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**VORTEX-INDUCED CRACKS ON STAY VANES OF A FRANCIS
TURBINE: AN APPLICATION OF EXPERIMENTAL AND NUMERICAL
ANALYSIS**

Ricardo Sampaio

Alexandre D'Agostini Neto

Ph.D. Humberto de Camargo Gissoni

Voith Hydro Ltda.

Rua Friedrich Von Voith, 825, São Paulo, 02995-000, Brazil

ricardo.sampaio@voith.com

alexandre.neto@voith.com

humberto.gissoni@voith.com

Vicente Borri

Renato José Baccili Castilho

CTG Brazil.

Rodovia Chavantes/Ribeirão Claro, km 10 – Chavantes, Brazil.

vicente.borri@ctgbr.com.br

renato.castilho@ctgbr.com.br

Abstract. *Stay Vane cracks on a 105 MW, 73 m head Francis turbine have been reported since 1974 and this cracks issue was never completely solved. Although Voith Hydro was not the original manufacturer of the turbine, all the information was available to execute an engineering diagnostic of the reported problem and to propose a profile modification able to eliminate the cracks occurrence.*

This work describes the activities performed for diagnosing the Vortex Induced Vibration phenomenon occurring at stay vane profiles with associated cracks history and the resulting trailing edge modification. Firstly modal analysis by the Finite Element Method and by an analytical model based on the plate and potential flow theories were used to evaluate the natural frequencies of the stay vanes both in air and water. Results obtained from a bump test in air performed at site were used to evaluate both methods. Then stay vanes vibration was measured indirectly at the prototype. The combination of modal analysis and experimental data revealed that the second natural frequency of the stay vanes was being excited.

The actual stay vane profiles were obtained by 3D measurement techniques and transient Computational Fluid Dynamics simulations were performed to numerically reproduce the phenomenon occurring in the original stay vane profile and to develop and validate a profile modification able to eliminate the vortex shedding. The geometrical modification was implemented at site and a second measurement vibration campaign happened on April 2017 revealing that the second natural frequency is no longer being excited. Although a higher frequency vibration was measured, in August 2017 there was a visual inspection of the vanes and no cracks were found.

Keywords: *Stay Vanes, Vortex Induced Vibration, Vortex Shedding, Indirect Measurement*

1. INTRODUCTION

Vortex Induced Vibration (VIV) is a well-known vibration mechanism and the first published case of a stay vane failure related to VIV was in 1968 (Goldwag and Berry, 1968). Up to now at least 27 other cases were reported (Gissoni, 2015), demonstrating that although it is not a new problem, it still remains challenging for operation and maintenance teams around the world. The occurrence of cracks at stay vanes of hydraulic turbines directly affects the availability of the power unit due to the long period required for the repair of the damaged parts. Therefore, a deeper understanding of the vibration mechanism is necessary to avoid component failures.

Common investigations of the vibrational behaviour of stay vanes usually involve strain-gauge measurements, which in one hand allows a direct assessment of the dynamic stresses of the studied component but on the other hand, requires an outage of the power unit for instrumentation and assembly of the measurement chain. Indirect measurements applied together with detailed background information provided by modal analysis can give a very good indication about which mode of the stay vane is being affected by the vortex induced phenomenon (Neto, *et al.*, 2016).

This work characterizes the vibrational behaviour of the stay vane by means of accelerometers installed on the bottom ring gallery, i.e. outside the water flow, thus considerably reducing the stopped time of the power unit. Then, a transient Computational Fluid Dynamics (CFD) simulation is performed to characterize the VIV phenomenon on the original stay vane profile and, afterwards, a change in geometry is proposed to eliminate it.

The Power Unit (PU) studied is a 105MW, 73m head Francis turbine which has records of cracks on the stay vanes since 1974 (Gummer and Hensman, 1992). The stay ring is composed by 24 vanes that can be divided into four geometry groups being group 1 (vanes 1 to 7), group 2 (vanes 8 to 13), group 3 (vanes 14 to 19) and group 4 (vanes 20 to 24). A top view of the stay ring is shown on Fig. 1 with the red circles identifying the vanes from group 4 which have a history of cracks occurrence.

