Synchronized Multi-camera and LED-illumination system for multi perspective cavitation observation and 3D reconstruction

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ABSTRACT

Experimental investigations on the formation, expansion and dynamics of cavitation processes are very important for the understanding of complex cavitation phenomena and for the validation of numerical calculations.

Cavitation dynamics also generates pressure fluctuations and acoustic phenomena. The latter is investigated in the HiOcav joint project. The quantitative characterization of cavitation is the task of the subproject at the University of Rostock. Cavitation phenomena are recorded with high-speed videos from different perspectives to provide in future a three-dimensional reconstruction.

The cavitation dynamics will be correlated with acoustic measurements to understand and predict the generation of pressure fluctuations as predicted in [S. Berger et al.]. This paper explains the optical measurement system developed at the cavitation tunnel K21 of the University of Rostock and first measurement results.

The optical measuring system consists of 12 cameras, which are able to take pictures in the range of 1 kHz. The cameras are synchronized with a series of LED flash lamps to capture shadow images of the tip vortex cavitation with high spatial and temporal resolution from 12 different perspectives. In parallel, acoustic measurements are carried out with an array of hydrophones and two body-sound microphones.

With further cameras are the dynamics of the sheet cavitation and the nuclei concentration recorded in parallel. One challenge is the reduction of glare effects at the interfaces. Therefore, the images are recorded with a short time delay.

The synchronization of all components is based on a developed FPGA based trigger circuit, which synchronizes the cameras and LEDs in the microsecond range.

Keywords

Cavitation observation, 3D reconstruction, Multi-camera, Multi-perspective, LED-flash-illumination.

1 INTRODUCTION

Here we present works for the joint project "HiOcav". It is a project funded within the framework program "Maritime Technologies of the Next Generation" of the Federal Ministry of Economic Affairs and Energy Germany. The project partners are Mecklenburger Metallguss GmbH, ThyssenKrupp Marine Systems GmbH, Otto Piening Schiffspropeller und Wellenanlagen GmbH, Schiffbau-Versuchsanstalt Potsdam GmbH, Technische Universität Hamburg Harburg and the University of Rostock.

Cavitation of propellers causes a number of problems. In addition to erosion and the reduction of the propeller's efficiency, cavitation can lead to strong vibrations of the ship's structure. Loss of comfort or the functionality of technical equipment and installations on board is impaired. In addition, the dynamics of cavitation are a major cause of noise in the oceans.

The investigation, understanding and prognosis of these cavitation-induced pressure fluctuations is the subject of the joint project. In particular, the HiOcav project deals with the improved prognosis of the pressure fluctuations of higher order caused by the interaction between sheet and tip vortex cavitation. A measurement technique was developed by the University of Rostock for this purpose, with which the recording of the cavitation dynamics can be realized both in model tests and in large-scale setups.

In the previous KonKav projects the cavitation application and the erosive effect of cavitation were investigated. For this purpose, optical measuring techniques for the determination of the nuclei concentration and for the statistical description of the cavitation expansion were developed and used by various project partners. Time-resolved cavitation dynamics were not recorded at that time. But especially the temporal changes of the cavitation volume generate pressure fluctuations. These pressure fluctuations manifest themselves in acoustically perceptible effects.

In order to establish a correlation between these pressure fluctuations, the cavitation type and the cavitation location, the cavitation volume must be highly resolved temporally and locally and recorded synchronously with the pressure fluctuation measurements. Due to the rapid development in the field of cameras and lenses, such quantitative dynamic measurements to understand the cavitation effects are possible for the first time in the HiOcav project.

2 MATERIAL AND METHODS

The objective of the measurement technology development for the observation of cavitation dynamics in sheet and tip vortex cavitation is a multi-camera system which can capture temporally and spatially high-resolution videos from different perspectives. The cavitation expansion, the cavitation layer thickness, the three-dimensional movement of the tip vortex and the geometry change of the tip vortex are to be recorded with a temporal resolution of up to 2 kHz.

In order to realize this, a whole series of subsystems are required that allow synchronized recording from different perspectives. Figure 1 shows the different electrical subcomponents.

