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Experimental analysis of the operation of a small Francis turbine equipped with an innovative aeration device

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Abstract. Development of hydropower as renewable energy source is an actual trend within the worldwide energy strategy. Thus, the manufacturers and operators of hydraulic turbines are currently engaged in their ecological use. Some of the solutions tested for the development of environmentally-friendly turbines are the aeration devices. Their aim is to increase the dissolved oxygen level in the flow discharged from the turbines in order to improve the quality of the aquatic life downstream hydropower plants. The present paper presents the experimental analysis of an innovative air injection device influence over the main operation parameters of a small Francis hydraulic turbine. The aeration device is mounted downstream turbine runner, at the entrance of the turbine draft tube. The tests are focused on determining the operating parameters evolution of the turbine - generator assembly and the vibrations in the shaft bearings and in the casing of the unit during normal regime and with different injected air flow rates. The pressure in the elbow of the draft tube is recorded, in order to determine the influence of the air injection over the flow at the runner outlet. Six operating regimes of the turbine are analysed, between a minimum power output value and a maximum value. For each operating point various air flow rates are injected in hydraulic system, between 1% and 8% water flowrate. The results will present the influence of the air injection over the dynamic behaviour of the turbine-generator unit.

1. Introduction

In the current context of environmental policy, one of the EU targets is that the renewable energy sources must attain a share of at least 27% in the final energy consumption, by 2030 [1]. Worldwide, hydropower is the largest renewable energy source, and further development is expected in the energetical mix configuration. Moreover, increasing the use of unpredictable renewables, especially wind and solar power, will lead to an amplification of the hydropower use for fast regulation, balancing and large-scale storage, with changing demand and changing wind and solar conditions.

At the same time the environmental consequences need to be carefully evaluated and addressed. Maintaining the quality of the water is a major objective from ecological, economical and sustainable development point of view, but also a condition when using it for energy production [2]. The dissolved oxygen (DO) from water represents a main parameter which contributes to the preservation and development of the aquatic habitat.

Aeration devices and techniques started to be tested and implemented in hydraulic turbines design with different degrees of success, their main objective being the increase of DO level in the discharged water [3-7]. The principle is mainly based on injecting air in the water flow that passed through the runner. Still, air injection can affect the turbine efficiency and introduce additional instability in the flow. This limits the air flow rate to 3 % of the water flow rate or in some particular cases 5%. In order to not affect sensitively the hydraulic performance, the air flow rate must not exceed 3% of the flow rate of the discharged water [8]. The efficiency of aeration in hydro power plants (HPP) is usually expressed by the void fraction

$$\phi = \frac{Q_{air}}{Q_{water}} < 3\% \quad (1)$$

where Q_{air} is air flow rate, respectively Q_{water} is the water flow rate.

Also the process of air injection requires energy to be operational, so the general energy consumption of the plant increases.

In the present paper an innovative aeration device is tested in order to evaluate its influence over the operation of a small horizontal Francis turbine. The device is mounted downstream the turbine runner, at the entrance of the draft tube and is non-intrusive (the hydraulic geometry of the turbine is conserved). Its innovative character is represented by the fact that the dispersion of the air is made assuring an increased gas-liquid contact area and a longer retention time [9]. The analysis is focused on determining the operating parameters evolution of the turbine - generator assembly and the vibrations in the shaft bearings and of the casing of the turbine during the turbine operation across the entire load domain, for different values of injected air flowrate. Also, the pressure in the elbow of the draft tube is monitored, in order to evaluate the influence of the air injection over the flow structure at the runner outlet.

2. In site measurements

The aeration device is installed on a horizontal Francis hydro-generator unit (figure 1) downstream the turbine runner, before the draft tube elbow. The turbines has 18 m rated head, 2 m^3/s rated flowrate and 375 rot/min rotational speed. The turbine-generator unit power output is 318 kW.

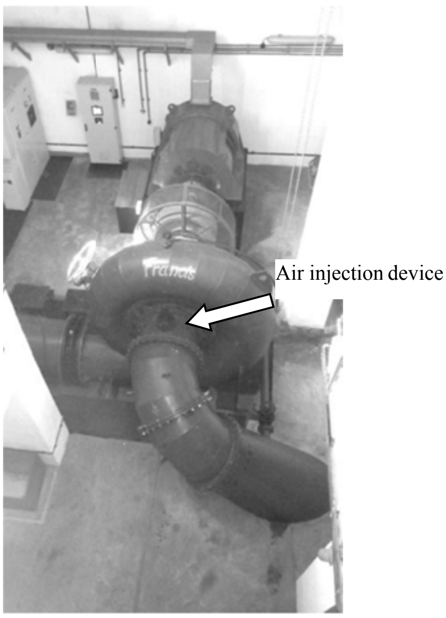

Figure 1. Small hydro turbine-generator unit tested with the aeration device.

