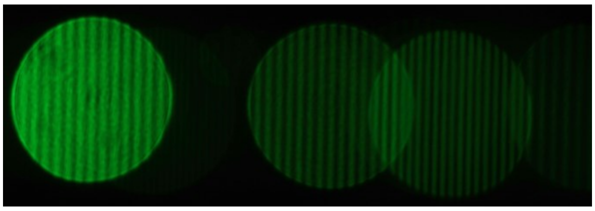

Figure 2. Recorded fringe pattern of 3 air bubbles in water illuminated by a 532nm laser beam

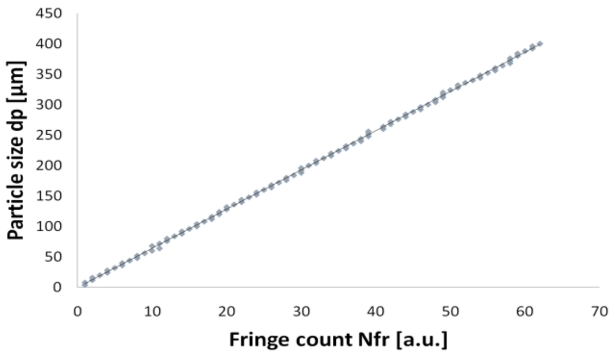

Figure 3. Relation between fringe count and particle size for 532nm laser and perpendicular polarization in a scattering angle of 81 degree

Because of the linear dependence between fringe count and particle size a conversion factor κ can be assumed.

$$N_{fr} = \kappa d_p; \quad N_{fr} = kad_p$$

The conversion factor κ only depends on the scattering angle (direction of observation), refractive index of the medium (e.g. water 1.333), refractive index of the particle (e.g. air 1.0) and on the angular aperture a of the imaging optics, which can be calculated from the focal distance and entrance pupil diameter. Therefore the conversion factor can be calculated beforehand without calibration.

Figures 4 to 6 provide calculations of the normalized conversion factor k for bubbles in water based on Mie-scattering. In Figure 4 the conversion factor normalized on the angular aperture a is shown as function of the scattering angle.

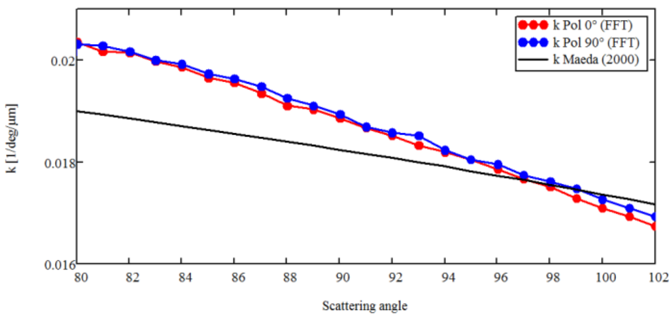

Figure 4. Aperture normalized particle size/fringe count conversion factor calculated by Mie scattering for a bubble in water (Scattering angle: 80 deg to 102 deg, laser wavelength: λ=532nm, relative refractive index: m=0,75

Only a slight change between 0.02 fringes deg^{-1} μm^{-1} and 0.017 fringes deg^{-1} μm^{-1} can be seen. The red and blue lines show the fringe distance estimation based on FFT method for both polarizations of the laser with an angular spacing of one degree. The black curve represents an analytical solution for reflection and first order refraction given by Maeda [1], which seem to be invalid in the investigated range of the scattering angle from 80 deg to 102 deg.

In Figure 5 the modulation depth of the fringes is plotted. This is a direct measure of the fringe contrast in the images (Fig 2). The modulation decreases for smaller scattering angles. A good compromise is an observation angle of 90 deg. Both polarizations have the same moderate modulation of about 50%. Therefore the illumination layout becomes independent of the laser orientation.

