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Structural Dynamic Analysis of Vertical Bars of Turbine Protection Trashracks of Hydroelectric Plant

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Abstract: Trashracks of hydroelectric plants are very important equipment because they are responsible for protection of hydraulic turbines against impact of floating bodies. These structures are basically constituted by horizontal beams and vertical bars that are subjected to action of dynamic loads resulting from flow of water. Objective of this study is to analyze vertical bars of trashracks subjected to action of water flow. In other words, to analyze the responses of structure, and the behavior of water flow, using the calculations of structures dynamics coupled with computational fluid dynamics techniques (CFD). For execution of these analyzes, is utilized the commercial software CFX version 14. These results calculated are the stresses, displacements of the vertical bars, and the profile of velocities of flow. Considering the model proposed, seven analyzes are executed with different values of speeds in order to compare the numerical data calculated by the software with values experimentally obtained. Finally, a modal analysis of a vertical bar is shown in order to verify the results.

Key words: Trashracks; Fluid-Structure Interaction; Turbulent Flow; Computational Fluid Dynamics.

1. INTRODUCTION

One of the most important functions of hydroelectric plants trashracks is protection of turbines against impact of floating bodies that can collide with the blades. Due to this importance, analysis of these structures must be executed in order to avoid failures. Considering the type of load caused by fluid flow, the analysis should be considered based on the dynamic structures.

In accordance with Nascimento et al.(2003), a model of trashrack of a large machine of hydroelectric plant considering the problem of fluid-structure interaction is presented. Modal characteristics were determined considering the structure submerged in water and air. According to the author, natural frequencies of the structure submerged in water are lower than natural frequencies when the structure is in air.

Studies of Sadrnejad (2002) emphasize that loads that cause failures in trashracks have dynamic nature, i.e., it is important to understand the dynamic characteristics of structures of trashracks. In accordance with Nguyenand Naudascher (1991), are presented several experimental studies and results of flow in trashracks bars considering parallel and oblique flows.

According Perez et al. (2006), a study of the fluidynamic behavior of the entrance-impeller interaction of a hydraulic disc pump through numerical simulations, using a three-dimensional numerical model by means of the commercial code CFX allowed to know and to understand the behavior of the problem for the simulated conditions. According to Hribernik et al.(2013), it is presented a research for different types of designs of trashracks submitted to fluid flows. A numerical analysis ANSYS CFX is executed in order to calculate the velocity of approximation of the fluid. Objective is to determine an optimized design of equipment that minimizes the loss of load, i.e., maximizes the efficiency of machine.

Standard NBR 11213 (2001) presents an analysis to verify the vibration in the bars. According to this standard, there is a relationship between the natural frequency of the vertical bars of trashrack and the excitation frequency due to the vortices. I. e., for a safe design against vibrations, the ratio between frequencies should be greater than 1.5, considering 25% of obstruction of area for passage of fluid.

According Kolkman and Jongeling (2007), there is an excitation due to the periodic pulsation in the flow generated by pumps and turbines (this frequency is calculated through the velocity of rotation divided by the number of blades). This excitation is a cause of vibration on the bars. All kinds of damages must be observed. However, these damages, in most cases, are located in the lower panels. Some bars are broken by fatigue, and others simply disappear.

According to Ghamry and Katopodis (2012), the results of numerical analyzes of turbulent flow flowing between the vertical bars with different geometries and spacing of bars in penstocks are presented. Simulations were prepared using two types of turbulence models: the model of Navier-Stokes of Medium Reynolds and stress model of Reynolds. Some experimental results were used to validate the turbulence models. According to Colman (2006), the selection of an appropriate turbulence model is a critical step in the set up of a fluid flow simulation, as it is expected that this choice will have a significant impact on the validity of the results.

According Nguyen and Naudascher (1991), there are three main types of excitations induced by the fluid flow. The first is the excitement produced by turbulence, known as buffeting. This phenomenon is the response of the structure due to random excitation generated by turbulence. This excitement has random nature for obvious reasons. Generally, this excitation has small amplitudes and can result in fatigue failure. The second is the instability or excitation induced by vortices. And the third is the self-excitation.

