Assessment of Remote Cavitation Detection Methods with Flow Visualization in a Full Scale Francis Turbine

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Abstract

This paper describes the experimental investigations carried out in the Francis turbine at Svorka power plant operated by Statkraft in Norway. The unit, with a head of 260 m, can deliver a maximum output load of 25 MW. The rated flow rate is 11 m^3/s and the machine rotates at 600 rpm. The turbine runner shows cavitation pitting on the suction side of the blades but some blades present more erosion than others. Moreover, preliminary studies based on remote monitoring of vibrations and acoustic emissions in this particular unit have predicted risk of erosion at high loads and the presence of a draft tube swirl affecting the cavity dynamics. In order to assess the sensitivity of these methods and the validity of the predictions, several acrylic-glass windows have been installed on the draft tube wall to visualize the runner outlet flow during operation. A high speed camera has been used to record the flow field during the tests with rates up to 5000 frames per second. A cavitation detection system has been installed comprising three high-frequency uniaxial integrated electronics piezoelectric (IEPE)-type accelerometers and an acoustic emission sensor, mounted in the turbine guide bearing pedestal and a guide vane arm. In particular, a series of measurements at different operation conditions have been carried out to correlate the simultaneous camera observations with the acceleration and acoustic emission overall levels in high frequency bands. The preliminary analysis of the camera records permits to certify the existence of erosive blade cavitation with the closure region close to the eroded areas at high loads. It can be seen that cavitation appears only in some blades and that it presents different cavity sizes for the same operation condition. As the load increases towards maximum powers, both the number of blades with cavitation and the size of the cavities grow. Moreover, the overall vibration levels also rise as expected.

Keywords: Francis turbine, cavitation erosion, high speed flow visualization, cavitation detection, vibration, acoustic emission

Introduction

Hydraulic turbine manufacturers and operators have to face with the drawbacks of suffering cavitation erosion when the units operate outside the best efficiency point. Currently, most of the machines require regular visual inspections to detect the extent of the erosion in order to replace the removed mass of material and to avoid a catastrophic failure. Obviously, this type of planned preventive maintenance is costly because it requires long machine shutdown. A most efficient procedure should be based on the predictive condition monitoring. For that, a remote measurement equipment is installed in the turbine and the adequate signal processing techniques are applied continuously without stopping the turbine.

In this direction, Flow Design Bureau AS is developing a cavitation erosion system to detect and predict the risk of erosion in hydraulic turbines with the help of UPC and NTNU. For that, a series of experiments have already been carried out in the Svorka power plant located near Surnadal in Norway. The plant is owned by Statkraft AS and Svorka Energi AS. The vertical shaft unit is a Francis turbine with a head of 260 m, rotating at 600 rpm and providing a maximum output power of about 25 MW. The runner has 15 blades and the wicket gate has 20 guide vanes. The turbine specific speed is 0.585 and the maximum turbine performance is reached around 21 MW.

This machine is of interest because it suffers aggressive erosion on the suction side of the runner blades close to the trailing edge as it can be seen in the photograph presented in figure 1. This type of erosion is caused by cloud cavitation detaching from the blade leading edge [1]. The methods used to predict cavitation are based on induced high frequency vibrations and acoustic emissions measured on the turbine guide bearing and the guide vanes [2].

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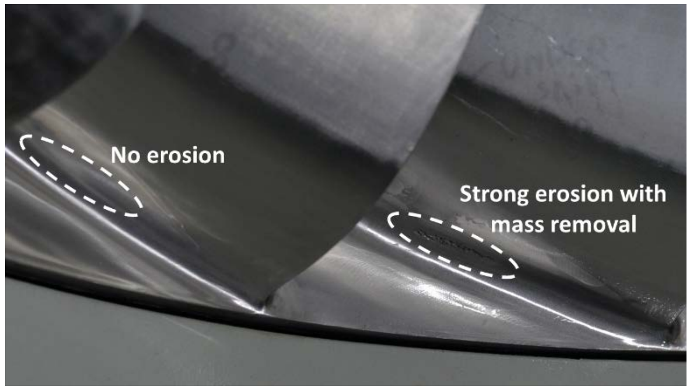

Figure 1. Photograph of the runner showing one blade with erosion and the contiguous one without erosion.

