Interferometric Particle Imaging for cavitation nuclei characterization in cavitation tunnels and in the wake flow

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Abstract The requirements of the KonKav project made it necessary to find a suitable technique for particle characterizations in cavitation tunnels and in the wake flow of a ferry ship. This paper depicts the possibilities of the Interferometric Particle Imaging (IPI) technique for applications in cavitation research. Furthermore recommendations for modifications of the known IPI technique [1] are provided to solve different issues in the cavitation application. We had to take the influence of long measurement distances, the limited optical and mechanical access into account while modifying the measurement system. A possibility to obtain an appropriate focal point for IPI measurements is found. Segmentation and classification methods for different particle types are investigated. Based on these methods the resulting bubble and nuclei concentration of the measurements in cavitation tunnels and the full scale measurement is calculated. The procedure of obtaining the concentration is also specified.

1. Introduction

Rudder and propeller cavitation causes vibrations, erosion and damages of ships. Cavitation also impairs the vessel efficiency. Therefore a reliable prediction for cavitation is required, which also consider experimental results and numerical calculations for model size and full scale [2].

The developments presented in this paper were funded by the Federal Ministry of Economics and Technology (BMWi) in the KonKav-project (Forschung zur KOrrrelation von KAVitationseffekten und Erosion unter Berücksichtigung von Wassereigenchaften und Nachstrom). The correlation of cavitation and erosion considering water quality and wake flow was investigated in the project. Project partners are the Hamburg Ship Model Basin (HSVA), Potsdam Model Basin (SVA), Technical University of Hamburg Harburg (TU-HH), Flensburger Schiffbau-Gesellschaft (FSG) and the University of Rostock. The KonKav project consists of three phases with the following experimental parts.

- KonKav I: Influence of water quality to cavitation and comparison of different cavitation tunnels
- KonKav II: Full scale velocity and nuclei characterization measurements in the wake flow and scale effects
- KonKav III: Investigation of cavitation erosion

Cavitation and cavitation effects are influenced by water quality. One important parameter is the nuclei concentration, namely the bubble concentration. Whereas the oxygen saturation, pressure and other global parameters are routinely measured in cavitation tunnels, the bubble concentration and bubble size distribution was completely unknown. Therefore the objectives of KonKav include measurement of nuclei concentrations in cavitation tunnels (in KonKav I) and in the wake flow of a vessel (in KonKav II). The University of Rostock developed the measurement techniques as well as applied these techniques to generate input and validation data for the project partners.

The applied optical measurement techniques can estimate nuclei concentrations by using interferometric particle imaging (IPI) and can measure flow velocities by PIV in the wake flow of a model and full scale ship. The present paper refers to the particle characterization by IPI technique. Measurements in model basins and cavitation tunnels with IPI technique were performed in the HYKAT and in the K22 of the Hamburg Ship Model Basin (HSVA), in the K15A of the Schiffbau-Versuchsanstalt Potsdam (SVA) and in the K21 of the University of Rostock. The measurements on the RoRo ferry ship Amandine are recorded in July 2012 and in April/May 2013.
2. Applied Techniques

Cavitation on marine propellers is influenced by the water quality. In addition to oxygen saturation, velocity and pressure also nuclei in the inflow induce cavitation inception. Small bubbles can enter the tip vortex of the propeller blade and will be expanded to cavitation structures (see Fig 1). Therefore the number concentration of the bubbles directly influences the prediction of cavitation inception.

![Fig 1 Bubble induced cavitation.](image)

2.1 Phase Doppler technique

In a first step phase Doppler measurements were performed for nuclei concentration measurements in the cavitation tunnels. The results show, that the disperse phase is dominated by solid and non-spherical particles. For most operation points of the cavitation tunnel the number concentration of bubbles is a magnitude smaller than the concentration of solid particles. The solid particles in the cavitation tunnels arise from abrasion, paintings, previous PIV measurements and organic substances and cannot be removed from the water. The phase Doppler system can only measure homogeneous spherical particles but can classify non-spherical particles for validation. Because of the high number of non-spherical solid particle a statistical approach was developed to correct the bubble size spectra and number concentration. Nevertheless, for low bubble concentration the statistical correction fails. Furthermore the detection volume of the phase Doppler technique is too small to get reliable bubble statistics in an appropriate measurement time for bubble concentrations of less than 10/cm³. Typical measurement times were in the order of 10 minutes.

