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Damage of hydroelectric power plant trash-racks due to fluid-dynamic exciting frequencies

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Abstract

This work is concerned with damages of trash-racks of hydroelectric power plants excited by the flow passing around them, and with the analysis of virtual mass effect on the natural frequencies and mode shapes of the trash-racks. A model for simulation of the flow passing through a big trash-rack regarding the effect of its obstruction due to aquatic plants accumulation is presented. The vortex shedding frequencies has been determined for several operating conditions. A finite element model has also been developed for analysis of the modal characteristics of the trash-rack. The fluid-structure interaction effect or hydroelastic vibration structure has been included in this model and the modal characteristics have been determined regarding the structure immersed in water and in air. Furthermore, the natural frequencies and vortex shedding frequency approaches have indicated that the trash-rack damages are probably due to operating at resonant conditions.

Keywords: trash-rack, hydroelectric machine, modeling, fluid-structure, flow simulation

1 Introduction

The trash-rack structures of the hydroelectric turbines have the purpose of restricting the entrance of materials of considerable dimensions together water, which can cause damages to the generating machine, particularly to the pre-distributor, distributor, spiral casing and runner turbine itself. These structures are exposed to variable excitation forces acting superimposed to the static force forming a complex dynamic system. This complexity is due to fluid and structure coupling, which is referred as fluid-structure interaction problem. Furthermore, 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 electrical distribution system. In view of this, the water flow rate varies and can induce dangerous fluid dynamic conditions, damaging the trash-rack; the second one is the excessive accumulation of materials onto the trash-rack. In this case, besides provoking adverse fluid dynamic conditions, the accumulated materials impose some restriction in the production due to load loss of the machine, as well as the overloads

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that are unavoidably induced on the trash-rack. Since the trash-racks are often not designed for those overloads, sometimes the damage occurs even before the load loss to be noticed by the production. In critical situations, the trash-rack gets 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 (mainly the *Egerla Densa)* onto the trash-racks of runner turbines is becoming worse in some hydroelectric companies of Brazil due to 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 ideal conditions for its proliferation during the summer period. In view of this, a lot of trash-rack damage problems have been appearing due to fluid-structure interaction, so 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 aspect ratios, [2, 10, 11, 21, 22], and the authors have demonstrated 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. Moreover, there are several works concerned specifically about the design and fluid-structure interaction of trash-rack, [7, 13–15, 18].

Normally, the structures or apparatus are constituted by groups of profiles as, for instances, transmission towers, offshore platforms, chimneys, tubes in heat exchangers, trash-racks, etc. The aerodynamic characteristic analyses of those groups have had high importance in the field of engineering, since they can create destructive aerodynamic effects. According to [20] the fluid-dynamic forces behavior acting upon a group of structures, as well as the pattern of vortex shedding, are very different from the structures analyzed separately. The flow behavior passing through structural profiles with rectangular cross-section is affected by a variety of factors or influence parameters. Among the more analyzed parameters it can be mentioned the incidence angle, aspect ratio and blockage ratio.

In the flow around rectangular cross-section structures there is a formation of vortex along the lateral faces, where the wake behavior depends on the Reynolds number and of the aspect ratio. The authors [16] carried out a numerical study of flow around rectangular cross-section cylinders with aspect ratios between 3 and 9 and Reynolds number equal to one thousand. The results have indicated that the flow is characterized by shedding, separation and re-attachment of the shearing layer on both lateral surfaces. Also, similar results have been experimentally obtained of patterns flow on lateral surfaces of rectangular cross-section cylinders using several aspect ratios and Reynolds number equal to 400, [12].

Simulations with groups of parallel structures of rectangular cross-section and different gaps have also been accomplished [9]. The authors used the DNS (Direct Numerical Simulation) technique with flow velocity of 0.29 m/s and using different blockage ratios. Their results show that vortex shedding happens in an independent manner on each body for higher blockage ratios. Moreover they observed a certain synchronized time for emission of the vortex. However, when the blockage ratio decreases, for instance to 1.5, the wake of vortex changes completely and there is interference of the flow around a bar on the other one.

This work presents an analysis of a real trash-rack structure focusing on the behavior of the flow downstream of the structure to determine the exciting frequencies at several operating conditions. For model simplification and domain definition the parameters such as aspect ratio and blockage ratio have been taking into account. The modal characteristics were also analyzed through a finite element model including the fluid-structure on the free vibration of the trash-rack. In this particular structure it has been noticed high probability of operating at resonant condition, since the exciting frequency of shedding vortex can become coincident or close to of one natural frequency of the structure.

2 Geometric description of the analyzed trash-rack

In this section the geometric characteristics of the analyzed trash-rack will be described. A sketch of one part of the whole trash-rack structure is shown in Figure 1. This trash-rack belongs to a big hydroelectric power plant in Brazil, in which serious problem of failure in the trash-racks happens during the summer period caused by the excessive accumulation of aquatic plants onto them. Fourteen generating machines driven by Kaplan turbines compose this hydroelectric power plant. The installed power capacity of the plant is 1411.2 MW, and each generating machine has rated power of 100.8 MW, nominal flow rate of 511 m^3/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 that case the operating 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 entrance of water, which are part of the system to supply water to the turbine. In the entrance of each mouth there is a metallic grid structure (trash-rack), which constitutes the protection part of the whole supply water system. The entire trash-rack measures 12.150 m wide by 21.975 m 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 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, which has grid form measuring 2.40 m wide by 4.37 m high. It is composed basically by twenty rectangular cross-section beams of 0.152.4 x 0.0143 m disposed vertically and by five horizontal round rods measuring 0.038 m in diameter. The trash-rack is made of steel material. Individual panels are screwed to the concrete piers in eight symmetrical points placed at the upper and lower ends of four vertical beams, as indicated in Figure 1.

