MEASUREMENT SYSTEM BY PRINTED THIN PRESSURE SENSOR ARRAY

Martin Dimitrov*, Peter Pelz*, Alexandra Lyashenko**, Ardeshir Hakimi Tehrani ** and Edgar Dörsam **

Technische Universität Darmstadt, Chair of Fluid Systems (FST), Magdalenenstr. 4,
D-64289 Darmstadt, Germany*
Technische Universität Darmstadt, Institute of Printing Science and Technology (IDD), Magdalenenstr. 2,
D-64289 Darmstadt, Germany **
E-Mail: peter.pelz@fst.tu-darmstadt.de

At the Chair of Fluid Systems a system for measuring high dynamic surface pressure has been developed. This measurement system is used for detection of surface stress due to cavitation. A piezoelectric PVDF-membrane is used to build the measurement system and to detect of higher frequencies events. The thin membrane has many advantages concerning the usage in the context of fluid machines. The electrodes were manufactured on the sensor surface in various ways, including printing technologies. The printed electrodes are realized by the Institute of Printing Science and Technology.

Keywords: piezoelectric sensor, PVDF-membrane, spatial and temporal resolution, cavitation.
Target audience: measurement systems, hydraulic machines, cavitation.

1 Introduction

A thin pressure sensor finds many areas of interesting applications where the use of standard pressure transducers takes high design effort or simply is not possible. One of these applications is the acquisition of the kinematic and dynamic processes of cavitation. These processes are spatially distributed and happen in the temporal range of microseconds. From the perspective of research a measuring system is of interest which can record the cavitation events on a solid surface spatially and temporally resolved. This new knowledge can be used to validate and refine models of cavitation collapse (see /12/, /13/). From an industrial point of view, investigations of the damaging effects of cavitation are of most interest. The location and intensity of cavitation load at various operating points is of importance.

The measurement task obtained from research requires highest demands towards the measuring system - a temporal resolution of less than 1 µs, spatial resolution of 10 pixels/mm² and channel number > 1000 to record the pixels distributed over the interesting area, robustness and long life to measure several cavitation events before the sensor is damaged, low interaction with the flow profile, application to curved surfaces and many more. For the second measurement task (detection of cavitation damage), two solutions that have already been applied are possible. The first one is the acoustic method and the second is the plastic deformation of thin metal layer. Both methods belong to the state of the art and have been developed in essential parts at the Chair of Fluid Systems. Thus, the advantages and disadvantages of both methods are well known to FST. The acoustic method uses a hydrophone as sensor which is positioned near the cavitation area. From its signal the acoustic power can be determined, which can be compared as an indicator of the cavitation intensity (/16/). The method returns a relative statement between several operating points or machine versions. A major disadvantage is the lack of spatial resolution and following from this the ignorance whether the damaging pressure loads take place near the surface or far away from it inside the flow. In contrast to that, this measurement system is simple in usage.

The second alternative method for the detection of cavitation is the plastic deformation of thin metal layers named *PitCount* (see /14/, /16/). In such measurements, coating thin layers of metal such as copper are positioned below the cavitation area. These layers are damaged by cavitation and the damage is measured optically. As result, a two-dimensional map of the damages on the investigated surface called *damage-map* is ascertained. This measuring method provides spatially resolved results of the cavitation damage but no temporal resolution.

The existing measurement systems for measuring cavitation cannot satisfy the high requirements from research and industry yet. For these reasons, the measurement system presented here has been developed, which comprises of a PVDF[1]-sensor (consisting of PVDF-membrane, electrodes and connectors pads), measuring amplifier and data acquisition system. It is able to measure spatially and temporally resolved pressure histories on the surface and thus combines the advantages of the existing methods described above.

2 Sensor Design

The measurement tasks explained in Section 1 primarily require a bandwidth that extends into megahertz range from a measurement system for cavitation. The piezoelectric sensors can be evaluated as suitable from this point of view. The piezoelectric materials are represented as crystals, ceramics and almost unknown as plastics. The last type - plastics - has the advantage for the desired application that it is not as brittle as crystals or ceramics. This property helps to design long-life sensors because the cavitation loads occur in pulses with high pressures. A further advantage of the flexible plastics is that it can easily be attached to curved surfaces as they typically appear in flow systems. A piezoelectric thermoplastic named PVDF, which is available as thin membrane (9 µm to 100 µm), satisfies the stated requirements.