2.1. *Experimental set-up*

The objective of the experimental analysis is to evaluate the influence of the air introduction, over the operation of the hydro-generator assembly. In a previous paper [10] a part of the experimental analysis was presented regarding the mechanical behaviour at best efficiency point operation. In the present work, both the determination of energetic and mechanical behaviours of the unit is aimed.

The efficiency measurements are carried out according to IEC 60041 standard [11]. The measured parameters are: water levels upstream and downstream the turbine, the pressure at the turbine inlet, the flowrate and the hydro-generator power output. The uncertainty of the tests resulted below 1.5%. During tests, the guide vanes' opening, s, is used as a control parameter, thus it is also measured. As the air will be introduced at the entrance of the draft tube elbow, a pressure sensor is located right below the aeration devices, in order to monitor the pressure in the water during the air injection at the runner outlet. The pressure transducer has an accuracy of 0.5%.

In order to evaluate the mechanical behaviour of the unit, vibration measurements are carried out. Four piezoelectric accelerometers and two pairs of displacement probes are used. Their location is presented in figure 2.

The displacement probes are mounted on vertical and horizontal direction (1, 2, 3 and 4) on the radial bearing (RB) and radial-axial bearing (RAB) of the unit. Two accelerometers are mounted on the casing of the radial axial bearing (RAB), in radial and axial directions (5 and 6), and the others two are mounted on the turbine casing, downstream turbine runner on axial direction (7) and on the draft tube, downstream aeration system, on radial direction (8).

All parameters are recorded simultaneously using an acquisition system with 25 kHz frequency on each channel.

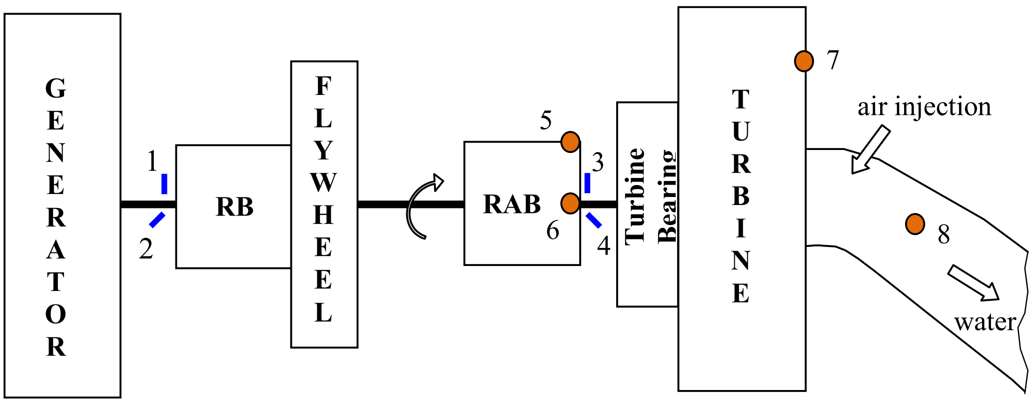

Figure 2. Schematic of the turbine-generator assembly, bearings and sensors placement (1-4 displacement probes, 5-8 piezoelectric accelerometers). [10]

2.2. *Measurement procedure*

In order to analyse the influence of the aeration device over the hydro generator-turbine assembly, a testing procedure is developed. The unit is operated over a power output range between a maximum of 130 kW and a minimum of 10 kW, given for the available head conditions. In figure 3 the exploitation characteristic of the turbine is presented ($\eta = f(Q, H)$) and the analysed operating points are marked in red (numbered from 1 to 6). The parameter that was kept constant during air injection is the guide vanes opening, s (%). For each turbine operating point, several air flow rates between 0 and 8% of the turbine water flow rates are injected (figure 3 and table 1).