With the advancement of computational tools, mainly the elements finites software for applications in structural design, nowadays it is possible to model structures optimized in order to minimize weight. However, it must take special care when analyzing structures subjected to dynamic loads. Especially structures subject to fluid flow. This paper presents a simplified model of numerical analysis of vertical bars of trashracks, considering fluid-structure interaction. First of all, a model with five vertical bars is presented. Considering this model, seven analyzes are elaborated in order to compare the numerical results with experimental results. These experimental results are the same presented in paper of Nguyen and Naudascher (1991).

2. FORMULATION OF PROBLEM

Problem studied in this paper is an analysis of structure considering the action of water flow. Considering that the hydromechanical equipment has the function of protecting the turbine against impact of floating bodies, the geometry of control volume was defined in order to analyze the problem. Object of analysis is the lowest region of trashrack. This region presents the highest probability of failure due to high velocities. The geometry of the five vertical bars the bars was designed with the following dimensions: 650 x 50 x 9.5 mm. Distance between bars is 150 mm. And, dimensions of volume of control are 6039 x 900 x 650 mm.

Dimensions of volume of control were defined by the following manner: Upstream distance of trashrack was considered as 1510 mm that represents twice the hydraulic diameter. Downstream distance of the trashrack was considered to be 4529 mm, which is six times the hydraulic diameter. These data have been defined in order to obtain best results for computational fluid dynamics analysis, mainly in the downstream region of trashrack.

3. METHODOLOGY

According Nguyen and Naudascher (1991), vibration of vertical bars of a trashrack depends primarily of structural properties and conditions of support. Structures submerged in water have natural frequencies different than natural frequencies calculated for structures not submerged in water.

Studies of induced vibrations by flows, in accordance with Parkinson (1974) and Novak (1971), cited by Nguyen and Naudascher (1991), it is common to associate a frequency of excitation with the natural frequency n, where V is velocity and d is the dimension of the body perpendicular to the flow. In this case, d is the thickness of vertical bars. In the other words, the reduced velocity can be calculated by the following expression:

$$U = \frac{V}{(n.d)} = \frac{f}{(n.S)} \tag{1}$$

so:

$$S = \frac{f.d}{V} \tag{2}$$

where S is Strouhal number. In the case where there is resonance, f = n, and it can easily conclude that the reduced speed is the inverse of Strouhal number, U = 1 / S.

Geometric factors that affect the vibration of the bars are: shape of cross section of the bars, the reason depth per thickness c / d, the relative spacing s / d (where s is the distance between center to center of vertical bars), and the angle of incidence of flow symbolized for θ.

Some relevant structural properties include n calculation:

$$n = \frac{M.i_v}{l^2}.\sqrt{\frac{E}{\delta_{steel} + \frac{0,7.c}{d}.\delta}} \tag{3}$$

which is the natural frequency of vibration of vertical bars submerged in water. In Equation (3), l is the length of the bar between supports, E is the longitudinal modulus of elasticity of the material of bars, i_v is the radius of gyration and M is the coefficient mode (function of conditions of supports of bar). In this case, M = 11.2 / π for double clamped bar. ρ_{steel} and ρ are densities of steel and water, respectively. For a submerged structure in water, n may be taken as the natural frequency of the structure in water.

Classification proposed by Shiraishi and Matsumoto (1983) reflects the state of the art of aerodynamic research on cylindrical structures such as bridges with large spans and high-rise buildings. The typical response of the flow rectangular profile is presented in Nguyen and Naudascher (1991).

The magnitude a represents the amplitude of vibration, i.e., there is a value of reduced velocity where the amplitude of vibration increases very much. Profiles of bodies submerged in fluid are divided in three groups. Value of relationship between c and d for different profiles defines the type of group of profile.

Mesh of structural model has five vertical bars. And the elements format were defined by hexahedra. After the definition of meshing of structural model, it is possible to define the mesh of fluid. It is important that the analysis of the fluid flow considers that the alignment of the mesh has the same direction of the velocity of flow. For this reason, it is defined the mesh of volume of control with prisms or hexahedra elements.

Structural model boundary conditions are defined in the following manner: two tips of vertical bars are fixed on the upper and lower faces. Boundary condition of fluid-structure interface is applied on wet area of the vertical bars of trashrack. The condition of loading is applied considering a pressure equivalent to 3.0 meters of water column on the faces perpendicular to the flow velocity. This pressure is defined in accordance with standard ABNT NBR11213 (2001). This pressure is applied considering a time of 2.0 seconds. Model analyzed in this paper is a simplified model. For this reason, the pressure of 3.0 mwc was defined. For a more detailed model, it would be necessary to include the reservoir dimensions.

