Modal Dynamic Analysis of the Wicket Gate Mechanism from a Hydraulic Turbine

N. Dumitru, S. Dumitru, C. Copilusi, D. Semenescu and I. Geonea

***Abstract*— On this research experimental analyses have been performed in order to determine the wicket gate dynamics and stability from a 50 Megawatts Francis hydro turbine. The experimental tests were focused on the hydraulic group at starting maneuvers, nominal loads and stop. The wicket gate adjusting mechanism dynamic parameters were measured and also determined through numerical computations. These are: tensile strength from the mechanism connecting rod, turbine blades rotation angle, linear displacement of the actuating piston and torque from the mechanism connecting rod. A special attention was given to the vibration measurements and analyses of the hydro group and also to the vibration sources identification. The experimental results were also verified with the ones from a modal analysis by using finite element method. The obtained vibrations give essential information for the technical data evaluation of the analyzed mechanism. The vibrations experimental analysis performed in a period of time and also in frequency domain was completed with a modal dynamic analysis achieved with finite element method.**

***Index Terms*— Francis turbine, modal dynamic analysis, turbine runner, vibration, wicket gate mechanism**

I. Introduction

NOWADAYS hydro power plants have the highest operating efficiency of all known generation systems. These are largely automated and their operating costs are relatively low. Hydroelectric power plants also play an important role in water resource management, flood control, navigation, irrigation and in creating recreation areas. Francis turbines are most widely used among water turbines and the development of the Francis turbines in the last decade has opened up a large range of new application possibilities for this type. These advances, motivated by a search for maximum profitability, have become possible as the result of improved knowledge of the water flows in turbines and other hydraulic phenomena.

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A full investigation and intensive research are carried out and efforts are put forth in the improvement of turbine performance, for the selection of suitable materials and the construction design in consideration of difficulties imposed by mechanical, manufacturing and maintenance factors at the design stage.

The wicket gate or the main mechanism of the turbine has blades with adjustable position and its role is to speed up the current, guiding him in order to get the optimum action angle on the runner blades. The change of the wicket gate blades position is adjustable using a ring by means of levers and connecting rods. The adjustment ring is driven by servomotors. By changing the position of the blades, the value of the flow passing through the turbines is modified. Water leaving the director device put the turbine runner into rotational motion. The closing tension is created by a levers system with left-right thread. The system protection is provided by shear pins dimensioned to break and cut out the blade in order to not overstress the mechanism.

In the past, there was some research works presenting results of modal analysis in hydraulic runners but with measurements carried out in air [1]. Also some publications give only general data [7] but there are not on a detailed mode, by indicating the influence of the water on the modal characteristics of hydraulic turbine runners. Other publications like in [2], [4], [9], [3] present only numerical computations without comparing these with the ones obtained from experiments.

II. Wicket Gate Mechanism Experimental Tests

In order to determine the Francis turbine functional performances, an experimental analysis will be performed without affecting the turbine normal functionality. Thus, all the data acquisition hardware and transducers will be mounted on the wicket gate mechanism during turbine functionality on different modes. The hardware used for the turbine experimental tests consists on: a data acquisition system type Spyder 8 on 12 bytes; a condition signal type NEXUS 2692-A-0I4, with 0.01% linearity; Bruel & Kjaer accelerometers type 4391 (3 pieces) with 2% linearity; a linearity inductive transducer type WA300 with an error of 2%; an angular potentiometer type T127PA with 5 kΩ and 2% linearity; a force transducer type H4450-23, with a linearity of 3%. All these measurement systems were controlled through a notebook IBM ThinkPad R51 with proper licensed software installed. The recorded parameters were: F_tr(Newton) represents traction force installed at the pitchfork level of the wicket gate mechanism; Rot_Pal(degrees) is the angular displacement of the movable blade; Crs_Lin(millimeters) – linear displacement of the actuating pyston; AccO_Pal(millimeters/sec^2) is the horizontal acceleration on superior bearing of the movable blade; AccV_Pal(millimeters/sec^2) is the vertical acceleration on superior bearing of the movable blade; AccO_Lag(millimeters/sec^2) is the horizontal acceleration of the turbine superior bearing.