2.2 Interferometric particle imaging

To overcome the problems of the phase Doppler technique an in-situ measurement technique with larger measurement volume, a higher data rate and reliable solid particle/bubble discrimination is required. In KonKav the IPI technique was adapted for nuclei measurement in cavitation tunnels and in the wake filed of a vessel. The fundamental of the IPI technique can be found in e.g. [1] or [3]. Before presenting results, the necessary adaptions of the IPI technique for nuclei measurements will be described in the following sections.

IPI nuclei measurements

The optical configuration of the IPI technique had been optimized for bubble size measurements. A linear relation between bubble size and fringe spacing exists for scattering angles between 80deg and 100deg for both polarization components. For this scattering angle the fringe conversion factor is in the order of k = 0.02deg·µm⁻¹ (fringes per aperture angle and bubble size in micrometer). The used apertures were in the order of 20mm and the working distance was about 300mm. This results in a minimum bubble size of about 20µm. The former phase Doppler measurements show, that only bubbles larger
than 30µm exist in the in-flow of the propeller, because small bubbles are dissolved in the water during a circulation in the cavitation tunnel. Because of higher intensity a scattering angle between 85deg and 90deg was chosen for the measurements in cavitation tunnels. For full scale measurements a scattering angle of 81deg was chosen. Furthermore only one polarization component holds a sufficient fringe modulation.

In comparison to the standard IPI setup only a single laser beam without laser light sheet optics were used for illumination. There are a number of advantages by using a laser beam for the respective application of nuclei measurement:
- The high number concentration of solid nuclei generates a huge number of defocussed images. By using a laser light sheet the particle images overlap strongly and image processing becomes impossible. By using a single laser beam only a reduced number of particles are imaged and the overlap is reduced.
- The higher intensity of a focused laser beam results in a higher scattered intensity. Instead of an expensive high power pulse laser with limited repletion rate a simple continuous wave laser without optics can be used. The data rate depends no longer on the repetition rate but is given by the frame rate of the camera.
- The image processing becomes much more efficient by using high frame rates with limited number of particle per image (maximum 10) along a well-defined region of interest.
- The installation and adjustment of laser, optics and camera are straight forward.

In general, a reduced illuminated volume results in a reduced data rate and therefore a longer integration time for same statistical uncertainty. For the specific application, the orientated inflow is scanned by the laser beam. With a high frame rate and reduced image processing time a similar statistical uncertainty can be reached for the same time.

Separation of bubbles and solid particles

In cavitation processes only bubbles interact as nuclei. Micro bubbles are expanded in low pressure regions and form cavitation structures e.g. in-stationary tip vortex cavitation. In the investigated applications a huge number of small solid particles like organic particles, sand grain, abrasions and also tracer particles from PIV experiments in cavitation tunnels disturb the nuclei concentration measurements. Therefore spherical shaped bubbles were separated by their IPI interference fringe system.

If the particle is inhomogeneous or rough the interference pattern differs from periodic fringes. This is utilized the discrimination between bubbles and solid particles [4] & [5] (see Fig 2).

<table>
<thead>
<tr>
<th>Bubbles</th>
<th>Small solids</th>
<th>Large solids</th>
<th>Crystal</th>
</tr>
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Fig. 2 Examples of interference pattern from different particle types in a Gaussian laser beams

Optimized focal plane position

The recorded size of the defocused particle images depends on the aperture of the optics and the focal plane. An approximation of the effects for different focal planes can be calculated by optic simulation. An example is depicted in figure 3. The bubble has a
diameter of 40µm and an interference pattern of 13 fringes is generated. For real lenses a caustic occurs by the spherical aberrations of the lens. The wave front is disturbed and therefor the fringe pattern is deformed (compare Figure 3 and Figure 4d). This causes in the real measurement a blurred contour of the fringe pattern and complicates the particle detection and image processing.