Due to the condition of loading, analysis is defined as transient structural or simply dynamic analysis.

Boundary conditions used on computational fluid dynamic analysis are: initial velocity and pressure at inlet and outlet respectively. Another condition utilized is: symmetry condition on the faces of the volume control (in plane perpendicular to the z axis).

In the fluid inlet zone, the boundary condition of input of velocity and the inlet temperature was defined. Fluid flow type is set as turbulent flow, with the values of k and ε defined. In the zone corresponding the lateral faces of the volume of control: it is defined symmetry condition in the plane perpendicular to z-axis. And, in the outlet zone of the fluid: it is defined as output fluid velocity. Output pressure is determined equal to 0 Pa.

CFX software solves the iterative process of solution until that certain specified stopping criteria can be reached. These stopping criteria are specified for the equations if continuity and energy and for the velocities in x, y, z. If $V = 3.1$ m/s, $Re = 432{,}945$, that represents a turbulent flow.

4. RESULTS AND DISCUSSIONS

Results of Von Mises stresses obtained are shown in Figure 1. Results are presented for an instant of time equal to 0.4 seconds. Results of deformation in the direction of the z-axis are presented in Figure 2. Results are shown for an instant of time equal to 0.4 seconds.

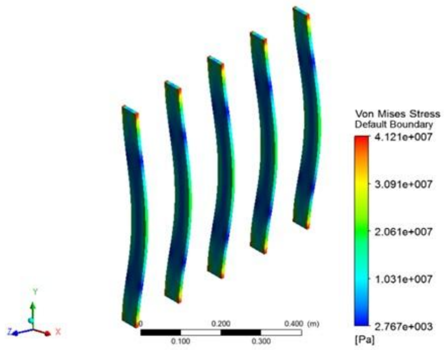

Figure 1. Von Mises stresses results of vertical bars.

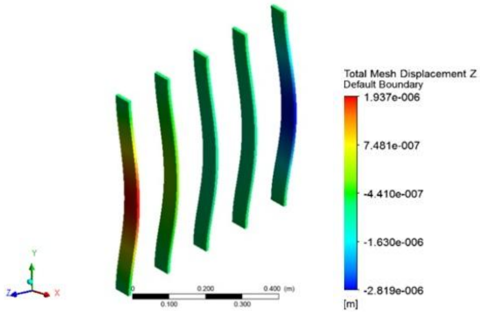

Figure 2. Deformations results in the direction of z-axis of vertical bars.

ZX plane was defined in order to visualize the profile of velocities calculated. Figure 3 presents the details of profile of velocities calculated through the computational fluid dynamics analysis. This figure shows the regions where appear the vortices of flow. These vortices are the main type of excitation induced through the flow.

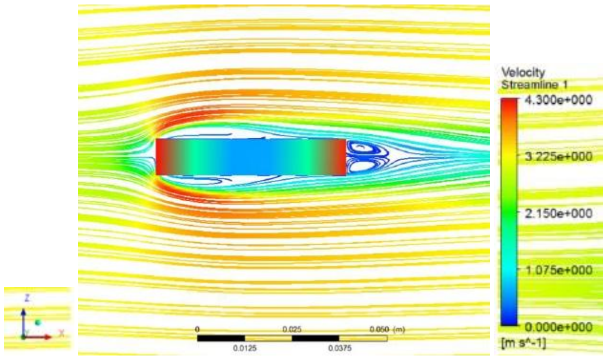

Figure 3. Detail of profile of velocities of fluid dynamics analysis.

4. 1. Comparison between Model Results and Experimental Results

Considering the simplified structural model of five vertical bars, this can be checked, considering a structural point of view. Considering that the analytic solution of beam clamped on two tips is known, it is possible to compare the results obtained numerically and experimentally.

Considering the analytical data, stress can be calculated considering a beam with two tips clamped, subjected to a distributed load due to pressure of 3 meters water column. The difference between the Von Mises stress results obtained analytically, and numerically by software is 11.12%. This difference can be explained due to the contribution of pressure generated by the velocity of flow.