All these parameters were measured by creating a test measuring scheme which consists on creating of a half bridge strain gauges type LY5mm/120 Ω on H4450-23 pitchfork, similar as in case of the force transducer. The H4450-23 pitchfork with half bridge strain gauges is shown on figure 1. The T127PA angular potentiometer and 4391 force transducers were mounted as it shown in figure 2.

Fig. 1. The H4450-23 pitchfork with half bridge strain gauges

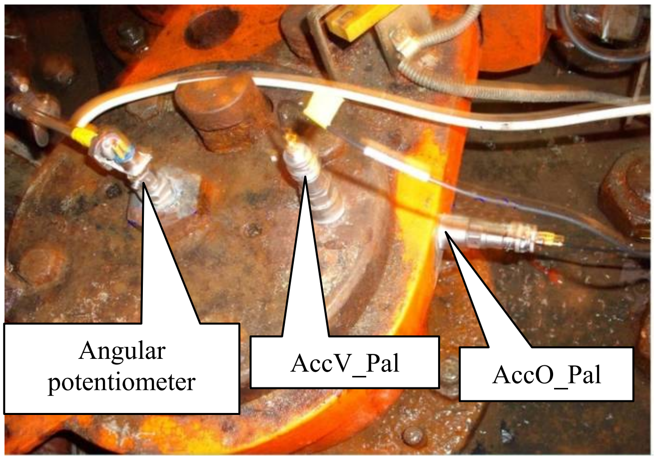

Fig. 2. Measuring the angular variation and acceleration of the movable blade superior bearing

The horizontal acceleration of the turbine superior bearing was measured with AccO_Lag(meter/second^2) accelerometer and the linear displacement of the hydraulic cylinder was measured with a linear displacement transducer as it shown in figure 3. The WA300 linear inductive transducer has its rod fixed on servomotor shell and the end connected to the cylinder rod. By starting and stopping the hydro-group, synchronization between this and the acquisition system was done. Also all the mentioned parameters were acquired in real-time measurements with a sampling rate enough to cover the vibrations frequency domain (this represents the most extended frequency domain which is about 1÷300). The recordings during experimental tests were performed on the following conditions: sampling rate was about 1200 samples/sec and the recording time was 30 minutes (which include the interest process dynamics). The following turbine functionality modes were performed for the experimental tests: starting on an electricity load of 50 MegaWatts during 1457 seconds; constant power functionality mode; stopping the hydro group in a time interval of 328 seconds. For each test, the experimental data were stored in a data files useful for further analyses.

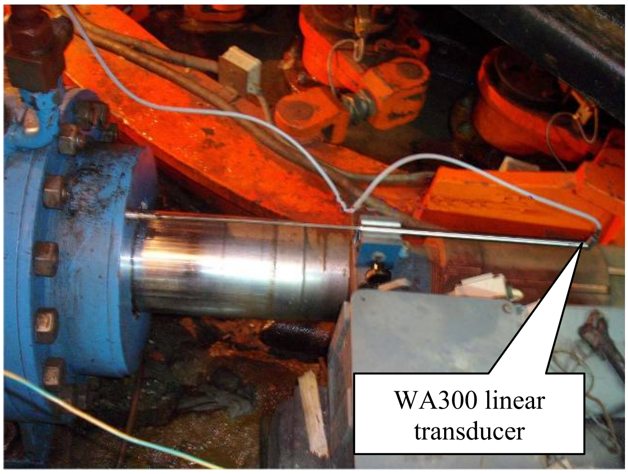

Fig. 3. Horizontal accelerometer mounted on turbine and the linear displacement transducer placed on hydraulic cylinder

III. EXPERIMENTAL DATA ANALYSIS

The processed data were analyzed in time and frequency domains. The used experimental data were considered the ones from the first experimental test which is the hydro group starting at electricity load of 50 MegaWatts during 1457 seconds. When the turbine was turned on, the electrical power was loaded on a constant level. For the time domain analysis, the acquired data were divided in 14 distinctive zones and for each zone average values were determined for: actuating force and angular displacement of the movable blade, hydraulic cylinder linear displacement and the accelerometers extreme values. A software interface during data acquisition in real time is shown in figure 4.

