MODEL OF HYDROELECTRIC POWER PLANT TRASHRACKS INCLUDING FLUID-STRUCTURE INTERACTION

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Abstract. This work is concerned with virtual mass effect on the natural frequencies and mode shapes of trashracks of hydroelectric power plants excited by the flow pass on the structure. When the structure is in contact with the water or immersed in water, the vibration of the structure is transferred to the water and give rise to water motion. As a result, there is an increase in the kinetic energy of the water. Because of increase in the kinetic energy, the natural frequencies of the structures in contact with water decrease significantly compared to the natural frequencies in air, although the mode shapes maintain a stationary behavior. Another very common problem that can occur in a hydroelectric plant trashrack is the excessive amount of aquatic plants accumulated on it. As a result, the flux induced vibration changes due flux velocity variation and there is an overload, which can cause damage on the structure. This work presents a trashrack model of a big hydroelectric machine considering the problem of fluid-structure interaction or hydroelastic vibration structure. The modal characteristics have been determined considering the structure immerse in water and in air. Also, it has been made approaches to verify damage risk as a function of overload induced by aquatic plants accumulated on the trashrack.

Keywords. Trashrack, Hydroelectric, Modeling, Fluid-Structure

1. Introduction

The trashrack structures of the hydroelectric turbines have the purpose of restricting the entrance of materials of great dimensions together with the water, which can cause damages to the generating machine, particularly to the pre-distributor, distributor, spiral casing and turbine itself. On these structures variable excitation forces act superimposed to the static force forming a complex dynamic system. This complexity is due to the fluid and structure coupling, which is referred as fluid-structure interaction problem. Besides, two other problems can be added; the first one is the frequent machine operation in partial loads for compensate the electricity demand variation in the electric distribution system. As a result the water flow rate varies and can induce dangerous fluid dynamic conditions, damaging the trashrack; the second one is the excessive accumulation of materials onto the trashrack. In this case, besides provoking adverse fluid dynamic conditions, the accumulated materials impose some restriction in the production due to the load loss of the machine, as well as the overloads that are unavoidably induced on the trashrack. Since the trashracks are often not designed for those overloads, sometimes the damage can occur even before the load loss is noticed by the production. In critical situations, the trashrack get damaged, being “swallowed” by the turbine, causing serious problems.

In the last years it has been observed that the problem of excessive accumulation of aquatic plants (*Egerla Densa)* on the trashracks of turbines is becoming worse in some hydroelectric of Brazil due to the uncontrolled proliferation of those plants in the dam as a consequence of organic residues emptied by the industries along the course of the river, creating the ideal conditions for its proliferation during the summer period. As a result, a lot of damage problems have been appearing on the trashracks due to fluid-structure interaction, and the hydroelectric companies have great interest in this subject.

A number of researchers are trying to identify the physical phenomena of fluid-structure interaction and describe them adequately. There are solutions in the literature showing how to proceed for many different structure geometries and form ratio, for instance (Zhou & Cheung, 2000; Kwak & Amabili, 1999; Yang et all, 1997; Amabili, 1996; Kwak, 1996), and they have been demonstrating through theoretical and experimental works that the natural frequencies of the structures in contact with water decrease notably, and the vibration modes practically do not change. Also, there are several works concerned specifically to the design and fluid-structure interaction of trashrack (Matsumoto et all, 1998; Naudascher & Rockwell, 1994; Nguyen & Naudascher, 1991; Crandall et all, 1975; Sell, 1971).

2. Simplified fluid-structure interaction modeling

Let's consider a simple mass, spring and damping system submerged in a rest fluid, under which acts a harmonic force with oscillation frequency ω. Then the response of the system will be a harmonic displacement of maximum amplitude X_0 given by,

$$x = X_0 \text{ sen } \omega t \tag{1}$$

and the velocity and acceleration of the system can be derived from Eq. (1) as,

$$\dot{x} = X_0 \omega \cos \omega t \tag{2}$$

$$\ddot{x} = -X_0 \omega^2 \text{ sen } \omega t \tag{3}$$

The motion of the structure makes appear a fluid force F, which acts on the structure and can be expressed in terms of a trigonometric series as,

$$F = \sum_{i=1}^{N} (a_i \text{ sen } i\omega t + b_i \cos i\omega t) \tag{4}$$

where a_i and b_i are constant coefficients if the vibration amplitude of the structure in contact with water are constant, too. Now if the higher order terms of the Eq. (4) are neglected then the force acting on the structure is reduced to,

$$F = a_1 \text{ sen } \omega t + b_1 \cos \omega t \tag{5}$$

Comparing the coefficient terms a_1 and b_1 of the fluid force in the Eq. (5) with the amplitude terms of the acceleration and velocity of the structure represented by Eqs. (3) and (2) respectively, it can be seen that the fluid force components act in phase with the vibrations of the structure, therefore, the equation of the fluid force can be rewritten in terms of the vibratory behavior of the structure as,

$$F = -A_{xx}\ddot{x} - B_{xx}\dot{x} \tag{6}$$

$$A_{xx} = \frac{a_1}{X_o \omega^2}, \quad B_{xx} = -\frac{b_1}{X_o \omega} \qquad 7)$$

