XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Increasing the Overall Efficiency of Hydro Power Plants by Using Virtual Prototyping in the Design of High-Performance Hydromechanical Assets

Rodrigo C. Quadros[1], Lucas G. Fonçatti[1]

[1]*Mechanical Systems Area, Institutes of Technology for Development - Lactec*
Comendador Franco Ave., 1341, Jardim Botânico. Curitiba, 80215-090, Paraná, Brazil
rodrigo.quadros@lactec.org.br, lucas.foncatti@lactec.org.br

Abstract. Intake racks play a very important role in the prevention of accidents and premature failures in Hydroelectric Power Plants. As a primary function, the racks act as filters, preventing the passage of large particulates and debris to the hydraulic turbine. However, intake rack designs, historically, do not take into account extensive analysis, and there are many cases of failures in these structures, which despite appearing simple, require adjustments to the actual operating conditions, in addition to the operational complexity of these devices. Thus, the use of novel techniques, virtual prototyping focused on numerical simulations of CFD (computational fluid dynamics), FEA (finite element analysis) and FSI (fluid structure interaction), allows the development of optimized designs for these assets. In conjunction, the use of FEA allows the evaluation of the new intake rack geometry considering, through FSI coupling, the dynamic pressure exerted in each specific region of the component, and no longer average values as used by standard but for the entire component, allowing a more global and assertive view of the mechanical stresses induced by its operation.

Keywords: Virtual Prototyping, Numerical Simulations, Design Optimization.

1 Introduction

Hydroelectric power generation assets play a fundamental role in the Brazilian energy matrix, with the majority of its generation coming from this source. There are 218 hydroelectric power plants currently in operation, which add up to 103 gigawatts (GW) of installed power, or 56.31% of the country's total energy production capacity (at the date 2022, May). Several are the components that are designed and influence the operational performance of a hydropower. A chronic problem, which affects many of these enterprises, are failures in intake racks (trash racks) - by obstruction or even rupture due to high mechanical stress - which lead to pressure losses and frequent need for maintenance or even replacement of these components.

The use of intake rack panels at the water intake of a HPP (Hydroelectric Power Plant) or SHPP (Small Hydroelectric Power Plant) is primarily intended to protect the hydraulic turbine from potentially hazardous debris that is present in river courses and dam reservoirs. Water intake rack structures have been in use for many decades; however, the time taken to design and adapt these structures to the actual operating conditions of a power plant is not always in line with actual need. With this, there are potential risks that a structure that has as its main objective the protection of the turbine in the course of debris, can present failures, and the failed part can be sucked into the penstock of the intake and cause extensive damage to the structure and the driving set (turbines and other parts), in cases of accidents.

Based on this assumption, the correct design of structures for intake rack panels shows that, besides being essential items for the safety of the operation, they should also have the least possible obstruction, in order to maximize the generation efficiency, minimizing the head losses right at the beginning of the penstock.

During the preparation of several works and case study evaluations, among which we cite "Recovery and New Design of the GJR HPP Gratings" (*Recuperação e Novo Projeto de Grades para UHE GJR*) and "Instrumentation and Monitoring of Water Intake Gratings for the GJR HPP" (*Instrumentação e Monitoramento* *das Grades de Tomada d'Água de UHE GJR*), both carried out in partnership with Copel Geração e Transmissão S.A (COPEL GET). The possible causes of failure of the structures of the intake rack panels of the GJR HPP (Governador José Richa Hydroelectric Power Plant) were surveyed, as shown in Fig. 1, where characteristic failures of the racks are presented. Historically, since its construction, the plant has presented repeated failure problems in the panels of UG-04 (generating unit number 04). In order to mitigate such failures, studies were conducted on the operational conditions of the adduction region of this UG in the GJR HPP. Through the results obtained from the original panel designs in relation to fluid dynamic and structural simulations, structural improvements were proposed with the objective of reducing the number of failures, adapting the original design and maintaining the geometric characteristics to allow the correct installation. Throughout this paper, several other studies will be presented, demonstrating the possible improvements and gains from a structural design linked to the understanding of the existing flow in the intake rack panels, with the use of virtual prototyping tools for the assessment of HPPs and SHPPs.