On Figure 4, the point no 2 represents the one where the second zone starts and it corresponds to the Francis turbine start. Also it could be observed the water intake on the

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turbine mobile blades and these corresponds to the step intervals until no 13.

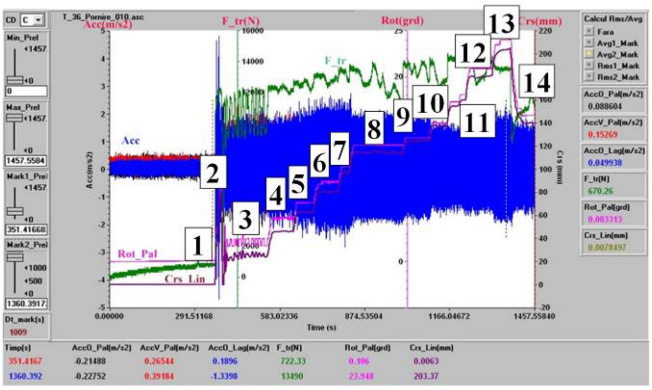

Fig. 4. An interface of the acquired data in real time when hydro group was started

According to this interface the measured data were extracted and these are shown through figures 5, 6 and 7. These data represents the hydro group dependence between accelerations and the produced electrical power. The highest recorded vibrations were the ones from turbine bearing. The highest vibration values where recorded on 20 to 25 MegaWatts and 45 to 50 MegaWatts intervals. These values are usual ones and it fits to the admissible limits of the rotating electrical machines category where the turbine can be found.

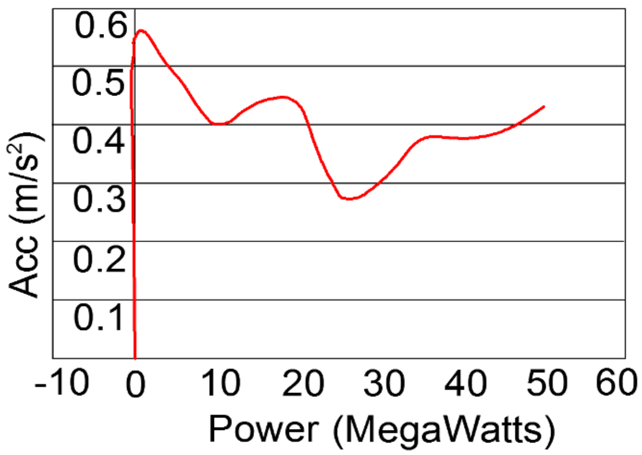

Fig. 5. Horizontal power – acceleration characteristic inside of the blade bearing