The coefficient A_{xx} refer to the added mass, which is generally given in terms of mass per unit of length. The component of the fluid force $-A_{xx}\ddot{x}$ is applied to the structure due to the inertia of the fluid created by the motion of the structure, and acts with same sign, frequency and phase of the inertia of the structural mass. The coefficient B_{xx} corresponds to the added damping, and the component of the fluid force $-B_{xx}\dot{x}$ is applied to the structure due to the damping induced by the water, Blevins (1990). Considering a single degree of freedom system submerged in water, the motion equation can be given by,

$$m\ddot{x} + c\dot{x} + kx = F \tag{8}$$

where m, c and k are the mass, structural damping and stiffness of the system, F is the fluid force applied and x is the displacement of the system. Introducing the Eqs. (6) and (7) into Eq. (8) the free vibration of the system can be given by,

$$(m + A_{xx})\ddot{x} + (c + B_{xx})\dot{x} + kx = 0 \tag{9}$$

in which the effects of the added mass and damping are considered. In the case of system modeled with multi-degrees of freedom the simplified fluid-structure interaction modeling can also be used and the free motion equation will be given in the matrix form as,

$$([\mathrm{M}] + [A])\{\ddot{x}\} + ([C] + [B])\{\dot{x}\} + [K]\{x\} = 0 \tag{10}$$

If the structure has certain symmetries and the beams and rods have constant traversal sections, then it will not be so difficulty to introduce the effect of the added mass and damping in model of the structure, Blevins (1984). The [A]

and [*B*] matrices contain the added mass and damping coefficients due to the system motion along of each symmetry axis, and can be naturally incorporated by the simple increment of the mass and damping added in the structure.

The modal characteristics approach of the system can be obtained from the Eq. (10) taking the damping matrices equal to zero and solving the eigenvalue problem. The added mass always reduces the natural frequencies of the structure in comparison to those measured in the air. The importance of the added mass in the dynamic analysis of a structure can be estimated through the ratio between the fluid density surrounding the structure and the medium density of the structure. The effect of the surrounding fluid in the natural frequencies and modes shapes is not significant in relatively compact structures if the fluid density is much smaller than to medium density of the structure. Thus, it can be said that the air that surrounds most of the structures doesn't affect its natural frequencies and mode shapes. However, the water can play a significant role in free vibration of marine structure, such as structures of platforms of extraction of petroleum, ships and immerged pipes.

In the last years several studies were accomplished with the purpose of evaluating the added mass for distinct geometries, different boundary conditions and submitted to several flow conditions. In this sense stands out the work of Blevins (1984), where he gathered a vast literature on theoretical and experimental works on the subject and presents the values of added masses for a great variety of geometries with different form ratios, for two and three-dimensional cases, some of them showed in the Fig. (1).