A preliminary investigation [3] has already demonstrated the feasibility of the installed measuring system and the applied signal processing techniques to monitor the activity of runner blade cavitation for unit operation above the best efficiency point (BEP). The results are consistent with the hypothesis that the highest risk of erosion would occur at full load. At this operating condition, the main hydrodynamic frequencies would force the shedding of cloud cavities, thus increasing their aggressiveness. Moreover, a draft tube instability modulating the runner blade cavitation dynamic behavior with periodic character has also been detected above BEP with maximum pressure pulsation levels at full load. Obviously, such detailed predictions could not be directly verified because the flow field inside the runner and draft tube cannot be observed in industrial environments such as any actual hydro power plant.

To the authors' knowledge and unfortunately, no literature reporting flow visualizations of blade cavitation in full scale prototypes can be found. Only in reduced scale model tests with transparent draft tube walls some limited research has been carried out to validate the cavitation remote monitoring techniques [4] which is not sufficient to validate the current methods in real machines. The typical design of the test rigs differs in many aspects from the full scale units. For instance, the signal transmission paths, the cavitation dynamic behavior and the level of aggressiveness might present significant differences that are not well known specially operating outside the BEP.

Consequently, it has been decided to design, construct and mount several transparent acrylic-glass (PMMA) windows around the draft tube wall that allow to visualize the cavitation flow exiting a Francis runner during operation. The final goal of the experimental investigation is to evaluate and validate the erosive cavitation remote measurements and procedures that permit to predict erosive cavitation and to estimate its aggressiveness.

Flow visualization setup

In order to have visual access to runner areas with detected cavitation erosion, three pipe-stubs were added to the draft tube into which 0.2 m diameter acrylic-glass bolts were fitted. In addition, a 0.42 m diameter acrylic-glass bolt was produced to replace the manhole cover. All the bolts surfaces were machined in such a fashion that allowed direct line-of-sight towards the erosion zones as indicated by the lines plotted in the outline presented on the left of figure 2. At the time of writing, the acrylic-glasses have been fitted twice in the pipe-stubs and the manhole. More specifically, they have been exposed to water between 2 and 3 days total, without presenting any observation of cracking or discoloration.

As it could be detected in a series of preliminary tests, the axis of the draft tube presents a gas-filled core for all the operation conditions as shown on the right of figure 3. The size of this cavitating vortex grows as the unit operates far from the BEP and obviously blocks the vision of the runner. Consequently, the camera had to be pointed away from the draft-tube center and given the current window positions the visible runner blades were observed when passing in front of the spiral casing end.

The high-speed camera used, model Photron® FASTCAM SA5, allows a frame-rate up to 7000 frames per second (f.p.s.) while still maintaining maximum resolution (1024x1024 pixels). During unit operation, the flow field was recorded with frame rates of 4000 and 5000 f.p.s., which correspond to a runner motion between frames of 0.9° and 0.72°, respectively, given the turbine rotating speed (10 Hz). As the field of view exceeds 24°, more than the angular separation between two consecutive blades could be recorded. The camera mounted a 50 mm f 1.8 lens with the Nikon f-mount and it was focused on the blades eroded areas through one of the two smaller bolts located at the draft tube

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top. Professional photographic lights were used that lighted through the manhole bolt and through the other smaller bolt located at the top.

Figure 2. (a) Outline of the acrylic-glass windows mounted on the draft tube with the adequate vision angle to see the blades; (b) photograph showing the flow visualization tests.

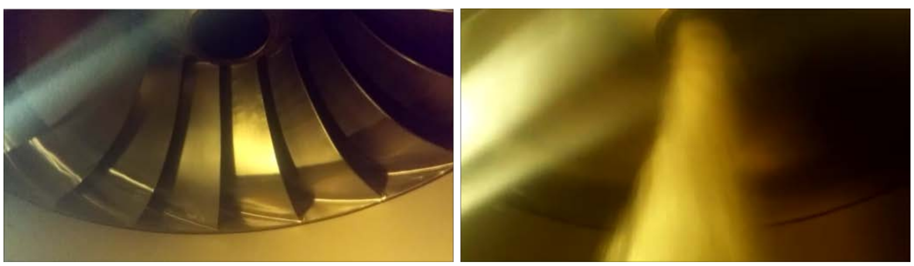

Figure 3. Vision of the runner from the manhole with the machine stopped (a) and with the machine operating at 19 MW (b).

