Optical methods for nuclei spectra characterization in cavitation tunnels

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SUMMARY

The paper investigates the phase Doppler and time shift technique for quantitative water quality and cavitation characterization in five different cavitation tunnels. The phase Doppler technique is well established for sizing of spherical droplets and bubbles. By contrast, the application of the time shift technique to bubble size distributions is novel. We also present an extension to distinguish between bubbles and solid particles, which employs post processing of phase data and polarization information. Both techniques are compared with regard to their benefits and drawbacks in the context of water quality measurements.

INTRODUCTION

In the framework of a joint research project between Hamburg Ship Model Basin (HSVA), Potsdam Model Basin (SVA), Technical University of Hamburg Harburg (TU-HH) and University of Rostock, supported by the Federal Ministry of Economics and Technology (BMWI), quantitative measurements for determination of water quality and its influence on cavitation processes (Brennen 1995) are performed. The goal of the project is a reliable prognosis of cavitation on ship propellers based on experiments in cavitation tunnels. Experts in ship testing laboratories are able to accurately describe and evaluate cavitation because of their long experience. In addition, numerical simulations are considered.

Nevertheless, there is lag between quantitative water quality parameters like oxygen saturation and especially bubble size distribution, and quantitative statistical description of cavitation processes, like sheet thickness and cavitation volume. To provide comparable water quality parameters between different cavitation tunnels as input and validation data for numerical simulation more quantitative information is required.

In this paper we present experiments and results using optical laser measuring methods for water quality characterization as number of nuclei, bubble size concentration and distribution and solid particle concentration.

The main focus is on bubbles in the micrometer region. Their volume concentration and size distribution changes during measurements due to bubbles induced by cavitation. Investigations show, that the change in bubble concentration correlates with circulation time in the tunnel.

Solid particles are also of interest with regard to the nuclei spectrum, as they influence the cavitation behavior. Hence, we propose two methods to distinguish between solid particles and bubbles. The first method is based on the well known phase Doppler technique. The second method is part of the novel time shift technique.

EXPERIMENTAL SET-UP

The experiments were performed in different cavitation tunnels, namely in K15A (SVA Potsdam), K21 (University of Rostock Rostock), K22 (HSVA Hamburg), K27 (TU Berlin) and

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HYKAT (HSVA Hamburg). Each tunnel poses different challenges especially with regard to optical access, dimensions and nuclei concentration.

Under the assumption of no cavitation occurring in front of the working section we can expect a homogeneous inflow. It is then sufficient to capture the nuclei spectrum at one representative point in the model inflow.

Phase Doppler Technique

Laser Doppler anemometry (LDA) is a standard measurement technique for flow measurements in cavitation tunnels. Extending the LDA with additional detectors allows for the measurement of bubble sizes by the phase Doppler technique. For these measurements we require a scattering angle of 88° (Albrecht et al. 2003) and consequently two windows perpendicular to each other.

According to the laws of geometrical optic, the three phase Doppler detectors with different off-axis angles ψ provide two independent phase differences proportional to the bubble diameter ((Albrecht, Borys et al. 2003))

All phase Doppler measurements are performed with a commercially standard two-component phase Doppler system by Dantec Dynamics (Figure 1). The optical setups need to be adapted to each cavitation tunnel and are summarized in table 1.

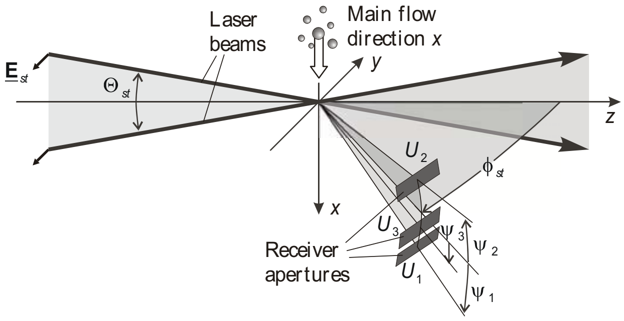


Figure 1: Optical configuration of a three detector standard phase Doppler system (from (Damaschke 2003))

Transmitter focal length	1000mm	310mm	310mm
Receiver focal length	600mm	1000mm	1000mm
Cavitation Channel	K15A/K27	HYKAT	K15A
Objects	2D/3D-profil	propeller	Propeller
Beam diameter	969µm	151µm	151µm
Nominal detection area	0.375mm²	0.097mm²	0.058mm²
Meas. Range (max. D_p)	730µm	378µm	227µm

Table 1: Used phase Doppler configurations and locations.