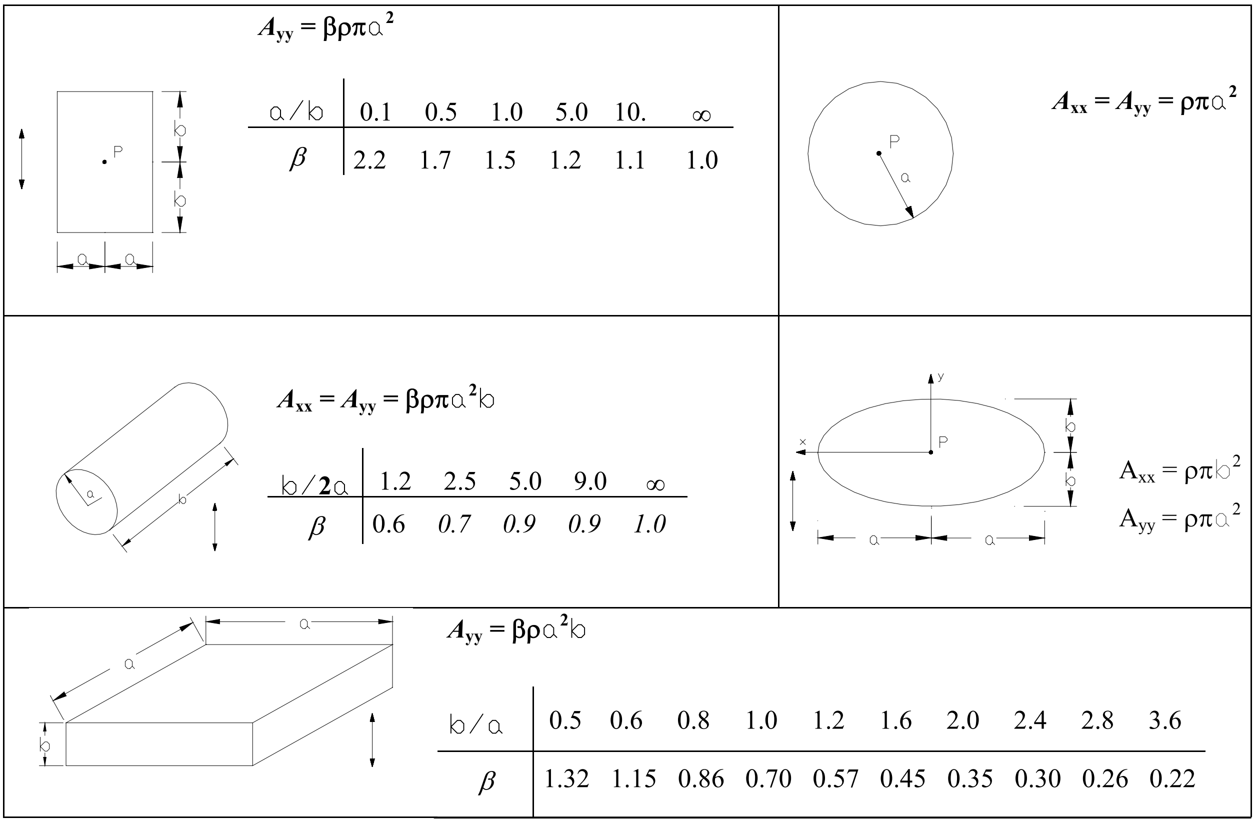

Figure 1. Added mass values for different geometries and form ratios, Blevins (1984).

3. Geometric description of the trashrack analyzed

In this section the geometric characteristics of the trashrack analyzed will be described. This trashrack belongs to the Souza Dias hydroelectric power plant, which is located in the Paraná river in Brazil between the São Paulo and Mato Gosso do Sul States. In this hydroelectric plant a serious problem of failure in the trashrack comes happening during the summer period caused by the excessive accumulation of aquatic plants on it. This hydroelectric power plant is composed by fourteen generating machines driven by Kaplan turbines. The installed power capacity of the plant is 1411.2 MW, and each generating group has nominal power of 100.8 MW, nominal flow rate of 511 m3/s and nominal net head of 22 meters. Eventually some machines can operate in partial loads to control the energy demand variation in the whole electricity distribution system, and in this case the operation flow rate will be different (less than) from the nominal flow rate.

For each one of the generating machines there are two big spaces (mouths) for the entrance of water, which is part of the system to supply water to the turbine. In the entrance of each mouth there is a grating metallic structure (trashrack), which constitutes the protection part of the whole supply water system. The entire trashrack measures 12.15 meters wide by 21.975 meters high, and consists of twenty-five identical smaller individual racks (panels) stacked five high in each of five columns supported by concrete piers. In fact, for analysis effect each panel fastened at the concrete piers can be considered as a structure that supports loads independently of the other panels. Figure (1) shows the constructive characteristics and the main geometric dimensions of an individual rack (panel), which has grating form measuring 2.40 meters wide by 4.37 meters high. It is composed basically by twenty rectangular section beams of the ABNT 1045 steel material with dimensions 6 in. x 9/16 in. x 4,37 meters disposed vertically and by five horizontal round rods, also of the ABNT 1045 steel, measuring 1.5 in. in diameter by 2.4 meters in length. The individual panels are screwed at the concrete piers in eight symmetrical points placed at the superior and inferior ends of four vertical beams, as indicated in the Fig. (2).