On the basis of a higher Young's modulus ($2.1 * 10^{-9}\ N/m^2$), a higher speed of sound ($2.2 * 10^3\ m/s$) and the fact that the PVDF can be produced in such thin layers, sensors can be designed with mechanical natural frequencies in the range several MHz up to GHz. The electrical characteristics of the sensor and the used measurement amplifier change the frequency band of the system, but the range of several MHz can still be reached.

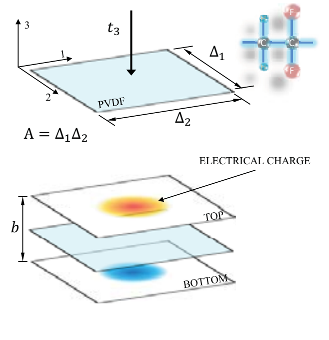

Figure 1: piezoelectric PVDF membrane under load - Distribution of the electric charge on the surface of the membrane

2.1 Sensor Array - Spatial Resolution

Under mechanical stress, electric charges can be measure locally at the membrane's surface – see Figure 1. Depending on how the membrane is polarized, a positive electrical charge on the top side and a negative charge at the bottom side of the PVDF-membrane can be measure, if the membrane is under mechanical load. This physical effect in spatial direction 3 (transverse piezoelectric direction) is given by

$$\frac{q}{A} = d\, t_3 + \varepsilon\, \frac{u}{b}. \qquad \text{Eq. 1}$$

With q as the electrical charge on the sensor surface A, d_{33} piezoelectric charge coefficient, t_3 is the force with which the surface is debited in axis 3, ε_{33} is the permittivity and b is the PVDF-membrane thickness. Each electrical charge on the sensor surface generates an electrical potential u. In this case the mechanical load is not directly proportional to the electrical charge. In order to avoid this term, a charge amplifier must be used. A charge amplifier keeps the potential u on the electrode constant, and thereby the term vanishes, so that the equation takes the form

[1] Polyvinylidenfluorid $C_2H_2F_2$

$$\frac{q}{A} = dt_3. \qquad \text{Eq. 2}$$

If the voltage of the sensor is measured, the following equation must be used

$$\frac{u}{A} = gt_3b, \qquad \text{Eq. 3}$$

with g as the piezoelectric charge coefficient. The latter method to gather information provided by the sensor via the voltages is sensitive to noise, cable length and is only used in special cases.

Pressure sensors generally have the requirement that the spatial pressure gradient on the sensor surface is zero.

In the case that the pressure-loaded area is smaller than the sensor surface, the charge can be measured at discrete areas of the membrane surface – see Figure 2. By the discrete measurement points on the surface the intensity of the mechanical load can be measured locally. This sensor has $n \times m$ measurement points, which can be called *pixels*. This pixel structure is useful when the number of pixels is small, because each pixel uses one channel of the amplifier. Accordingly, $n \times m$ channels must be set up and digitized. An almost insoluble challenge is the design of the signal wires on the top side of the sensor for large numbers of pixels, because these establish pressure-sensitive surfaces as well. Another problem of this sensor is the wire or cable construction between sensor and amplifier, as with growing number of pixels the total cable size increases.