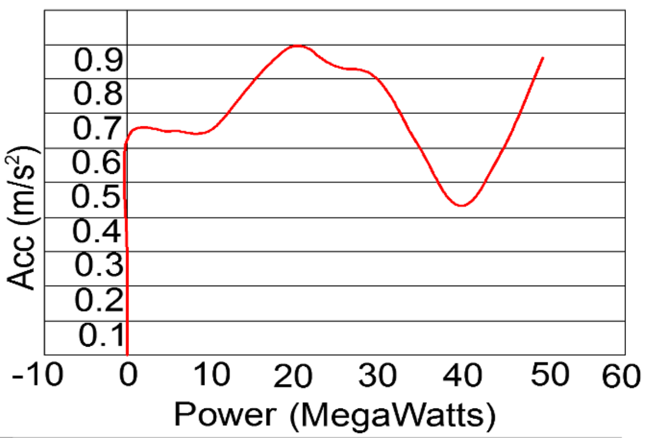

Fig. 6. Vertical power – acceleration characteristic inside of the blade bearing

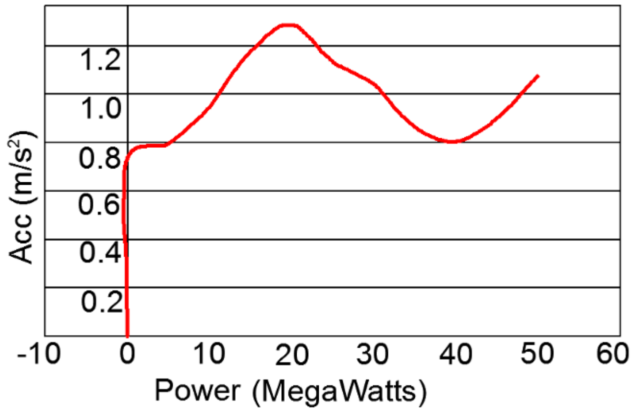

Fig. 7. Horizontal power – acceleration characteristic of the entire turbine

For the frequency domain analysis, the following hypotheses were assumed: the interest frequency domains for the parameters with highest dynamic evolution were analyzed and also the hydro group functionality involves hydrodynamic vibrations with extended frequency domain; eliminating the aliasing phenomena and Nyquist theorem which suppose that the sampling rate frequency of an analogical signal must be at least doubled as the highest frequency value from the acquired signal spectrum.

On practical applications by using Fourier analysis, there were developed and implemented fast signal analysis techniques called FFT – Fast Fourier Transform and these are used through this research. With the aid of these a frequency analysis was performed for the 13 zones according to the figure 4. For each zone Fourier analysis was done on recording with an interval of 100 seconds.

By taking in account that the original record was done at 1200 samples/second and the entire data record was on 1457.5 seconds, it can be observed that to each parameter corresponds a data original vector with the length of 1.749.080 samples. The computation system limited performance forced to divide at 2 the work vectors (by reading from 2 to 2 the acquired values)

The Fourier transformer was performed on vectors with length of 65536 samples, which result a frequency resolution of 0.0091Hertz and a frequency band of 300 Hertz (the number of samples from positive part of frequency domain is half from the number of samples from time domain).

There were represented the frequency spectrums of bearing mobile blade horizontal acceleration, which corresponds to 1...13 zones and respectively the frequency spectrums of bearing turbine horizontal acceleration from the same zones. According to this, there were selected the fundamental and harmonics values of 1, 2, 3 order. These values represent the harmonic frequency and amplitude.

The spectral harmonic dependency was represented by taking into account the electric power for each zone mentioned above, where the vibrations were recorded at the superior bearings level from turbine and mobile blade. On figures 8 to 11 a comparative analysis is shown between RMS values and spectral domain of bearings from mobile blade and turbine.

The Francis turbine wicket gate mechanism need to assure the controlled water intake at the turbine runner level and to control the debit in the sight of a desired electrical power achievement at the electric generator terminals.

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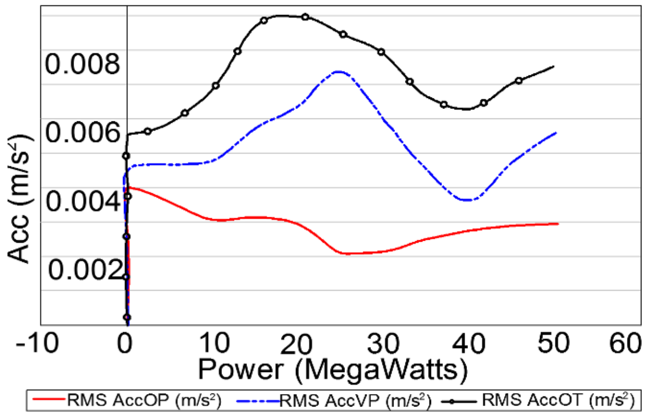

Fig. 8. Effective value dependence between accelerations and electrical power

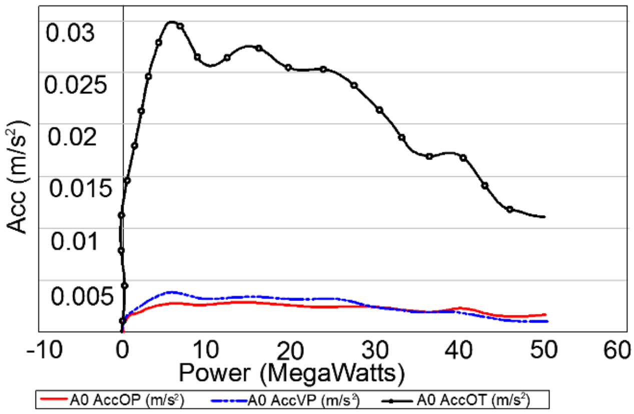

Fig. 9. Spectral analysis for fundamental harmonic dependence and electrical power

