HDNC - A Novel Technique for Cavitation Nuclei Characterization and Particle Count Concentration Measurements

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Abstract

Depicted is the Hydrodynamic Nuclei Concentration (HDNC) measurement technique. This technique is an interferometric particle characterization technique based on the Interferometric Particle Imaging (IPI) technique. Based on the laser light scattering of particles is the size of spherical bubbles estimated. A classification method provides information about the particle type. In junction with the possibility to estimate the measurement volume is bubble size based particle count concentration estimated. The technique was applied on a ConRo ferry ship called "Amandine" travelling between Rotterdam and Dublin. Depicted are especially the fluctuations in the particle count concentration by bubble clouds in the wake of the ferry. Furthermore depicted is a new particle segmentation technique based on the particles phase information..

Keywords

Particle concentration — Bubble cloud — Particle characterization

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INTRODUCTION

Cavitation impairs the efficiency and causes vibrations, erosion of a vessel [1]. Therefore are cavitation prediction models important for the design process but not sufficient reliable at the moment. Ship model basins and cavitation tanks are required to predict the full scale vessels cavitation behavior.

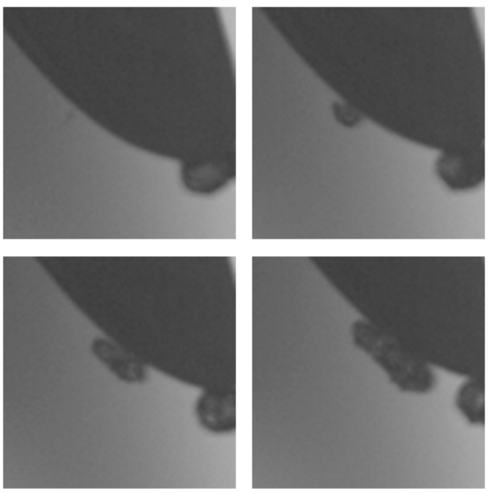


Figure 1. A bubble expanding at propellers surface recorded with a high speed camera and stroboscopic illumination

The water quality has an important influence for the cavitation inception [2] & [5]. Therefore nuclei count concentration and the nuclei size distribution in the vessels wake flow affects the cavitation behavior. For example are bubbles expanded in low pressure (suck side) and collapsing at high pressure (draught side) regions near the propellers surface (fig. 1).

The KonKav project was founded by the Federal Ministry of Economics and Technology (BMWi) in Germany to investigate the influence of water quality to cavitation processes. Model scale and full scale measurements of the nuclei properties were performed. Project partners are the Flensburger Schiffbau-Gesellschaft (FSG), Hamburg Ship Model Basin (HSVA), Technical University of Hamburg Harburg (TU-HH), Potsdam Model Basin (SVA) and the University of Rostock.

The Hydrodynamic Nuclei Concentration (HDNC) technique was during the KonKav project developed. The HDNC technique is a size calibration free technique and combines moderate hardware and alignment effort with the ability to measure bubble size distributions in the 5..400 µm range and bubble count concentrations depending on the optical configuration. The estimation of the nuclei spectra is in the application strongly influenced by the often 10 times higher solid concentration compared to the gas bubble concentration in the Irish Sea. Therefore is the classification process of the HDNC technique essential for a reliable cavitation nuclei distribution statistics.

1. METHODS

The HDNC technique is based on the scattering behavior of nuclei in a laser beam [4]. The illuminating laser beam from an inexpensive 532nm DPSS laser defines the dimension of the measurement volume in combination with an industrial camera with imaging optics. The usually applied scattering angle between the camera and the laser is 90 deg because of easy alignment and polarization invariance [2]. In case of the described full scale setup is a scattering angle of 81 deg applied because of the much higher available intensity. At this angle is the polarization of the laser beam important for the modulation depth of the signal. The laser had to be aligned correctly. Fig. 2 depicts the principle of measurement.