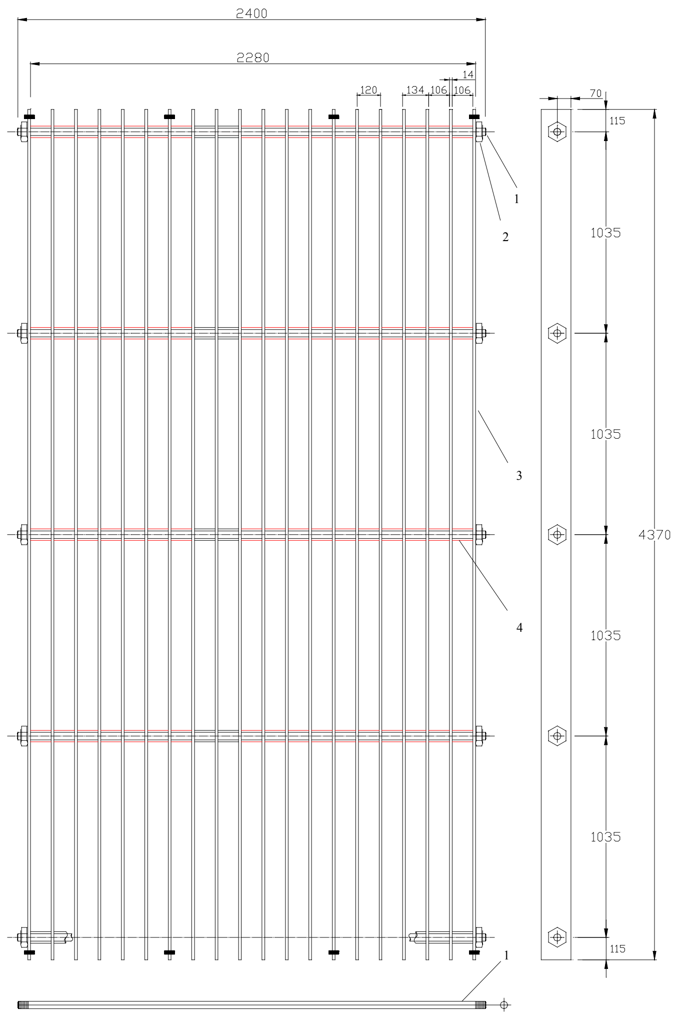

Figure 2. Sketch of an individual rack structure of the whole turbine trashrack.

4. Finite element model for the individual rack structure

As the individual rack structure (panel) works independently of the other panels, then it doesn't suffer dynamic effects from the neighboring panels, so it can be modeled to simulate the modal characteristics of the whole trashrack. The vertical beams and horizontal rods, as showed in the Fig. (2), were modeled by the finite element method as 3D elastic elements. This element allows tension, compression, torsion and flexural efforts and it is possible to attribute to it up to twelve degrees of freedom, six degrees for each nodal point of the element: linear and rotational motion in the three directions. The mass matrix of this element including the added mass effect can be given by,

$$[\overline{M}]^e = \rho AL[M]^e + A_{xx}L[M]_x^e + A_{yy}L[M]_y^e + A_{zz}L[M]_z^e \quad (11)$$

where $[M]^e$ is the mass matrix of the element, $[M]_x^e$, $[M]_y^e$ and $[M]_z^e$ are the added mass matrices, ρ is the material density, A is the cross-section area of the element, L is the length and A_{xx} , A_{yy} and A_{zz} are the added mass coefficients given in mass per unit of length in the three directions.

The added mass matrices can be obtained using part of the mass matrix of the element. The $[M]_x^e$ matrix is obtained taking the elements of the rows and columns 1, 4, 7 and 10 from the mass matrix, Eq. (12), and taking the other elements equals to zero. In the similar way, the $[M]_y^e$ matrix is given taking the elements of the rows and columns 2, 6, 8 and 12 from the mass matrix and making the other elements equals to zero. Finally, the $[M]_z^e$ matrix is obtained taking the rows and columns 3, 5, 9 and 11 from the mass matrix maintaining the other elements equals to zero.

The mass and stiffness matrices of the element have the form,

$$[M]=\begin{bmatrix}
1/3 &&&&&&&&&&& \\
0 & A_z &&&&&&&&&& \\
0 & 0 & A_y &&&&&&&&& \\
0 & 0 & 0 & J_x/3A &&&&&&&& \\
0 & 0 & -C_y & 0 & E_y &&&&&&& \\
0 & C_z & 0 & 0 & 0 & E_z &&&&&& \\
1/6 & 0 & 0 & 0 & 0 & 0 & 1/3 &&&&& \\
0 & B_z & 0 & 0 & 0 & D_z & 0 & A_z &&&& \\
0 & 0 & B_y & 0 & -D_y & 0 & 0 & 0 & A_y &&& \\
0 & 0 & 0 & J_x/6A & 0 & 0 & 0 & 0 & 0 & J_x/3A && \\
0 & 0 & D_y & 0 & F_y & 0 & 0 & 0 & C_y & 0 & E_y & \\
0 & -D_z & 0 & 0 & 0 & F_z & 0 & -C_z & 0 & 0 & 0 & E_z
\end{bmatrix} \tag{12}$$

where,

$$A_{y,z}=\frac{13}{16}+\frac{6}{5}\left(\frac{r_{y,z}}{L}\right)^2 ;\quad B_{y,z}=\frac{9}{10}-\frac{6}{5}\left(\frac{r_{y,z}}{L}\right)^2 ;\quad C_{y,z}=\left[\frac{11}{210}+\frac{1}{10}\left(\frac{r_{y,z}}{L}\right)^2\right]L$$