The measurements in combination with time shift technique are performed with the lowest transmitter focal length (f=310mm) because the time shift technique requires a small beam waist.

Bubbles are detected via a coincidence check between two phase differences. The phase difference values are visualized in a 2D phase plot as shown in Figure 2 and 3 for a typical measurement. Larger divergence from the inclined line (sphericity region) indicates deviant estimated diameter, i.e. from non-spherical, rough or inhomogeneous particles, like solid particles. Because the phase Doppler system assumes homogeneous spherical particles the diameter for signals outside the sphericity region cannot be measured. Signals in the sphericity region represent spherical bubbles, as seen in Figure 3 by the cluster near the sphericity line.

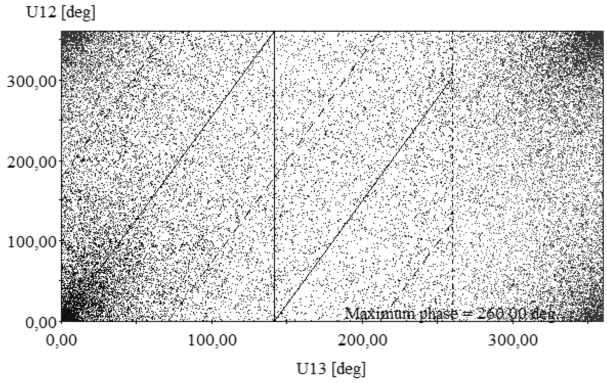


Figure 2: PDA phase plot without bubbles.

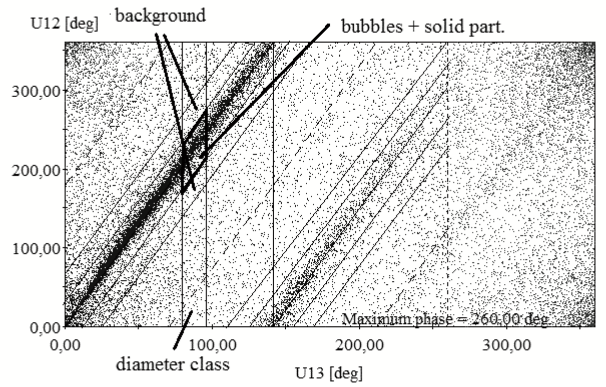


Figure 3: PDA phase plot with signals from bubbles and solid particles.

To estimate a bubble size distribution a novel background subtraction of solid particle signals is used. Figure 3 illustrates the method. The inner region near the sphericity line contains both correlated bubble measurements and solid particle measurements with random correlation. The data outside the correlated signal is used to estimate the uncorrelated background signals. Since the uncorrelated phase differences from solid particles are inhomogeneously distributed over the phase plane (see Figure 2), the estimation of the background has to be applied in the vicinity of the spherical line. The remaining particle signals are considered bubbles.

To evaluate the concentration and bubble size distribution from the remaining signals, the dependency between detection area and bubble size needs to be considered. Because the scattered intensity from small particles is less than from large particles the detection are depends on bubble size. Large particles are detected in a larger volume and therefore generally overestimated. The phase Doppler detection volume is nearly rotation-symmetric around the optical axis. In z direction it is limited by a slit aperture acting as a spatial filter. Consequently, the mean signal amplitude of detected bubble and also the burst length in flow direction is a measure for the cross extension of the detection area. The absolute size of the detection volume depends on the intensity of the incident laser beams, the imaging optics, photo detector sensitivity and further parameters. Therefore the detection volume size must be estimated from the bubble signals. For each measurement the mean trajectory length is estimated. Figure 4 shows the measured (dot) and the mean burst lengths (gray line), on which the evaluation of the concentration distribution is based. The particle number in each size class is weighted by detection area and the correction results in a more reliable size distribution and bubble concentration. Hence, influences from varying lighting conditions, polarization or detector adjustment can be minimized.