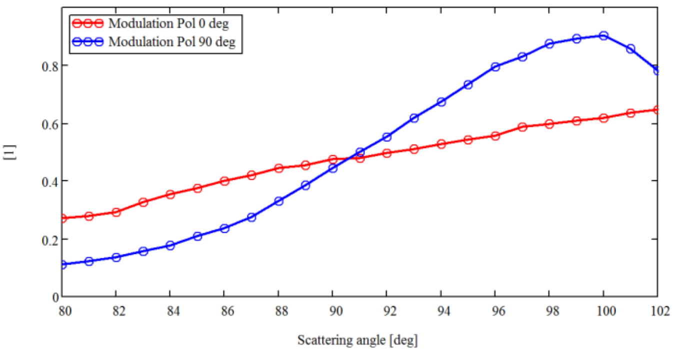

Figure 5. Fringe modulation respectively image contrast calculated by Mie scattering for a bubble in water (Scattering angle: 80 deg to 102 deg, laser wavelength: λ=532nm, relative refractive index: m=0,75a)

Last layout criteria for the scattering angle and polarization are shown in Figure 6.

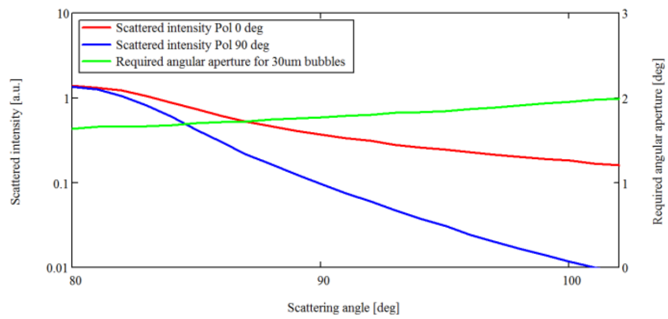

Figure 6. Scattered intensity calculated by Mie scattering for a bubble in water (Scattering angle: 80 deg to 102 deg, laser wavelength: λ=532nm, relative refractive index: m=0,75a) and required angular aperture for sizing a 30µm bubble

The image quality and SNR goes mainly with the scattered intensity (red and blue curve in Fig. 6). Smaller scattering angles provide higher image intensities but with lower modulation (Fig. 5). The intensity for 90 deg polarization drops rapidly down for higher scattering angles. Therefore in terms of intensity 0 deg laser polarization should be used. Also a compromise can be found for a scattering at about 90 deg. The intensity is only a quarter (26%) of the intensity at 80 deg but the image modulation is about two times higher (Figure 5). It should be noted, that the image intensity is not a measure for the particle size, because the particle can be located inside the laser beam at different positions with different incident intensities. Therefore the image intensity depends also on particle position but cannot be larger than a maximum value. Nevertheless the fringe pattern intensity can be utilized for detection volume correction algorithms. The idea of the correction procedure was presented in [5]. On the right axis the required angular aperture for sizing at least 30µm bubbles is plotted. The smallest size corresponds with one fringe in a defocussed image.

Finally the optical layout can be summarized for the actual measurement problem of bubbles sizing. The flow is illuminated by a Nd-YAG laser with parallel polarization. For increasing intensity the laser was not equipped with any additional light sheet optics as known from IPI [2] or ILIDS [1] techniques. Because of homogeneous nuclei distribution in the inflow and the convection of the fluid all nuclei move temporally through the measurement volume. The scattered light was observed under 90 degree with a defocussed camera.

From previous phase Doppler measurements in cavitation tunnels it was known, that bubble concentrations are comparatively small [4]. The number concentration of the disperse phase is dominated by small solid particles, like crystals, abrasion, paint remains and organic components like alga fragments. Often 10 times more solids are in a wake flow than bubbles. Therefore the bubbles images must be separated from the images generated by solid particles, to provide reliable input and validation data. Only bubbles interact as cavitation nuclei. The separation was performed on the different scattering behavior of solid particles compared to homogenous spherical bubbles (Figure 7).