Vibration and acoustic emission measurement

A cavitation detection system was installed that consisted of three high-frequency uniaxial integrated electronics piezoelectric (IEPE)-type accelerometers (AC) and an acoustic emission sensor (AE) mounted in the positions indicated in figure 4. Two of the accelerometers separated 90°, TGB1 and TGB2, were mounted on the turbine guide bearing pedestal using studs glued to its base that in turn screwed onto the sensor. Their axes were orientated in radial direction relative to the shaft axis. The other accelerometer, GV, was mounted at the top of a guide vane shaft using similar studs. Its axis was parallel to the shaft axis. The acoustic emission sensor, TGB, was also mounted on the guide bearing pedestal using a spring-loaded magnetic holder. Silicone grease was used between the sensor surface and the base surface. A preamplifier, supplied by a constant voltage source, was used to condition its signal.

All data recording was made using National Instruments (NI) hardware in conjunction with LabView® software. Signals were recorded using an NI cDAQ-9178 chassis. The accelerometers were conditioned and digitized using an NI 9234 IEPE module and the AE sensor using an NI 9215 AI [V] module. Accelerometer signals were recorded at 51200 samples per second (S/s) and the AE sensor at 250 kS/s. Several raw data time segments, each of 20 seconds duration, were recorded at each steady operation condition.

High speed observations and cavitation detection results

Based on the previous results [3] it was decided to concentrate the measurements and visual records in operating conditions ranging from the BEP (21 MW) up to full load (25 MW) in steps of 1 MW. The inspection of the runner blades just before the tests had shown that some blades were more eroded than the rest. In fact, only some blades presented strong mass removal and others did not show any significant mark. For example, such differences can be clearly seen in figure 1 where two consecutive blades are shown.

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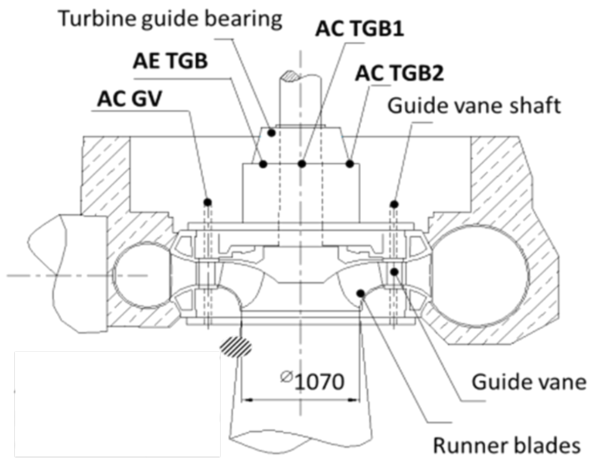

Figure 4. Location of the acceleration and acoustic emission sensors on the turbine guide bearing pedestal and guide vane shaft.

After analyzing the video records and identifying the 15 blades, it has been possible to compare their cavitation conditions among them for all the operation conditions. As it can be seen in figure 5, not all the blades present suction side cloud cavitation. For instance, blade number 6 appears not to suffer cavitation at all for any power output. On the contrary, blade number 14 is free of cavitation at BEP but develops cavitation for the rest of higher output loads.

The global results regarding the presence of cloud cavitation for all the blades and operation conditions are summarized in table 1. Here it must be reminded that the field of view only corresponds to a narrow zone located next to the end of the spiral casing and no information about the evolution of the cavitation conditions as the runner blades span the whole circumference is available.

Firstly, it can be noted that only blade number 10 shows cavitation for all the loads including the BEP (21 MW). Then, cavitation starts at 22 MW for blades number 5, 13 and 14. At 24 MW, blades number 4, 6, 11 and 12 do not show cavitation yet. Operation condition at full load (25 MW) requires a special comment. Due to the significant increase of bubbles inside the flow, all the images appear excessively blurry and it is not possible to identify the presence of any type of large scale cavities. This unexpected behavior might be due to a deficient turbine setting point that reduces the available Net Positive Head (NPSHA) especially at full load.

