6th IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, September 9-11, 2015, Ljubljana, Slovenia

STUDY OF CAVITATION IN PUMP - STORAGE HYDRO POWER PLANT PROTOTYPE

Tine Cencič

Soške elektrarne Nova Gorica, Slovenia

Marko Hočevar

University of Ljubljana, Faculty of Mechanical Engineering, Slovenia

Brane Širok

University of Ljubljana, Faculty of Mechanical Engineering, Slovenia

ABSTRACT

An experimental investigation has been made to detect cavitation in pump – storage hydro power plant prototype suffering from cavitation in pump mode. Vibrations and acoustic emission on the housing of turbine bearing and pressure fluctuations in the draft tube were measured and the corresponding signals have been recorded and analyzed. The analysis was based on the analysis of high-frequency content of measured variables. The pump – storage hydro power plant prototype has been operated at various input loads and Thoma numbers. Several estimators of cavitation were evaluated according to coefficient of determination between Thoma number and cavitation estimators. The best results were achieved with a compound discharge coefficient cavitation estimator. Cavitation estimators were evaluated in several intervals of frequencies.

KEYWORDS
cavitation, pump turbine, Thoma number, cavitation estimator

1. INTRODUCTION

In the recent years energy production from renewable sources has increased. The increased dependence on weather conditions on renewable energy production led to design of pump storage hydro power plants with high installed power and operation away from best efficiency point. In water turbines unwanted cavitation phenomena may occur at off-design operation and lead to degradation of efficiency, excessive vibrations and cavitation erosion.

In the short review we will focus on experimental detection of cavitation. The traditional approach of cavitation detection is based on measurements and analysis of vibrations or acoustic emission on stationary parts of the machine. Several authors performed model tests, fewer reports are from prototypes, while some authors also show comparisons between both.

* *Corresponding author:* Soške elektrarne d.o.o., Nova Gorica, Slovenia, phone: +386 41 933 985, email: tine.cencic@seng.si

Models tests have advantage over tests on prototypes given that turbine is more easily accessible and sensors can be mounted near sources of cavitation. On the model test Escaler [1] made cavitation measurement on the Francis turbine. It was found out that acceleration measured on the turbine bearing of a Francis turbine can be used to detect outlet and bubble cavitation. Radial sensor orientation measures signals of higher amplitude than axial- a frequency band from 10- 15 kHz was found suitable to analyze the highest frequency content. Kern et al. [2] and Rus et al. [3] performed an investigation on the Kaplan model by simultaneously measuring with the hydrophone, high frequency pressure sensor and acoustic emission sensor. They also performed visualization [4] to connect these measurements with visual appearance of cavitation, something that is very difficult to do on the prototype. Avellan et al. [5] compared model tests and prototype tests, emphasizing the importance of model testing. It was also observed that the cavity development in centrifugal pump is fully controled by the discharge coefficient.
In prototype turbines inacessibility and long distances between source of cavitation and measurement locations complicate measurement procedures and signal analysis. Pressure sensors are frequently installed in or around inspection doors below the runner. Pressure and acoustic sensors are mounted on guide vanes plugs, turbine bearing case, while draft tube wall is rarely accesible. Escaler et al. [6] carried out an experimental investigation to evaluate the detection of cavitation in hydraulic turbines both for models and prototypes. The methodoloy was based on the analysis of structural vibrations, acoustic emission and hydrodynamic pressure measurement in the machine. Bajić et al. [7] performed vibroacoustic measurements and multidimensional analysis on a prototype Francis turbine. In this case the multidimensional analysis was employed a huge quantity of high- frequency data was acquired and a high number of sensors distributed over a turbine were used. Escaler et al. [8] performed a test in a prototype Francis turbine using a vibration sensor sensor fixed on the rotation shaft. It was observed that a relatively low frequency range (from 3- 6 kHz) taken on the shaft are analogous to the acoustic emmission measurements in a higher frequency range taken on the turbine guide bearing. Shi [9] used a standard deviation to show the cavitation intensity. If the properties of operation can not be change is for the owner of the powerplant important to make a prediction of the cavitation erosion for choosing appropriate maintenance and repair periods [10].
Substantial effort was invested to detect cavitation in prototype turbines. Until now no general detection procedure exists. Further problem represent cavitation erosion, which is not easily related to cavitation incidence. The reason lies in complexity of the cavitation phenomenon and limitations of measurement or CFD procedures. In spite of this, the aim of this paper is to find the cavitation estimators, which will sucessfully quantify cavitation intensity in the prototype turbine based on vibration and acoustic emission measurements on the bearing housing and pressure measurements in the draft tube. By filtering of the measured variables in selected frequency intervals we were able to establish cavitation estimators and group them in combined cavitation estimator.