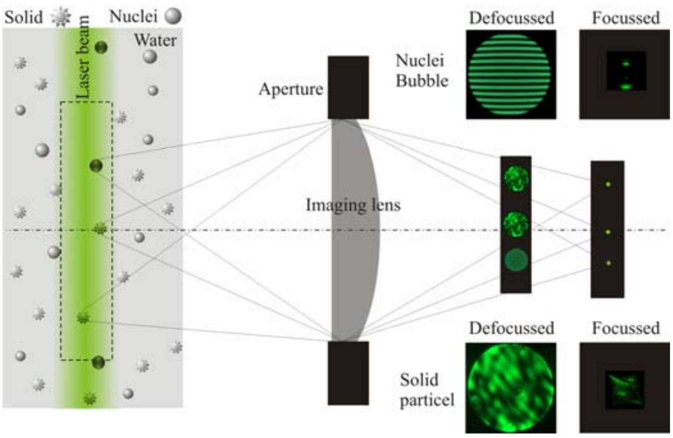


Figure 2. Principle of the HDNC technique [7]

Required are two optical accesses for the laser beam and the defocussed camera. The nuclei are depicted defocussed inside the focal length. The light waves with the origin at the glare points on the particles surface interfere with each at the imaging plane and provide interference pattern to the analysis.

The interference patterns are typical structured for different particle types. Homogenous spherical particles (like µm gas bubbles in water) have two dominant glare points at the specified scattering angle.

A fringe pattern occurs therefore in the imaging plane. The spacing between the fringes is proportional to the nuclei size. A calculation utilizing a Mie theory code provides the conversion factor between fringe count and particle size [5].

A particle with an inhomogeneous surface structure (like a solid in the water) has more than two dominant glare points on the surface. Therefore are speckle pattern visible in the imaging plane. Solid sizing algorithm is based on [6].

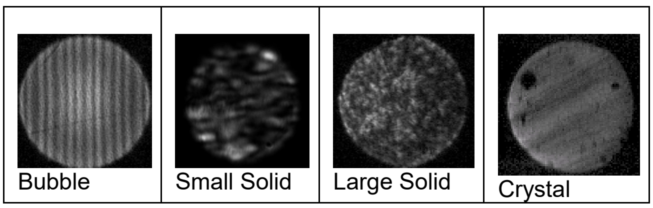


Figure 3. Interference pattern of different particle types

Fig. 3 depicts the observable interference pattern for different particle types.

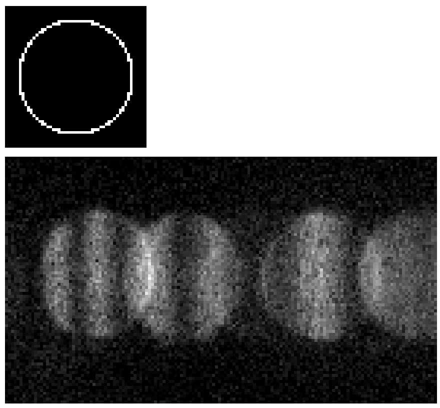
The different analysis steps in the HDNC technique are depicted in fig. 5. First step is the acquisition process. To obtain a good analysis performance it is necessary to select a focal position where the Nyquist criteria is fulfilled for the interference fringes of a nuclei and a good separation is available for close aligned particles. A trade-off is required for the focal position. An algorithm based on a quality function was implemented to achieve the right position. This quality function utilizes an edge detection to obtain image edges. Those edges are summed up to a value per image. In case of total defocussing is the sum of gradients low because everything is mixed up. In case of a sharp image in focus the value has a maximum. But two other local maxima can be observed. One local maximum is inside of the focal distance. A third little lower one is outside the focal distance. The higher local maximum inside of the focal distance is the best focal point for the HDNC measurements [5].

The scattered intensity is proportional to the square of the nuclei size: $I_s \sim d_p^2$. A similar algorithm is therefore applied to obtain the right shutter time for the applied global shutter camera and the laser intensity. Calculated is a histogram for a frame. If the full dynamics range is used the shutter time should be shorter to obtain also very large nuclei. If the shutter time is shorter fewer photons can reach the camera and blooming effects disappear. A longer shutter time is required to measure also smaller, lower scattering nuclei because of the cameras limited dynamics range.

After the acquisition of the nuclei images is a background subtraction required to become more accurate in particle segmentation and spectral analysis. The resulting in nuclei sizing and classification becomes therefore also more accurate. In a testing setup could be shown that the system noise is 0.56 µm (standard deviation in case of mono disperse drops).