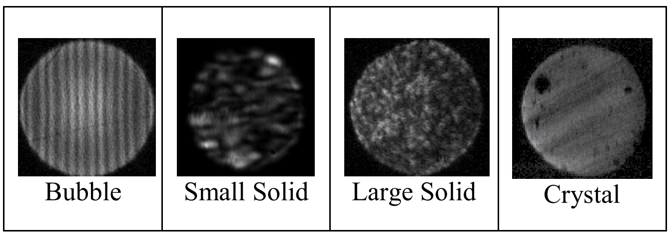

Figure 7. Example of defocussed images from different particle types from [5]

Inhomogeneous, rough and arbitrary formed particles generate more than two glare points. The waves from multiple glare points interfere and generate more complex interference pattern. The glare points for small solid particles are located closed together and therefore a coarse interference pattern (speckle) can be imaged. Large particles generate a fine grained interference pattern. A crystal has usually facets. This causes overlaying fringe pattern of different frequencies in well-defined direction, where the fringe pattern looks irregular. A discrimination and classification method for bubbles and solid particles can be developed on the spectral characteristics of the defocussed images by using power spectral density

(PSD) and FFT processing [6]. Properties like the number, height and width of local maxima in the imaging and spectral range are normally used for classification. In the specific application vertical oriented fringes must be separated from other structures. Another feasible classification parameter was found by using the ratio of the column-wise sum of line-wise FFT and line-wise PSD calculations. This parameter includes the fringe orientation as well as the coherent spectral image information. Best classification results were achieved by combination of both techniques.

III. HARDWARE SETUP

As described in the previous section the setup consists of a laser and a camera in a specific scattering angle. For most applications a perpendicular observation (90 deg scattering angle) seems to be a reasonable tradeoff between scattered intensities, image modulation, diameter resolution and optical aberrations and image distortions.

The HDNC technique was applied in cavitation tunnels and on a vessel [4], [5], [8]. The optical configuration for the full scale measurement can be seen in Figure 8 with measurement distances up to 5 meters.

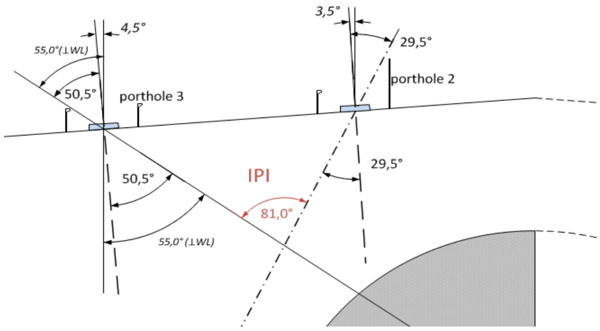

Figure 8. Optical setup on the freight ferry Amandine from [6].

Low image intensities occur for large measurement distances in the meter range. For such application scenarios smaller scattering angles are advantageous (see Fig. 6). The full scale measurements on the ferry ship Amandine are therefore performed at 81 deg. For standard applications in cavitation tunnels a 90 deg camera location is preferred because of an easy mechanical setup and polarization invariance.

The angular aperture defines the minimum measurable particle size, in general given by one or two fringes in the defocussed images. For measurements in cavitation tunnels fast-lens objectives with large aperture diameters were used.

The array sensor parameters mainly influence the size range and of the HDNC technique. The maximum bubble diameter is given by the Nyquis criteria. The fringe number can be reconstructed, if a fringe covers at least 2 pixels. The size range can be increased by increasing the defocussing. Nevertheless, the image intensity decreases and the overlap between defocussed images can appear. The latter ones degrade the particle classification and fringe count estimation.

Beside a high resolution a high frame rate decreases the required measurement time for reliable nuclei statistics. By imaging a process velocity of 1m/s and a laser diameter of 1mm every 1ms a statistical independent measurement can be taken. This requires frame rates over 1000 frames/s, which is possible by using high speed cameras. Nevertheless, such cameras store the image information on an internal memory and continuously real time measurements become impossible. Therefore a line camera could be the device of choice. This camera type can provide the fastest possible frame rates for CCD/CMOS technology camera systems.