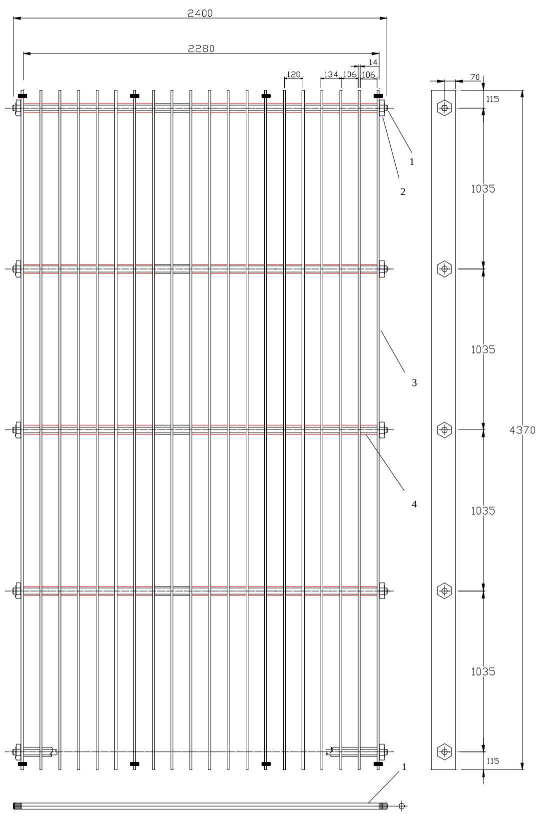


Figure 1: Sketch of an individual rack structure, which is part of the whole turbine trash-rack

3 Flow modeling

Up to some years ago, the main available tool for analyzing the motion of fluids around rigid bodies was the experimentation. However, more recently there was a considerable scientific and technological progress in computer science and numerical methods applied to fluid flows which allowed changes in that scenery, creating conditions for the development of advanced software for flow simulation, which can be considered equivalent in importance to the experimental methods, in terms of problem solutions and contribution to scientific progresses of this knowledge area. Nowadays, the numerical simulation and the experimentation are widely used in practical problems of the engineering, involving turbulent flows.

Turbulent flow is characterized by the presence of non-stabilities and non-periodic oscillations of velocity, pressure, temperature and density of the fluid, which depend on the time and of their position in the space. Another factor that can also characterize the turbulent flows is the multiplicity of scales of the wake structures, where the largest structures are directly related to the low frequencies of fluctuations, and are strongly controlled by the geometry of the contours of the flow. The smallest structures are related to the high frequencies of fluctuations and are more controlled by the viscosity of the fluid.

A flow with high Reynolds number, due to high value of velocity, induces wake structures of small-scale, which in magnitude order are smaller than the characteristic dimensions of the problem (boundary). Hence, the numerical simulations of that flow type are normally carried out employing models whose meshes of numerical discretization are extremely small to assure that every scale of the wake structures are appropriately represented. If the model is intended to accurately predict the flow behavior and to analyze turbulent flow in details, it is important adopting simulation of large eddies through the three-dimensional solution of filtered Navier-Stokes equations, while the smallest structures must be modeled using sub-grid-scales models, [4].

In this section a numerical simulation of the flow passing through the trash-rack of a big turbine will be presented. The main goal of this analysis is determining the frequency of vortex emission for several operating conditions under which the trash-rack is submitted due to aquatic plants accumulation and the change of flow velocity.

3.1 Representative flow equations

The laminar or turbulent incompressible fluid flow can be mathematically represented by the mass conservation and momentum equations (Navier-Stokes equations). The solution of these equations can be obtained for a set of initial and boundary conditions. In the complete form, these equations are non-linear and their analytical solutions are very complex and have difficult convergence, [8]. The incompressible water flow through the trash-rack is turbulent and a direct numerical simulation is not practical for the engineering purpose of this work, so the flow was computed using LES – Large Eddy Simulation, with the large eddies being computed and the smallest eddies being modeled, [19]. This modeling introduces the filter concept, [17]. Considering the hypothesis of incompressible flow and that in practical situation the length of trash-rack's components is very long compared with its width and thickness, the flow was considered as two-dimensional. Then, the filtered governing equations of motion are in rectangular coordinates as follow:

the continuity equation,

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = 0 \tag{1}$$

the momentum equations,

$$\frac{\partial \bar{u}}{\partial t} + \frac{\partial (\bar{u}\,\bar{u})}{\partial x} + \frac{\partial (\bar{v}\,\bar{u})}{\partial y} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x} + \frac{\partial}{\partial x}\left(\nu\frac{\partial \bar{u}}{\partial x} - \tau_{xx}\right) + \frac{\partial}{\partial y}\left[\nu\frac{\partial \bar{u}}{\partial y} - \tau_{xy}\right] \tag{2}$$

$$\frac{\partial \bar{v}}{\partial t} + \frac{\partial (\bar{u}\,\bar{v})}{\partial x} + \frac{\partial (v\,\bar{v})}{\partial y} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial y} + \frac{\partial}{\partial x}\left[\nu\frac{\partial \bar{v}}{\partial x} - \tau_{yx}\right] + \frac{\partial}{\partial y}\left(\nu\frac{\partial \bar{v}}{\partial y} - \tau_{yy}\right) \tag{3}$$