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
21MW	-	-	-	-	-	-	-	-	-	Y	-	-	-	-	-
22MW	-	-	-	-	Y	-	-	-	-	Y	-	-	Y	Y	-
23MW	Y	-	-	-	Y	-	-	-	-	Y	-	-	Y	Y	-
24MW	Y	Y	Y	-	Y	-	Y	Y	Y	Y	-	-	Y	Y	Y
25MW	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?

Table 1. Summary of the observations regarding the presence of blade suction side cavitation on all the 15 blades for operation conditions from 21MW up to full load at 25 MW. [Y] means that cavitation is detected, [-] means that it is not detected and [?] means that visualization information is not clear enough to distinguish its presence.

A more detailed observation of the flow field at 24 MW shown in figure 6 permits to clearly see the large-scale types of cavitation taking place when blades number 10 and 13 pass in front of the vision angle. As already commented, the closure region of the cloud cavitation on the blade suction side is observed as well as other forms of cavitation such as vortex shedding cavitation at the blade trailing edge and draft tube vortex rope cavitation from the runner hub.

The overall RMS vibration acceleration and acoustic emission levels in the frequency bands from 18k to 20k Hz and from 95k to 97k Hz, respectively, have been plotted as a function of output load in figure 7. These results correspond to the average values from measurements taken in two different days. The data show that the levels increase with output load which corresponds to the increase of the number of blades with cavitation and the cavity sizes. The values in both guide bearing accelerometers are quite similar meanwhile the values in the guide vane are higher. The trends

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from the two accelerometers and the acoustic emission sensor located on the guide bearing are analogous but the trend observed in the guide vane accelerometer differs slightly.

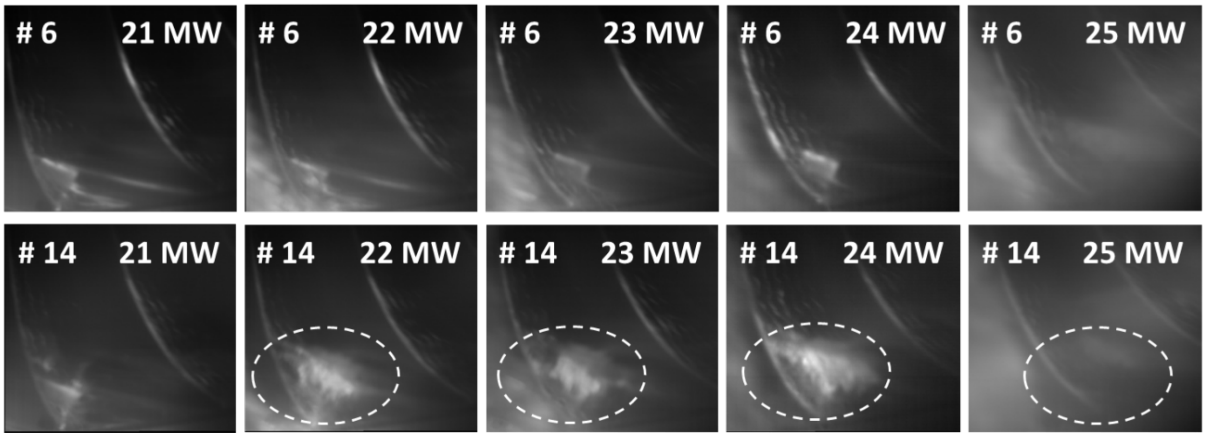

Figure 5. Flow visualization on blades number 6 (upper row) and number 14 (lower row) for operation conditions ranging from 21 MW up to full load at 25 MW. Suction side blade cavitation is observed for blade number 14 starting at 22 MW meanwhile blade number 6 does not exhibit cavitation at any operation condition.