Two nuclei detection algorithms based on template matching with a template in aperture shape are implemented. Usually a circular template like in fig. 4 a depicted is correlated with the nuclei image fig 4 b.

a)



b)

Figure 4. a) Template image in aperture shape
b) Nuclei interference pattern image [8]

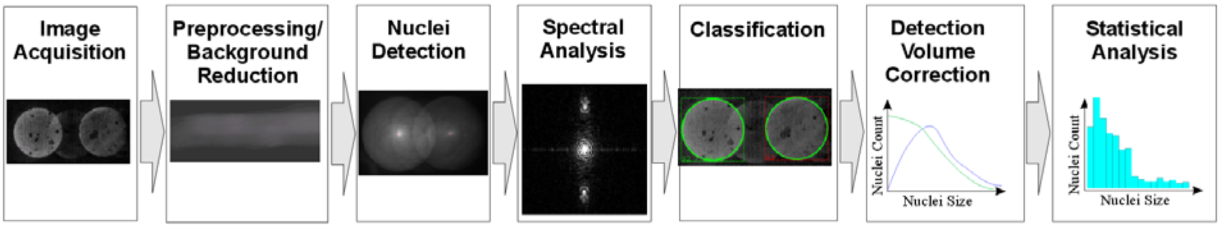


Figure 5. Analysis Flow of the HDNC technique [7]

The correlation by the template matching provides an image with local maxima at the position of the nuclei like in Fig. 6a).

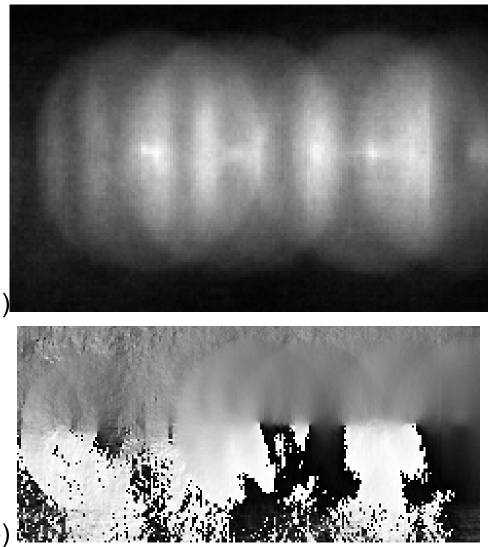
a)
b)


Figure 6. a) Correlation result from template matching
b) Phase information [8]

By a sine and cosine weighted template and a correlation for each of both is it possible to calculate the phase information for the particles image. This more sophisticated calculation method allows the detection of the nuclei center more accurate. Each point has therefore a value and a phase. This represents a vector for each pixel. In case of nuclei hits every vector the nuclei's center point.

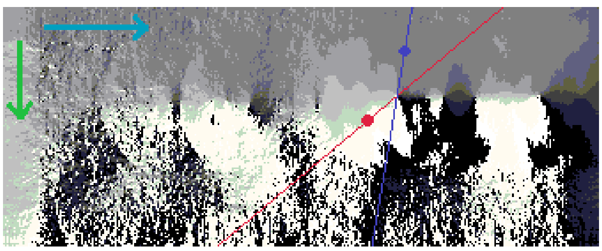


Figure 7. Two crossing vectors (red, blue) from the phase Information [8]

In other cases is no fix crossing point observable. By obtaining the count statistics of hitting vectors for each point is therefore a nuclei's centers detection possible. The higher accuracy is provided by a function fit through the vector hit count image. The local maximum of the fitted function provides the sub pixel accurate particle position. The phase information based method required much more complex calculations than the simple template matching method. Therefore is the analysis much slower. On a modern Intel i7 is the template matching possible with 10 to 15 frames per second with ~10 particles per image. The phase information based technique requires in the current implementation minutes per frame.

The applied classification of bubbles and solids relies on differences in the spectral characteristics (compare fig. 3). Fringe pattern have one sharp dominant peak in the PSD spectrum and speckle pattern have multiple minor peaks for each nuclei. Furthermore is the ratio of those peaks relevant. If the dominant peak is much higher than the second highest peak fringes will be observable. If more frequencies are mixed like in a speckle pattern the difference between highest and second highest peak becomes lower. The width of the peaks is a relevant quality criterion for the evaluation of the nuclei's interference pattern sharpness. With this information it's possible to classify into solids and bubbles.

A detection volume correction is necessary because of the Gaussian beam profile of the laser and the relation between particle size and scattered intensity (I ~ dp2) [3]. Therefore is the detection probability a function of the particle size. A correction method was implemented to overcome this issue [5].

The statistical analysis provides the information about the nuclei size distribution, the nuclei count concentration and the relation between bubble and solid count.

2. RESULTS AND DISCUSSION

In [7] is a comparison between the HDNC and the standard phase Doppler (PD) technique documented. Result of the comparison was that the HDNC is able to obtain similar quality nuclei size and count concentration results in much shorter measurement time for low concentration applications. A further improvement is the much lower hardware and calibration effort.