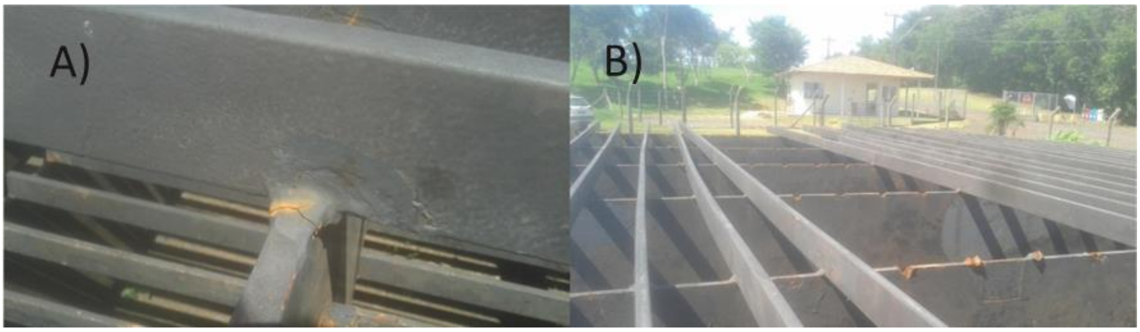

Figure 1. A) Pass-through crack between the front vertical bars and the rack panel tray; B) Failure caused by cracks, with subsequent removal of the vertical bars.

In addition to the approach of structural analysis of the structures, the use of virtual prototyping also presents the viewpoint of design optimization for new grating structures for water intake. Whether it is optimization from the point of view of withstanding the various loads imposed on the structure, it also occurs from the point of view of reducing the area obstructed by the panels and consequently reducing the head loss.

2 Virtual Prototyping

The water intake rack models presented in this work contemplate a wide range of work done in virtual prototyping themes for such structures. Among the analyses that will be addressed is the fluid dynamic analysis of the water flow in the reservoir of the HPP/SHPP that passes through the intake grids. This behavior of the fluid flow from the reservoir to the penstock, flowing through the grating panels, allows the analysis of the vortex induced frequencies of the various component parts of the intake racks, as well as the dynamic pressure, under various load conditions, to which they are subjected. This type of study also aims to analyze the differential static pressure between upstream and downstream, in order to quantify the pressure drop generated by a given grating model and possible improvements (pressure drop reduction), in high performance models.

Along with the fluid dynamics section, there are also structural analyses performed in a virtualized environment. In this case, FEA-based simulations are conducted to evaluate, not exclusively, vibration modes, harmonic analysis, structural reliability, among others. The connection between the information obtained via CFD is essential for the preparation of FEA analyses. To this end, fluid-structure interaction (FSI) is performed.

2.1 CFD – Computational Fluid Dynamics

The CFD tool used in this study is ANSYS™ FLUENT®. To obtain the flow as close as possible to reality, bathymetry data for the proximity region of the reservoir to the intake grids are used in conjunction with the excavation data and construction project of the HPP/SHPP under analysis. The numerical model used was the finite volume model, using the RANS (Reynolds Average Navier-Stokes), k-ω SST transient formulation for the turbulence model, SIMPLE (Semi-Implicit Method for Pressure Linked Equations) pressure-velocity coupling and the use second order upwind models.

