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MONITORING BY INTEGRATED PIEZO SENSORS OF A TURBINE BLADE SUBMITTED TO CAVITATION

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ABSTRACT

With the integration of a growing share of renewable energies, hydroelectricity is expected to play a major role in adjusting power generation to demand. So with increased availability requirements, more severe operating modes, the need for monitoring systems is becoming more pressing.

The objective of this study is to demonstrate the feasibility of a diagnosis by UT structural health monitoring system using guided waves generated by piezoelectric patches embedded in the structure to be inspected.

A representative sample was instrumented and placed in a test loop enabling to varying different water flow parameters.

Three scalar indicators were tested and their evolution were recorded as the water flow parameters were modified. While two indicators were sensitive to all variations in flow parameters, the third one only reacted to the parameter of interest, namely the appearance of cavitation which is responsible for the premature degradation of turbine blades by material pull-out

This approach could also apply to the condition monitoring of turbine blades and the detection of damage such as cracks or pull-outs of materials related to cavitation, corrosion or abrasion, or the monitoring of penstocks.

1 INTRODUCTION

With the integration of a growing share of renewable energies, the energy sector is undergoing profound changes and in particular the emergence of new issues related to the stability of electricity networks. Hydroelectricity is expected to play a major role in adjusting power generation to demand.

However, this use of hydroelectric turbines places a heavy load on the machines. With increased availability requirements, more severe operating modes, the need for monitoring systems is becoming more pressing. It can become a differentiator between turbine manufacturers.

Ultrasound is commonly used in many industrial sectors for the detection, localization and characterization of defects in structures.

The objective of this study is to demonstrate the feasibility of a diagnosis of hydroelectric turbine structures and associated components by US control for integration into a structural health monitoring system. The designed system should be able to detect the appearance of the cavitation and so allow to adapt the flow rate to avoid cavitation and preserve the structure from the possible resulting damages.

In the literature, we can find several research papers dedicated to the online monitoring of damage induced by cavitation phenomena by non destructive techniques [1]–[3] but to our knowledge there are no papers dealing with the early detection of the cavitating regime of a water flow.

The proposed technique consists in using guided waves generated by piezoelectric patches embedded in the structure to be inspected.

The exploratory experimental study showed the potential of this technique for detecting cavitation, which is a violent phenomenon responsible for the premature degradation of turbine blades by material pull-out.

A representative sample of a turbine blade was instrumented and placed in a test loop enabling to vary different water flow parameters such as, flow velocity, pressure or the angle between the foil and the flow direction.

Three scalar indicators were tested and their evolutions were recorded as the water flow parameters were modified.

While two indicators were sensitive to all variations in flow parameters, the third one only reacted to the parameter of interest, namely the appearance of cavitation.

This shows that it might be possible to design an SHM system relying on several scalar indicators each of them being sensitive to different kind of flaws.

Possible applications of this approach could be, for example, the condition monitoring of turbine blades and the detection of damage such as cracks or pull-outs of materials related to cavitation, corrosion or abrasion, or the monitoring of penstocks.

2 EXPERIMENTAL SETUP

Cavitation is a violent phenomenon that can appear in hydraulic machines submitted to a high flow rate and that can lead to premature damage of turbine blades by material pull-out and/or erosion. In the context of using hydroelectricity to adjust the power generation to the demand, it is very important to be able to detect the

cavitating flows and then stop them by tuning the flow rate.

The objective of this research work was to detect rapidly the cavitation of a water flow around hydraulic turbine blades, in real time and online.

Our system, that has been described in [4] consists in several piezoelectric disks of 12mm in diameter and 1mm thick, bonded or embedded in the structure to be tested (Figure 1).

Those patches are used to generate and detect guided waves that propagate in the structure and interact with it.

The recorded signals on each sensor are used to compute scalar numbers we call Damage indexes (DI) that will be sensitive to changes in the condition of the structure to be tested.

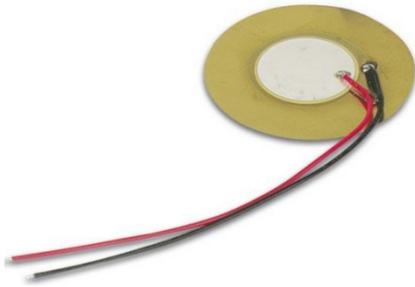


Figure 1. Typical piezoelectric patch used in this work

A representative sample of a hydraulic machine blade has been instrumented with four sensors similar to the one depicted in Figure 1. The dimensions of the foil were 195x52x4,8 mm³. The sensors were bonded on the surface and protected by a water-proof resin (Figure 2).