Therefore was the HDNC technique chosen during the KonKav project for full scale onboard measurements on the ConRo ferry ship "Amandine" and was applied at different ship model basins and cavitation tunnels (K15A, HYKAT, K22 and K21).

The full scale measurement is applied at 81 deg scattering angle because of limitations in the mechanical and optical accessibility [1]. Two port holes above the propeller allow the alignment of the laser and the camera in the correct position and define the measurement volume in front of the propeller to observe the inflow. Fig. 8 depicts the applied hardware on the ConRo ship.

a)


b)


Figure 8. Applied measurement hardware on the “Amandine” mounted on a linear and rotary stage to the porthole

a) Laser head
b) Camera and optics

Nuclei bursts occur approx. every 10 seconds with different particle count concentration intensities. Fig. 9 depicts the count concentration curve for a video recorded in the Celtic Sea. Therefore is the corrected nuclei count concentration not constant.

The nuclei bursts found in the wake flow of the Amandine are a significant difference between the model testing facilities and the full scale investigation. Usually is the goal for testing facilities to reach almost constant flow and pressure conditions during the tests. In the reality are those constant flow conditions not available also in the sense of nuclei count concentration. Between the lowest and highest nuclei count concentration is a factor of 10. Also the solid concentration was not constant in the Celtic sea during the measurement period of 42s.

The solids count is in mean around 9.17 times larger than the bubble count and has also large variations (5..40 per frame) during the measurements in the Celtic Sea.

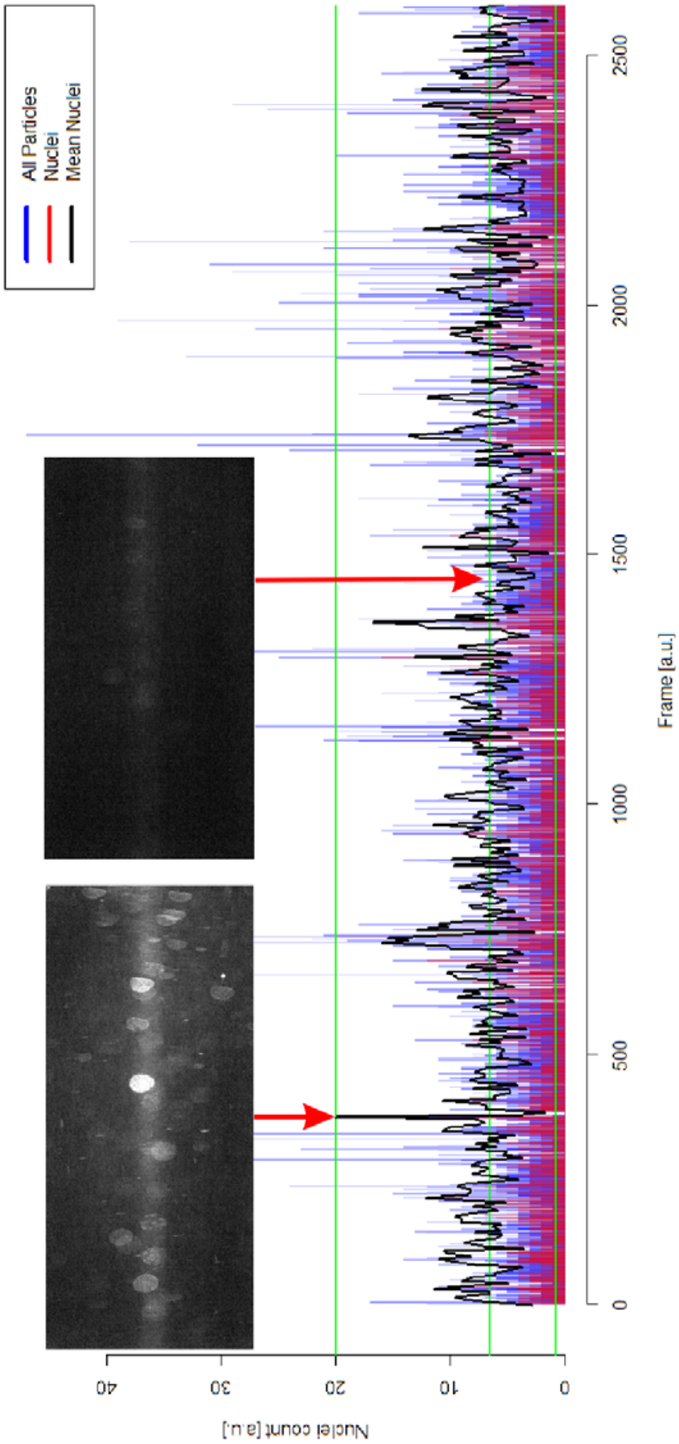


Figure 9. Measurement sample of 42 seconds recorded in the Celtic Sea (green min, mean and max lines for nuclei)