Starting from the master computer, are the 12 embedded systems controlled. Each system consists of a camera (IDS uEye UI-3060CP-M), a liquid lens (Corning Varioptic Caspian C-C-39N0-160), an Intel NUC Core i7-8559, a self-developed LED controller and a self-developed camera/lens controller. At low frame rates, an Intel NUC system is used for 2 cameras and 2 lenses each. For the synchronization of the system a proprietary development based on an AVnet MicroZed is used to trigger a corresponding number of channels synchronously. There are 40 individually programmable channels available, which can be used to define any trigger sequence. Typically one mode is used, which allows to trigger two cameras and two LEDs at the same time. The same perspective directions are then recorded with a time interval of 37µs, as this represents the minimum stable exposure time of the cameras (we found). The reason for this regime is the arrangement of the cameras and LED panels.

The cameras and flashes are arranged in two rings (Figure 2) around the cavitation channel K21 at the University of Rostock. The cameras that record the same perspective side by side must be triggered simultaneously with the corresponding opposite LEDs.

The rings to which the camera systems are attached consist of Item 8 profiles, which allow a very flexible and at the same time stable attachment and alignment of the individual components along the ring. Figure 2 shows the design drawing of the mechanical assembly and the real assembly on the K21. It can be seen that 6 camera systems each form part of a ring and are coupled via a special liquid prism in order to reduce optical distortions as much as possible. The LED panels are designed as stripes, which ensures that shadow images of the cavitation phenomena can be recorded without additional disturbing glare points. The LED panel lines consist of a multi-layer system of acrylic glass panes. The bottom layer is a mirror, followed by a thick transparent light-conducting layer and a diffuser layer. The LED flash light is coupled laterally into the light-conducting layer.

In order to determine the orientation of the images recorded by the cameras, a special, patent-pending calibration based on three laser beams, which stand in a certain precisely known geometric arrangement to each other, is used. The alignment of the cameras in space can be determined from the imaging of the laser beams using a developed trigonometric algorithm consisting of two single beam directions and two camera perspectives. This

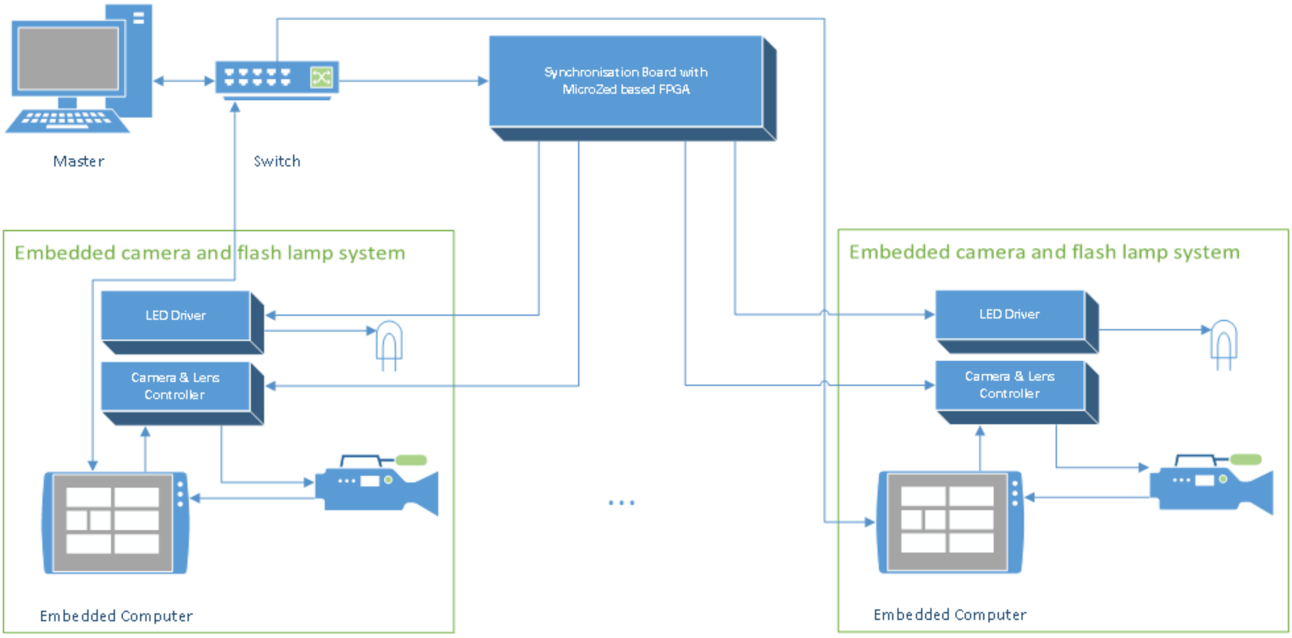
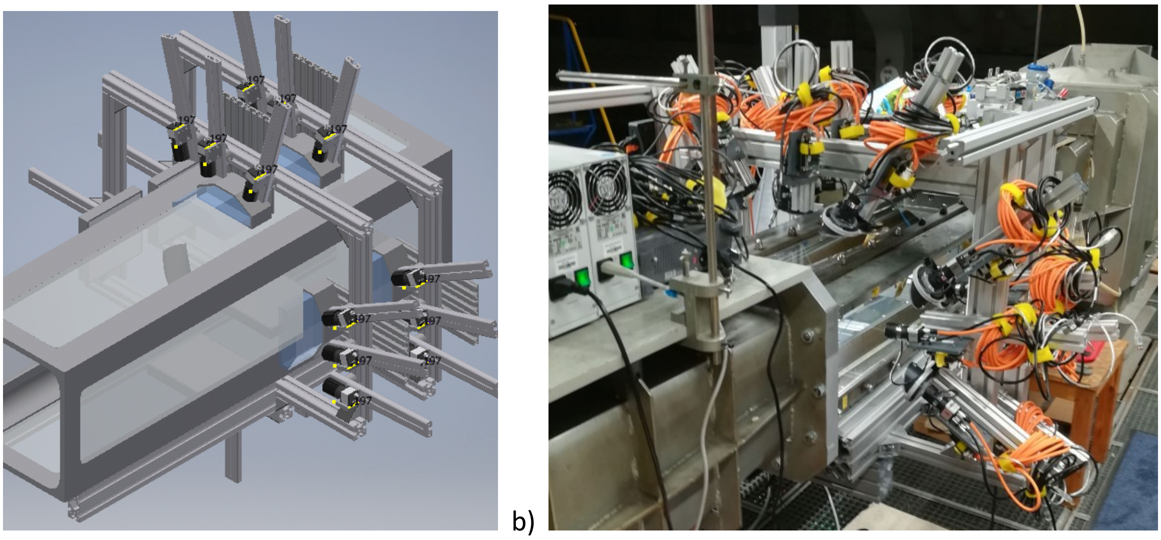