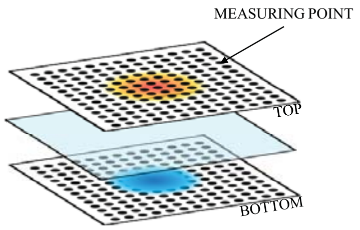

Figure 2: Sensor with spatial resolution - distribution of measuring points

To reduce the number of hardware channels for larger numbers of pixels an electrodes design as shown in the Figure 3 has been developed. On top of the PVDF membrane, electrodes are expanded over the entire width. These are called *row electrodes*. On the bottom side of the membrane, electrodes are placed over the entire height of the membrane - *column electrodes*. These electrodes form a matrix and each intersection point of one column and one row is forming a pixel. With this electrode configuration we have only $n + m$ amplifier channels for $n \times m$ pixels. The design simplifies the complexity of the sensor system, but it has some drawbacks. The sensor is constructed as an array of individual sensors that all generate electrical charges. However, because each pixel is electrically connected to his neighbours, can the electrical charge through entire array as voltage propagate. This happens because all piezoelectric pixels have a capacitance (capacitor plates), the sensor can be denoted a *capacitor matrix* as well. For that reason the signals from the rows and columns must be connected to the charge amplifier. For information on the signal processing beyond the charge amplifier, the reader is recommended to refer to paper /15/, which also provides a closer look at the evaluation of the capacity matrix.

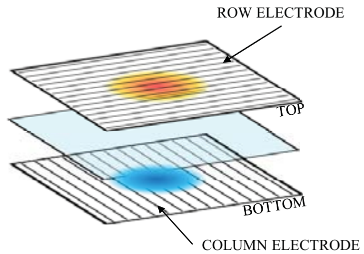

Figure 3: Sensor with spatial resolution - built with electrodes columns and rows

3 Design and Manufacture of the Electrodes

To produce the required electrodes, connector wires and pads on the PVDF membrane several different production methods were tested. The main challenge for all methods is the PVDF material itself. Its surface has low adhesive characteristics so that only few methods are able to apply an electrically conductive layer which simultaneously provides mechanical resilience. Another challenge is the accuracy of the electrode layout. The distance between the electrodes must be as small as possible but sufficient to protect against short circuit at the same time.

Another important task in the development of the measuring system is the wiring between the sensor electrodes and the printed circuit board with the charge amplifier. For this case the printed electrodes are connected to contact areas (pads) directly on the PVDF-membrane. The layout of the pads is designed for standard connectors that can be connected to the printed PVDF membrane. These connectors (ZIF-connectors) feature gold-plated pins and are pressed on the PVDF-membrane with a small force. That avoids the electrical activation of the PVDF membrane. Since this force is constant, it generates electrical charge or voltage only during plugging.

3.1 Flexible Printed Circuit Board

For the first sensor design, a standard method for production of flexible boards (also called FlexPCB) was used. For this method gold-plated electrodes are printed on thin polyamide films. The area between the electrodes and contact pads are covered with an electrically isolating coating - the green layer on Figure 4. This protects the wires from short-circuiting when the board is folded.

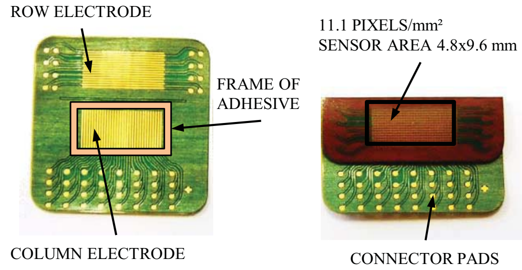

Figure 4: flex PCB technology – sensor with 512 pixels and pitch of 0.3 mm.

On the sensor surface, which is defined by the row and column electrodes, the PVDF-membrane is attached – see Figure 4. Around the membrane a frame of 5 µm thin acrylate glue is positioned. The FlexPCB board is folded around the PVDF membrane and glued under vacuum with the glue frame to manufacture one sensor. The vacuum ensures that the gold-plated electrodes are pressed onto the PVDF surface and therefore the electric charge is supplied to the charge amplifier. At the same time, the vacuum is the biggest drawback of this sensor design. When the vacuum is lost, the electrodes are not in contact with the PVDF membrane any more and the measurement data might get corrupted.

The advantage of this manufacturing technology is the reachable size of the structures. The electrodes and the distances between them can be made up to 50 µm small. The sensor of Figure 4 has electrodes with a width of 150 µm and 512 pixels. This sensor has a total thickness of approximately 100 µm.