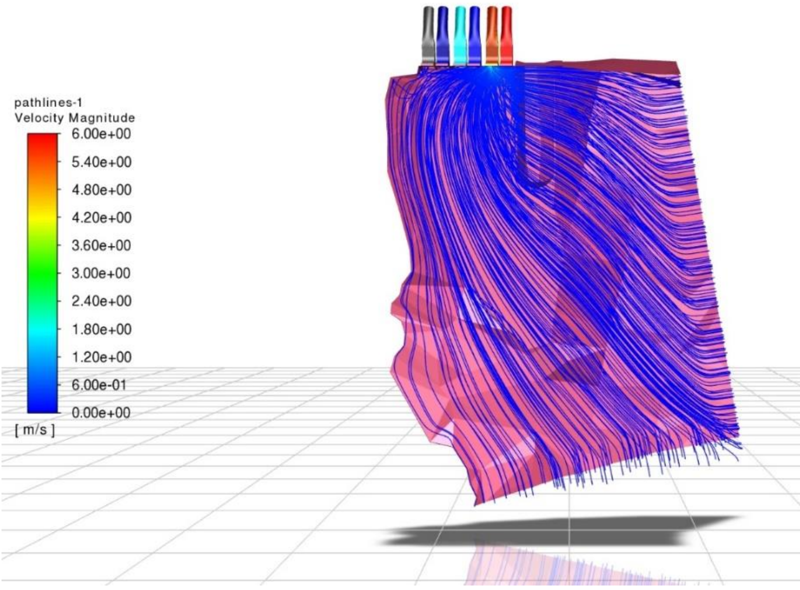

Figure 2. Geometry of a HPP reservoir and its velocity field, when operating with only 1 generating unit (GU).

Remark 1: Water flow in the reservoir. The flow analysis in the reservoir has the function of enabling the knowledge of the pressure and velocity fields that enable, in a second step, to know the static and dynamic pressures at each of the points of interest. These pressure fields are used to survey, not exclusive to: vorticity of the flow in proximity to the grate panels, velocity of approaching water on the grate panels, dynamic pressure subjected to the structure, static pressure upstream and downstream, among others. The flow in the reservoir can be seen in the Fig. 3, where a large vortex is observed in front of one of the generating units. This phenomenon occurs in the daily operation of HPP, and was not detected in the design phase and small scale tests.

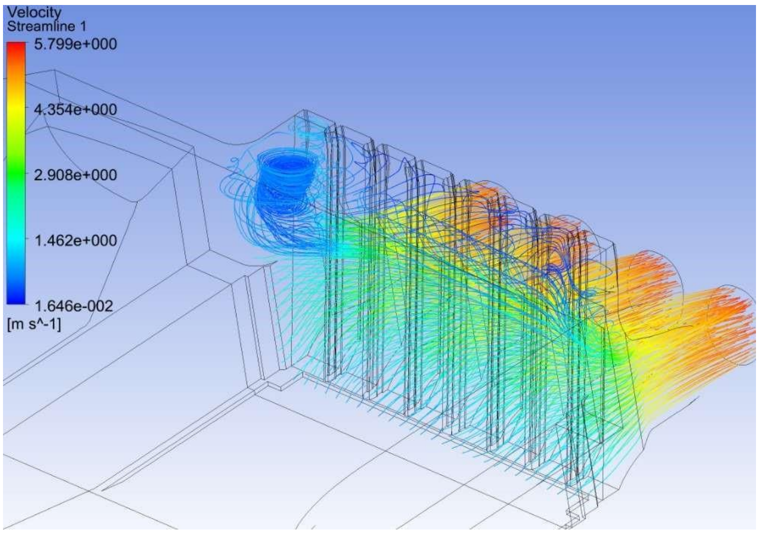

Figure 3. Streamlines (color map as a function of velocity) of water flowing through the grid panels to the penstock.

Remark 2: Vortex generation. The formation of a vortex shedding is reported, in several case studies, as one of the main causes of failure in panels of water intake gratings, in which, simplistically, the oscillation frequency of the flow, in a given operational condition, is similar to one of the natural frequencies of the structure. Figure 4 shows the characteristic frequencies that are obtained via analysis of the lift and drag forces, in time, by using the FFT (Fast Fourier Transform).