The particle size distribution and the corresponding particle count concentration distribution are depicted on fig 10. The most measured particles are in the range between 20 to 150 µm. This matches the range that can be found in literature for cavitation nuclei sizes [9].

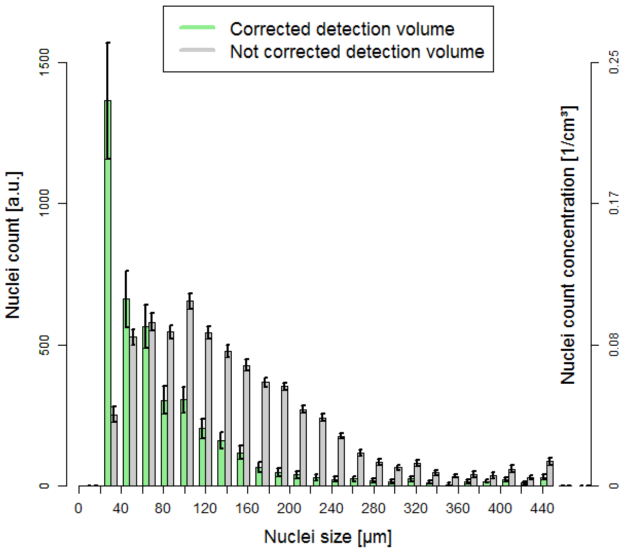


Figure 10. Particle size and particle count concentration distribution for the measurement on the “Amandine” with error bars.

3. CONCLUSION

The HDNC technique allows cavitation nuclei characterization measurements in different and also harsh environments like a ferry ship. The spectral classification method allows the separation of nuclei from solid particles. The developed segmentation techniques allow fast or more precise localizations of the particles. The nuclei size and count concentration can be estimated. A measurement of the particle concentration variation below a full scale ship was depicted.

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REFERENCES

[1] A. Kleinwächter, E. Ebert, R. Kostbade, and N. Damaschke, "Concept for optical full-scale measurements on ship propeller inflow and bubble size distribution," presented at the 8th International Symposium on Cavitation (CAV2012), Singapore, 2012.

[2] E. Ebert, K. Domke, W. Kröger, and D. Nils, "Particle characterization system for industrial and naval applications," in *8th International Conference on Sensing Technology*, Liverpool, UK, 2014.

[3] H.-E. Albrecht, M. Borys, N. Damaschke, and C. Tropea, *Laser Doppler and Phase Doppler Measurement Techniques*. Berlin Heidelberg New York: Springer-Verlag, 2003.

[4] T. Kawaguchi, Y. Akasaka, and M. Maeda, "Size measurements of droplets and bubbles by advanced interferometric laser imaging technique," *Measurement Science and Technology*, vol. 13, pp. 308-316, 2002.

[5] E. Ebert, A. Kleinwächter, R. Kostbade, and N. Damaschke, "Interferometric Particle Imaging for cavitation nuclei characterization in cavitation tunnels and in the wake flow," presented at the 17h Int Symp on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 2014.

[6] S. González Ruiz, M. R. Vetrano and J. van Beeck, Feasibility of using glory and speckle patterns for sizing spherical and irregular particles", von Karman Institute for Fluid Dynamics, Chaussée de Waterloo 72, 1640 Rhode-St-Genèse, Belgium und Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussel, Belgium

[7] E. Ebert, W. Kröger, N. Damaschke, Hydrodynamic Nuclei Concentration Technique in Cavitation Research and Comparison to Phase-Doppler Measurements, CAV2015, December 2015, Lausanne Switzerland, accepted

[8] K. J. Weder, Kreislokalisierung mit harmonischen Ortsfiltern für die HDNC-Partikeldetektion, 2015, Bachelor thesis, University of Rostock, accepted

[9] J. Carlton, J., Marine Propel lers and Propulsion Second Edition, 2007, Butterworth-Heinemann, Oxford .