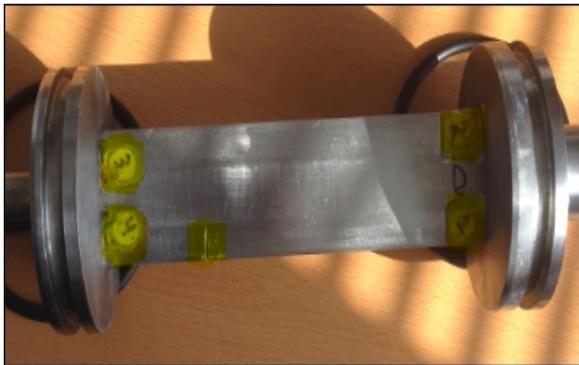


Figure 2. Instrumented sample.

Then this sample has been mounted in a water tunnel in which the flow characteristics can be varied. The actual presence of cavitation can be observed through an observation window in front of the sample (Figure 3).

In Figure 3, we can see through the window the foil that has been mounted vertically and placed in a flow that will go from right to left. The angle between the flow axes and the foil flat surface was 3°. The sensor #4 was used as an emitter/receiver and the sensors #1, #2 and #3 were used as receivers only. The excitation was a 300 kHz sine burst of 5 cycles and a peak to peak amplitude of 10 V.

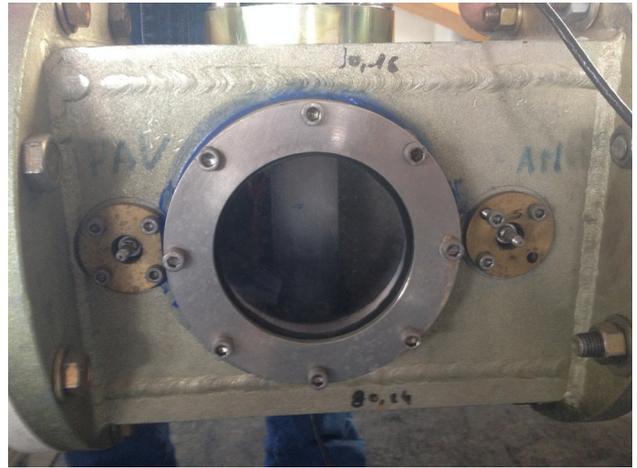


Figure 3. Water tunnel with its observation window.

The signals were digitized, observed and recorded by a 4 channel Lecroy Waverunner oscilloscope.

Three different *DIs* were calculated and plotted in real time for each channel.

In a previous paper [5], we presented different possible *DIs* and compared their performances with respect to various criteria such as sensitivity, computing time, energy cost...

In this study we decided to test the following *DIs*, that are scalar numbers allowing to compare a measured signal $s_n(t)$, to a reference signal $s_{ref}(t)$ that have been acquired in a supposed healthy state of the tested piece.

$$DI_1 = \frac{\sum_1^N |g(s_n(t)) - g(s_{ref}(t))|}{\sum_1^N |g(s_{ref}(t))|} \quad (1)$$

$$DI_2 = \frac{\sum_1^N |g(s_n(t))^2 - g(s_{ref}(t))^2|}{\sum_1^N |g(s_{ref}(t))^2|} \quad (2)$$

$$DI_3 = \frac{\sum_1^N |g(s_n(t)) - g(s_{ref}(t))|^2}{\sum_1^N |g(s_{ref}(t))|^2} \quad (3)$$

where g is a transform that is applied to the waveforms and N is the number of samples in the transformed signals. In this study, g is the Fast Fourier Transform (FFT) of the time signals.

Those Damage Indexes are normalized and will evolve from 0 if the measured signal is identical to the reference one to 1 in case of total breakage of the structure between the emitter and the receiver (no wave transmitted at all).

In Figure 6 are presented the *DIs* calculated on sensor #4 in pulse echo mode.

3 EXPERIMENTAL RESULTS

3.1 Cavitation detection experiment

In Figure 4 we present typical signals after filling the tunnel with water. At this stage the water is still, there is no relative velocity between the foil and the fluid. So there is almost no influence of the fluid on the behaviour of the guided waves and since the signals are very close to the reference ones, so the DI are almost zero.