In the previous paper [10] only the vibrations analysis of the unit operating in the regime corresponding to the best efficiency point of the hydro-generator, with no air injection and with different quantities of air are injected were presented. It is shown that the influence of the air injection was observed only in the records from the accelerometer mounted on the draft tube. The acceleration spectra amplitudes show a decreasing tendency while increasing the injected air flow rate. In the present work, the results will be presented for all six operating regimes of the unit and for all air flow rates considered.

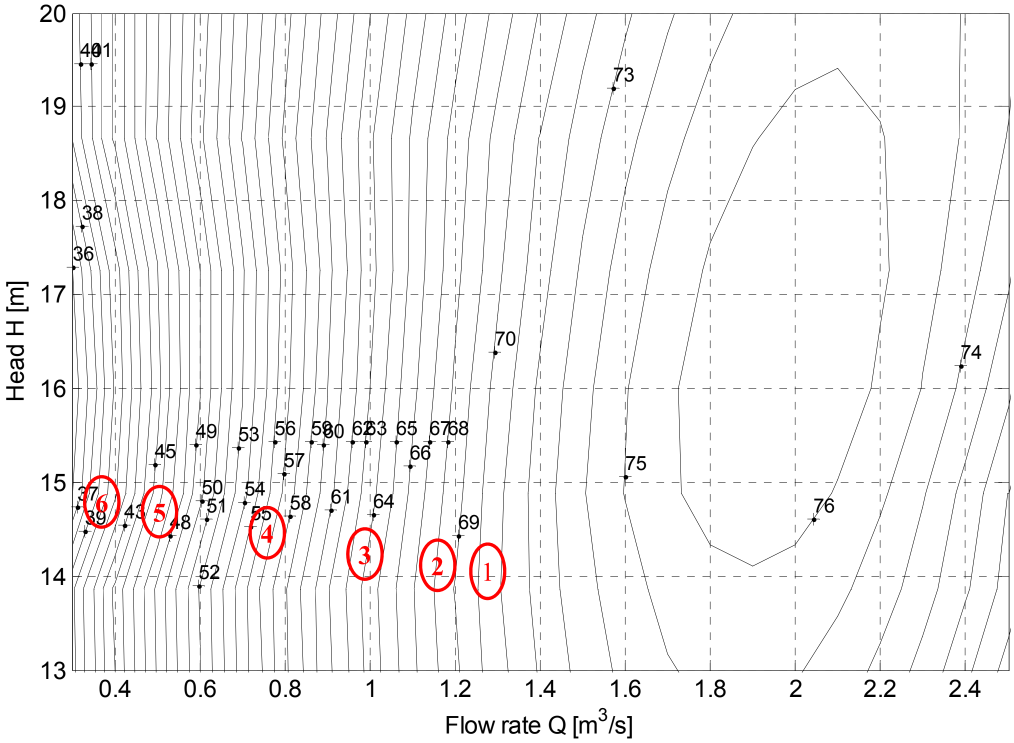

Figure 3. Exploiting characteristic of the Francis turbine and analysed points [12].

Table 1. Operation regimes.

Operating point	Guide vane opening [%]	Q_{air}/Q_{water} [%]						
1	95.7	0	1.14	2.05	2.96	3.99	5.01	8.25
2	87.4	0	1.15	1.89	2.85	3.79	4.76	6.46
3	75.2	0	1.24	1.94	2.81	3.93	4.78	6.72
4	60.1	0		1.74	2.84	3.61	4.63	6.43
5	45.2	0			2.48		4.43	6.03
6	30.7	0				3.55		5.87

3. Results

3.1. Energetic behaviour

In order to emphasis the air injection influence over the turbines performances, the efficiency variation in function of the relative injected air flow rate is determined. In figure 4 the relative efficiency values ($\eta_{rel} = \eta/\eta_{max}$, where η_{rel} is the relative efficiency, η is the determined efficiency and η_{max} is the maximum experimental efficiency) are presented for all six operating points of the unit, characterised by the guide vanes opening, *s*, from 30.7% to 95.7%.

Analysing the results, it can be seen that a maximum efficiency decrease of 2.8% occurs for an injected relative air flow of around 5%. Still, for operating points with low guide vanes opening values (s = 30.7% and s = 45.2%) the air injection leads to an increase of the efficiency. In order to better understand this increase, the variation of the pressure in the draft tube cone is presented for the six operating points, without and with air injection (figure 5). It can be seen that the air injection, for operating points characterised by low guide vane openings, leads to an increase of the pressure level in the draft tube. As the head of the turbine is defined as the difference between the upstream and negative hydraulic energy reported to gravity, by increasing the pressure downstream the turbine, the head is decreased. Thus, the consumed hydraulic power is decreased for an almost constant electrical power output, so the efficiency of the unit is increased. The results obtained are consistent and for higher values of guide vanes opening, where the efficiency decreases with the increase of injected air flow.