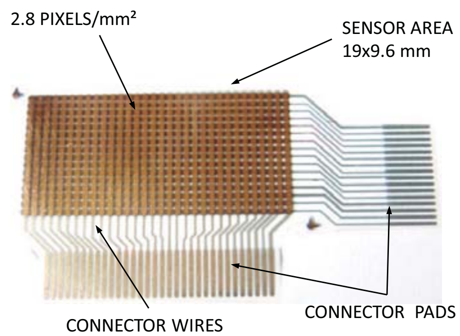

Figure 5: sensor with sputtered electrodes

This technology was used to manufacture a sensor prototype with 4224 pixels, which was installed in a test rig (cavitation channel) at FST. Measurement data from the sensor are presented in Section 4.

3.2 Sputtering

As another manufacturing method to apply the electrodes and connector pads directly on the PVDF-membrane, the sputtering technique was selected. In the "*Cressington Sputter Coater 108 auto/SE*" a thin gold layer under a protective atmosphere of argon could be deposited - Figure 5.

Primarily, the surface of the PVDF membrane was activated in the plasma system "*Nano of Diener Electronic*" during 15 minutes, so that the gold layer adhesion could be improved. To achieve the desired electrode layout negative masks were utilized. The masks were laser cutted from stainless steel with a thickness of 0.3 mm. During the sputtering, the PVDF- membrane was coated on both sides with a pure gold layer of 82 nm thickness.

The manufacturing of the electrodes with this method shows good results concerning the realizable electrode designs and at is gently to the PVDF membrane the same time. Unfortunately, the adhesion of the gold layer on the PVDF surface is too low so that the contact area for the connector is destroyed by the connector pins itself. Thus, this sensor would not be able to sufficiently resist the high pressure impacts due to cavitation.

3.3 Screen Printing

Screen printing is a very suitable and favourable method for the production of printed structures. From these reasons, attempts were made to apply the electrodes on the PVDF-membrane by means of this technology. In Figure 6, a sensor produced by screen printing with structures of 300 µm width is shown.

A silver conductive adhesive from the company *Panacol (Elecolit 414)* was used as ink for the printing process. The printing experiments were done on a screen printing machine *KAMMANN-K15Q SL* with a printing speed of 0.50 m/s. After complete drying of the adhesive layer at air with a temperature of 25°C, the printed layer provides an excellent adhesion on the PVDF surface. The adhesive is also slightly elastic, thereby improving the mechanical properties of the sensor structure.

Unfortunately, a problem occurred during the printing process: The adhesive used as printing ink in the experiments (which is untypical for the printing methods) was dried during the short time of the process and the printing screen was choked in several areas. By this reason, the continuation of the printing experiments was not possible as well as the printed layers were broken in some areas (see *Figure 6*).

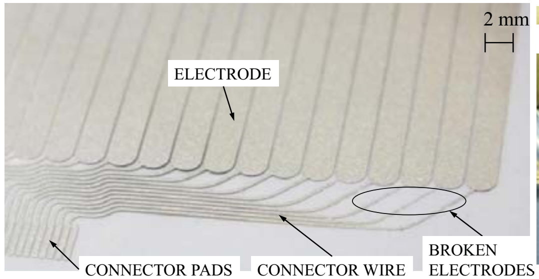

Figure 6: Screen printed PVDF membrane with silver conductive adhesive

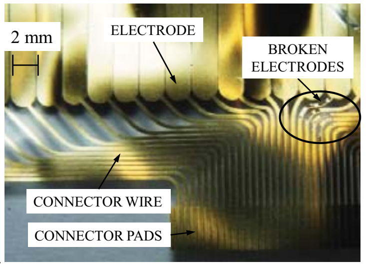

Figure 7: Screen printing on PVDF-membrane with nanosilver ink

A possible solution of this problem was to test a special nanosilver ink for the screen printing - *Figure 7*. With this printing ink, the electrodes were printed on the PVDF without big challenges and a good resolution (about 150 µm) was realizable. However, the result was not useful: (i) The nanosilver ink (like the sputtered layers) provides only poor adhesion forces on the surface of the PVDF membrane. (ii) The usual way to achieve the required electrical properties with printed conductive inks is to sinter them at temperatures higher than 100 °C. These high temperatures caused deformation of the PVDF membrane. By means of higher temperatures, the conductivity of the ink is improved but the sensitivity of the sensor membrane is reduced and the mechanical deformations are bigger - see /9/.