Considering the experimental results, they are utilized the results obtained in Nguyen and Naudascher (1991). These experimental results are shown for various types of profiles, velocities and angles of incidence. Main characteristic is obtained through the identification of the region where there is resonance. I.e., when the natural frequency is equal to the excitation frequency. From the point of view of fluid-structure interaction analysis, the following procedure was prepared in order to verify the numerical model. First, it is calculated the reduced critical speed, i.e. the speed U where the excitation frequency is equal to the natural frequency. With this reduced velocity, it is calculated the velocity of incidence of flow that produces the strain in the z direction. This procedure was repeated for 7 values of speeds. And, with the results calculated, the graph of Figure 4 is elaborated.

Dimensions of the bars are 650 x 50 x 9.5 mm. Therefore, the ratio c / d is 5.26, which means that the bar is classified as Group II, second Nguyen and Naudascher (1991).

In order to verify the numerical model for analysis of fluid-structure interaction, a graph is elaborated considering the relative amplitude vibration (a / d) versus the reduced speed U. In this chart, it can view the area where there is resonance. I.e., the excitation frequency is equal to the natural frequency. In this case, the amplitude of vibration tends to be increased. As shown in the Figure 4, the vibration amplitude begins to increase significantly after the reduced speed reaches the value of 1 / S that indicates resonance.

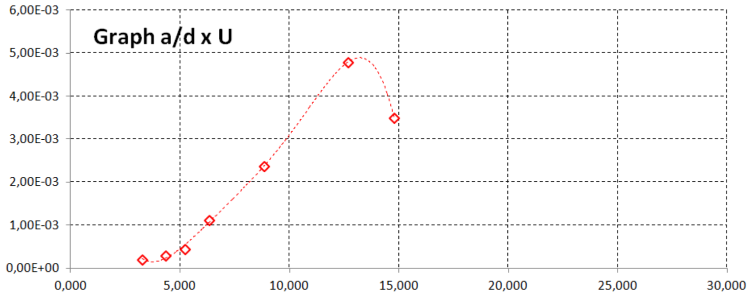

Figure 4. Chart reduced speed versus vibration amplitude.

4.2. Modal Analysis of a Vertical Bar

In order to evaluate the response obtained by Equation (3), it was executed a modal analysis of a vertical bar without the presence of fluid. The same dimensions and boundary conditions are considered. Natural frequency of 117.47 Hz was obtained for the first mode vibration (bending in z direction). Results of the modal analysis were obtained using the commercial software ANSYS Workbench. Results are in accordance with the expected, because it is known that the presence of the fluid decreases the value of the natural frequency.

Using Equation (3), the natural frequency of a vertical bar in water is 99.76 Hz. Therefore, the difference of first natural frequency between the vertical bars with and without the presence of fluid is approximately 15%.

5. CONCLUSIONS

Results are in agreement with expectations. I.e., results of stresses are in accordance with the analytical calculations. Considering the pressure of 3 meters of water column, according to NBR 11213 (2001), acting on a beam with two tips clamped, the exact analytically calculated stress is 36.66 MPa. Numerical calculation showed a maximum stress of 41.24 MPa at t = 0.4 s, on the region of tips of bars. Numerical analysis results showed a variation of stress of 11.12% when compared with theoretical analysis due to the fact that numerical analysis considers beyond of pressure of 3.0 meters of water column, the influence of the dynamic pressure exerted by the flow.

With respect to fluid-structure analysis, the results are satisfactory. Since the resonance region was identified in the chart vibration amplitude versus reduced velocity. Seven analyzes at different speeds were prepared. Although the graphic presents a region where there is a peak of amplitude, this peak is not exactly in the region where the reduced speed is the inverse of Strouhal number, which characterizes the resonance region. This fact can be easily explained because the Strouhal number was obtained from the graph that relating the c / d of bar of the cross-sectional, according to Nguyen and Naudascher (1991). Second NBR 11213 (2001) is presented another way to calculate the Strouhal number. According to this standard, the Strouhal number is greater in magnitude. This fact can explain the differences obtained in the numerical and experimental analyzes.

Despite of the trashrack design presents a good structural rigidity, especially in the direction parallel to the flow. However, if the speeds are too high, the trashrack may fail due to deformations in the z direction. It is highly recommendable to check the relationship between the natural frequency and excitation frequency of the bars. According to the analysis developed in this paper, the vibration amplitude increases greatly when the excitation frequency is equal to the natural frequency, which is the principle of resonance. According to the standard NBR 11213 (2001), the relationship between the natural frequency and frequency excitation must be greater than 1.5.

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