where the sub-grid-scale (SGS) stresses,

$$\tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j = L_{ij} + C_{ij} + R_{ij} \tag{4}$$

must be modeled. In the Eq. (4), $L_{ij} = \overline{\bar{u}_i\bar{u}_j} - \bar{u}_i\bar{u}_j$ are the Leonard stresses; $C_{ij} = \overline{\bar{u}_i u'_j} + \overline{u'_i\bar{u}_j}$ are the cross terms and $R_{ij} = \overline{u'_i u'_j}$ are the SGS Reynolds stresses. Based on the work [1], the Leonard plus the cross terms are modeled as,

$$L_{ij} + C_{ij} \cong \frac{\Delta_k}{12}\frac{\partial \bar{u}_i}{\partial x_k}\frac{\partial \bar{u}_j}{\partial x_k} \tag{5}$$

and the Reynolds SGS stresses are modeled using the Smagorinsky eddy viscosity as,

$$R_{ij} = \frac{2}{3}k\delta_{ij} - 2\nu_t S_{ij} \tag{6}$$

where the eddy viscosity is defined as,

$$\nu_t = (C_s\Delta)^2 \left|\bar{S}\right| \tag{7}$$

in which C_s is the Smagorinsky constant, $\Delta = (\Delta_x\Delta_y\Delta_z)^{1/3}$ is the filter width, $\left|\bar{S}\right| = \sqrt{\bar{S}_{ij}\bar{S}_{ij}}$ and the deformation rate tensor is $\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$.

A model based on the finite volume method has been employed for simulation of the water flow through the trash-rack. The domain was meshed by control volume and the equations were discretized in the space and time. The system of equations resulting from the discretization was solved in a segregated way, in which each equation of momentum is solved alone and sequentially.

3.2 Domain for flow simulation

For analysis of the incident flow through the panel a two-dimensional domain has been defined regarding only a part of the panel, as indicated in Figure 2. This defined domain can be appropriated to reproduce the flow behavior with satisfactory accuracy based on the geometric dimensions of bodies in the flow. It allows the development of a relatively simple reduced two-dimensional model that could precisely describe the involved phenomena. The simplified model to a two-dimensional domain doesn't reduce its accuracy since the length of the vertical bars of the system is significantly larger than the dimensions that determine their cross-section. Another interesting factor to highlight is that the simplified model allows accomplishing less expensive simulations in terms of time for data processing. This time would be definitively larger with a more detailed model.

The dimensions of the two-dimensional domain are indicated in Figure 3. That rectangular domain possesses total length X in the flow direction and width Y in the perpendicular flow direction. Xe denotes the distance from the entrance of the domain to the attack edge of structure, and Xd denotes the distance from the escape edge to the exit of the domain. The Xe and Xd values were taken in way to guarantee that the inherent flow phenomena could be observed perfectly, i.e., in way to allow the analysis of the formation and visualization of vortex shedding even beyond the developed wakes. On the other hand, the dimension Y has

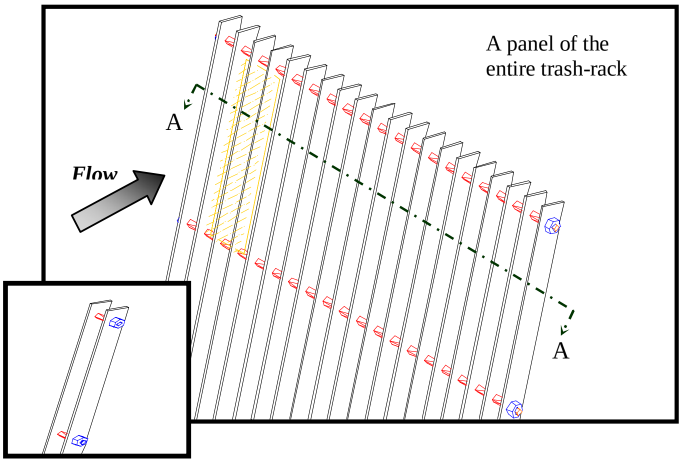


Figure 2: Marked area on the panel for definition of flow domain

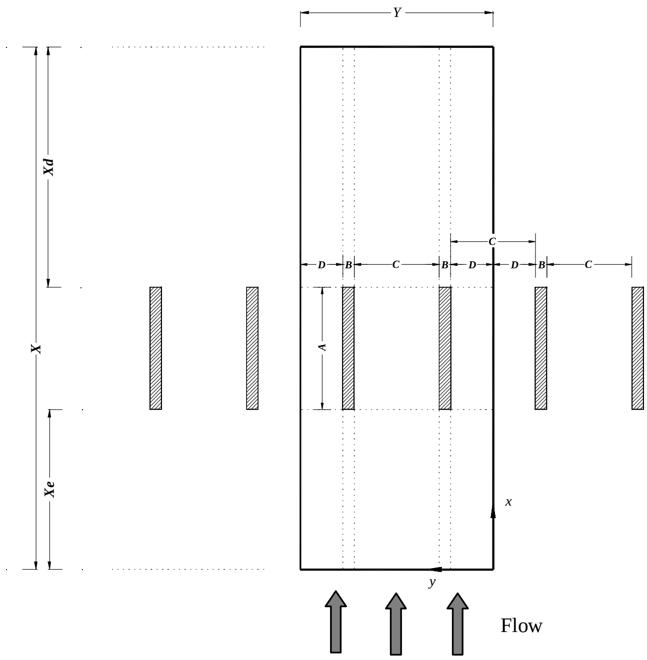
been strategically defined to impose symmetrical boundary condition at the lateral faces of the domain.