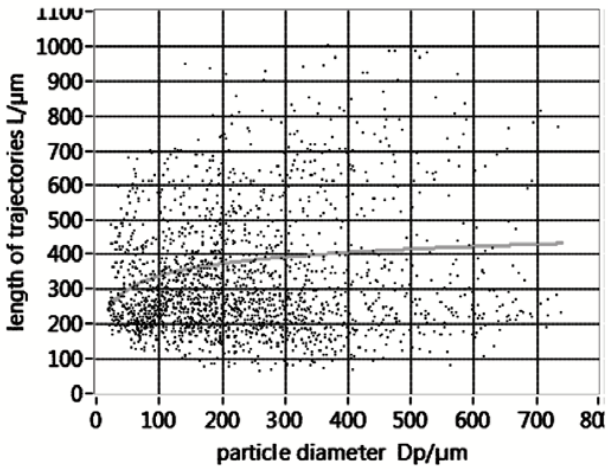


Figure 4: Scatter plot of burst length as function of measured particle diameter (only for validated signals).

Time Shift Technique

The time shift technique TST analyses backscattered light from a thin laser light sheet while particle crossing (Damaschke, Nobach et al. 2002); (Albrecht, Borys et al. 2003); (Kretschmer, Höhne et al. 2011).

This light sheet is projected into the same measurement volume as the laser Doppler and phase Doppler laser beams.

Due to the detector placement in the backscatter region at a scattering angle of about $\vartheta=\pm150°$, only one optical access is required. This is the main advantage of the time shift technique for measurements in cavitation tunnels

As shown in Figure 5, particles in air generate several scattering orders. With a light sheet smaller than the particle size the scattering orders arrive at the detectors time shifted. Spherical particles produce mirrored time shifted signals at two symmetric arranged receivers.

If one scattering order is dominant, the time difference between the signal maxima is proportional to the particle diameter and inversely proportional to the velocity.

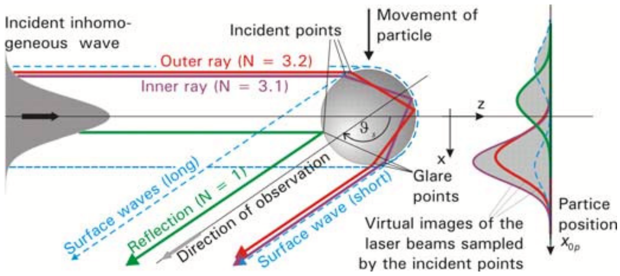


Figure 5: TST Signal generation, adapted from (Damaschke, Nobach et al. 2003)

In Figure 6 the optical configuration is illustrated. An additional Laser Doppler System measures the particle velocity. This laser Doppler is projected through the same transmission optics as the time shift light sheet. The beam waist with dimensions of 30 x 600 µm is created with an adjustable mirror and astigmatic optics. The light source is a blue polarised laser diode with 445nm wavelength and a maximum output power of 1W.

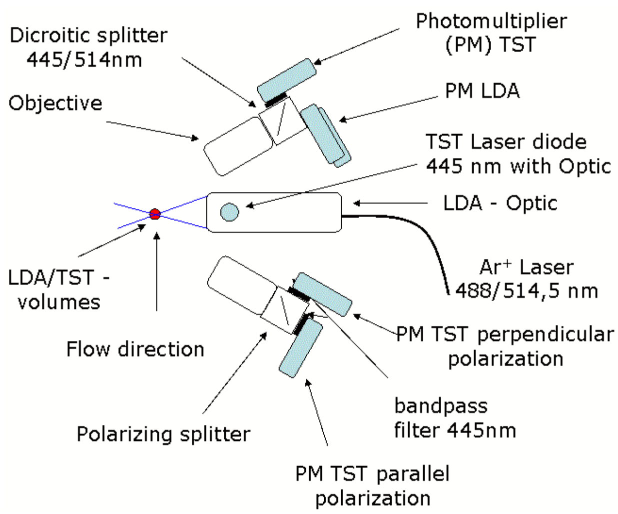


Figure 6: Optical configuration for the time shift technique

As opposed to phase Doppler signals, not only micro bubbles with ideal scattering properties, but also solid particles and larger bubbles can be recorded. Based on the polarization of the backscattered light a bubbles and solid particles can be distinguished. While spherical bubbles conserve the polarization, solid or deformed particles alter the polarization. To discern the polarization, one receiver is equipped with two detectors and a polarization splitter.