3.4 Coating in Combination with Lasing

As another manufacturing technology for the sensor electrodes, a combination of coating and lasing was evaluated. By means of the coating proofer, a thin layer of conductive silver adhesive (same material as used as printing ink above) was coated as a full area of size 200 mm x 200 mm. In the second step, the layout of the electrodes was lasered by means of a fiber laser with wavelength 1064 nm (*KBA-Metronic Lasersystem F-9020*). The coated layer is removed from the PVDF membrane to the extent of creating electrically isolating areas between the electrodes without destructing the PVDF-membrane. The insulation between the electrode areas is defined by the diameter of the laser spot - 50 microns.

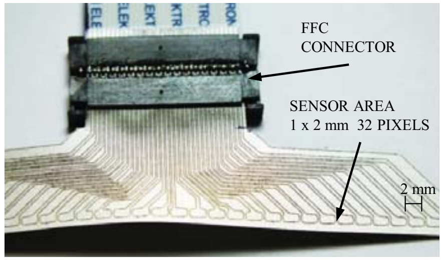

Figure 8: PVDF Sensor manufactured with lasing. The coated PVDF-membrane is coupled with a ZIF-connector.

The coating with lasing technology enables to manufacture the connector wires between the sensor area and the contact pad very precisely. With this method, a fully functioning one-dimensional sensor prototype was manufactured. The sensor was connected to the circuit board with charge amplifier with a ZIF connector – see Figure 8. This manufacturing method provides excellent results for sensors that have electrodes on only one side of the membrane. These pressure sensors can be designed to increase the electrical charge as a monopole. Unfortunately, this charge amplification is very sensitive to signal noise. It is not possible to utilize this method for the production of a sensor matrix as shown in Figure 3, because the laser beam passes through the PVDF membrane and removes any coating at the other side of the membrane as well.

4 Measurements inside Cavitation Channel

4.1 The Sensor in the Test Rig

For investigations of cavitation, a test rig was set up at the Chair of Fluid Systems. Nozzles of different shapes can be measured in the test rig. The nozzles are operated in a way so that cavitation arises in the divergent part of the nozzles. Among other cavitation effects, its damaging consequences on the nozzle surface are investigated. Before the new measurement system with PVDF-sensor has been developed, the cavitation damages were measured by means of the PitCount method. This method is very time consuming and complex to apply for high quality measurements of cavitation damage but provides damage-maps of the nozzle surface with spatial resolution. These maps can be used as references for the new measuring system (PVDF-sensor) validate the measured cavitation-induced surface damages.

A flow stall can be generated at the narrowest point of the nozzle by means of a convergent-divergent nozzle geometry - see Figure 9. In the test rig, different operating points of the nozzle can be set by changing the pressure and flow velocities. The nozzle's operating point is represented by two dimensionless parameters:

$$\sigma = \frac{p_2 - p_v}{\frac{\rho}{2}\bar{U}^2} \qquad \text{Eq. 4}$$

the cavitation number and

$$\mathrm{Re} = \frac{\bar{U}H}{\nu} \qquad \text{Eq. 5}$$

Reynolds number.

The pressure at the outlet of the nozzle is denoted as p_2, the vapor pressure as p_v, the average flow velocity at the nozzle inlet as $\overline{U}$, the geometrical height of the nozzle inlet as H, and the kinematic viscosity as ν. All measurements presented in this paper were carried out at the operating point characterized $\sigma = 5.45$ and $\mathrm{Re} = 2.75 \mathrm{x} 10^5$. At this flow condition, a cavitation cloud is formed behind the narrowest point of the nozzle. It is convected in flow direction and collapses under the increasing pressure in the divergent part of the nozzle (see Figure 9). These cloud formations and collapses happen periodically with a frequency f of 43 Hz or Strouhal number given with $St = \frac{fH}{\overline{U}} = 0.4$. The position of the cloud collapse depends on σ, Re and the nozzle shape.