It is important to stand out that the Strouhal number, and consequently, the frequency of vortex shedding are not strongly sensitive with respect to the variations of the Xe and Xd domain dimensions, [1]. Moreover, there isn't a well-defined rule to take these parameters and, in general, the experience or preliminary simulations should be used to adopt them.

3.3 Initial and boundary conditions

To establish the initial and boundary conditions used for simulation of the flow through the panel let's consider the flow velocity component u in the main flow direction and the flow velocity component v in the perpendicular direction (corresponding to the x and y axes in Figure 3, respectively). For boundary condition at the entrance of the domain a uniform velocity profile is prescribed, with $u = U_\infty$ and $v = 0$. On the other hand, the prescription of the boundary condition at the exit is normally a little more complicated because the flow pattern in that region practically is not known. A very used boundary condition at the exit is taking a null gradient for the u variable, maintaining the v variable null, equivalent in admitting that the flow at this border of the domain is already completely developed. In fact, this condition should only be admitted if the exit border of the domain is located at a considerable distance of the body on which the fluid is passing.

The model has been developed considering only a part of the panel, and the domain has been taken at a position in which the lateral borders have acquired a condition of symmetry. Thus, that symmetry has allowed taking the conditions $v = 0$ and $\partial u/\partial y = 0$ for the lateral contours of the domain.



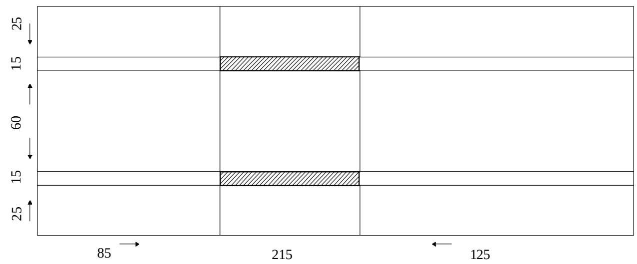
Parameter	Dimension (mm)
X	652.4
Y	240.6
Xe	200.0
Xd	300.0
A	154.2
B	14.3
C	106.0
D	53.0

Figure 3: Basic dimensions of the domain for modeling (cut A-A view on the Figure 2)

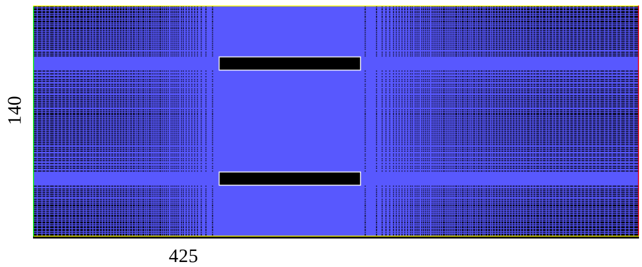
3.4 Discretization procedure of the model

A turbulent flow is more significantly affected by the presence of a wall than a laminar flow. In a turbulent flow the viscous effects close to the wall have a strong influence on the fluctuations of tangential velocity, reducing the gradients at the areas close to the walls. On the other hand, out of these areas, the turbulence is rapidly increased by the action of the turbulent kinetic energy. Therefore, in the numeric simulations to precisely capture those nuances, i.e., to capture the appreciable differences of the flow behavior at different areas of the domain, it is indispensable to use meshes quite refined for the model at the areas close to the walls.

Figure 4 shows the discretization meshes developed for the model. As it can be seen, it has been taken a discretization with moderate and non-uniform resolution, which is refined at the proximities of the solid structures. In Figure 4(a), the shown arrows indicate the direction in which the concentration of meshes increases inside of a certain area, and the numerals indicate the amount of parts in which this area was divided for the meshes definition. Concisely, there are well-defined areas with different concentrations of meshes, and inside of each one of those areas the concentration increases with the approach to the rigid bodies. Figure 4(b) illustrates the whole discretization mesh of the model, in which the clearest areas indicate that there is a greater concentration of meshes.



(a)



(b)

Figure 4: (a) Number of meshes for each defined area; (b) Representation of meshes concentration

4 Flow simulation results

The fundamental aim of the flow simulation is determining the frequencies of vortex shedding that appear at exit edges of the trash-rack induced by the passage of the water that moves the hydraulic turbine. That simulation, in dynamic terms, can point out dangerous operating conditions for the structural integrity of the trash-rack, for instance, operations at resonant conditions.

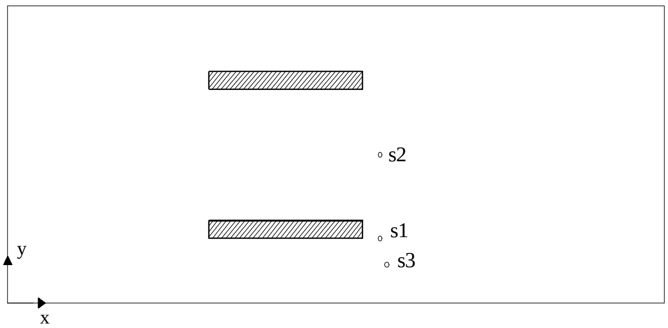
The operating conditions of a hydraulic turbine trash-rack can vary due to two basic factors: the hydroelectric machine operation in partial loads to compensate the change of daily demand of energy in the distribution system, and the excessive accumulation of aquatic plants onto the trash-rack. The operations in partial loads happen with smaller flow rate than the design flow rate (nominal), and consequently, with smaller fluid velocities going by the trash-rack. On the other hand, admitting that the machine maintains constant its generation power, the excessive accumulation of aquatic plants onto the trash-rack induces an increase in the water velocity due to reduction of the water passage section area.