In Figure 7 the setup of the time shift system is shown on the K21 at University of Rostock. Both, transmitting and receiving optics are mounted on one holder and traverse system.

Figure 7: Experimental setup at K21. center: LDA transmitter, TST laser diode and light sheet generation, left and right: adjustable receiver optics with dicroitic and polarization beam splitter and two photomultipliers each side.

The laser Doppler and time shift data are recorded with integrated high-speed digitizers from National Instruments and streamed to hard disks. For maximum recording performance we analyse the results offline in Labview.

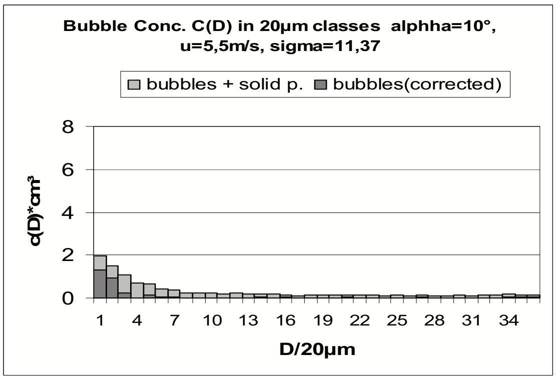
The signal and data processing algorithm filters the raw data and calculates the time-shift for the each individual valid particle. Therefore several adjustable validation parameters can be activated. Combined with the additionally recorded laser Doppler information the size of each event can be calculated.

To validate the system we record and analyze the raw data of the 3 channels from a commercial Dantec PDA system.

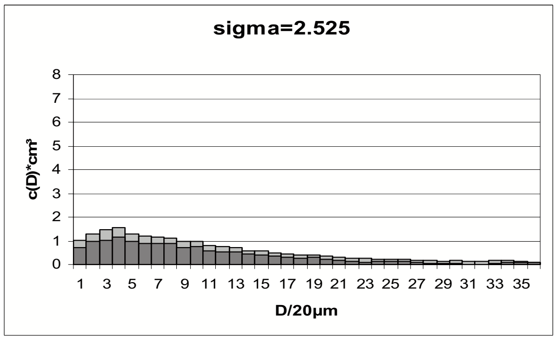
PHASE DOPPLER RESULTS

A typical cavitation experiment in this project has 7 tunnel settings, with different cavitation numbers. Beginning with normal or overpressure without cavitation, the cavitation number is decreased to cavitation inception. After the next steps with abundant cavitation must be the pressure higher for termination of cavitation. We observe a hysteresis, caused by changing the quality of circulating water, especially the solved and free gas content.

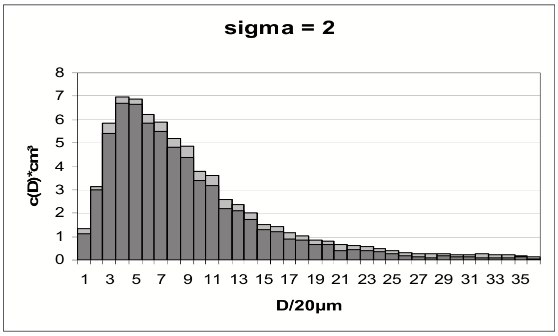
Figure 8 a)…e) show the size distribution of the number concentration for 5 steps by observation a 2D-profil NACA 66_2-415 with 10° pitch by u=5.5m/s in the K15A channel (SVA Potsdam).