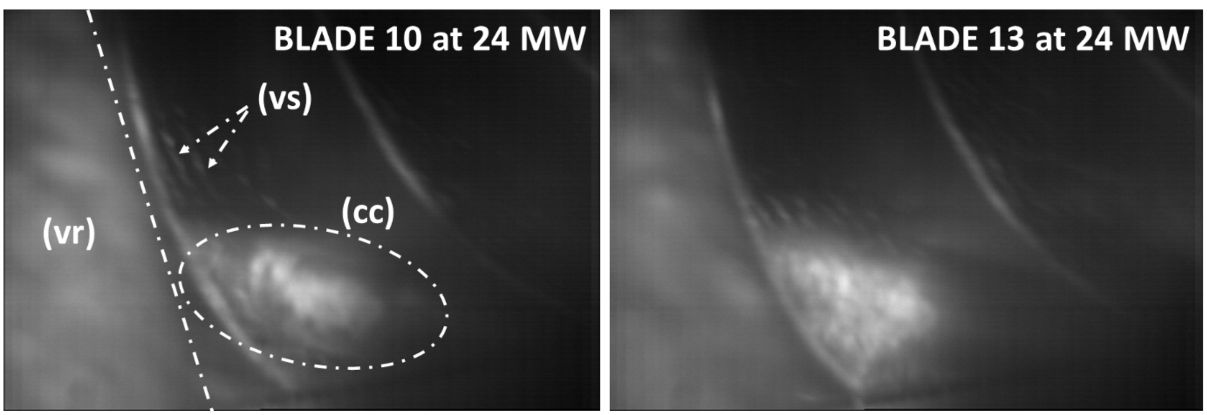

Figure 6. Zoomed view of the flow field at 24 MW when blades 10 (left) and 13 (right) pass in front of the vision angle that permits to identify cloud cavitation on the blade suction side (cc), vortex shedding cavitation at the blade trailing edge (vs) and draft tube vortex rope cavitation from the runner hub (vr).

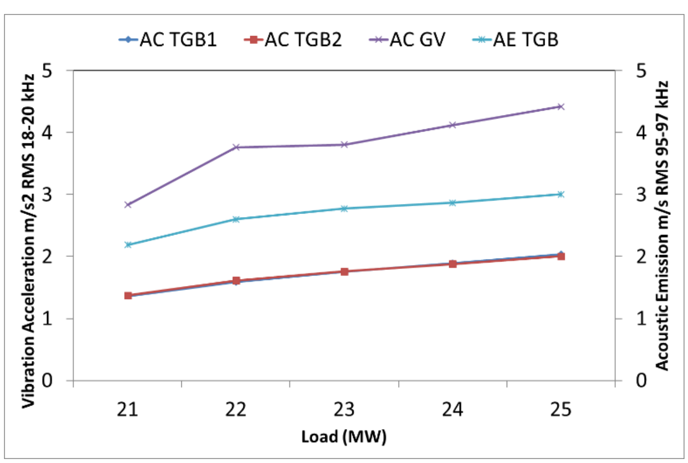

Figure 7. Overall RMS vibration acceleration and acoustic emission levels in the frequency bands [18k-20k Hz] and [95k-97k Hz] respectively, as a function of output load.

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Conclusion

This work demonstrates the feasibility of installing visual access points on full-scale Francis turbine draft tubes to investigate cavitation phenomena inside the runner. The main objective is focused on answering at which turbine operation condition blade erosive cavitation takes place and how many runner blades are attacked. Analysis of video records taken with a high-speed camera has allowed identifying and quantifying runner cavitation from BEP up to full load. It has been observed that cloud cavitation on the blade suction side is responsible for the observed erosion. Surprisingly, cavitation is present in some blades even at BEP. As the load increases towards maximum powers, the number of blades with cavitation increases and the size of the cavities grows. Cloud cavitation seems to vanish at full load but it might be masked by the high bubble content of the main flow provoking images that are blurry. Based on overall measurements of cavitation erosion intensity obtained from induced noise and acoustic emissions with methods presented in previous works, a good correlation with the visual observations has been obtained. The remote cavitation measurements also suggest growing cavitation intensity from BEP towards full load, the latter with maximum aggressiveness, which is in agreement with the observations. Another significant confirmation is that the cavitation clouds are present only at selected runner blades, thus explaining the presence of erosion only at particular blades.

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