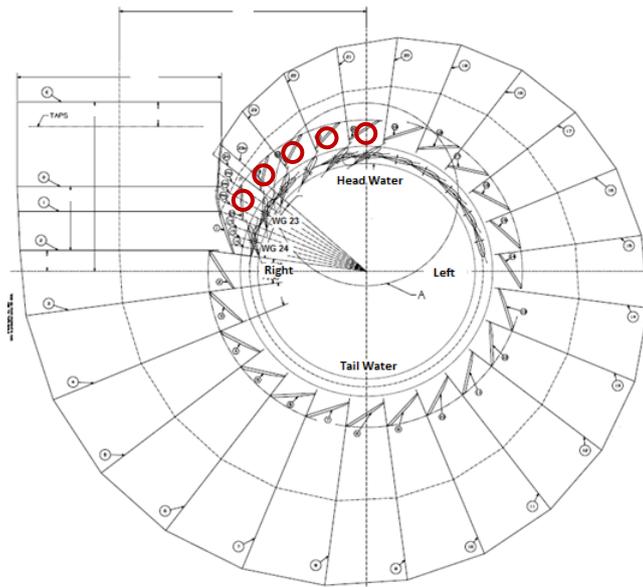


Figure 1. Stay ring top view. Red circles highlight vanes from group 4.

2. METHOD

A comprehensive study was performed starting with a modal analysis on Ansys®15 to obtain, by the Finite Element (FE) method, the natural frequencies, both in air and water, of the theoretical geometry of the stay vane. The 3D model used represents 1/24 of the stay ring and in order to model the water mass around the vane fluid-acoustic elements type FLUID 30 were used. Figure 2 shows the first three mode shapes found and the calculated results are presented at Tab. 1.

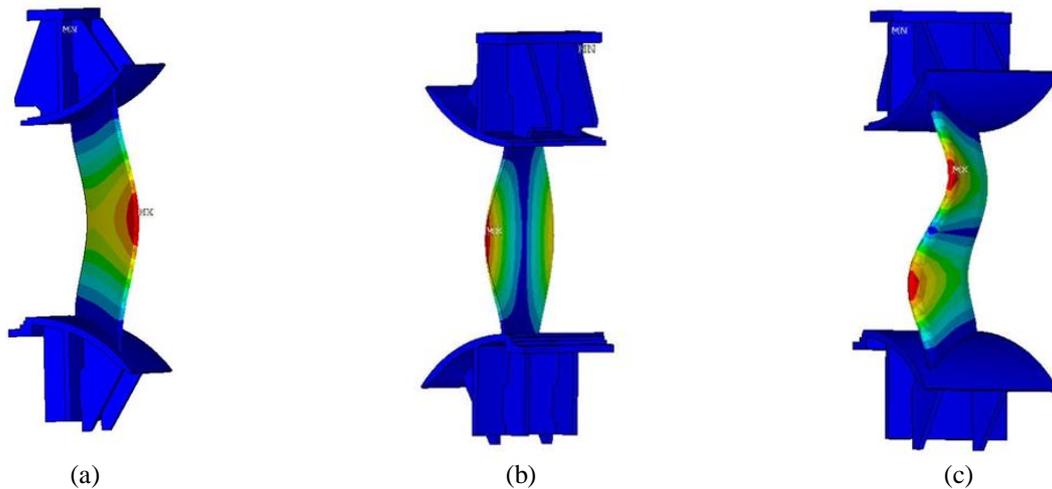


Figure 2. Stay Vane mode shapes: (a) First bending mode, (b) first torsional mode and (c) second bending mode.

Along with the Finite Element modelling, an analytical approach was also considered to evaluate the natural frequencies in air of a plate with clamped-free boundary conditions (Gissoni, 2005) and to handle the added mass effect (Gissoni, 2005), thus allowing the evaluation of the natural frequencies in water.

An Experimental Modal Analysis was performed on PU04 in order to determine the actual eigen-frequencies of the stay vanes and its results were compared with the ones obtained from both the numerical and analytical methods. The summary of the results is shown at Tab. 1.

Table 1 - Summary results for natural frequencies.

<i>Method</i>	<i>1st Nat. Freq. [Hz]</i>	<i>2nd Nat. Freq. [Hz]</i>	<i>3rd Nat. Freq. [Hz]</i>
Analytical in air	115	177	314
FE in air	137	197	363
Bump Test (air)	130	200	330
Analytical in water	66	133	180
FE in water	75	150	248
Analytical Reduction factor	0.57	0.75	0.57
FE Reduction factor	0.55	0.76	0.68

As the results by FE in air agree more with the experimental ones from the bump test, this method was chosen as reference to provide the natural frequency values of the stay vanes in air and in water. It is noteworthy that the variable height of the vane, as can be seen at Fig. 3 (a), affects the accuracy of the analytical approach once it assumes a constant value.