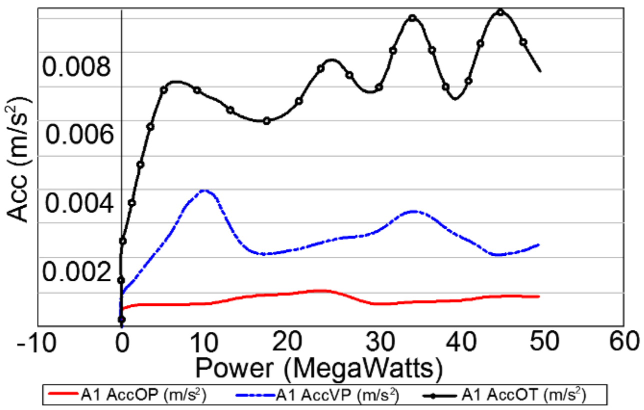

Fig. 10. Spectral analysis for first order harmonic dependence and electrical power

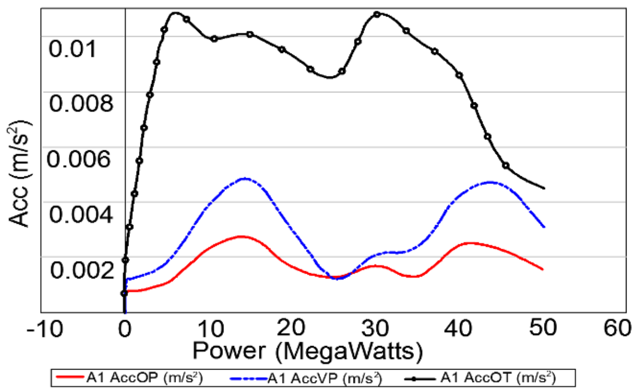

Fig. 11. Spectral analysis for second order harmonic dependence and electrical

A wicket gate mechanism consists on:

- a set of 16 mobile blades which can spin around on their own axis. These blades have the possibility of rotation on a vertical plane with a maximum angle of 30 degrees and on a closed position will close the intake system and doesn't let the water to get inside at the turbine runner level;
- two hydraulic servomotors with a linear displacement of 300 millimeters;
- the actuating system which has the role to convert and transmit the motion from the hydraulic servomotor linear displacement (Crs_Lin) to the mobile blades (Rot_Pal) as an angular variation.

The vibration analysis and their interpretation generated at the turbine runner level and wicket gate mechanism resumes on time and frequency domains and identify three major sources of vibrations such as:

-the water flow which goes through the wicket gate mechanism to turbine blades generates large scale vibrations;

-the turbine runner on rotating motion at a 428 rpm generates vibrations of 7.142 Hertz. These are mechanical ones and consist on fundamental harmonic (for a perfect equilibrated runner) and harmonics of first and second order for non linearity;

-electromagnetic vibrations resulted from the electric generator. These consists the fundamental harmonic and the ones of one to five order. Also these are in a straight connection with the generator electrical power.

IV. HARMONIC ANALYSIS USING FINITE ELEMENT METHOD

The purpose of this analysis is to determine the stress, elastic displacements and deformations of the runner blades depending on frequency domain. It was designed a 3D model of a blade with wicket gate mechanism. This is shown on figure 12.