In Figure 5 are presented signals and their spectra measured when the flow rate was high enough to trigger the cavitation in the tunnel around the foil. Slight differences between the measurements and the references are observed on the waveforms as well as in their spectra. Those differences will result in a variation in the DI s.

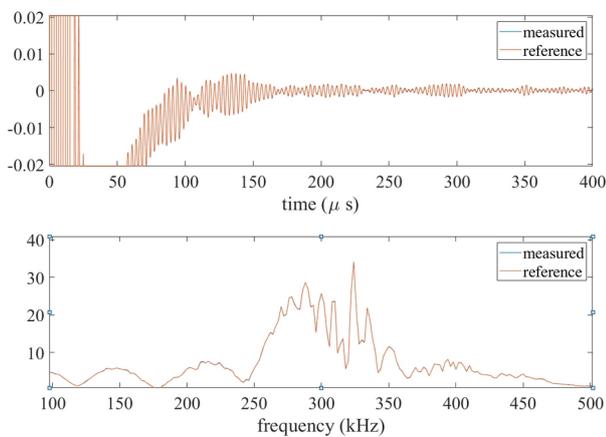


Figure 4. Typical signals (top) and spectra (below) obtained in water without flow rate.

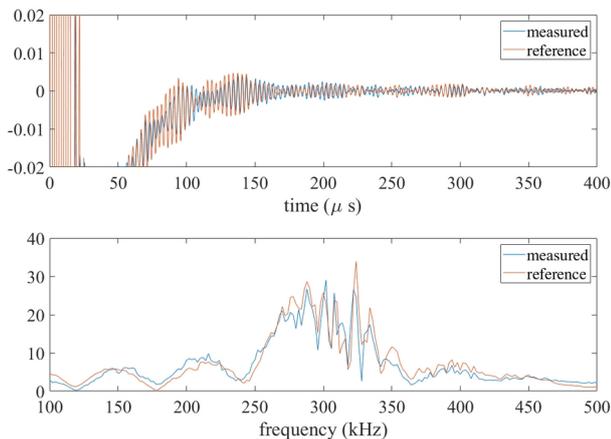


Figure 5. Typical signals (top) and spectra (below) obtained in water in the cavitating flow.

The main results we obtained in the case of cavitation detection are reported on Figure 6. To check the sensitivity of our DI s to the flow conditions, we started the experiment and set the 3 DI s to zero. This is achieved by choosing the current measured signals as reference.

The tunnel was empty of water and we recorded about 70 signals. We can observe that the 3 DI s remain very close to zero. Then the tunnel has been filled with water. This change in the environment of the foil is detected by DI_1 and DI_2 , while DI_3 is insensitive. Then round the 100th acquisition the flow rate is increased progressively and again DI_1 and DI_2 , react a lot and increase but DI_3 remains almost unchanged. When the flow rate is stabilized, the DI s stay constant and then vary at each increase (around acquisition 150 and 200). Finally at around acquisition #300 all the DI increase brutally exactly at the same moment at which the cavitation is observed through the observation window.

The most important fact is that DI_3 is also increasing showing its sensitivity to cavitation.

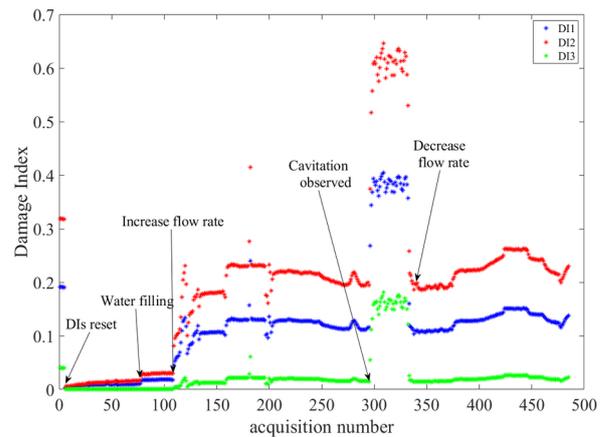


Figure 6. Measured DI s on the instrumented blade submitted to a water flow.

3.2 Impact experiment

Actually, DI_3 has been found insensitive to the flow characteristics, but sensitive to the condition of the foil.