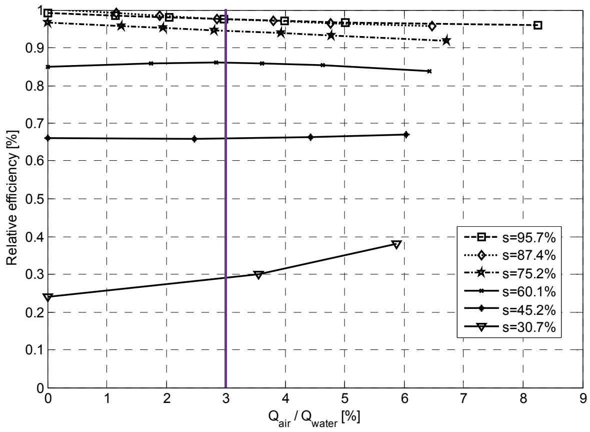

Figure 4. Hydro generator- turbine efficiency for the six operating points, without and with air injection.

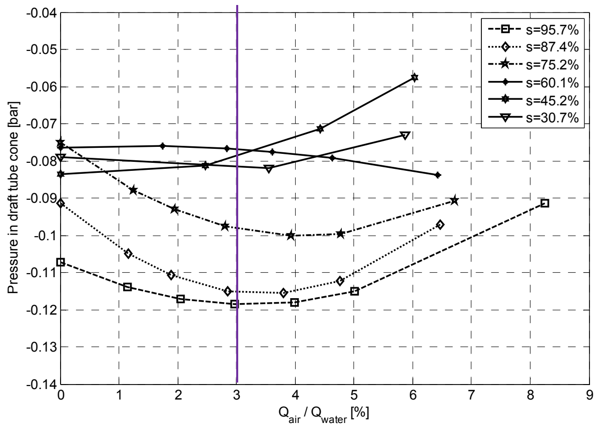

Figure 5. Pressure level in the draft tube cone for the six operating points, without and with air injection.

3.2. Mechanical behaviour

In order to analyse the influence of the injected air over the mechanical behaviour of the unit during operation, the vibrations are measured in the shaft bearings and in the casing of the unit. The vibration analysis as predictive maintenance and diagnose of mechanical systems is a common practice in industry [13-15]. It implies time-domain and frequency domain analyses.

Time analysis is based on the vibration signals recorded with the displacement sensors. The vibrations characteristics can be presented as shaft orbits. In figures 6 and 7 are presented the orbits obtained for the signals recorded in the radial bearing (RB) and the radial –axial bearing (RAB) for the first analysed operating point (s = 95.7%), with no air injected. The elliptical shape shows a slight preload that forces the shaft. The direction of the orbit displacement is coherent with the direction of the flow entering the turbine impeller.

Analysing all the orbits, the maximum displacement of the shaft varied from 0.02 mm to 0.06 mm in the radial –axial bearing (RAB), and from 0.02 mm to 0.025 mm in the radial bearing (RB), in function of the unit load. No influence of the quantity of injected air was observed. For exemplification, in figures 8 and 9 are presented the orbits obtained for the signals recorded in the radial bearing (RB) and the radial –axial bearing (RAB) for the first analysed operating point (s = 95.7%), with the maximum quantity of air injected (8.25%).

For a detailed dissection of the signals, frequency domain analysis is required. The frequency domain analysis is carried out on a number of 2^{14} samples, and as the sampling period for the vibration signals is of 0.04 ms, it resulted in a “cutting frequency” of 12.5 kHs. The purpose of this analysis is to identify the main components in the amplitude spectra and to compare them in the case of no air injection to the ones when different air flow rates are injected.

The time domain signals were subjected to the Fourier analysis technique, using FFT function from Matlab, and the frequency spectra were obtained. In order to correctly evaluate the results, the characteristic components of the machine must be determined. Thus, the frequencies values corresponding to the rotational speed, the number of runner blades and guide vanes are firstly determined.