2. PUMP- STORAGE HYDRO POWER PLANT

The power house of pump turbine Avče (Fig. 1) is located on the terrace on the left bank of Soča river, Slovenia. The pump turbine Avče started operation in 2009. Instaled power in turbine mode is 185 MW, while in pump mode it is 180 MW. Net head in pump mode is H_{ep} 521 m, while rated discharge is Q = 34 m³/s. The available volume of water storage is V_k = 2,170,000 m³.The turbine is submerged below lower accumulation basin while located at 49 m above the sea level.

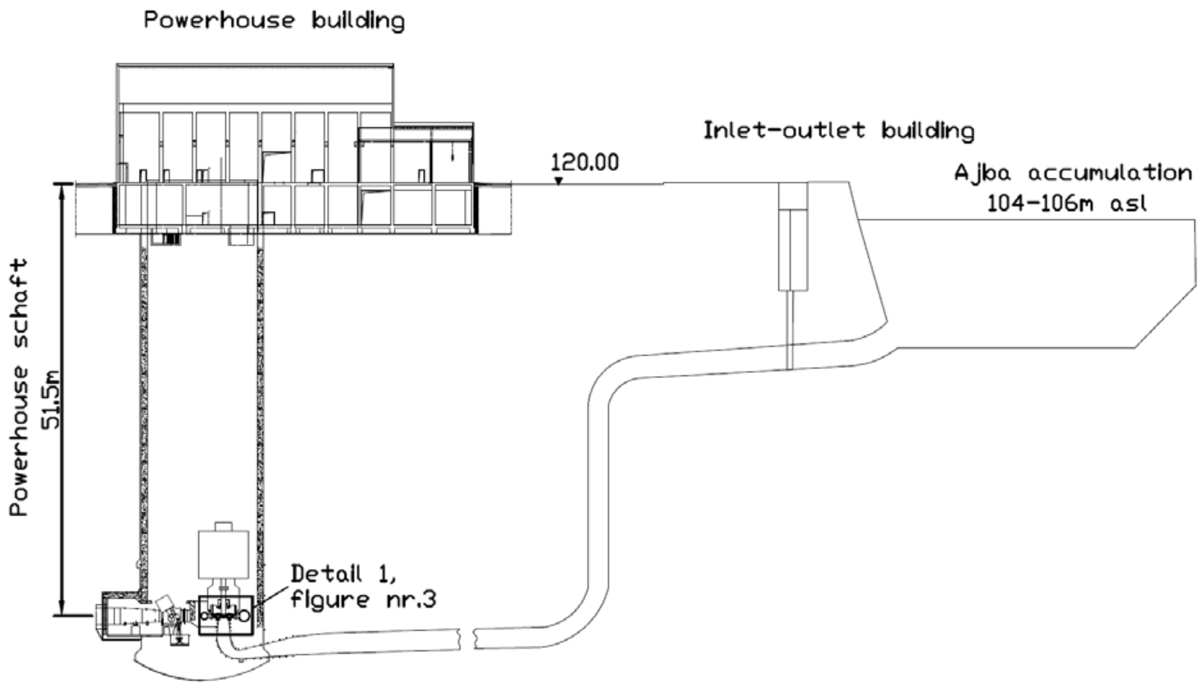

Figure 1. The power house of pump- storage hydro power plant Avče

2.1. Pump turbine Avče model testing

In the model acceptance test the visual observation of cavitation on runner blades was performed in pump and turbine mode of operation. Figure 2 shows areas of visual cavitation bubbles appearance in the pump mode during the model acceptance test. These areas correspond well to the areas of cavitation erosion, which was evaluated during inspection after 3000 hours of operation on the prototype. When pump turbine operates in the pump mode and at low discharges, the inception cavitation in pump mode starts at higher Thoma numbers than when pump turbine operates at high discharges. This is occurring because the discharge coefficient is changing the relative flow velocity incidence angle at the impeller, which strongly affects the pressure distribution on the inlet [5].
The cavitation damage on the prototype was not observed in positions, which according to the model acceptance test correspond to locations of visible cavitation in turbine mode of operation. Because of this in this paper we will only study cavitation in the pump mode of operation.
The cavitation damages on the prototype were in the expected range and did not exceed the value according to standard IEC 60609-1.