$$D_{y,z}=\left[\frac{13}{420}-\frac{1}{10}\left(\frac{r_{y,z}}{L}\right)^2\right]L ;\quad E_{y,z}=\left[\frac{1}{105}+\frac{2}{15}\left(\frac{r_{y,z}}{L}\right)^2\right]L^2 \tag{13}$$

$$F_{y,z}=\left[\frac{1}{140}+\frac{1}{30}\left(\frac{r_{y,z}}{L}\right)^2\right]L^2 ;\quad r_{y,z}=\sqrt{\frac{I_{y,z}}{A}}$$

$$[K]=\begin{bmatrix}
AE/L &&&&&&&&&&& \\
0 & a_z &&&&&&&&&& \\
0 & 0 & a_y &&&&&&&&& \\
0 & 0 & 0 & GJ/L &&&&&&&& \\
0 & 0 & d_y & 0 & e_y &&&&&&& \\
0 & c_z & 0 & 0 & 0 & e_z &&&&&& \\
AE/L & 0 & 0 & 0 & 0 & 0 & AE/L &&&&& \\
0 & b_z & 0 & 0 & 0 & d_z & 0 & a_z &&&& \\
0 & 0 & b_y & 0 & c_y & 0 & 0 & 0 & a_y &&& \\
0 & 0 & 0 & -GJ/L & 0 & 0 & 0 & 0 & 0 & GJ/L && \\
0 & 0 & d_y & 0 & f_y & 0 & 0 & 0 & c_z & 0 & e_y & \\
0 & c_z & 0 & 0 & 0 & f_z & 0 & d_y & 0 & 0 & 0 & e_z
\end{bmatrix} \tag{14}$$

where,

$$a_{y,z} = \frac{12EI_{y,z}}{L^3} \qquad b_{y,z} = -\frac{12EI_{y,z}}{L^3} \qquad c_{y,z} = \frac{6EI_{y,z}}{L^2}$$

$$d_{y,z} = -\frac{6EI_{y,z}}{L^2} \qquad e_{y,z} = \frac{4EI_{y,z}}{L} \qquad f_{y,z} = \frac{2EI_{y,z}}{L} \tag{15}$$

The individual rack showed in the Fig. (2) was modeled with 393 finite elements, 288 elements for the vertical beams and 105 elements for the horizontal rods. The joints between the rack and concrete piers were considered as rigid joints, therefore all movements at these points were restricted.

The dynamic analysis of the trashrack presented in this work has just been limited to the lower order frequencies and mode shapes, which could be excited by fluid dynamic forces that appear due to water passing through the trashrack. The modal characteristics of the panel have been determined not considering the damping. Of course, the natural frequencies and mode shapes vary lightly in function of the damping quantity. However, it is known that the difference between the natural frequencies with and without damping is not so important in this case, so it is acceptable to analyze the results of the simulation without damping. Also, if the damping is introduced in the free vibration equation of the system, the eigenvectors will be complex and the maximum relative amplitude of each coordinate doesn't happen simultaneously, making the geometric visualization of the modes shapes so much difficult.

5. Modal characteristics approach

In this section the results of the dynamic analysis performed on the structure, Fig. (2), will be presented with the purpose of showing how much the effect of added mass influences the natural frequencies of the trashrack. Table (1) presents the values of the seventh first natural frequencies of the panel with and without the added water mass effect, as well as the reduction values in the natural frequencies with the immersed structure. In general, it was observed that the natural frequencies considering the added mass effect were about 30% smaller than the frequencies considering the panel vibrating freely in the air. Therefore, this comes to confirm the great importance of introducing the additional mass effect in the model of the submerged structures like the trashrack, since the differences between the natural frequencies of both conditions are significantly big. There are many investigations being developed with the purpose of arriving to a deeper understanding of the added mass effect, especially in more complex structures. In this work the reductions found out in the values of the frequencies are in agreement with the reductions obtained in other works, which also have analyzed the influence of the submersion on the modal parameters of the structures (Yang et all, 1997 and Amabili, 1996), respecting, of course, the differences in the geometry of the structures in each work. It is also noticed that the values of the first natural frequencies of the panel are relatively low, indicating that there is a great probability of the structure to operate in resonant conditions, since most of the fluid dynamic forces act on the panels at low frequencies, Di Giunta (2002).

Table 1. Natural frequencies of the trashrack with and without added mass effect.