In this analysis it is admitted that occur a simultaneous and uniform accumulation of aquatic plants onto the structure. The amount of aquatic plants accumulated will be represented by a percentage of obstruction of the water passage area, which will change the average value of the flow velocity. Hence, it has been taking discrete hypothetical cases seeking to simulate several operating conditions of the trash-rack. Table 1 presents the following parameters for the considered cases: average flow velocity, Reynolds number and obstruction ratio. Case 1 represents the design operating condition of the machine, i.e., operating with nominal power and without the presence of any plant accumulation onto the trash-rack. In the other cases it has been considered a certain percentage of obstruction due to plant accumulation. The probability of obstructions more than 40% is very small and it is known that if an obstruction of that magnitude happens, the machine should probably stop due to severe load loss.

Table 1: Considered operating conditions for analysis

Cases	Obstruction (%)	Average Flow Velocity (m/s)	Reynolds Number
Case 1	0	1.000	14300
Case 2	10	1.0630	15200
Case 3	20	1.1918	17042
Case 4	30	1.3675	19555
Case 5	40	1.5949	22807
Case 6	50	1.9139	27368

The theoretical frequencies of vortex shedding were obtained through numerical sensors implemented in the developed model. The numerical sensors are capable of registering the amplitude of the velocity component in the y direction with the time, at predetermined position within of the defined domain of the flow. In this work were implemented three sensors (s1, s2 and s3), which were positioned at different points within the domain, as shown in Figure 5, trying to make sure the positions that could provide the best data regarding the dynamic of the vortex emission.



Sensor	***x coordinate (mm)***	***y coordinate (mm)***
s1	370.00	53.00
s2	370.00	120.30
s3	373.85	31.55

Figure 5: Numerical sensors positions within the domain

The three sensors have produced, in some way, data about the frequency of vortex shedding when the water goes by the structure. However, the best results were obtained through the sensor s3. The sensor s2 is very far from the effects produced by the vortex shedding, predominating consequently, a typical noise signal. The signal of the sensor s1 is very contaminated by undesirable noises produced by the re-circulation of the fluid at the exit border of the structure and due to composition of the vortexes formed at both sides of the structure.

Figure 6 shows the image of the wake of vortexes shedding formed downstream of the body at a given computational time, representing the isovorticity lines for the case 5, with Reynolds number Re = 22807. It can be observed that due to high value of the aspect ratio (10.8), there is a tendency of forming vortex at the lateral surfaces of the structure, which is in agreement with the experimental work [12], respecting, of course, the appreciable difference in the Reynolds number of both cases. Also, it can be verified that, in spite of the high Reynolds number, there is no visible interaction among the wakes leaving each structural profiles due to high value of the blockage ratio (7.4), which is in agreement with results presented in the literature, for instance, by [9].

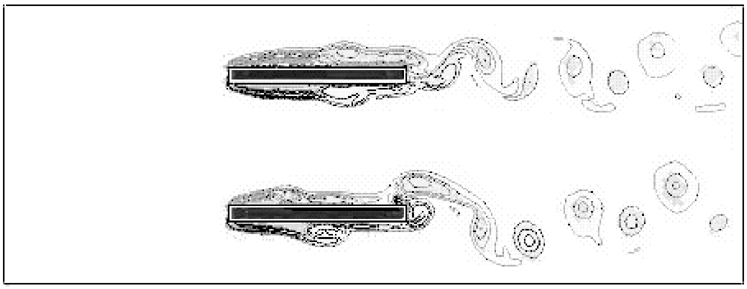


Figure 6: Isovorticity lines observed for the case 5, time = 6.3 s

Figure 7 shows the signals of velocity in the y direction obtained through the numerical sensor s3 placed in the wake of vortexes downstream of structure, as well as the amplitude spectra of those signals for the cases 1, 3 and 5. The signals of the other cases follow the same pattern. The charts show the periodic characteristic of the signals. That periodic characteristic confirms the regular and alternated behavior of shedding vortex emission. The spectra present a peack of amplitude well-defined at frequency of vortex shedding from the lateral surface of the structure, and it is the exciting frequency under which the trash-rack is submitted. Moreover, it is observed small amplitude acting at double frequency of the first one, which actually is the response to the coupling effect of emission of vortexes on both sides of the structure. Table 2 presents the frequencies of vortex shedding for each analyzed case.