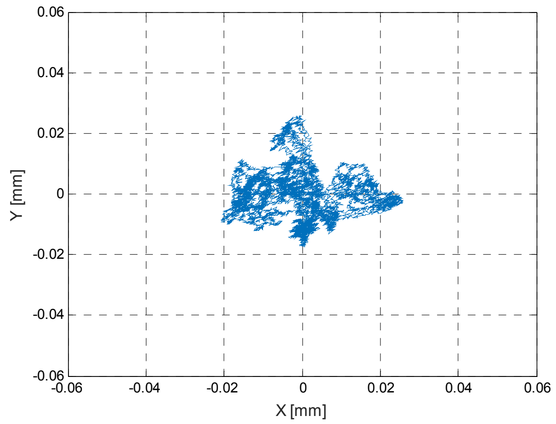

Figure 6. Shaft orbit in the radial-axial bearing, for operating point corresponding to s = 95.7%, no air injection.

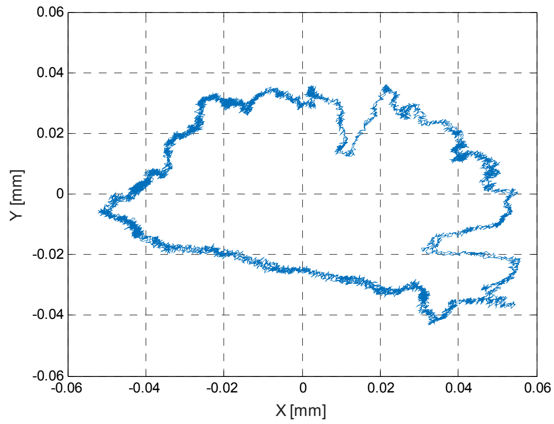

Figure 7. Shaft orbit in the radial bearing, for operating point corresponding to s = 95.7%, no air injection.

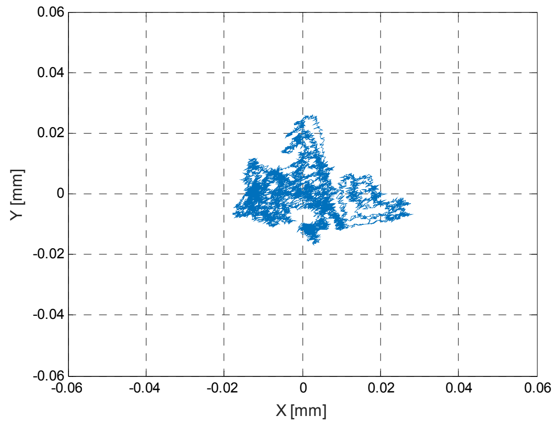

Figure 8. Shaft orbit in the radial-axial bearing, for operating point corresponding to s = 95.7%, 8.25% air injection.

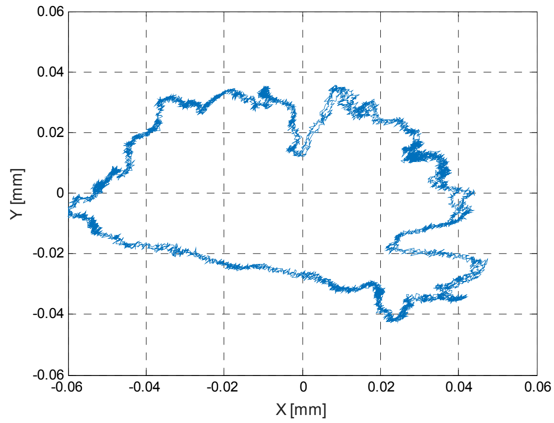

Figure 9. Shaft orbit in the radial bearing, for operating point corresponding to s = 95.7%, 8.25% air injection.

The time domain signals were subjected to the Fourier analysis technique and the frequency spectra were obtained. In order to correctly evaluate the results, the characteristic components of the machine must be determined. Thus, the frequencies values corresponding to the rotational speed, the number of runner blades and guide vanes are firstly determined.

For the analysed unit, the frequency corresponding to the rotational speed is $f = n/60 = 375/60 = 6.25$ Hz. The frequency corresponding to the runner is the frequency characteristic of the rotational speed multiplied with the number of runner blades, $f_R = f \cdot N_R = 87.5$ Hz ($N_R = 14$ blades). The frequency corresponding to the interference between the runner blades and the guide vanes is $f_{R\text{-}GV} = f \cdot N_R \cdot N_{GV} = 1.4$ kHz ($N_{GV} = 16$ blades).