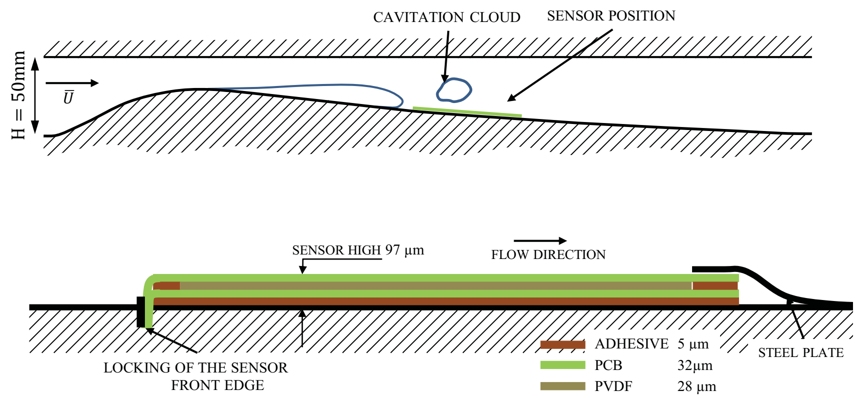

Figure 9: Side view of the cavitation nozzle and section drawing from the PVDF-sensor

The sensor is positioned in a way that the cloud collapses happen right above it for the chosen operating point.

The sensor prototype used for this experiment is manufactured with FlexPCB technology (see Section 3.1) and has 66 x 64 electrodes with an electrode pitch of 1 mm. For the measurements presented here, the electrodes are connected in pairs and the last two rows are not used. The result is a sensor with a spatial resolution of 0.5 pixel/mm² and 32 × 32 electrodes. The PVDF membrane between the FlexPCB board has a thickness of 28 µm, so that the total thickness of the sensor is less than 0.1 mm – see Figure 9. The inner space of the sensor is connected with a vacuum pump which maintains vacuum during the whole measurement.

The front edge of the sensor is exposed to the high flow velocity. Despite the small thickness of the sensor (approx. 0.1 mm), the flow tends to remove it from the surface. To prevent this, the sensor is locked into the nozzle with its forward edge - see Figure 9. Furthermore, the sensor areas for cable routing and even the FFC[2]-cable are covered with a steel plate of thickness 0.3 mm. This protects the mechanically sensitive areas of the sensor from the cavitation load.

4.2 Charge Amplifier, PCB design and Data Acquisition

For reasons described in the Section 2.1 each electrode of the sensor is connected to one channel of a charge amplifier. The sensor has 1024 pixels and its area is quadratic with 32 column and 32 row electrodes. The total required 64 channels of the charge amplifier and AD converter are realized on a circuit board, which has been developed by FST - compare Figure 10.

The charge amplifiers are designed with CMOS inputs, so that the input impedance of amplifiers is high. The electrical charges from the electrodes are amplified as monopoles (the electrodes measure the charge of only one side of the PVDF-membrane). The lower cut-off frequency is set between 100 Hz and 18 kHz, so that the noise signal (frequency converter of the pump up to 20 kHz and the 50 Hz ambient noise) is kept small. The upper frequency limit of the bandwidth for all measurements is at 1 MHz.

The measurement of the sensor signals at the output of the charge amplifier can be realized in two ways with this measurement system: (i) the simpler way is to measure the analog signals at the output of the charge amplifier directly. For this, two measurement boards which were able to detect the 64 measurement channels with a maximum sampling rate of 66 kHz per channel were used. This way, the (slow) data acquisition is used to generate damaging maps from the measurement data. The low sampling rate is sufficient for the damage-maps, because the maps are determined by means of integral methods.

The second way to measure the signals from the charge amplifiers is via 64 high speed AD-converter (up to 10 MHz per channel) on the board. This way of data acquisition will be used in future cavitation researches.