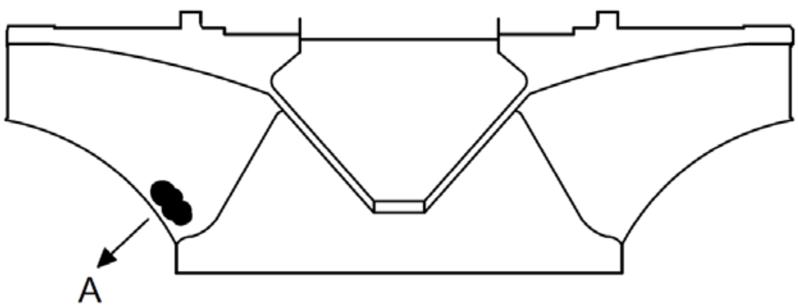

Figure 2. Schematics of occurence of cavitation in pump mode (area A)

3. MEASUREMENT EQUIPMENT

The position of installation of sensors and their mounting method greatly influences detection of cavitation. In general, we want to install sensors as close to the source of cavitation as possible. This is largely possible in cavitation tunnels and model turbines, but is difficult in prototype turbines. In prototype turbines, noise from various other sources is imposed on cavitation signals from sensors. Noise can be either mechanical noise from bearings, non-cavitation flow fluctuations, auxiliary pumps, electromagnetic noise due to presence of strong electromagnetic fields and long cable runs, etc. According to some already installed cavitation monitoring systems [6] [7] [8] [9] [11], cavitation sensors are usually mounted at the turbine guide bearing, on the guide vane plug and on the draft tube wall. Similar installation was followed in this paper, measurements were performed using pressure, vibration and acoustic emission sensors. Locations, where individual sensors were installed, are shown in Fig. 3.

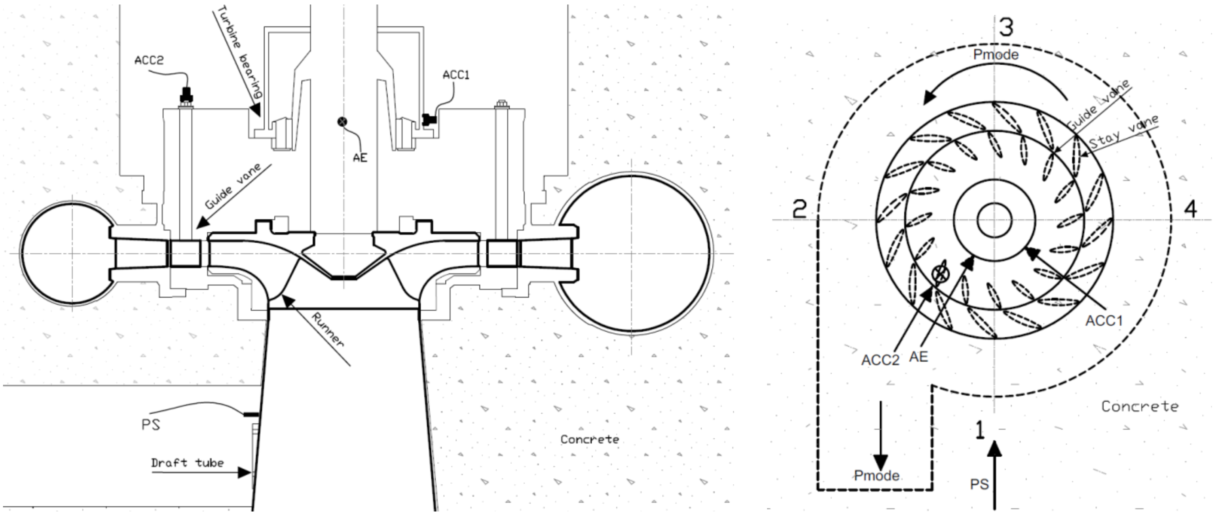

Figure 3. Installation of sensors (detail 1 of the fig 1) showing: (left) view from side; (right) view from top (AE - acoustic emission sensor, ACC1 and ACC2 acceleromets 1 and 2, PS - pressure sensor).