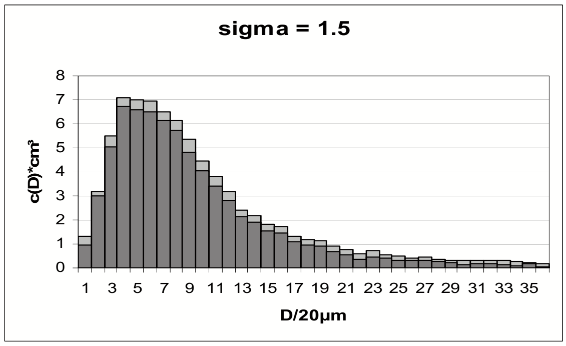
a)



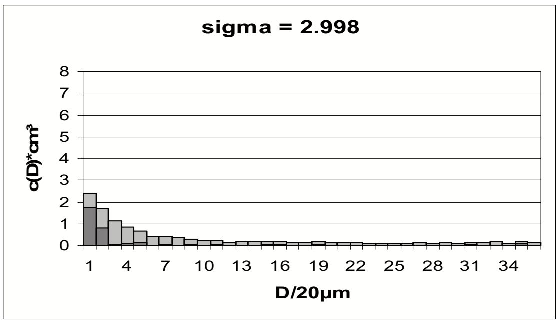
b)



c)



d)



e)

Figure 8: Bubble number concentration distribution for a) overpressure, b) cavitation inception, c) and d) abundant cavitation and e) cavitation desinence.

The example measurement is one of several hundred measurements, most of them not yet processed and evaluated.

The light gray bars show the number concentration without solid particle correction. The solid particle correction reduces the ghost bubble as can be seen the dark gray bars. The correction works properly for larger sizes. For size classes smaller 4 (smaller than 70µm) the correction algorithm works not perfect. Nevertheless the number concentration reduces for small bubbles significantly as can be seen in Figure 3b. Therefore the main part of the bubble size distribution can be corrected.

The O_2 Saturation, measured by normal pressure changes from 80.6% to 75.1% after the experiment. For the start setting no bubbles were detected. By reducing σ first bubbles appear at σ=2.5 and the concentration increases for smaller cavitation numbers. By increasing the cavitation number in Figure 8e the bubble size distribution show again no bubbles.

Figure 9 shows, that the bubble concentration especially in the steps 3 and 4 are not constant since the solved gas concentration decrease in this time interval.

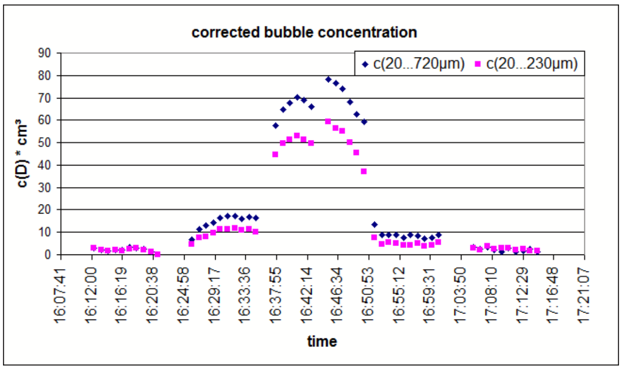
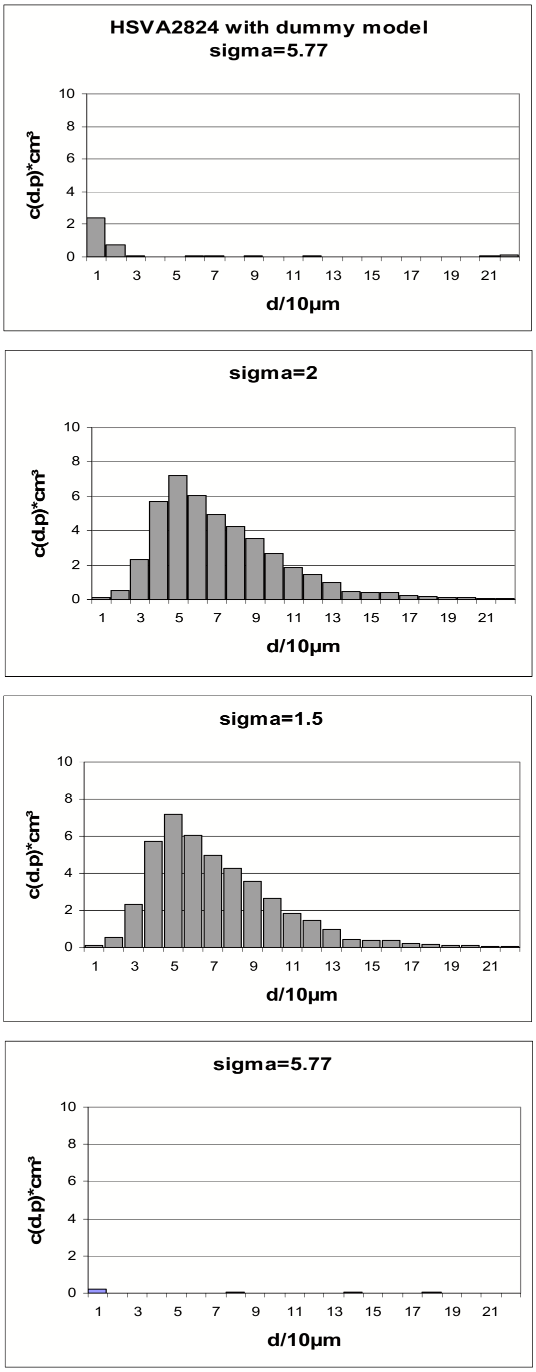