4.3 Damage Map

A measurement with PitCount was used as reference for the measurement of a damage map by means of the PVDF-sensor. Both measurements were conducted for the nozzle operating point $\sigma = 5.45$ and $\mathrm{Re} = 2.75 * 10^5$. In the PitCount measurement, a copper membrane was exposed to the cavitating flow for two hours. After that, the membrane was analyzed optically. The resulting PitCount damage map is shown on Figure 11 below. The location of the PitCount damage-map and the PVDF-sensor slightly differ in flow direction. Reason for this

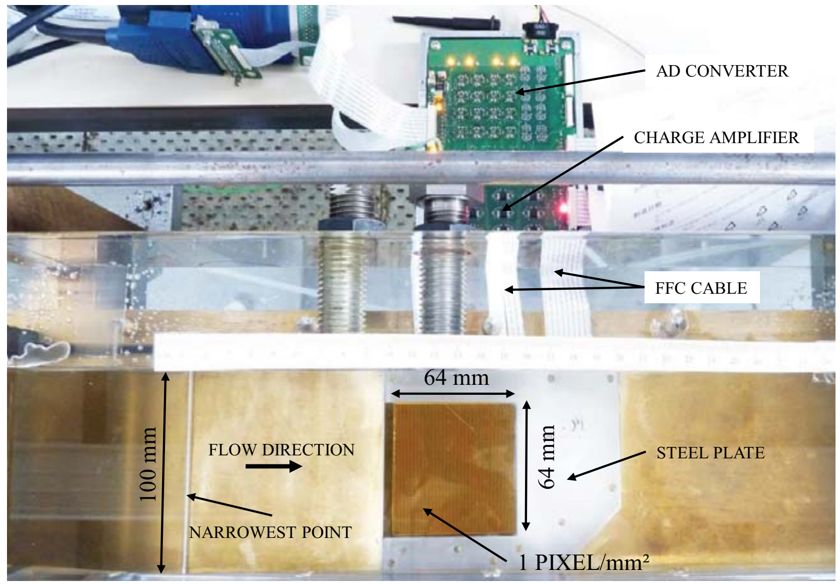

Figure 10: Top view of the channel test rig with a 2D Sensor (1024 pixels), manufactured with flex PCB technology

is the cable routing of the PVDF sensor in the nozzle. This has no relevance to the absolute position of cavitation damage - the main damaged areas can be measure with both measurement methods.

The sensor signals were measured with the analog measurement cards with 60 kS/s. For the evaluation of the measured were first created pressure maps ($\boldsymbol{PM}$) from each sample. A pressure map $\boldsymbol{PM}$ represents the pressure distribution on the sensor surface in the sample i for 1024 pixels. The amplitude of the pressure distribution is relative and is calculated during the evaluation of the sensor array, as described in /15/.