Figure 1: Subcomponents of the recording system



a) b)

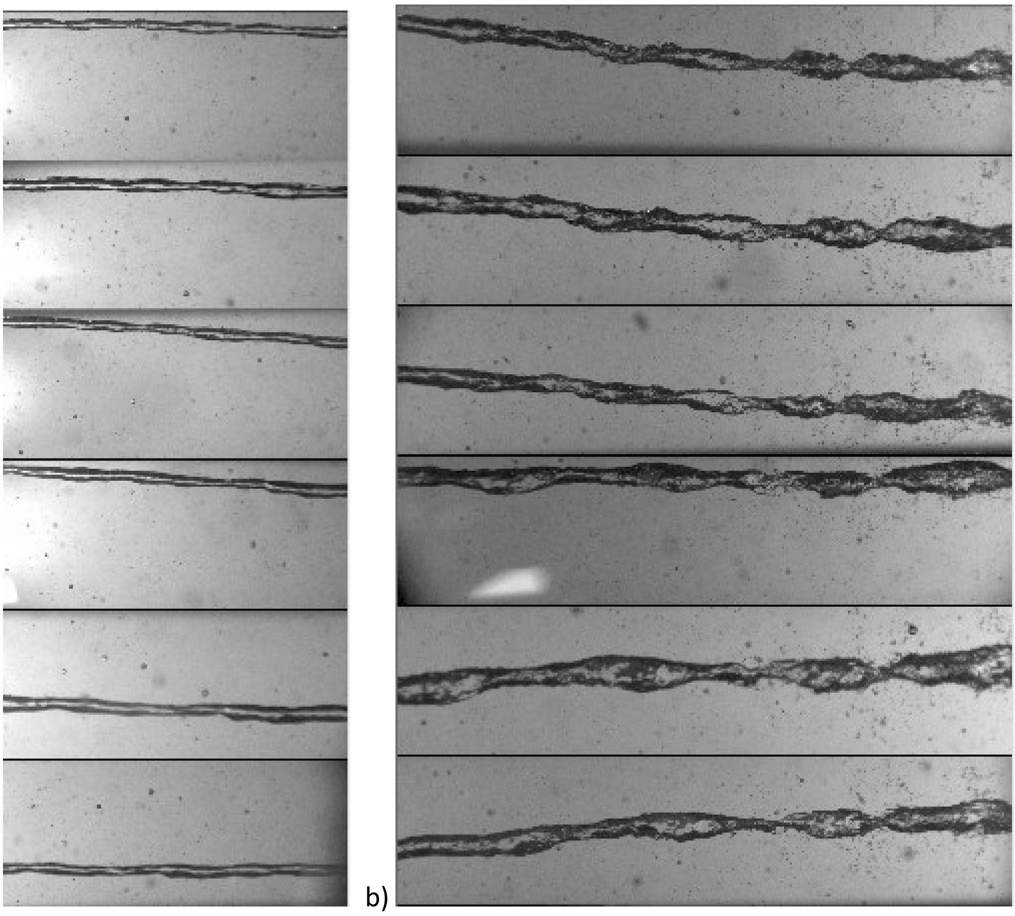
Figure 2: a) Design drawing of the mechanical setup and b) a picture of the real setup on the K21