Modes	Natural Frequencies of the Structure (Hz)	Natural Frequencies of the Immersed Structure (Hz)	Frequencies Reductions due to Added Mass Effect
1	8.19	5.67	30.7%
2	16.68	11.58	30.6%
3	24.96	17.42	30.2%
4	25.92	17.94	30.8%
5	32.86	22.74	30.8%
6	41.91	29.00	30.8%
7	57.62	39.92	30.7%
		Average	30.65 %

Figure (3) shows the mode shapes of the lower order natural frequencies for the trashrack obtained through the simulation when the added mass effect is introduced in the model. In this analysis it has been verified that practically there is no difference between the mode shapes with the structure vibrating in the air and the modes with the structure vibrating under water, i.e., considering the added mass due to the immersion. Actually, the works of (Amabili, 1995; Kwak, 1996 and Espinosa & Gallego, 1986) there were already verified experimentally that the mode shapes are very close or are practically the same ones under the influence of the water.

It can be seen that the relative modal displacements of the mode shapes presented in the Fig. (3) happen at a perpendicular plan with respect to the steam flow direction, probably due to the fact that the stiffness modulus (*EI*) in that plan of the panel is smaller. It is important to remind that is also in this plane that act the alternate excitation forces on the structure as a result of the flow vortices induced by the water passing through the vertical beams. Normally, these alternate forces happen at low frequencies, so could excite some natural frequencies. On the other hand, the relative modal displacements for the forth and fifth vibration modes (not represented in this work) happen in the same direction of the main stream flow.

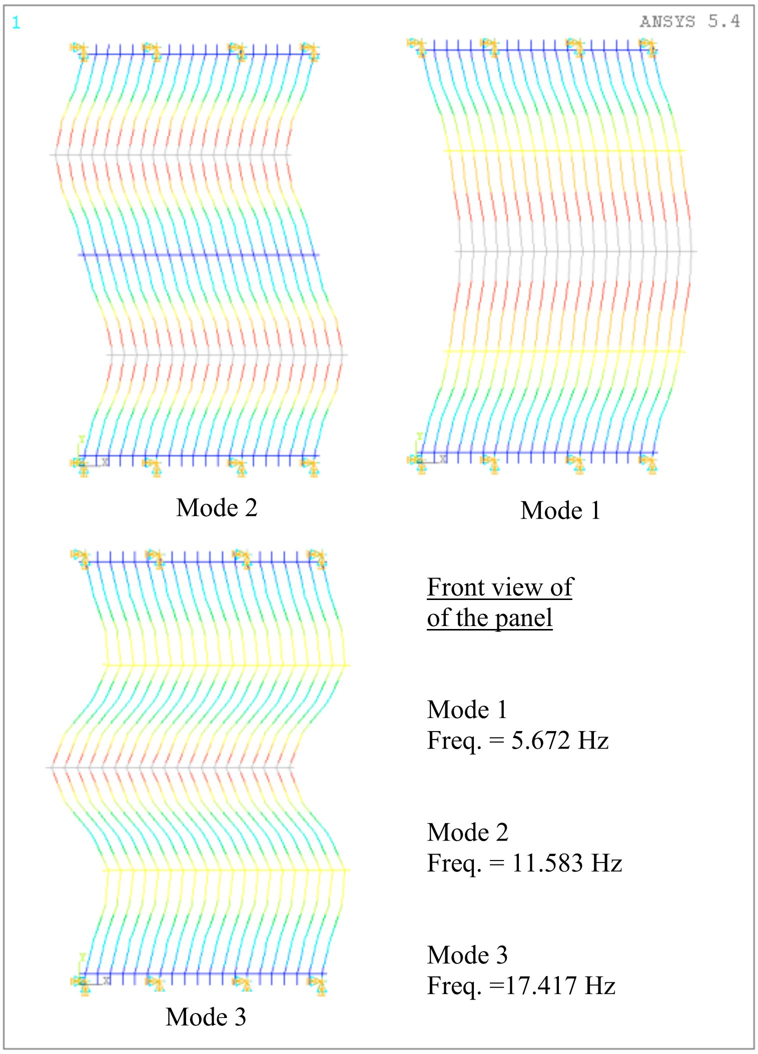

Figure 3. Mode shapes of an individual rack with the added mass effect.