High frequency pressure sensor (PS) was installed in a metal service door opening, approximately 1.5 m below the runner (Fig. 3). Mounting of the pressure sensors closer to the runner was not possible, because above the door the pump turbine flow tract is sealed with concrete and inaccessible as shown in Fig. 3. Above the runner, as measure on the model reported by Rus et al. [2], a thick turbine cover prevents installation. Drilling of bores, large enough for sensor installation, through the turbine cover was not possible due to strength issues. The high frequency pressure sensor used was an ICP general purpose quartz PCB Piezotronics type 111A26 sensor. A suitable cavitation sensor could also be a hydrophone as used in [2] [3] but because of problems of sealing the use of this sensor was denied by the power plant operator. The characteristics of the ICP sensor are pressure range 0-35 bar, 145 mV/bar sensitivity and resonant frequency ≥ 400 kHz.
The acoustic emission sensor (AE) was installed on the turbine cover. We used Kistler AE-Piezotron Sensor type 8152B1. The sensitivity of the sensor was 57 $dB_{ref\ 1V/(m/s)}$ and the frequency range was from 50- 400kHz. Apart from high frequency pressure and acoustic emission sensors, two accelerometers with medium frequency range were used. The first accelerometer was installed on turbine cover near the turbine bearing (ACC1). It was oriented in the radial direction perpendicular to the pump turbine shaft. The second accelerometer (ACC2) was mounted on the pump turbine governor guide vane. It was mounted on the top of

the guide vane, oriented axially with the pump turbine axis. Similar positions of vibration sensors have been also used in a Francis turbine by Escalier et al. [8]. Both accelerometers were stud mounted.
For data acquisition, a National Instruments NI 6351 data acquisition board with 16 bit resolution was used. High frequency sensors PS and AE were sampled with frequency 1 MHz non simultaneously. Both medium frequency accelerometers were sampled simultaneously at a frequency of acquisition 200 kHz per channel. Sampling interval was for all sensors 5 s. Measurement data was stored to disk for later analysis. Analysis of measurement data was performed using National Instruments Labview software. During operation, all operational data from pump turbine was recorded using power plant own measurement and control system.

4. RESULTS AN DISCUSSION

Different sensors have been used in the current experiment as shown in section 3 *Measurement equipment*. Measured variables were after the data acquisition software filtered with Butterworth band pass filter of the first order. High pressure sensor measured data were filtered in the frequency interval from 100 kHz to 300 kHz, AE sensor from 50- 150 kHz while vibration sensors ACC1 and ACC2 were filtered in the frequency interval from 20 kHz to 40 kHz.
In comparison to other works, that present the cavitation intensity in the frequency spectrum in this paper we used also a cavitation estimator. Root mean square (RMS) of measured variables was selected as the simple cavitation estimator. It was found that Shi [9] presented cavitation intensity with the standard deviation estimator.

$$X_{rms} = \sqrt{\frac{\sum_{1}^{N} x_n^2}{N}} \tag{8}$$

In the above equation N is number of measurements and x_n is measured variable, which was in our case either pressure, vibrations or acoustic emission.
As already mentioned before, measurements of cavitation in pump storage prototype turbines are loaded with several sources of noise, among them are most prominent mechanical noise from bearings, hydraulic flow fluctuations and electromagnetic noise. We will here assume, that cavitation is the sole source contributing to measurements of pressure fluctuations, vibrations and acoustic emission. We will later justify the assumption with the agreement of with known patterns of behavior regarding changes of Thoma number and discharge coefficient.

4.1. Compound discharge coefficient cavitation estimator

The results of measurements are shown in Fig. 4. The frequency interval is for sensors ACC1 and ACC2 from 10 to 20 kHz, AE from 50- 150 kHz and PS from 100- 300 kHz. Results are grouped in three intervals of discharge coefficients. Results suggest presence of cavitation, when the pump turbine operates in low range of discharge coefficients. In this case the three intervals of discharge coefficient were selected: more than 0.5, between 0.48 and 0.5 and bellow 0.48. The measurement result also shows that cavitation is present when Thoma number is low. From the results we can notice that the cavitation is increasing if the discharge

coefficient is reduced. In general a fair correlation between measured variables with both vibration sensors, acoustic emission sensor, a high frequency pressure sensor and discharge coefficient was present.
Several authors report that cavitation intensity depends on the incidence angle of the flow and depending on the design of the impeller [5]. For a low discharge coefficient, the flow incidence is increased and cavitation appears in the region of the leading edge of the turbine impeller. Similar behavior was also observed in our experiment. In centrifugal pumps, leading edge cavitation is most common type of cavitation and is also responsible for cavitation erosion.