makes it possible to calibrate the entire system without a physical target in the cavitation channel.

3 EXPERIMENT

In the HiOcav project are experimental data sets for the validation of numerical calculations generated. The cavitation dynamics will be recorded synchronously optically and acoustically. Furthermore, the HDNC measurement technique [Ebert & Ebert et al.] is used to determine the water quality. Due to the complexity of the measuring technique to be developed in the project, the cavitation tunnel K21 of the University of Rostock was used to test the design of the measuring system under real conditions. First optical measurements in the cavitation tunnel of the University of Rostock on the in [S. Berger et al.] developed hydrofoil are therefore presented here. In addition to the validation of the measuring system, these measurements also aim to provide optical data and to correlate them with acoustic signatures of cavitation phenomena. With the help of the acoustic signatures, pressure fluctuations of propellers in larger channels can later be assigned to the cavitation phenomena with less effort in optical measurement technology.

A model of the MARIN Ellipse-11N-Foil, adapted by the Technical University Hamburg Harburg and



a) b)

Figure 3: Tip-Vortex from 12 different viewpoints recorded at the University of Rostock K21 cavitation cannel at 5 m/s, 9 deg angle of the foil and 500 mbar pressure a) depicts results from first ring and b) depicts the second ring synchronized images.

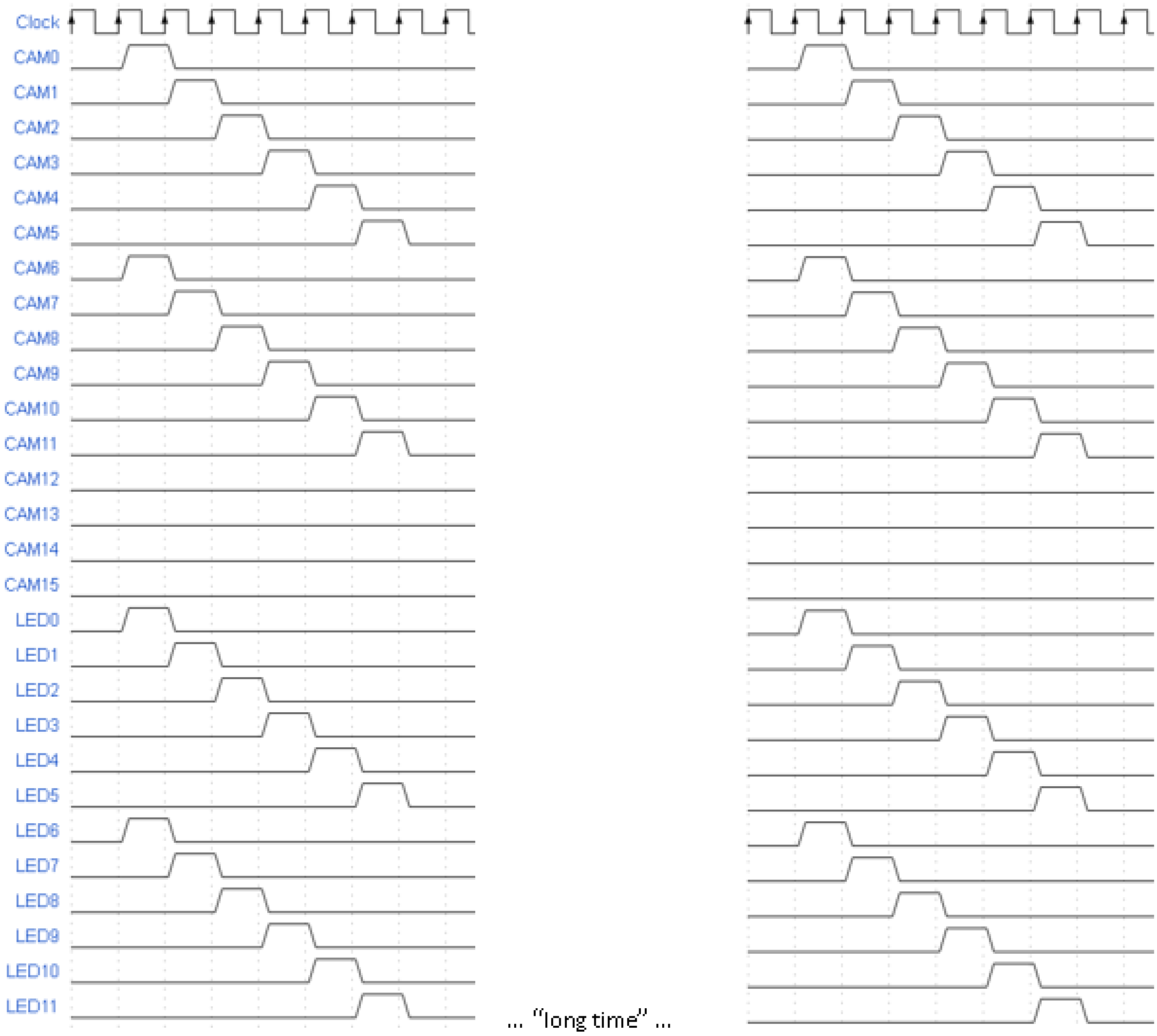


Figure 4: Timing Diagram (clock cycle is 37µs) of the applied FPGA trigger system based on AVnet Micro-Zed 7020 ("long time" means in case of the depicted recording approx. 20ms for 50 frames per second)