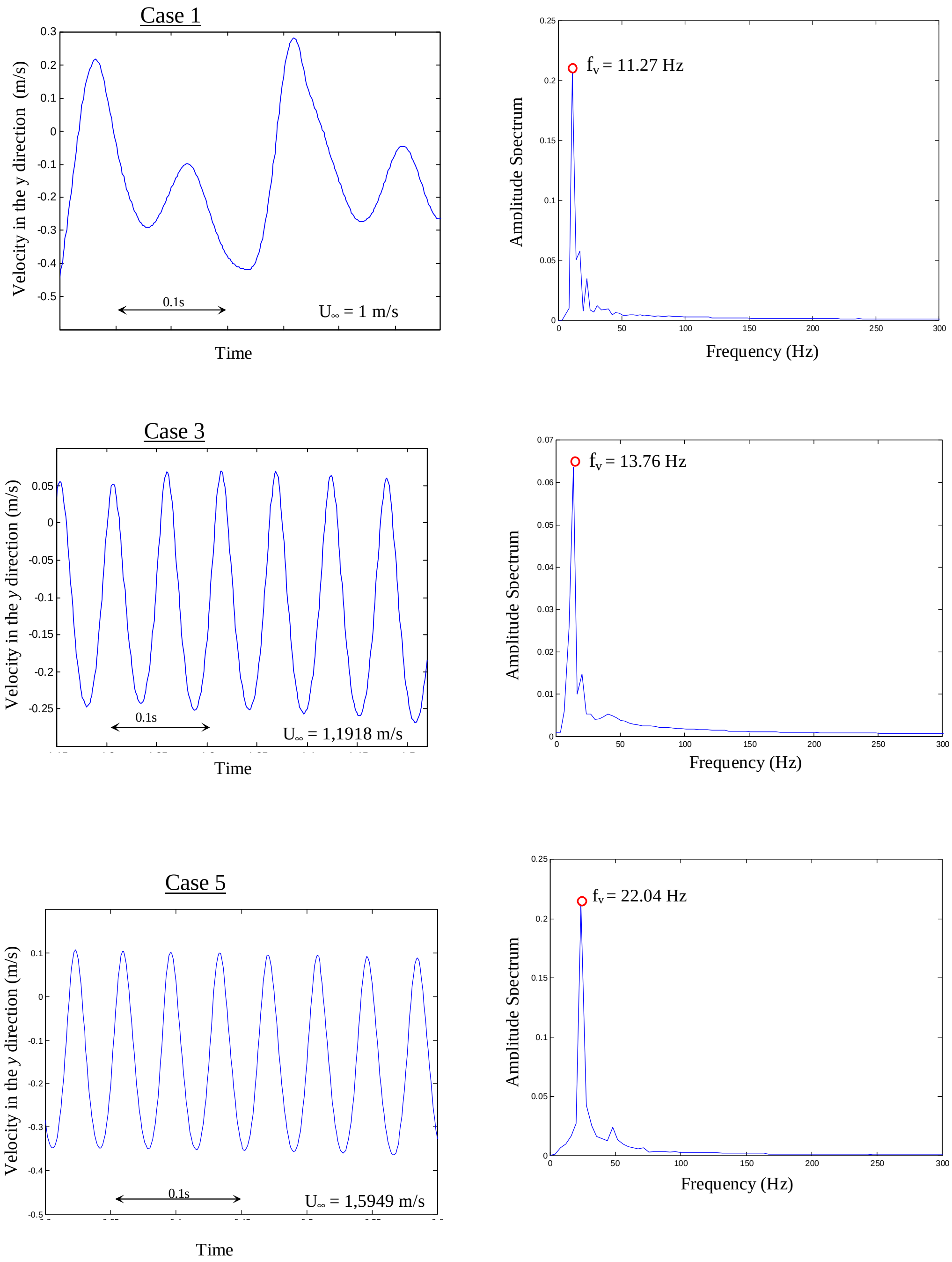


Figure 7: Signals of flow velocity in the y direction and amplitude spectrum for the cases 1, 3 and 5

Table 2: Frequencies of vortex shedding

Cases	Obstruction (%)	Average Flow Velocity (m/s)	Vortex Frequency (Hz)
Case 1	0	1.000	11.27
Case 2	10	1.0630	12.67
Case 3	20	1.1918	13.72
Case 4	30	1.3675	16.13
Case 5	40	1.5949	22.04
Case 6	50	1.9139	25.19

5 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,

$$x = X_0 sen\omega t \tag{8}$$

and the velocity and acceleration of the system can be derived from Eq. (8) as,

$$\dot{x} = X_0 \omega \cos \omega t \tag{9}$$

$$\ddot{x} = -X_0 \omega^2 sen\omega t \tag{10}$$

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

$$F = \sum_{i=1}^{N} (a_i seni\omega\, t + b_i \cos i\omega\, t) \tag{11}$$

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. (11) are neglected then the force acting on the structure is reduced to,

$$F = a_1 sen\omega\, t + b_1 \cos \omega\, t \tag{12}$$

Comparing the terms of the fluid force in Eq. (12) with the terms of the acceleration and velocity of the structure represented by Eqs. (10) and (9) 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,

$$F = -A_{xx}\ddot{x} - B_{xx}\dot{x} \tag{13}$$

$$A_{xx} = \frac{a_1}{X_o\omega^2}, \quad B_{xx} = -\frac{b_1}{X_o\omega} \tag{14}$$

The coefficient A_{xx} refers 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 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 damping induced by the water, [6]. Considering a single degree of freedom system submerged in water, the motion equation can be given by,

$$m\ddot{x} + c\dot{x} + kx = F \tag{15}$$

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. Inserting the Eq. (13) into Eq. (15) the free vibration of the system can be given by,

$$(m + A_{xx})\ddot{x} + (c + B_{xx})\dot{x} + kx = 0 \tag{16}$$

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 added and the free motion equation will be given in the matrix form as,

$$([M] + [A])\{\ddot{x}\} + ([C] + [B])\{\dot{x}\} + [K]\{x\} = 0 \tag{17}$$

If the structure has certain symmetries and the beams and rods have constant cross-sections, then it will not be so difficulty to introduce the effect of the added mass and damping in the structure model. The $[A]$ and $[B]$ matrices contain the added mass and damping coefficients due to 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. (17) by 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 dynamic analysis of a structure can be estimated through the ratio between the fluid density surrounding the structure and the average density of the structure. The effect of the surrounding fluid in natural frequencies and modes shapes is not significant in relatively compact structures if the fluid density is much smaller than to average density of the structure. Thus, it can be said that the air that surrounds most of 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 for petroleum extraction, ships and submersed pipes.