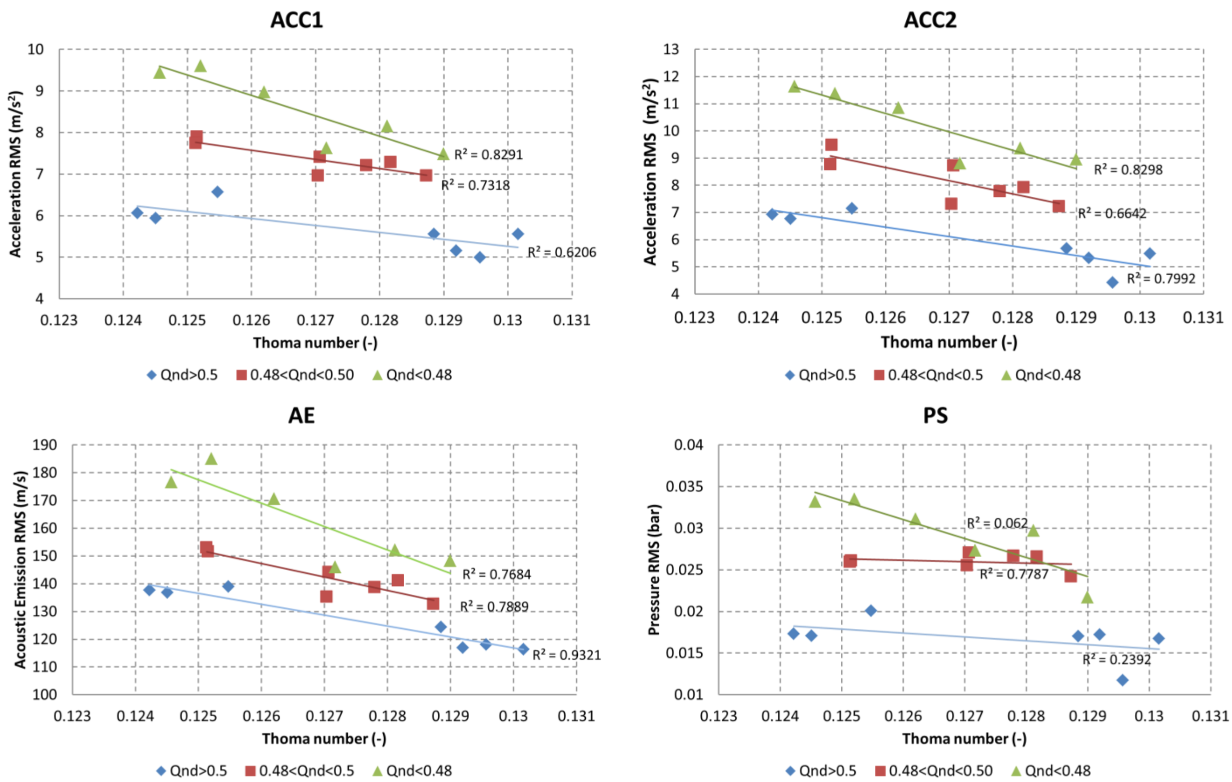

Figure 4. Results of measurements of vibrations, acoustic emission and pressure fluctuations, showing dependence of measured variables on three intervals of discharge coefficients.

Based on the results presented in Fig. 4 we wanted to set a compound estimator of cavitation which will include dependance on discharge coefficient. The goal of the new compound estimator is to estimate cavitation intensity at different Thoma naumbers and discharges. Also, the compound estimator should possibly be more convenient to link cavitation intensity cavitation with cavitation erosion. The new compound discharge coefficient cavitation estimator D_E is based on the discharge coefficient and the *RMS* estimator X_{RMS} from Eq. 8 of the measured varible as follows:

$$D_E = X_{RMS} \cdot Q_{nd}^{\;2} \tag{9}$$

Analysis of measured variables using discharge coefficient cavitation estimator D_E is shown in Figure 5. The frequency interval is for sensors ACC1 and ACC2 from 10 to 20 kHz, AE from 50- 150 kHz and PS from 100- 300 kHz.