manufactured by SVA Potsdam, is used. It showed a promising cavitation behavior in the simulation under the conditions which are possible at the K21 channel. It has turned out to be problematic that due to the small design of the K21 the cavitation number is more limited downwards than in larger cavitation tunnels [S. Berger et al].

4 RESULTS

A result of a synchronized optical recording of the adapted MARIN Ellipse-11N-Foil is depictured in Figure 3. The measurements from 12 different viewpoints were taken with the timing regime depictured in figure 4. The center flow speed of the channel was approx. 5 m/s and the foil was tilted with an angle of 9 deg in against the flow direction according to the recommendations in [S. Berger et al.]. The K21 was pressured to 500 mbar.

In figure 3 b) a very significant constriction zone can be seen on the right part of the images. This zone depicts the synchronization capability of the system. Between each of the images per ring is a delay of 37µs (one clock cycle in Figure 4) applied like the timing diagram depicts. This allows to illuminate the tip vortex for each camera only in direct backlighting. No glare points from other light sources were observed. The AVnet MicroZed 7020 based trigger system is able to synchronize 40 channels with an exact timing at the same time. 16 cameras, 16 LED flash lights and 8 channels for synchronization with the propeller shaft and the acoustic subsystem are provided. Two Cameras record the exact same point in time for two spatial positions. Therefore, two LEDs in the opposite position of the camera on the K21 are illuminated.

In addition to the 12 synchronized cameras, further cameras are planned for observing the sheet and cloud cavitation. For this purpose, the layer cavitation on the hydrofoil is illuminated laterally with a further commercially available LED panel and recorded with an additional IDS uEye camera. The camera can also be operated synchronized to the other 12 cameras of the tip vortex cavitation.