Figures 10 – 15 presents the amplitude spectra obtained from the displacement sensors and from the accelerometers, for the operating point corresponding to a guide vane opening of 95.7%, with no air injection.

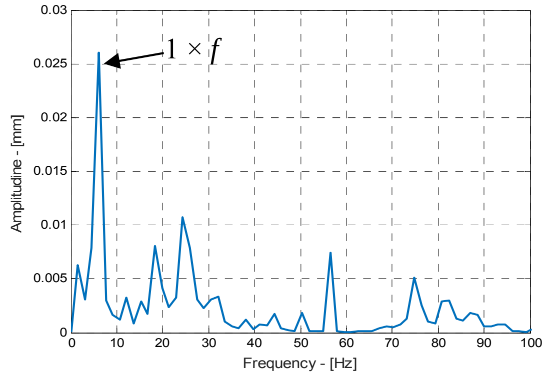

Figure 10. Amplitude spectrum of the vibrations obtained from displacement sensors on radial and axial direction, located on RAB.

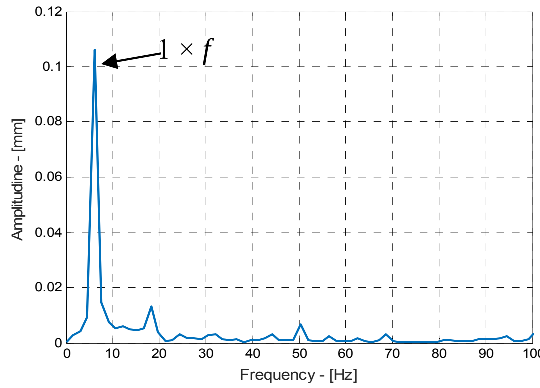

Figure 11. Amplitude spectrum of the vibrations obtained from displacement sensors on radial and axial direction, located on RB.

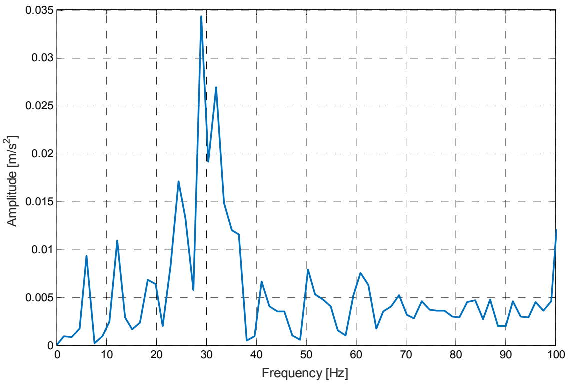

Figure 12. Amplitude spectrum for the vibrations recorded using the accelerometer located on the turbine casing, axial direction.

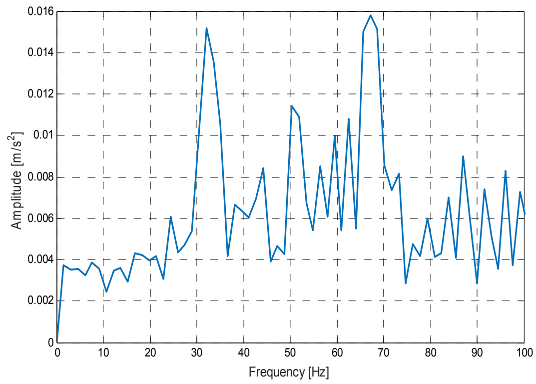

Figure 13. Amplitude spectrum for the vibrations recorded using the accelerometer located on the draft tube, radial direction.

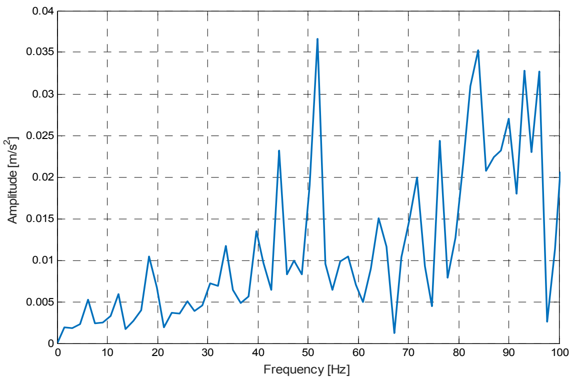

Figure 14. Amplitude spectrum for the vibrations recorded using the accelerometer located on the RAB, radial direction.