An optimized focal plane for the IPI recording can be specified by the calculation of a mean gray scale gradient (Laplace transform) for all images in a sequence. The result is a quality curve with three maxima for different specific focal points (Figure 4). The marked focal points a) to d) provide an impression of the particle separation situation.

a) Strongly Defocussed: The fringe patterns are too close together with a strong overlap. Results are low gradients in the calculation of the quality function.

b) Optimal separation of defocused images with high gradients in the quality function. This is best degree of defocussing for IPI recording.

c) Focused position: No interference pattern are observable no IPI recording possible.

d) Good separation of bubbles and therefore high gradients in the quality function. The image rays do not generate a caustic at the image border. Therefore the border of the images is slightly diffuse and the image detection is worse in comparison to position b)
Detection of the particles

For concentration measurement the individual particles must be detected. For reducing the overlap and decreasing the complexity of the image processing only a laser beam without laser light sheet optics was used. With this optical configuration the particle images are located along the imaged laser beam axis. Beside a simpler localization of the defocussed images the frame rate of the camera can be increased, because only an elongated rectangular ROI can be used.

For particle detection a correlation of the frames with a circular mask image is used. The geometry of the mask depends on the aperture shape and the size is pre-estimated from the image sequence. The maximum of the correlation function provides the position for each particle in the frame.

The reduced pixel number and the simpler image processing allow also continuously real time IPI measurements for the presented application. First real time experiments with an industrial camera and a DPSS laser were successful. During the test the IPI analysis algorithm achieved up to the 6 frames per second.

Classification of particles

Because of the large amount of solid particles in the flow, the bubble images with clear periodic fringes must be separated from speckle dominated or rotated images. This classification in bubbles (nuclei) and solids is based on Fourier analysis and autocorrelation function. The spectra from the Fourier analysis contain more information than only the particle size. The PSD has separated local maxima in case of bubbles and in case of a solid particle more local maxima occur in the 2D PSD [4]. Furthermore coherent structures of the fringes can be detected by Fourier transforms. Further important parameters of the PSD spectra can be identified for discrimination of bubbles and solid particles:

- Dominant peaks ratio
- Total count of local maxima
- Distance of dominant peaks
- Width of dominant peak
Spectral analysis of particles

For size estimation of the bubbles one-dimensional Fourier transforms are applied to each line of the detected bubble images. In case of the homogenous spherical particle the local maximum in the PSD yields the fringe count and so the particle size. The particle size is proportional to the fringe count. The conversion factor is determined by Mie calculations [3] & [4] for the specific geometrical properties of the experimental setup.

Concentration Calculation

The mean intensity of the particle image is a measure for the particle position in the laser beam according to its size class [3]. Small particles scatter less light and are therefore less intense than larger particles around. Large particles are also detectable in outer regions of the Gaussian laser beam. Figure 5 depicts this relation for an ensemble of 2360 detected bubbles separated into size classes. Model based curves are fitted to obtain the relevant parameters of the diameter dependent detection volume. Small particles are underrepresented in the measurement statistics. A measurement volume correction is required to overcome this issue. Two possible approaches for this correction have been investigated:

- The first method assumes that the recorded particle size distribution is a convolution of the real particle size distribution with the laser intensity distribution. A deconvolution of the recorded size distribution by the known laser distribution (calculated by the laser properties) provides the real existing particle size distribution.
- A second approach is based on the detection volume statistics similar to phase Doppler concentration measurements. A maximum intensity of the size class (green curve in Fig. 5) is calculated to obtain particles with outlier-intensities. These particles are removed from the dataset to calculate a corrected maximal intensity. Each particle size class has its own detection area in the laser beam which corresponds to a maximum and a mean image intensity of the whole particle ensemble in the size class. Together with the detection threshold (blue curve in Fig 5), which can be specified from the particle detection algorithm, the model based mean intensity curve (red curve in Fig. 5) can be fitted on the measured mean image intensities (red dots in Fig. 5). From the parameters of the detection volume model a correction factor for under- and over-estimation of the particle counts in each size class can be derived. The original particle count distribution (black open bars in Fig. 6) can be afterwards corrected (red bars in Fig. 6) and related to the standard laser beam volume to get the number volume concentration (Fig. 7). The uncertainty of the concentration estimation (error bars in Fig. 6 and Fig. 7) is related to the total number of detected particles in the specific size class.