Dynamic tests were also performed at site on PU04 with the machine in operation to characterize the vibrational behaviour of the stay vane. Accelerometers were installed at six different circumferential positions at the coupling region between the stay ring and the bottom ring as shown at Fig. 3, thus indirectly measuring the vibrations on the stay vanes.



Figure 3. Accelerometer installation position: (a) Cross section view and (b) Photo from the actual installation.

Despite being an indirect vibration measure, it was able to identify a characteristic peak frequency of 140 Hz rising at, approximately, 80% of the output until the maximum power available at the moment of the tests, as shown at Fig. 4. This indicated that the first torsional mode of the stay vane which corresponds to the 2nd natural frequency was being excited by the flow.

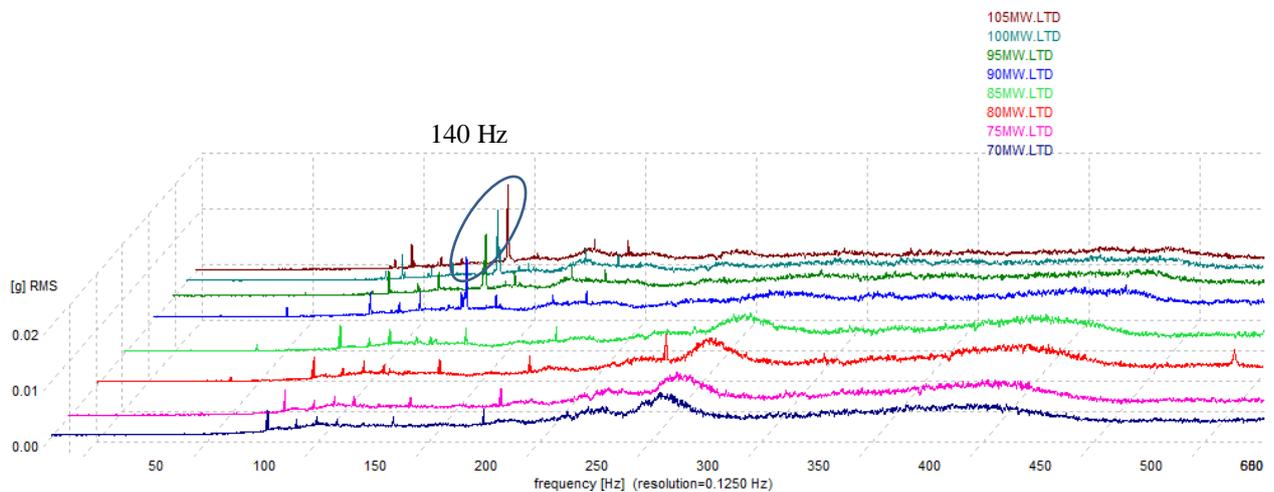


Figure 4. FFT as a function of the turbine output for original vane profile. Sensor installed at the stay ring.

A third step to characterize the vibrational behaviour of the stay vane was to perform a transient Computational Fluid Dynamic (CFD) simulation to reproduce the flow around the stay vane. Based on the cracks occurrence history, the geometry of stay vanes 22 and 23 were measured at site using a three-dimensional technique and vane 23 was used as the model for the numerical flow simulation with commercial software CFX®16. Figure 5 presents the measured geometry emphasizing the trailing edge.