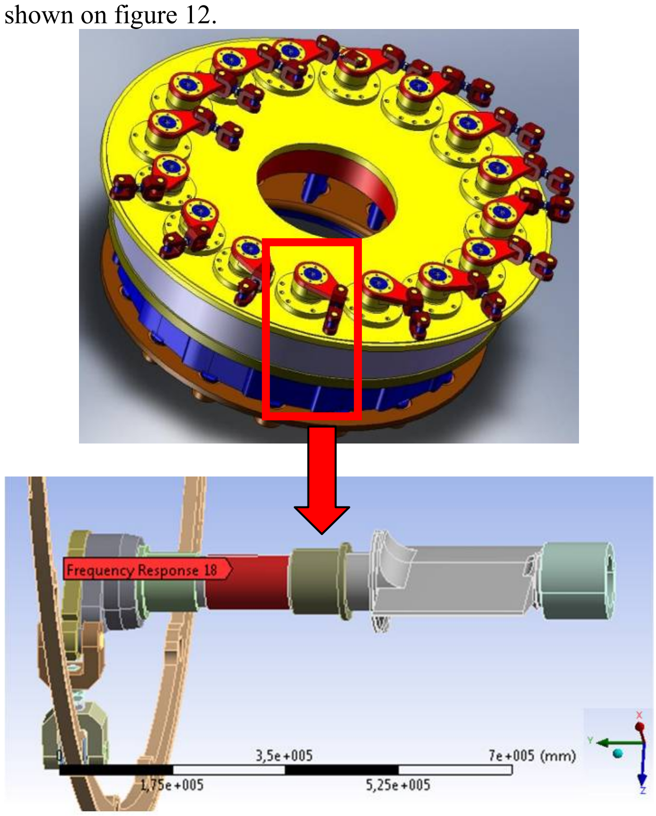

Fig. 12. The wicket gate virtual model used for frequency response analysis using FEM

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The software used for this analysis was ANSYS. The initial conditions was taken from the experimental tests which means the angular variation law of the wicket gate mechanism and the applied pressure on the blade surface was considered from [8] with a value of 5.9 MPa. For the harmonic analysis, two steps were followed when the natural frequencies were determined for 20 vibration modes. During harmonic analysis the frequency domain was set between 0 to 5 Hertz for 20 intervals. The desired results were obtained for the entire mechanical structure at known frequencies, but also on each component at the same frequencies. These results are presented on diagrams from figure 13 to 17.

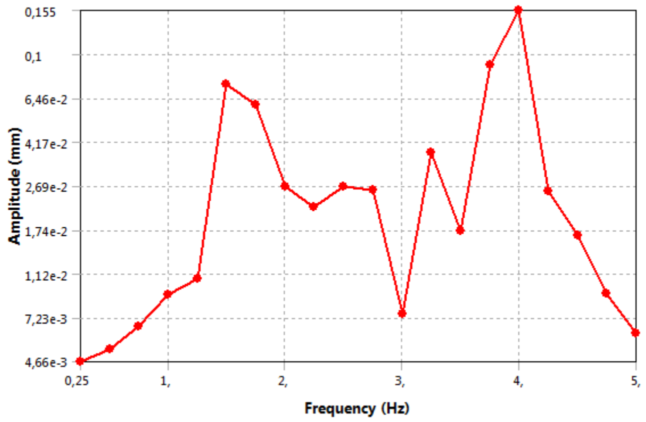

Fig. 13. Blade frequency response for the elastic displacements on y axis

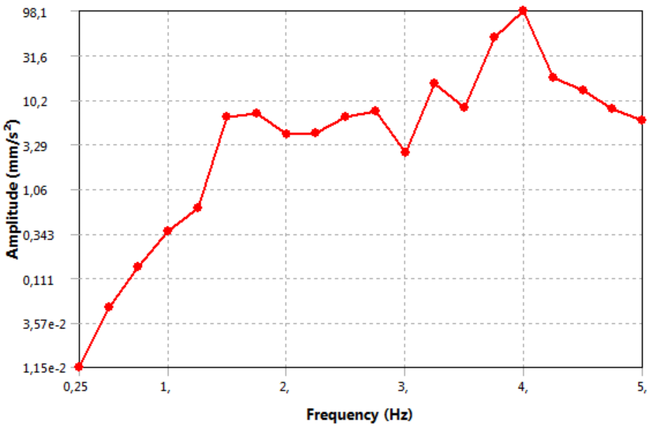

Fig. 14. Blade frequency response for accelerations on y axis

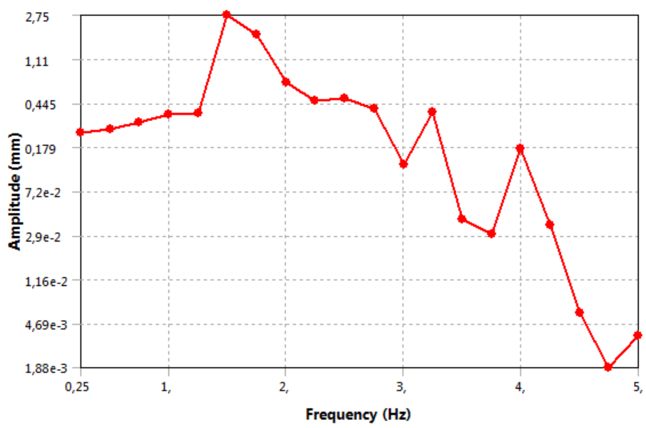

Fig. 15. Blade frequency response for elastic displacement on x axis

The maximum values for displacement and acceleration components on y axis are at a frequency of 4 Hertz and these are 0.15527 millimeters and 98.079 millimeters/sec^2.