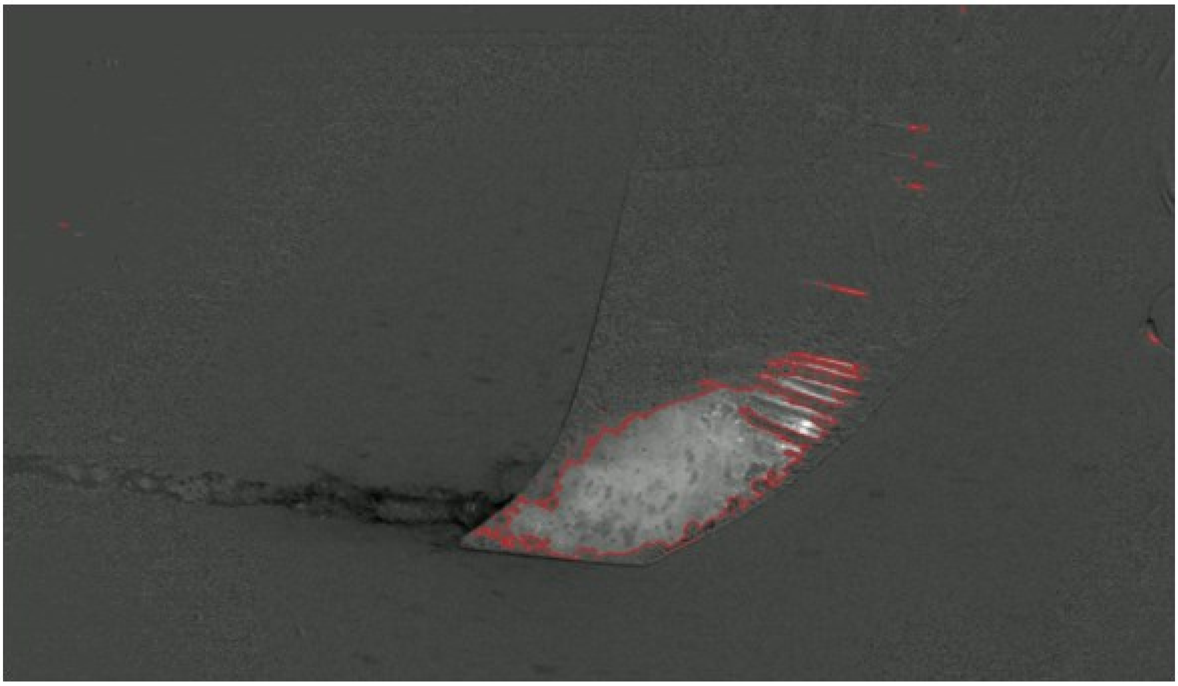


Figure 5: Example of automatic segmented sheet cavitation form a sample in University of Rostock K21 cavitation cannel at 5 m/s, 9 deg angle of the hydrofoil and 500 mbar pressure.