6. Static analysis

In this section an analysis carried out to get an approach of the static behavior of the trashrack will be presented. The model employed is not intended to accurately predict this behavior, but to just get an idea of the distribution and order of magnitude of the stresses acting on the panels of the trashrack due to the force that happens in direct consequence of the incidence and passage of the water through the structure and due to trashrack obstruction induced by the aquatic plants accumulated on it. Here, this force is considered as time invariant and the dynamic forces produced by the vortices and eventual turbulences are neglected. This static force is taking as uniformly distributed on the panel, and since the inertial forces are not included, the static equation is given by,

$$[K]\{u\} = \{F_{Dp}\} \tag{16}$$

where $[K]$ is the stiffness matrix, $\{u\}$ is the nodal displacement vector and $\{F_{Dp}\}$ is the pressure drag force distributed on the structure. The drag force depends on the flux velocity and on the projected area that obstructs the fluid passage, and the variation of the flux velocity and the obstructed area are functions of the amount of accumulated plants on the panel. These two parameters affect directly the magnitude of the drag force, and as result the stresses acting on the structure increase with the plant accumulation. The drag force can be calculated by the expression,

$$F_{Dp} = \frac{1}{2} C_{Dp} \rho A_p U^2 \tag{17}$$

where C_{Dp} is the pressure drag coefficient, ρ is the density of the water, A_p is the projected area and U is the average velocity of the fluid. Considering the panel with certain obstruction, it can be assumed the condition of high ratio form and admitted the hypothesis that it behaves as a plate normal to the flux direction, so that the pressure drag coefficient can be obtained from the curve of the Fig. (4) given in function of the aspect ratio, Fox and McDonald (1995).

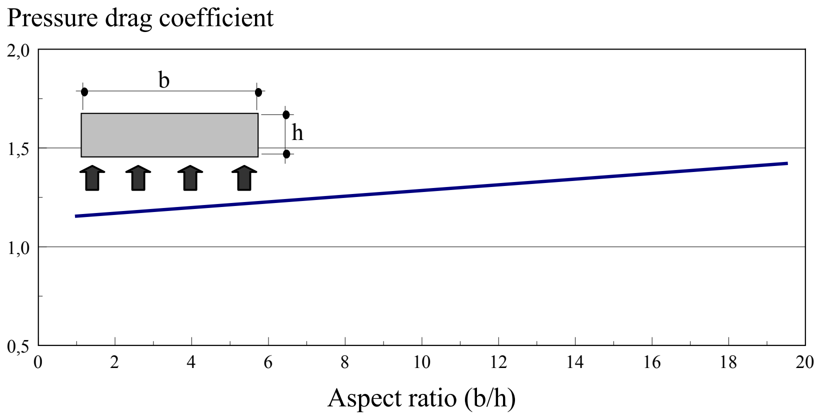

Figure 4. Pressure drag coefficient C_{Dp} as a function of the aspect ratio (*b/h)*, Fox and McDonald (1995).

The normal stresses acting on the structure can be calculated from the nodal displacements obtained by the solution of the Eq. (16), and can be given by,

$$\{\sigma\} = [E]\{\varepsilon\} \tag{18}$$

where [*E*] is the elasticity matrix and {ε} is the deformation vector, which can be calculated taking into account the nodal displacement through the equation,

$$\{\varepsilon\} = [D]\{u\} \tag{19}$$

where [*D*] is the differential operator matrix, Zienkiewicz (1979).

In this analysis the stresses have been calculated admitting that occur a simultaneous and uniform accumulation of aquatic plants on the panel. The amount of aquatic plants accumulated on the panel will be represented by a percentage of obstruction of the section of the water passage, which will change the average value of the flow velocity. Thus, it has been taking hypothetical cases seeking to simulate several operating conditions of the trashrack. Table (2) presents the simulated stresses due to static load acting on the panel for 9 cases of average flow velocity and the respective percentage of obstruction.

Table 2. Simulated stress acting on the panel for 9 cases of percentage of obstruction.

Cases	% of obstruction	Average Flow Velocity (m/s)	Maximum Stress (MPa)
1	0%	1.000	10.5
2	10%	1.0630	11.9
3	20%	1.1918	14.9
4	30%	1.3675	19.6
5	40%	1.5949	26.8
6	50%	1.9139	38.5
7	60%	2.3924	59.7
8	70%	3.1898	106
9	80%	4.7847	239

It has been observed that the maximum stresses acting on the trashrack, as indicated in the Tab. (2), occur in the horizontal rods close to the points where the panel is fastened at the concrete piers. Also, it has been noticed somewhat high stresses in the vertical beams whose ends are fastened at the concrete piers. Since the maximum allowed yield strength for the material of the structure is about 170 MPa, then the result shows that a failure due to the static force can only happen if there is a reasonable amount of aquatic plants accumulated on it, provoking a significant obstruction. On the other hand, it is known that the machine should probably stop due to a severe load loss if an obstruction more than

30% happens. Therefore, it can conclude that difficultly the trashrack will damage only due to static loads. In this case, a fluid dynamic force acting with frequency close to one of the natural frequencies of the trashrack can represent the most important factor of risk for its failure.