![Fig. 5 Dependence of mean particle intensity and particle size class](image-url)
Fig. 6 Detected bubble distribution (black open bars) and corrected bubble size distribution (red bars) with uncertainties (error bars)

Fig. 7 Corrected spectrum of bubble number concentration (integral number concentration 1.288 cm⁻³)

3. Experimental Setup

Two experimental setups are used for the measurements. The first setup is applied for a measurement at the Cavitation tunnel K15a at Schiffbau Versuchanstalt Potsdam (SVA) (Figure 8). A 300mW 532 nm DPSS cw-Laser was used for illumination of the measurement volume.
The particle images were recorded with a Vision Research Phantom V310 high speed camera and a Basler Scout industrial camera. For both a Nikon AF-S NIKKOR 50 mm 1:1.8 objective was used. The Basler Scout camera was located under a scattering angle of about 90deg and the Phantom camera at scattering angle of about 81 deg. The laser beam illuminates the flow from the bottom side of the cavitation tunnel through a PMMA window. The ship model was attached to top of the cavitation tunnel and the propeller was driven to obtain cavitation effects.

Among IPI measurements in the cavitation tunnel also nuclei measurements under a ferry ship were performed. The ferry was equipped with four portholes, which were used for full scale velocity measurements by PIV up to 5m distance. Two portholes were also used for IPI measurements (Figure 9a). A 200mJ DualPower Nd-YAG pulse laser from Dantec Daynamics A/S with a repetition rate of 15 Hz was applied for illumination (Figure 9c). The laser was coupled into the water by using flexible liquid prisms filled with water. The defocussed images were recorded by a Vision Research Phantom V12.1 high speed camera together with a Canon EF 400mm f/2.8L IS II USM a 400mm fixed-focal-length objective with large aperture. For reducing aberrations also a flexible liquid prism was used in front of the camera (Figure 9b).

The long distance between the measurement volume and the recording plane of the camera of 1180 mm causes problems in the system setup. The sea water contains huge number of scatters and therefore a considerable part of the light intensity is adsorbed. On the other hand the laser intensity is also limited by the porthole glass. We found that pulse energies larger than about 70 mJ could damage the porthole glass. The scattering angle between camera and laser was set to 81° because the scattered intensity had to be optimized for the long distance full scale measurements.
3. Example Results

3.1 Cavitation tunnel

One example bubble size distribution from SVA cavitation tunnel is illustrated in Fig. 10. 9220 bubbles and 51655 solid particles were recorded. The laser beam defined measurement volume for each frame was about 200 mm³. With the high speed camera 41800 frames were recorded with a frame rate of 1kf/s. About 5.6 times more solids than bubbles are in the water of the cavitation tunnel. By using the fringe conversion factor and the aperture size each fringe corresponds to a diameter change of 10.04µm. The mean bubble number concentration was estimated to 1.1 bubbles/cm³. The number concentration of the detected solid particles was in the same order of magnitude, which shows the need of bubble and solid classification. Furthermore the example illustrates the advantage of the larger measurement volume for this application with low number concentration. The effective measurement time was 42s. The point wise phase Doppler technique needs several hours to reach the same statistical uncertainty.
3.2 Full scale measurements

In a second application the particles in the wake flow of the ferry ship Amandine are measured (setup see Fig. 9). Sample defocused images can be seen in Figure 11a and 11b. The distributions shown in Fig 11c are recorded during a measurement journey in May 2013. Recorded were 6084 bubbles and 55808 solid particles in a measurement volume of about 270 mm³ and 21904 frames. About 9.17 times more solids than bubbles are in the free water. Because of the larger working distance, one fringe corresponds to a diameter class of 17.62 µm in this case. The mean bubble count concentration was estimated after correction to a similar value as in cavitation tunnels of 0.72 bubbles/cm³.
Fig. 11 Defocussed particle images in the wake flow of the Amandine sea water without bubbles. a) solid particles  b) bubble swarm in the wake flow  c) measured particle size distribution  d) particle classification

4. Conclusion
Adaptions and modifications of the Interferometric Particle Imaging technique allow nuclei concentration measurements in model basins and cavitation tunnels and in the wake flows of full scale vessels. Different optimization and analysis methods are developed, which allow a particle detection, classification as well as concentration calculations with a minimum of hardware effort. The IPI technique has in terms of robustness, measurement volume size, data rate, optical access, adjustment and financial effort advantages for industrial measurement applications in rough environments in comparison to other techniques like phase Doppler. The next step for future developments of the IPI technique could be the development of a smart camera system that can perform the analysis directly to speed up the online analysis process.

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6. References