In the last years several studies were accomplished with 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 [5], where it was gathered a vast literature about theoretical and experimental works on the subject and presents the values of added masses for a variety of geometries of different aspect ratios, for two and three-dimensional cases.

6 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 trash-rack. The vertical beams and horizontal rods, as shown in Figure 1, were modeled by the finite element method as 3D elastic elements. This element allows tension, compression, torsion and flexural efforts and it is possible attributing 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 regarding the added mass effect can be given by,

$$\left[\bar{M}\right]^{e} = \rho AL\left[M\right]^{e} + A_{xx}L\left[M\right]_{x}^{e} + A_{yy}L\left[M\right]_{y}^{e} + A_{zz}L\left[M\right]_{z}^{e} \tag{18}$$

where $[M]^e$ is the structural mass matrix of the element, $[M]_x^e$, $[M]_y^e$ and $[M]_z^e$ are the added mass matrices, ρ is the mass per unit of volume of the structural element, 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 symmetrical mass matrices $[M]^e$of one finite element have the form,

$$[M]^e = \begin{bmatrix}
1/3 & & & & & & & & & & & \\
0 & A_z & & & & & & & & & & \\
0 & 0 & A_y & & & & & & & & & \\
0 & 0 & 0 & J_x/3A & & & & & & & & \\
0 & 0 & -C_y & 0 & E_y & & & & & & & \\
0 & C_z & 0 & 0 & 0 & E_z & & & & & & \\
1/6 & 0 & 0 & 0 & 0 & 0 & 1/3 & & & & & \\
0 & B_z & 0 & 0 & 0 & D_z & 0 & A_z & & & & \\
0 & 0 & B_y & 0 & -D_y & 0 & 0 & 0 & A_y & & & \\
0 & 0 & 0 & J_x/6A & 0 & 0 & 0 & 0 & 0 & J_x/3A & & \\
0 & 0 & D_y & 0 & F_y & 0 & 0 & 0 & C_y & 0 & E_y & \\
0 & -D_z & 0 & 0 & 0 & F_z & 0 & -C_z & 0 & 0 & 0 & E_z
\end{bmatrix} \tag{19}$$

where,

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

$$D_{y,z} = \left[\frac{13}{420} - \frac{1}{10}\left(\frac{r_{y,z}}{L}\right)^2\right] L \quad ; \quad E_{y,z} = \left[\frac{1}{105} + \frac{2}{15}\left(\frac{r_{y,z}}{L}\right)^2\right] L^2 \tag{20}$$

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

The added mass matrices are then obtained using part of the structural mass matrix of the element. The $[M]_x^e$ matrix is obtained by taking the elements of the rows and columns 1, 4, 7 and 10 from the mass matrix, Eq. (19), and regarding the other elements equals to zero. In the similar way, the $[M]_y^e$ matrix is given by taking the elements of the rows and columns 2, 6, 8 and 12 from the mass matrix and making the other elements equal to zero. Finally, the $[M]_z^e$ matrix is obtained by taking the rows and columns 3, 5, 9 and 11 from the mass matrix preserving the other elements equals to zero.

The individual rack shown in Figure 1 was modeled using 393 finite elements, 288 elements for vertical beams and 105 elements for 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 trash-rack presented in this work has just been limited to the lower order natural frequencies and mode shapes, which could be excited by fluid dynamic forces that appear due to water passing through the trash-rack. The modal characteristics of the panel have been determined neglecting the damping. Of course, the natural frequencies and mode shapes vary lightly as 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 analyzing the results of the simulation without damping. Moreover, 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.

7 Modal characteristics approach

In this section the dynamic analysis performed on the structure, Figure 1, will be presented showing how much the effect of added mass influences the natural frequencies of the trash-rack. Table 3 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 regarding the added mass effect were about 30% smaller than the frequencies considering the panel vibrating freely in the air. Hence, this has confirmed the considerable importance of introducing the additional mass effect in the model of the submerged structures like the trash-rack, since the differences between the natural frequencies of both conditions are notably high.

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, [2,21], 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 onto the panel at low frequencies, as shown in section 4.

Table 3: Natural frequencies of the trash-rack with and without added mass

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 8 shows the mode shapes of the lower order natural frequencies of the trash-rack 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 immersion. Actually, it has already been verified experimentally that the mode shapes are very close or are practically the same ones under the influence of the water, [3,10].

It can be seen that the relative modal displacements of the mode shapes presented in Figure 8 happen at perpendicular direction with respect to the stream flow direction, since the flexibility of the structure is higher in that plan of the panel. It is important to remind that is also in the perpendicular direction that the alternate excitation forces act on the structure as a result of the vortexes shedding induced by the water passing through the vertical beams. Normally, these alternate forces happen at low frequencies, so they 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 mainstream flow.