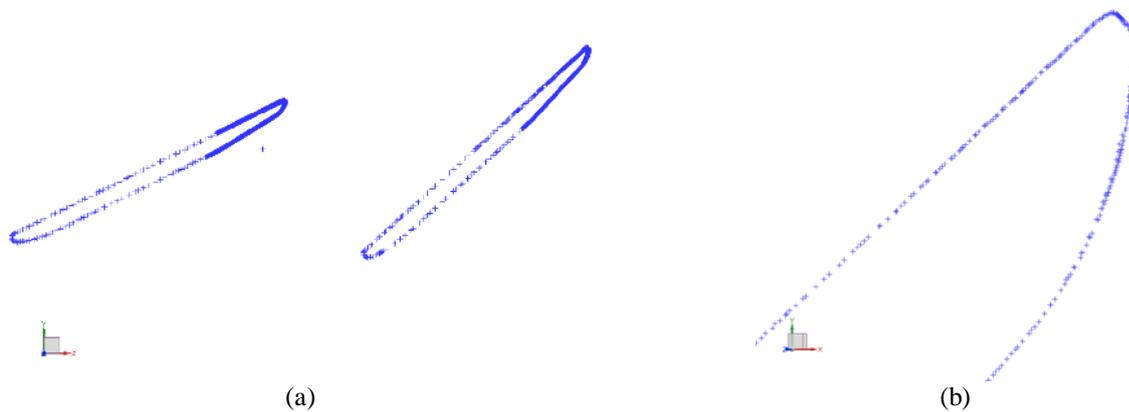


Figure 5. Three-dimensional geometry measurements: (a) Vanes 22 and 23 profiles and (b) vane 23 trailing edge.

3. COMPUTATIONAL FLUID DYNAMIC SIMULATIONS

CFD simulation of the selected stay vane was performed based on the Finite Volume Method and using $k-\omega$ SST as the turbulence model, it revealed that a periodical vortex shedding develops at the trailing edge of the stay vane, as shown in Fig. 6, with a vortex emission frequency of 122 Hz. The presence of a vortex shedding leads to an oscillating force with a frequency close to the second natural frequency of the stay vane, implying on higher dynamic stresses that may lead to nucleation and propagation of cracks.

Therefore, a geometrical modification, based on Voith Hydro's know-how, was proposed to eliminate the vortex shedding. The modification was designed to change as minimum as possible the original profile.

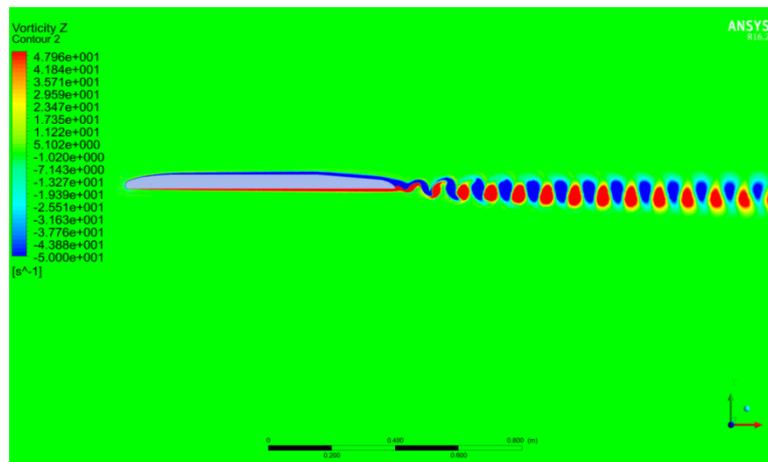


Figure 6. Vortex shedding at the trailing edge of the stay vane.

A new CFD analysis was performed with the modified profile using the same boundary conditions of the previous simulation. Results shown that the new geometry indeed eliminated the vortex shedding at the trailing edge, as can be seen on Fig. 7.

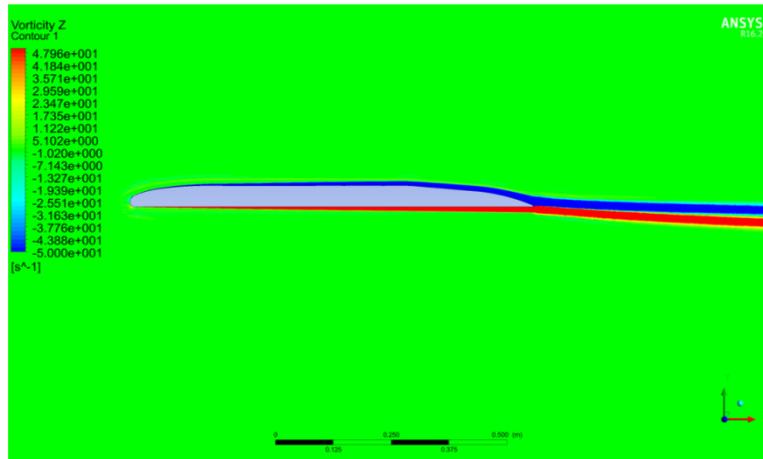


Figure 7. Simulation results of the modified profile.

4. MEASUREMENTS AFTER GEOMETRY MODIFICATION

After the trailing edge geometry of stay vanes 20 to 24 were changed, a new measuring campaign following the same settings as the measurements prior to the modification was performed at PU04 on April 2017. The results are shown at Fig. 8.