In the following we will check the ability of DI_3 to detect the appearance of a defect like a pitting or a material pull-out.

For this experiment, the tunnel was empty of water and the observation window opened in order to access the foil and damage it with the help of a punch and a hammer. To introduce the punches, we had to unmount the foil and take it out of the tunnel. We first check our ability to loosen and tighten the mounting bolts and reproduce the same stress condition on the foil.

Preliminary measurement showed that the best sensitivity to the stress condition of the foil and to the introduction of pitting was obtained in transmission between sensor #4 and sensor #1.

We present an example in Figure 7. At around acquisition #30 we loosen the bolt and the DI increases because the stress applied to the foil by the mount has changed. Then at acquisition #50 we tried to go back to the initial torque with the help of a torque wrench. We clearly see that the DI comes back to the reference level. This means that when the changes we operate on the structure are reversible, the DI recovers its reference level.

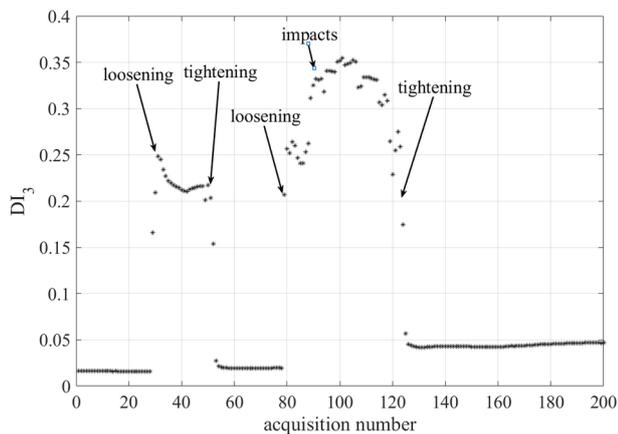


Figure 7. Measured DI_3 on the instrumented blade submitted to impact test.

At acquisition #80 we unmounted the foil and punched it several times on the opposite side with respect to the sensors positions (Figure 8). After each punch, we mounted again the foil in the tunnel, without tightening the bolts, and acquired waveforms.

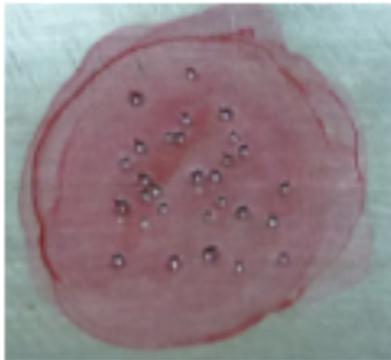


Figure 8. Photograph of the impacts introduced on the opposite side of the foil with respect to the sensors.

During this stage, the DI increases and changes in a complex manner because the stress applied to the foil is not controlled, but when we finally tightened the bolts to the initial torque level, we can see that the DI stabilized at a constant level a little bit higher than the one we had at the beginning of the experiment.

This is a typical behavior of the various DI we studied here, as well as also in other studies. When a permanent or irreversible change, like a damage, occurs on the structure, the DI never goes back to the reference level.

4 CONCLUDING REMARKS

The presented work showed that it is possible to develop a SHM system not only able to detect flaws such as pitting or material pull-out, but also the cavitation regime of a water flow in real time and online.

Among the three Damage Indexes that we monitored during the varying flow rate experiment, only one (DI_3) showed to be sensitive to the cavitation phenomenon. The two others were similarly sensitive to cavitation but also

to the changes in the flow condition (especially the flow rate).

The DI_3 indicator has also proven its sensitivity to the changes in the mechanical condition of the tested foil.

After validation of the reproducibility of the DI_3 response to the applied stress by the mount bolts, we showed that if small holes are introduced, to simulate pitting resulting from cavitation, the indicator will increase, allowing the detection of such flaws.

So we can imagine monitoring strategies in which some indicators will be especially calibrated to monitor the changes in the flow rate or any other environmental parameter, and others sensitive to the cavitation and the health state of the monitored structure.

Of course, for each application, a full preliminary study has to be implemented in order to determine the number and position of the sensors, the kind of signals to be used, the acquisition mode (pulse-echo or through transmission between sensors) and to define the indicators that meet the requirements and objectives of the monitoring system.

This approach can potentially be extended to other practical situations such as wind turbines blades, pipelines, penstocks for instance.

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