In case of stress and deformations for frequency of 1.75Hertz, these are 5.5449e-006 mm/mm and 8.2901MPa.

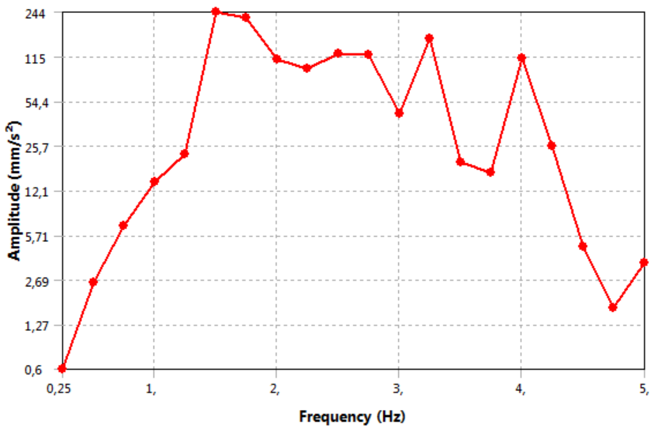

Fig. 16. Blade frequency response for accelerations on x axis

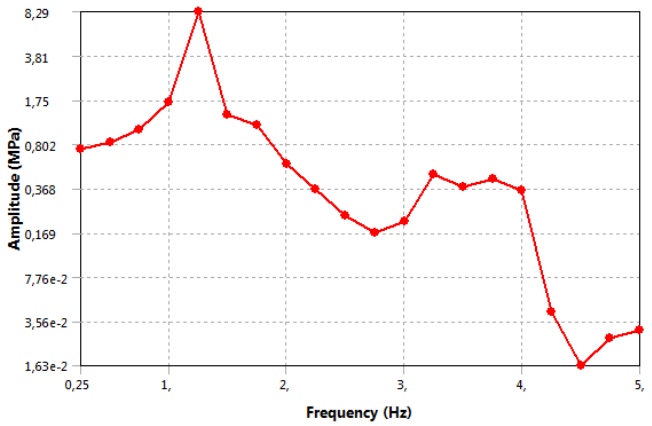

Fig. 16. Blade frequency response for normal stress on x axis

The displacements and accelerations maximum values on x axis are at a frequency of 1.5Hertz and these are 2.75 millimeters and 244.3 millimeters/sec^2. For stress at a frequency of 1.25Hz, there were obtained a value of 8.2901MPa.

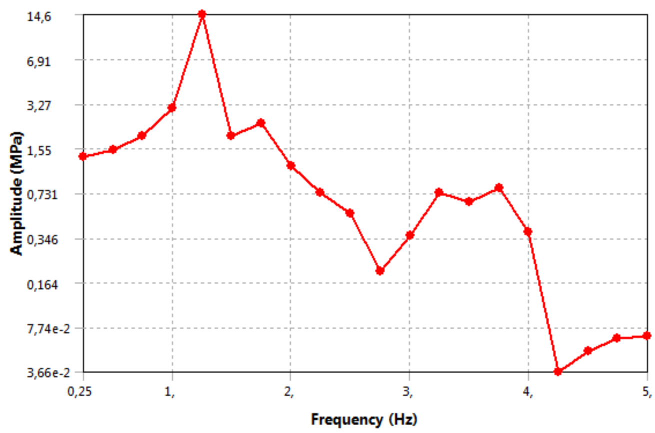

Fig. 17. Blade frequency response for normal stress on z axis

The maximum values of displacements and accelerations on x axis are at a frequency of 1.5Hertz and these are 3.1774 millimeters and 282.23 millimeters/sec^2. For stress at a frequency of 1.25Hz, there were obtained a value of 14.599 MPa.