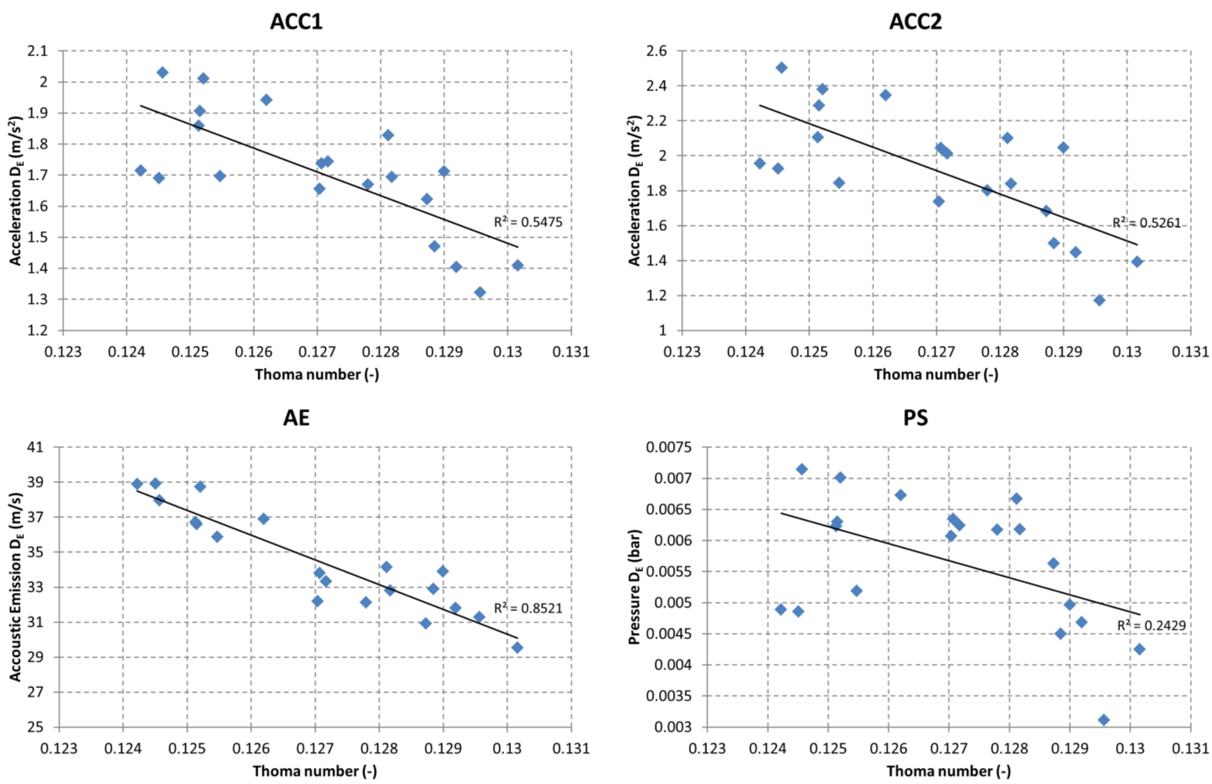

Figure 5. Discharge coefficient cavitation estimator (D_E) for different cavitation sensors

For results presented in Fig. 5, discharge coefficient cavitation estimator was evaluated using coefficient of determination.

The results in Figure 5 show that the most convenient sensor for the cavitation detection is the accoustic emission sensor. Apart from the AE sensor the accelometer mounted on the housing of the turbine guide bearing (ACC1) and the accelometer on the top of the guide vane (ACC2) show moderate agreement. The high frequency pressure sensor (PS) shows poor results, we assume that the reason for this is the distance to the cavitation source and method of installation.

5. CONCLUSION

Measurements and analysis of vibrations, acoustic emission or dynamic pressure in the high frequency range is a well- known technique for estimation of cavitation in pumps and turbines. We have shown that a RMS estimator of measured variables may be used to evaluate the cavitation intensity. Cavitation in pump – storage hydro power plant prototype in pump mode is dependent on the discharge coefficient and on the Thoma number. In the paper we show that a discharge coefficient cavitation estimator (D_E) can be used to estimate the cavitation intensity in the pump – storage hydro power plant prototype.
The most suitable cavitation sensor in the present study was the acoustic emission sensor. The analysis in intervals of frequencies show high value of the coefficient of determination through the entire frequency spectrum. Detailed measurements and analysis of the acoustic emission must be carried out to investigate the cavitation erosion process on the runner blades. In the future an estimation of cavitation erosion with the cavitation estimator may be used to predict the cavitation damage and to estimate the appropriate cavitation damage repair interval.