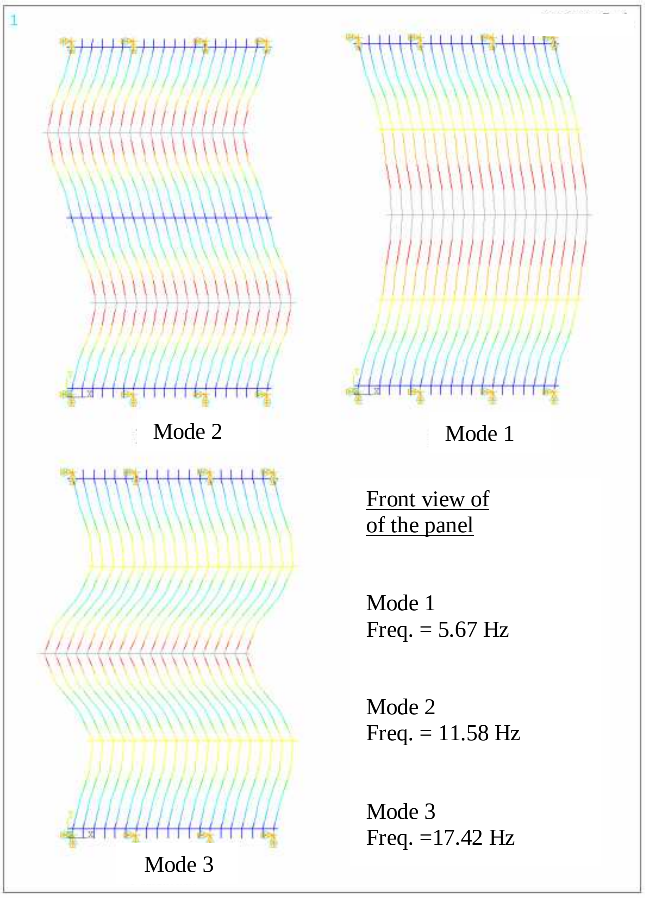


Figure 8: Mode shapes of an individual rack regarding the added mass effect

8 Natural frequencies and exciting frequencies approach

The main objective in analyzing the hydroelastic vibration in conjunction with the analysis of the flow behavior going by the trash-rack has been verifying if occur operations at resonant conditions. The natural frequencies of the structure obtained in the previous section, Table 3, should be compared with the exciting frequencies due to vortexes shedding obtained in the section 4, Table 2. Table 4 relates the conditions on which the natural frequencies of the structure are close to the exciting frequencies due to vortex shedding. These operating conditions can be dangerous and usually induce severe vibration levels, putting in risk the safety and the structural integrity of the trash-rack.

Table 4: Frequencies of vortexes shedding and natural frequencies comparison

Frequencies of vortexes shedding (Hz) - Flow Simulation Model		*Natural frequencies of the trash-rack (Hz) - Element Finite Model*	
Cases 1, 2 and 3	11.27, 12.67, 13.76	11.58	2^{nd} mode
Case 4	16.13	17.42 / 17.94	3^{rd} and 4^{th} modes
Case 5	22.04	22.74	5^{th} mode
Case 6	25.19	29.00	6^{th} mode

It is very difficulty to foresee and dynamically analyze all operating conditions in which the trash-rack can be submitted. The velocity of the water going by the structure can be significantly different in each position of the trash-rack, mainly at the regions close to the walls. Moreover, the obstruction due to plant accumulation cannot happen in a uniform way on the whole trash-rack, inducing areas with different water velocities. However, in analyzing some discreet conditions as presented in Table 4, it is verified that there is a high probability of happening operations at resonant conditions, which certainly have been contributing to the trash-rack damages.

The comparison shown in Table 4 reveals that even with very little plant accumulation (cases 1, 2 and 3 of the flow simulations), i.e., for an obstruction up to 20%, the probability of the 2nd vibration mode to be excited is very high, indicating a certain dynamic vulnerability of the trash-rack. Also, the 3rd and 4th vibration modes are feasible to be excited with approximately 30% of trash-rack obstruction (case 4 of flow simulation). Furthermore, frequency approaches has been verified even for modes of superior order. In view of this, it is possible that the damages are happening due the appearance of fluid-dynamic exciting forces at resonant frequencies acting upon the trash-rack. Of course, the trash-rack will also be submitted to the static effort due to aquatic plant accumulation.

9 Final remarks

There are a lot of problems associated with trash-rack failure in hydroelectric power plants. The trash-racks are subject to the most varied operating conditions because of the wide range of fluid velocities that it would normally be subjected, and to get reliable simulated results the models are normally very complex. The operating conditions of the trash-rack can vary because, in general, the daily demand of electric energy is not constant, and the hydroelectric machines frequently operate in partial loads. Another problem that occurs in some hydroelectric power plants of Brazil is the excessive accumulation of aquatic plant onto the trash-rack, changing its operating condition completely. A simplified model for flow simulation of a big trash-rack has been developed. It has been taken some discrete operating conditions regarding the effect of trash-rack obstruction due to aquatic plants accumulation. The result of that simulation indicates that the obstruction of the trash-rack alters the behavior of the flow significantly, imposing a wide range of variation of the frequency of vortexes shedding, increasing the probability of operation at resonant conditions.

To get a theoretical approach of the modal characteristics of the trash-rack, a model by finite element method has been developed. A simplified fluid-structure interaction modeling has been included due to submersion effect. It has been confirmed the effective needs to introduce the added mass effect in the trash-rack model due to submersion, so that the simulation of the modal characteristics became more reliable. The fluid-structure interaction approach employed in this work can be easily incorporated to the model of finite elements. The results obtained 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 trash-rack are about 30% smaller than the values of the natural frequencies of a non-submerged trash-rack, i.e., in air. Moreover, it has been verified that the added mass practically doesn't modify the mode shapes of the trash-rack.

The comparison among natural frequencies and exciting frequencies due to vortexes shedding indicates that the damages are probably consequences of the fluid-dynamic exciting forces acting at resonant frequencies, which impose severe operating conditions on the trash-rack.

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