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The obtained maximum elastic displacements during modal analysis at the natural frequency were 3.1417e-7[millimeters].

V. Conclusion

The experimental tests were performed for determine the wicket gate mechanism dynamics and stability from a 50 MegaWatts Francis turbine. A special attention during these tests was addressed to vibrations generated by the hydro group and analysis of these in order to identify the vibration sources. The evaluated vibrations give essential information about the technical status of the hydro group. Improper functionality of a hydro group can generate negative effects characterized through the following: generating turbulences inside the water jet which cause the appearance of hydrodynamic vibrations with high frequency and these will be transmitted to the entire turbine generating damages; high clearances inside the wicket gate mechanism which under the water jet influence can generate vibrations on a large frequency scale; by having situated the mobile blades proper frequencies in the hydrodynamic frequencies range and bringing these at a resonance level will generate vibrations on a tight frequency domain which affects the hydro group output electrical power. During the Francis turbine starts, by analyzing the diagrams from figures 8 to 11 it result that the main source of vibrations is represented by the hydro group formed by turbine and electric generator. The water flow through the wicket gate mechanism and its interaction with turbine blades, cause large scale frequency vibrations with a relative small impact at the level of the entire hydro group.

By analyzing the zone no 1, which corresponds to the open of the spherical intake vane and let the water to flow inside of the turbine, the obtained vibrations are hydrodynamic ones with a large scale frequency due to the water turbulences.

Zone no 2 corresponds to the mobile blades opening and water intake inside on turbine runner. This zone reveals instabilities on the hydraulic servomotor control, which leads to angular variations of the mobile blades and also on the runner water flow. This also amplifies the vibrations level.

For the zone no 3, it occurs a turbine synchronized functionality without connecting the generator to the electric network. Thus in this case vibrations are present at the wicket gate mechanism and turbine bearing level and these are characterized by fundamental harmonics on a large scale with a frequency of 7.14 Hertz, due to runner turbine angular movement. The missed harmonics shows that the turbine runner is a well equilibrated.

The zones no 4 to 7 corresponds to the electric load made in steps between 5 to 20 MegaWatts. These zones are characterized by an increase of large scale vibrations with a hydrodynamic nature by increasing the water flow and turbulences at the mobile blades level. It appears electromagnetic phenomena by generating the harmonic vibrations of fourth order.

For zones no 7 to 13 it correspond an electrical load of 25 to 50 MegaWatts, in the meantime the large scale vibrations characterized by a hydrodynamic nature will be decreased due to the optimized process of water flow at the wicket gate mechanism level. Also it raises the electromagnetic vibrations spectrum by generating the harmonics of fifth order.

After a closer analysis of the obtained results it can be remarked the following:

- when the hydro group start, the water flow enters on the blades area with a high instability which will lead to a strong variation of the forces and torques from the wicket gate mechanism. The consequence of these consists on the appearance of some vibrations with high amplitudes (it corresponds to zone no 2 from Figure 4);
- during turbine functionality without water, there are small instabilities on maintaining the synchronism angular rotation of the turbine runner. This will cause instabilities at the hydraulic servomotor level which will be also transmitted further to movable blades of the Francis turbine. Moreover this is characterized by a large scale vibrations appearance with high amplitude on zone no 3 (as it shown in Figure 4);
- when the water flow get inside the turbine blades, the turbulences created by the wicket gate mechanism will be decreased which also will decrease the vibrations level generated by the turbine runner and wicket gate mechanism (zone no 8 to 14 from Figure 4);
- by analyzing the diagrams from figures 8 to 11 it can be observed that from a vibrations viewpoint, the Francis turbine works perfect at a 30 to 50 MegaWatts electric load mode. When the Francis turbine works at a level of 15-25 MegaWatts, the hydro group is exposed to large vibrations and in this case is not recommended to perform maintenance operations at this electric load level (as it shown in Figures 5 to 7).

The obtained results from the harmonic analysis using FEM were also verified with the experimental ones during tests and these shown that there is no danger for the resonance phenomena appearance which can damage the Francis turbine.

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