6. ACKNOWLEDGEMENTS

The results presented here are a part of the doctoral research which was co-funded by the Slovenian Technology Agency– TIA, P-MR-10/131. Operation part financed by the European Union, European Social Fund.

7. REFERENCES

[1] Mohamed Farhat Xavier Escaler, "Cavitation monitoring of hydroturbines: tests in a Francis turbine model," Wagenigen, The Netherlands, 2006.

[2] Tomaž Rus, Marko Hočevar, Vesko Djelic, Brane Širok Igor Kern, "Study of topological structures of cavitation with dynamical analysis and computer aided visualisation," in *20th IAHR*, Brno, Czech Republic, 1999.

[3] Matevž Dular, Brane Širok, Marko Hočevar, Igor Kern Tomaž Rus, "An investigation of the relationship between acoustic emission, vibration, noise, and cavitation structures in a Kaplan turbine," *Journal of Fluids Engineering*, vol. Vol.129, pp. 1112-1122, September 2007.

[4] Igor Kern, Marko Hočevar, Matej Novak Brane Širok, "Monitoring of the cavitation in the Kaplan turbine," in *Industrial electronics. ISIE*, 1999.

[5] Francois A, "Introduction to cavitation in hydraulic machinery," in *The 6th international conference on hydraulic machinery and hydrodynamics*, Timisoara, Romania, 2004.

[6] Eduard Egusquiza, Mohamed Farhat, Francois Avellan, Miguel Cussirat Xavier Escaler, "Detection of cavitation in hydraulic turbines," *Mechanical Systems and Signal Processing*, vol. 20, pp. 983-1007, 2006.

[7] Bernard Bajić, "Multidimensionla Diagnostics of Turbine Cavitation," *Journal of Fluids Engineering*, vol. Vol. 124, December 2002.

[8] Mohamed Farhat, Eduaer Egusquiza, Francois Avellan Xavier Escaler, "Vibration cavitation detection using onboard measurements," in *fifth international Symposium on Cavitation* , Osaka, Japan, November 1-4, 2003, 2003.

[9] Zhaohui Li, Xuezheng Chu, Qingfu Sun Huixuan Shi, "Experimental Investigation on Cavitation in Large Kaplan Turbines," in *Third International Conference on Measuring Technology and Mechatronics Automation*, 2011, pp. 120-123.

[10] Kazuyoshi Miyagawa, Takanobu Komuro, Hidenobu Fukuda Masatake Maekawa, "Study of cavitation erosion on hydraulic turbine runners," in *Fifth international Symposium on Cavitation* , Osaka, Japan, 2003.

[11] Shi- Qing Wang Su- Yi Liu, "Cavitations monitoring and diagnosis of hydropower turbine on line based on vibration and ultrasound acoustic," in *Sixth international conference on machine learning and cybernetics*, Hong Kong, 2007.

[12] M., Farhat,M. Kaye, "Clasification of Cavitation in hydraulic Machines using vibration Analysis," *Proceedings of the Hydraulic Machinery and Systems 21st IAHR Symposium*, 2002.

8. NOMENCLATURE

A_d	intersection of the draft tube outlet	(m^2)
D	discharge diameter of runner	(m)
D_E	discharge coefficient estimator	
E	specific hydraulic energy	(J/kg)
f_f	fundamental frequency	(Hz)
H_a	atmospheric pressure at the tailwater level	(m)
H_{ep}	net head in pump mode	(m)
H_g	gross head	(m)
HL_{HP}	head loss in high pressure part of the waterway (between upper reservoair and entry of spiral case)	(m)
HL_{LP}	head loss in low pressure part of the waterway (between exit of draft tube and the tailrace of the lower reservoir)	(m)
K_{HP}	loss coefficient in high pressure part of the waterway	
K_{LP}	loss coefficient in low pressure part of the waterway	
N	number of measurements	
N	rotational speed	(rpm)
$NPSH$	net positive suction head	(m)
P	density of water	(kg/m^3)
P_v	vapour pressure of water	(m)
Q	Flow rate in penstock	(m^3/s)
Q_{nD}	Discharge coefficient (Pmode)	
R^2	coefficient determination	
$v_{2'}$	velocity at draft tube outlet	(m/s)
x_n	measured value	
$Z_{2''}$	pump inlet static head	(m)
Z_r	height of the spiral casing centreline above the standard level	(m)
σ	Thoma number	