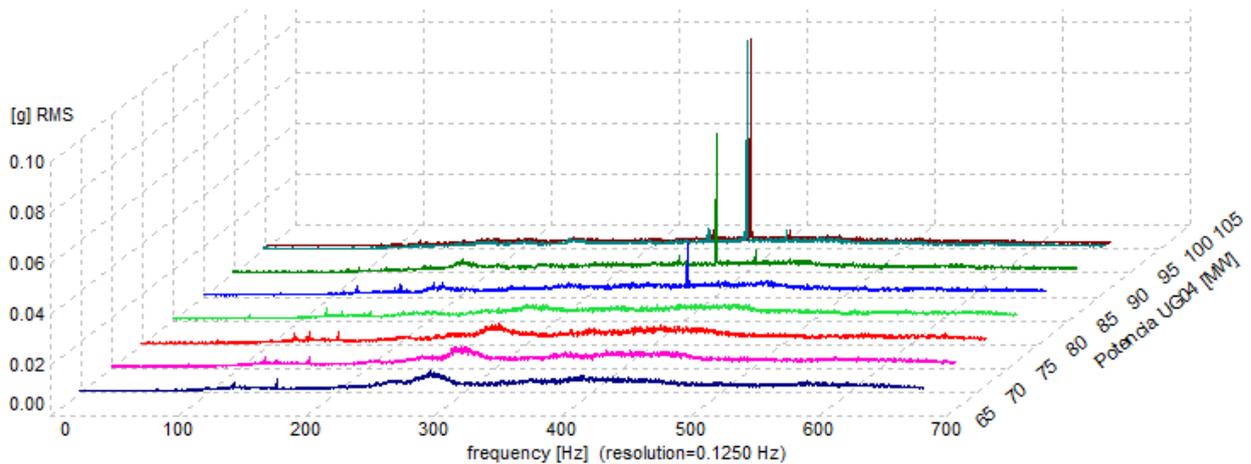


Figure 8. FFT as a function of turbine output for changed vane profile. Sensor installed at the stay ring.

Comparing Fig. 8 with Fig. 4 it is possible to notice that the characteristic peaks identified on the first measurements at approximately 140 Hz no longer exist indicating that the geometry modification proposed was able to eliminate the excitation of the first torsional mode.

However, another resonant behavior can be identified at a frequency of approximately 375 Hz. The very nature of the indirect measurement does not allow the conclusion that this resonance is actually related to the stay vanes, since the position of the sensor permits the measurement of many other components vibration. Furthermore, there is no record of modes other than the first bending or first torsional being excited at stay vanes (Gissoni, 2005) and this same study also demonstrated that stress amplitudes decrease as the order of the excited mode increases, thus reducing the chance of cracks propagation.

Further inspections at the stay vanes happened on mid of August 2017 and no cracks were found at PU04, reinforcing the idea that the measured resonant behavior was not associated with the stay vanes.

5. CONCLUSIONS

The results obtained from the indirect measurements at site together with the performed modal analysis indicated that the stay vane was being excited in the second natural frequency, which is the first torsional mode, with a frequency around 140 Hz.

Further investigations by CFD simulating the flow around the original profile confirmed the existence of a periodic vortex shedding at a theoretical frequency of 122 Hz which is close enough to the measured frequency to corroborate the assumption that cracks were a result of a resonance condition between the oscillating hydraulic forces and the first torsional mode of the vane.

The simulation of the modified profile showed no vortex shedding, thus mitigating the VIV phenomena and indicating that the change in the geometry would be effective. After the vanes were modified at site, indirect measurements with the same settings as the first ones revealed that the excitation at 140 Hz no longer appeared. On the other hand, a resonant behavior with a frequency of approximately 375 Hz emerged and a few considerations can be made:

- It is not possible to ensure that this resonance is related to the stay vanes as the measurement method is indirect and allows the measurement of vibrations from other components;
- There is no record of higher modes than the first bending and the first torsional being excited for stay vanes (Gissoni, 2005);
- Stress amplitudes decreases as the excited mode order increases (Gissoni, 2005), thus reducing the chance of cracks propagation.

A visual inspection was performed on August 2017 and no cracks were found at the stay vanes, reinforcing the effectiveness of the proposed solution as well as the assumption that the new measured resonance was not associated with the stay vanes.

6. REFERENCES

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