The calculations that are required to obtain the fringe count and the bubble size distributions are possible to be executed on a hardware platform. The ability of fast Matrix and Vector calculations are crucial for such a device. Some modern field programmable gate arrays (FPGAs), modern Graphics Processing Units (GPUs) and also Digital Signal Processors (DSPs) are able to perform these operations highly parallel. Multiple Fourier transforms are also possible in parallel by different library implementations for these devices. The required power density spectrum (PSD) of the interference pattern can be calculated. These kinds of devices can also perform cross correlations with a shape in aperture form to find the particles on the image.

At the moment a FPGA approach is favored because of the high flexibility in design and the possibility to generate a special application specific circuit (ASIC) at the end of the design process. Another important reason is that special industrial line cameras with an integrated FPGA are available.

First preliminary tests with an available RGB sensor from NEC (µPD8880 with >20.000 pixels @ ~400 lines/s) and a Spartan 6 PFGA (Digilent Nexys 3) were promising [9]. Also an implementation of a Fourier transform by the GPU was already investigated and the speed up compared to a usual CPU from a computer was in the range of factor 50.

A conservative assumption is that 100 frames per second could be achieved by these specialized processors. The reason to take these implementation variants into account is the request to design an online real time measurement system.

IV. RESULTS

The HDNC technique was compared to the Time shift and Phase Doppler techniques. A comparison test in a cavitation tunnel of a project partner has shown that the Phase-Doppler technique and the HDNC technique can deliver comparable results in terms of a corrected nuclei number concentrations (Fig. 9).

Variations in the particle number concentrations between the techniques are reasonable and are probably caused by the different measurement volumes and measurement times of both techniques. The elliptical detection volume of the phase Doppler technique was 0.016 mm^{-3}. For the HDNC technique the cylindrical detection volume was estimated to 0.067 cm^{-3}. The huge difference influences mainly the measurement time to get confidential statistical results. Whereas the phase Doppler technique requires about 10 minutes for a nuclei statistics the HDNC is able to generate such statistics in less than a second.

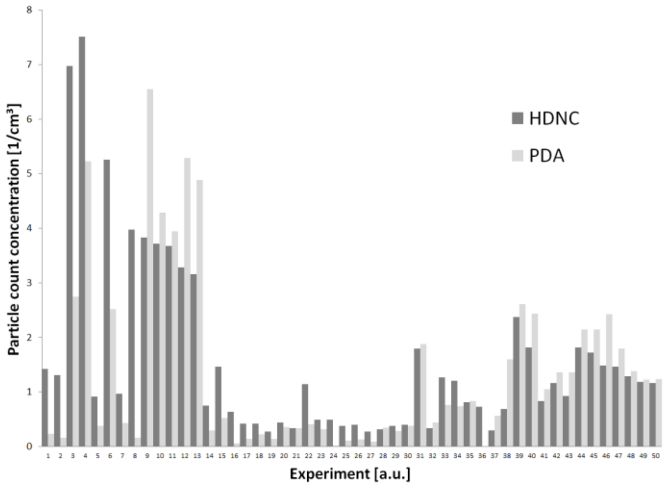

Figure 9. Comparison of a Dantec Dynamics PDA system measurement with the HDNC technique

A further essential advantage of the HDNC technique for characterization of disperse flows is the reduced complexity, the simple alignment and the low financial effort in comparison to standard techniques like phase Doppler technique. Summarizing the HDNC technique is able to solve the tasks in cavitation research from the KonKav project. Full scale measurements on the ship called Amandine and during the measurements in cavitation tunnels were successful. The extensions and adaptions of the IPI technique provides a reliable and robust measurement system that can be applied harsh industrial environments like a ferry ship.

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