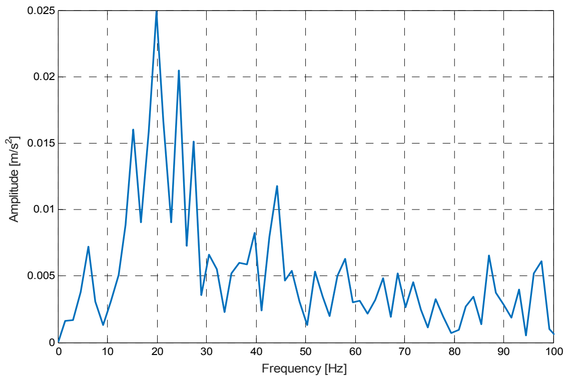

Figure 15. Amplitude spectrum for the vibrations recorded using the accelerometer located on the RAB, axial direction.

In the amplitude spectrum from figure 10, it can be seen that the higher amplitude is obtained for the component corresponding to the rotational speed of the unit. Also, its 3rd and 4th order harmonics are present. These indicate a misalignment of the shaft and bearing loose in housing [13]. In the amplitude spectrum obtained for the RB (close to the generator) the dominant component is also the one corresponding to the rotational speed and the 3rd harmonic is present (figure 11). Thus, the conclusions regarding the bearing misalignment and bearing loose are confirmed by the amplitude spectrum of RB.

In figures 12-15 the amplitude spectra for the vibrations recorded using the accelerometers are presented. It can be seen that the spectra are rich in components, suggesting an intense dynamic behaviour of the unit.

Further, the amplitudes of the main components from the spectra obtained for various values of air flow rate, for all six operating points are compared. In figures 16-21, the variations of the amplitudes spectra are presented in function of the injected air flow rates, for all operating points corresponding to a guide vane opening of 95.7%, with no air injection.

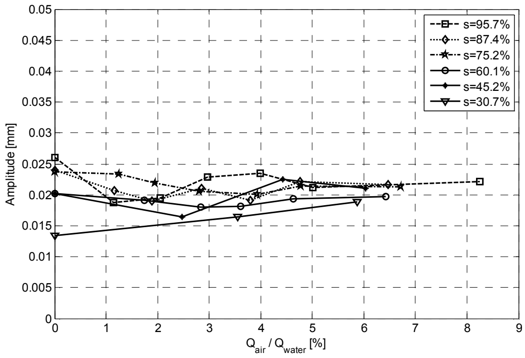

Figure 16. Variation of main component amplitudes of the vibrations obtained from displacement sensors on radial and axial direction, located on RAB.

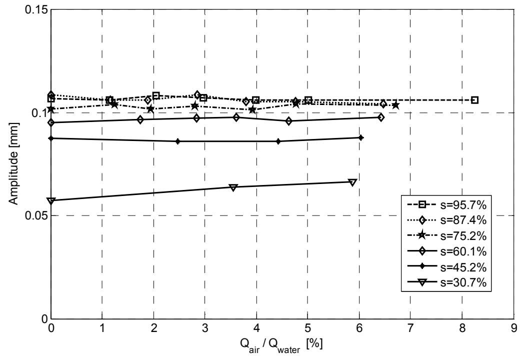

Figure 17. Variation of main component amplitudes of the vibrations obtained from displacement sensors on radial and axial direction, located on RB.

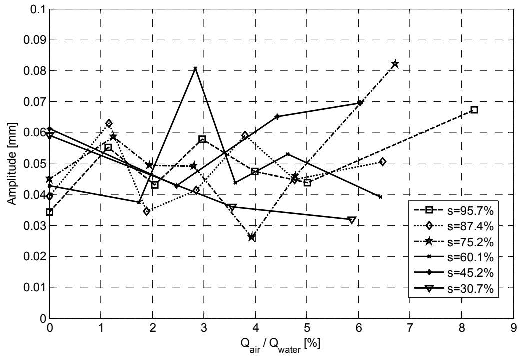

Figure 18. Variation of main component amplitudes for the vibrations recorded using the accelerometer located on the turbine casing, axial direction.