7. Conclusions

There are a lot of problems associated with trashrack failure in hydroelectric power plants. The trashracks are subject to the most varied operating conditions because of the wide range of velocities that it would normally be subjected, and to get reliable simulated results the models are normally very complex. To analyze the trashracks it is necessary to have a deep knowledge of the mechanisms of generation of static and dynamic forces produced by the fluid incidence, as well as the effect of the water on the vibratory behavior of them.

In this work it has been confirmed the effective need to introduce the added mass effect in the trashrack model due to the submersion effect, so that the modal characteristic approach became more reliable. The fluid-structure interaction approach employed in this work can be easily incorporated to the model of the structure. The results obtained in this analysis are quite in agreement with other published works that have tested other types of structures. It has been verified that the values of the natural frequencies for a submerged trashrack are about 30% smaller than the values of the natural frequencies of a non-submerged trashrack, i.e., in the air. Also, it has been clarified that the added mass practically doesn't modify the mode shapes of the trashrack.

The analysis of stresses induced by the static force reveals that is necessary a significant amount of aquatic plants accumulated in the trashrack so that a damage can happen, i.e., it is necessary that happens an obstruction of more than 70% of the area of the water passage, but difficultly the machine would work with high levels of obstruction due to high load loss imposed by these conditions. It is important to remind that the simplified model employed to calculate the drag force couldn't produce accurate results. This model is not intended to accurately predict the drag force, as well as the stresses acting on the structure, but it has been used to give an idea of the degree of severity of the static effort on the panel.

The results of this work indicate that trashrack damages are probably consequences of the combination of the static effort with resonance excitations. However, the fluid dynamic exciting forces acting at resonant frequencies can induce severe operating conditions of the trashrack, imposing a larger damage risk.

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9. References

Amabili, M., 1996, "Vibrazioni di sistemi com interazione fluido-struttura-metodi analitici, numerici e sperimentali", Phd Thesis, Universitá Degli studi Di Bologna e Di Firenze, Bologna.

Amabili, M.; Pasqualini, A. and Dalpiaz, G., 1995, "Natural Frequencies and Modes of Free-Edge Circular Plates Vibrating in Vacuum or in Contact with Liquid", Journal of Sound and Vibration, Vol. 188, Nº5, pp. 685-699.

Blevins, R. D., 1990, "Flow Induced Vibration", Second Edition, Van Nostrand Reinhold, New York, 450 p.

Blevins, R. D., 1984, "Formulas for Natural Frequency and Mode Shape", Third Edition, Robert & Krieger Publishing Company, Florida, 424 p.

Crandall, S. H.; Vigandee, S. and March, P. A., 1975, "Destructive Vibration of Trash Racks due to Fluid-Structure Interaction", Journal of Engineering for Industry, pp. 1359-1365.

Di Giunta, V., 2002, "Análise Estática e Dinâmica da Grade de Proteção da Tomada de Água de uma Usina Hidrelétrica", Máster Thesis, College of Engineering, UNESP, Ilha Solteira – SP, 127 p.

Fox, R. W. and McDonald, A. T., 1995, "Introdução à Mecânica dos Fluidos, 4th edition., Ed. Guanabara Koogan S. A., Rio de Janeiro.

Kwak, M. K. and Amabili, M., 1999, "Hydroelastic Vibration of Free-Edge Annular Plates", Journal of Vibrations and Acoustics, Vol. 121, pp. 26-32.

Kwak, M. K., 1996, "Hydroelastic Vibration of Rectangular Plates", Journal of Applied Mechanics, Vol.63, pp. 110-115.

Matsumoto, et all, 1998, "Aerodynamic Effects of the Angle of Attack on a Rectangular Prism", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 77/78, pp. 531-542.

Naudascher, E. and Rockwell, D., 1994, "Flow Induced Vibration - An engineering guide", 7 Hydraulic Structure Design Manual, International Association for Hydraulic Research, Rotterdam, 412 p.

Nguyen, T. D. and Naudascher, E., 1991, "Vibration of Beam and Trashracks in Parallel and Inclined Flows", Journal of Hydraulic Engineering, ASCM, Hydraulics Division, Vol. 117, Nº 8.

Sell, L. E., 1971, "Hydroelastic Power Plant Trashrack Design", Journal of the Power division Proceeding of the American Society of Civil Engineers, Vol. 63, pp.115-121.

Yang, Y. R. and Zhang, J. Y., 1997, “Frequency Analysis of a Parallel Flat Plate-Type Structure in still Water, Part II: A Complex Structure”, Journal of Sound and Vibration, Vol. 203, Nº. 5, pp. 805-814.
Zhou, D. and Cheung, Y. K., 2000, “Vibration of Vertical Rectangular Plate in Contact With Water on One Side”, Earthquake Engineering and Structural Dynamics, Vol.29, pp.693-710.
Zienkiewicz, O. C., 1979, “The Finite element Method”, McGraw-Hill Book Company.