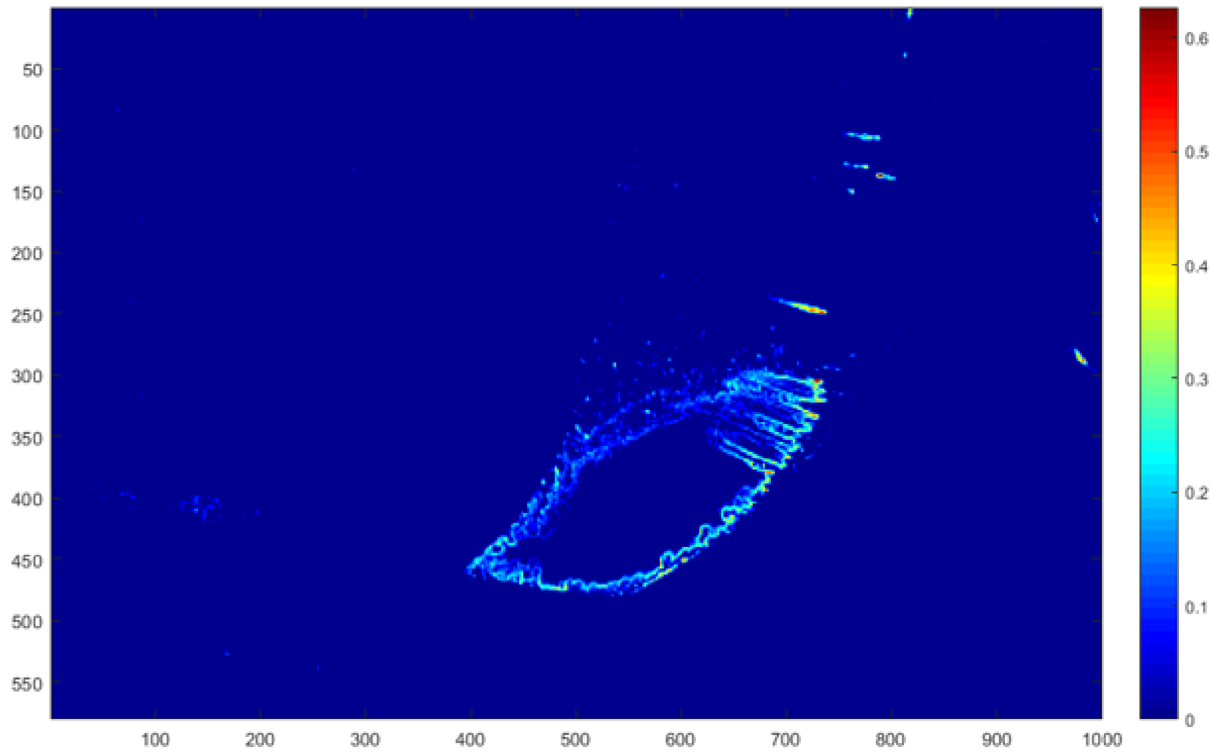


Figure 6: Histogram like occurrence statistics of sheet cavitation based on closed point chains of 22 images

An algorithm developed at the University of Rostock allows to calculate the extent of the sheet cavitation. For this purpose, a video is recorded of the hydrofoil without incident flow. An average image is calculated from the video, which functions as a background image for the evaluation of the hydrofoil images with inflow. Problems are camera noise, inhomogeneity in illumination over time and vibrations so that no single image can be used. But a sufficiently good background estimation can be obtained by averaging a number of about 20 images in our case. The floating point image of the background is subtracted from the floating point image of the in-flowed hydrofoil. The resulting image is gamma corrected and binarized. After this process it is ready for the edge detection and cavitation area detection. The binarized image is transferred by the algorithm from [S. Suzuki et al.] to logical objects consisting only of point lists. Retrieved are only outer contours with no chain simplification.

As a parameter it is also possible to obtain inner structures like "optical holes" in the structure coming from clear invisible water surfaces without foam and without total reflection. A second parameter allows to select a simplification of the point chain by reducing the number of multiple points in a small area to one point. The result is a coarser point chain which can be useful in some cases.

The result of this operation is a list of closed point chains representing the possible areas of sheet or cloud cavitation. At the moment is a selection done by the calculation of the area of the closed point chains included pixels. This allows a selection of specific closed point chains by thresholding the area values. A list of additional selection methods are possible on the closed point chains like selecting an interesting pixel point which has to be inside the chain, the outline length or curvature properties. A sample of the found outline is depicted in figure 5.

The automatically found outline of the sheet cavitation matches the visible cavitation phenomena quite well and allows a statistical analysis over time. In Figure 6 are the closed point chains of 22 images like in figure 5 summed up, normalized and plotted with false colors. The result is a kind of normalized 2D Histogram which depicts the occurrence probability of sheet /cloud cavitation at a certain point of the hydrofoil. 1.0 means there in every of the 22 images was the cavitation outline visible at that position and 0 means no cavitation was found. After several experiments the hydrofoil had small cavitation erosion damages on the surface. In the upper right region of figure 5 & 6 are some small cavitation phenomena visible which have a high probability. These are caused by the cavitation erosion damages.

5 SUMMARY AND OUTLOOK

The test series in the cavitation channel K21 of the University of Rostock have shown that the developed measuring technique is able to record cavitation phenomena with 12 synchronous cameras and to lay the foundation for a three-dimensional tip vortex cavitation reconstruction. In addition, an image processing method was developed to automatically determine the cavitation expansion on the hydrofoil. The outline allows a statistical evaluation of how likely cavitation is in a certain area of the hydrofoil and where it can often be expected.

In the future, the optical measurement techniques shown will be linked and correlated with acoustic measurements at K21 in Rostock. This is made possible by a hydrophone array, which is now installed on the cavitation channel. Furthermore, a measurement campaign is planned in which the signatures of the pressure fluctuations of propellers in the larger channel K15a of the project partner SVA can be assigned to the visible cavitation phenomena. In addition to the development of the measuring system, the project also aims at commercialization, which will be carried out by the project partner ForTech GmbH.

6 ACKNOWLEDGEMENTS

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