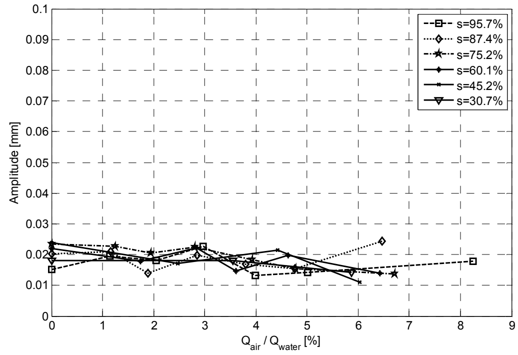

Figure 19. Variation of main component amplitudes for the vibrations recorded using the accelerometer located on the draft tube, radial direction.

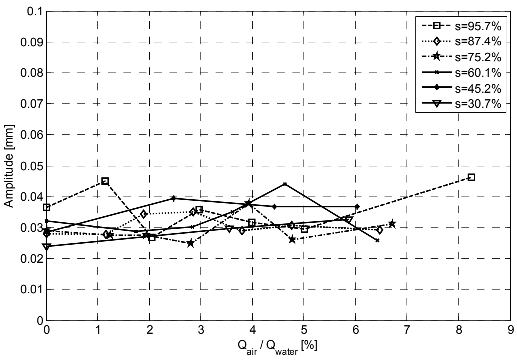

Figure 20. Variation of main component amplitudes for the vibrations recorded using the accelerometer located on the RAB, radial direction.

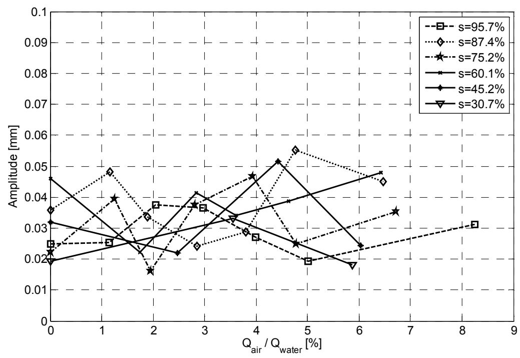

Figure 21. Variation of main component amplitudes for the vibrations recorded using the accelerometer located on the RAB, axial direction.

It can be seen that the air injection has no significant influence over the amplitudes from the spectra of the vibration signals recorded on the radial axial bearing and on the turbine housing. The only remarkable influence is observed in the amplitudes of the signals recorded at the draft tube (figure 19). It can be seen that increasing the air flow rate injected in water leads to a small decrease of the vibrations amplitudes. This can be explained by the fact that when injecting air into water, the hydrodynamic behaviour of the flow is affected. .

4. Conclusions

The paper presents the analysis of in site tests carried out on a small horizontal Francis turbine equipped with an innovative aeration device [9]. The device is mounted downstream the turbine runner, at the entrance of the draft tube. In the present work, both the determination of energetic and mechanical behaviour of the unit during operation without air injection and with different quantities of air injected is aimed.

The analysis is focused on determining the operating parameters evolution of the turbine - generator assembly and the vibrations in the shaft bearings and of the casing of the turbine during the turbine operation across the entire load domain, for different values of injected air flowrate. Also, the pressure in the elbow of the draft tube is monitored, in order to evaluate the influence of the air injection over the flow structure at the runner outlet.

In order to emphasis the air injection influence over the turbines performances, the efficiency variation in function of the relative injected air flow rate was determined. The results showed that the unit efficiency varies with the increase of injected air. Such that the efficiency decreased up to 1.6% for a void fraction of 3%, recommended by HPP users, and can reach up to 3% for a void fraction of 8%. To be specified some points show even slight gains in efficiency. The conclusion was also supported by the variation of the pressure in the draft tube cone presented for all operating points, without and with air injection.

In order to analyse the influence of the injected air over the mechanical behaviour of the unit during operation, the vibrations were measured in the shaft bearings and in the casing of the unit. The vibrations analyse results indicated a misalignment of the shaft and bearing loose in housing, and an intense dynamic behaviour of the unit. Still, the air injection showed no significant influence over the amplitudes from the spectra of the vibration signals recorded on the radial axial bearing and on the turbine housing. Thus, it can be stated that injecting air into water downstream the runner has no negative influence over the operation of the unit, from the structure point of view. The only influence is detected in the energetic performances of the unit, where the injection of air can lead to a decrease of the efficiency with 0-3% for a void fraction of 0-8%.

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