Figure 9: summarized particle concentrations in 60s steps for two ranges, corresponding to the results in **Figure** 8

A further example (Figure 10 and Figure 11) shows an experiment with Propeller HSVA 2824 in combination with dummy model by kT=0.29, n=28/s and u=4.287m/s with 4 tunnel settings.



a) b) c) d)

Figure 10: Bubble number concentration distribution for a) cavitation inception, b) and c) abundant cavitation and d) cavitation desinence.

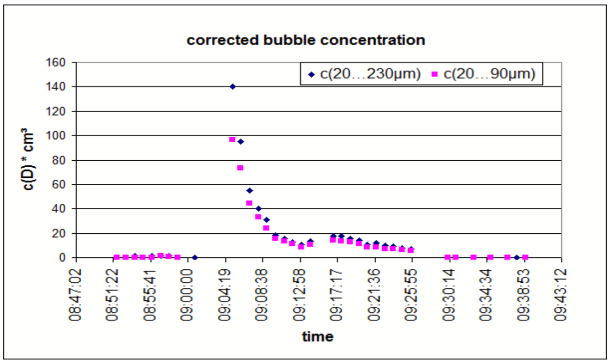


Figure 11: summarized particle concentrations in 60s steps for two ranges, corresponding to the results in Figure 10

CONCLUSION

Phase Doppler and time shift provide valuable insights into the nuclei spectrum in cavitation tunnels. The former is an established technique with commercially available equipment but can be improved by correction algorithms for solid particles. It is however restricted with regard to optical access and spherical particles. The time shift technique is still in an experimental stage but promises several significant improvements over phase Doppler in cavitation characterisation. First processed data show that the phase Doppler technique is able to characterize the bubble size concentration at different tunnel settings. Furthermore drifts of the bubble concentration during a constant operation can be verified by the technique.

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REFERENCES

Albrecht, H.-E., M. Borys, et al. (2003). Laser Doppler and Phase Doppler Measurement Techniques. Berlin Heidelberg New York, Springer-Verlag.

Brennen, C. E. (1995). Cavitation and bubble dynamics, Oxford University Press.

Damaschke, N. (2003). Light Scattering Theories and Their Use for Single Particle Characterization. Fachgebiet Strömungslehre und Aerodynamik. Darmstadt Germany, Technische Universität Darmstadt.

Damaschke, N., H. Nobach, et al. (2002). "Optical Particle Sizing in Backscatter." Applied Optics **41**(27): 5713-5727.

Damaschke, N., H. Nobach, et al. (2003). Laser Doppler Based Particle Chacterization with Backscattered Light. 9th International Conference on Liquid Atomization and Spray Systems. Sorrento Italy**:** 10-01.

Kretschmer, A., S. Höhne, et al. (2011). "Particle characterization with the Time-Shift-Technique." IEEE Sensors Proc.: 4.