[2] *Flat Flex Cable*

The sum of the pressure maps for a period of $T = 20$ s

$$DM = \sum_{i=0}^{T} PM_i \qquad \text{Eq. 6}$$

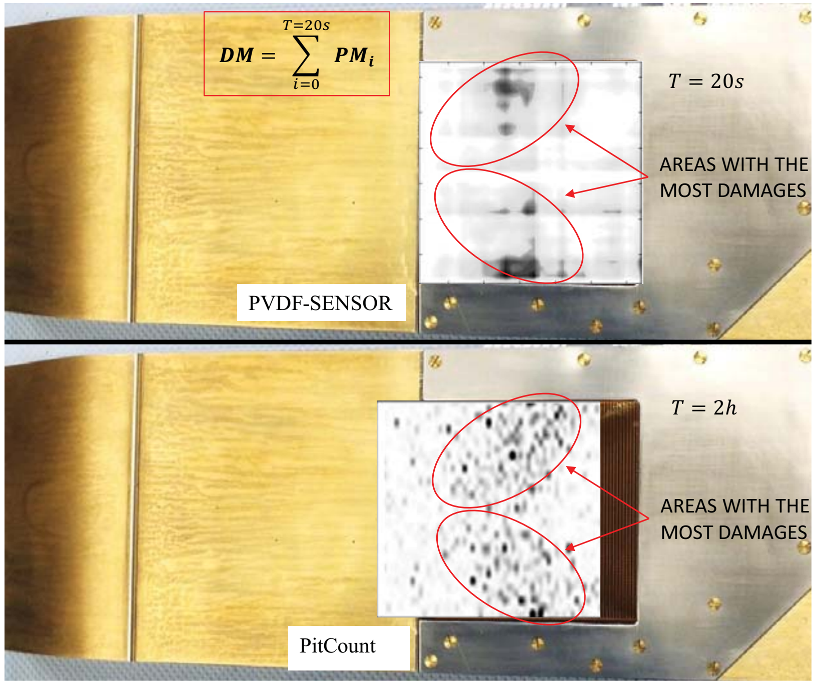

Figure 11: damage-maps: top-PVDF-sensor; below-PitCount, at the same operation point $\sigma = 5.45$ *and* $Re = 275e^3$

represents the damage-map $\boldsymbol{DM}$ from the sensor – see Figure 11. This kind of evaluation gives a relative statement about the pressure loads on the sensor surface.

From the damage map acquired by means of the PitCount method, two areas with the most damaged events can be defined. Their positions are symmetrical to the center line of the nozzle (c.f. Figure 10 below).

These two areas can be found in the damage-map acquired by means of the PVDF-sensor at the same position regarding the narrowest point of the nozzle as well. This shows that concerning the prediction of local cavitation erosion potential comparable results as from measurements with the Pitcount method during hours can be produced by means of the PVDF sensor within seconds.

Cavitation collapses are stochastically happening events in time even at one operating point. For this, the state, shape and the current environment of the collapsing cloud as well as the quality of the water are of great importance. For these reasons, an exact damage map could only be determined on base of an infinite measurement time $T{\sim}\infty$. However, the measurements with the PVDF sensor can make a qualitative statement about the damage to be expected on cavitation-exposed surfaces. For the measurement of damage maps of several operating points, one and the same sensor can be re-utilized. In contrast to that, a new copper membrane must be utilized for each measurement point when using the PitCount method.

The lifetime of the sensor, which was experimentally tested in this paper, resisted the aggressive cavitating nozzle flow for more than six hours. A calibration of the sensor is not necessary to create damage-maps in general, because the measurement with the PVDF-sensor gives a relative statement of the loads exerted on the surface.

5 Conclusion and Future Works

At the Chair of Fluid Systems Technology could be successfully developed measurement systems with PVDF-sensors for detection of cavitation damage. The current sensors can spatially measure the pressure history, with a resolution up to 11 pixels/mm². Because of its flexible composition and economical production (printing techniques), the sensor can be applied in many hydraulic systems on curved surfaces.

In future works the measurement system can be sampled faster than 10 MHz per channel, to investigate the temporal processes in cavitating clouds collapses. For this must be used the 64 high-speed AD-converters on the electronic board (Figure 10).

In the evaluation of damage maps a threshold level could be defined. This is defined for different materials and determines from which signal magnitude plastic deformation is to be measured.

Nomenclature

Variable	*Description*	*Unit*
q	Electrical Charge	$[C]$
d_{33}	Piezoelectric Charge Coefficient	$[C/N]$
A	Sensor Surface	$[m^2]$
F_{33}	Force in Axis 3	$[N]$
ε_{33}	Permittivity	$[As/Vm]$
g_{33}	Piezoelectric Charge Coefficient	$[V/m/N/m^2]$
b	Thinness of the PVDF-Membrane	$[m]$
σ	Cavitation Number	[-]
p_2	Pressure At The Outlet Of The Nozzle	$[Pa]$
p_v	Vapour Pressure	$[Pa]$
ρ	Density	$[kg/m^3]$
$\bar{U}$	Average Flow Speed on the Nozzle Inlet	$[m/s]$
Re	Reynolds Number	[-]
H	Nozzle Height	$[m]$
ν	Kinematic Viscosity	$[m^2/s]$

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