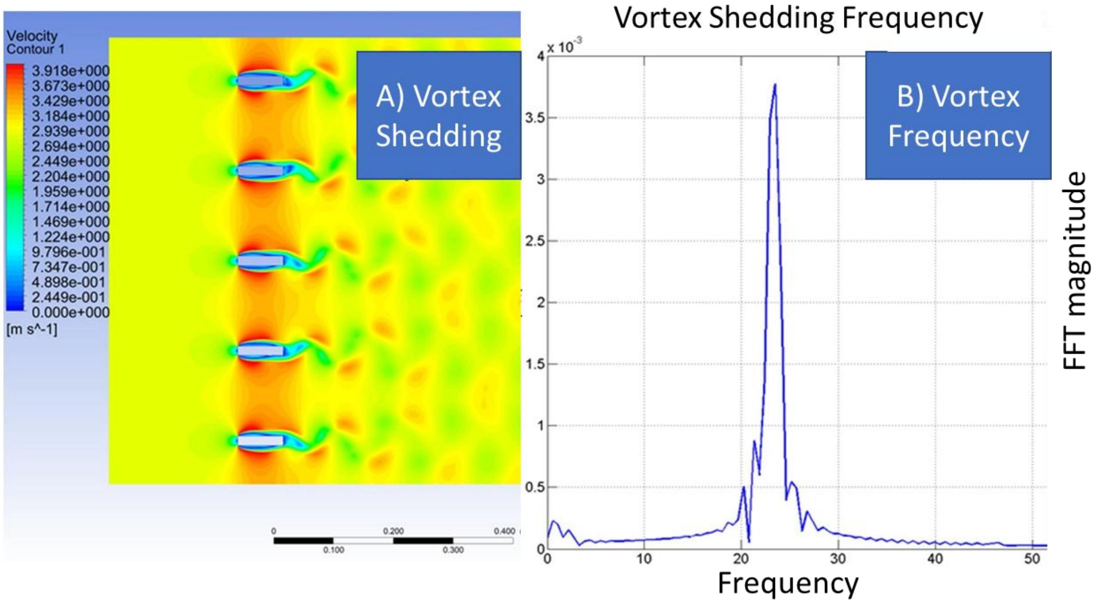

Figure 4. Velocity field (A) demonstrating the existence of alternating vortices and (B) the characteristic frequency of vortex shedding using FFT.

Remark 3: Static and Dynamic Pressures. Once the static and dynamic pressures are known, quantitative data can be inferred as the pressure differential in the upstream and downstream positions of the grid panels, through the difference in static pressure, analyzed at various and determined points. With the dynamic pressure, in each operational condition, it is possible to determine the total pressure to which the grid panel is subjected during operation of the generating unit, by transferring the pressure field on the surface of the grid panels between the fluid dynamic model and the structural model, using FSI (Fluid Structure Interaction) as shown in Fig. 5.

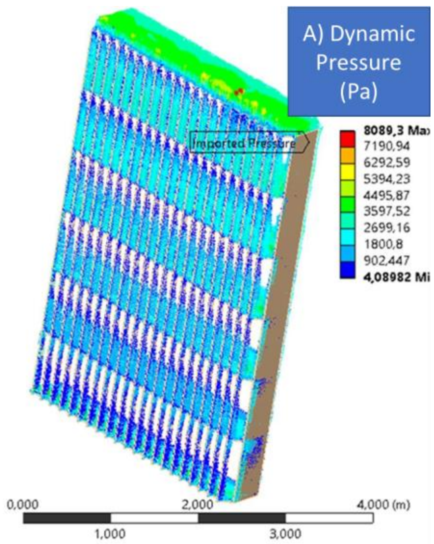

Figure 5. Dynamic pressure (Pa) passed to the structural model. Result obtained from CFD.

2.2 FEA – Finite Element Analysis

The finite element analysis (FEA) was chosen as a method to verify the structural conditions of the grate panels, including, but not limited to: modal and harmonic analysis, static and dynamic structural analysis, as a function of pressure fields, weight force from other panels and conditions. For such, the development of the virtual prototype of the grate panel structure, considered the use of adjacent panels, aiming to approximate the characterization of the support conditions (system boundary) as close as possible to the actual one.

Remark 1: Modal Analysis. The modal analysis of the grate panel structures has the objective of verifying the vibrating modes. The analyzed vibration modes are chosen by means of frequency limit criteria, defined as up to 60% above the maximum excitation frequency (by vortex), obtained empirically. Another assumption is that a criterion is defined in which there is a connection between the natural frequencies of the structure and the frequencies in an environment submerged in water. To this end, it will be considered that the existence of a volume of water around the grate panels reduces the natural frequency to a damped frequency with a value 60% of the natural frequency.

$$\left(Freq_{analysis}\right)_{máx} \leq Freq_{\text{vortex}} \cdot \frac{1+60\%}{60\%} \tag{1}$$

where "$Freq_{\text{analysis máx}}$" corresponds to the maximum frequency to be analysed and the "$Freq_{\text{vortex}}$" is the maximum frequency obtained via CFD for some intake rack part.

The value of 60% in the numerator of Eq. 1 corresponds to the safety factor of transmissibility curve and the value of 60% in the denominator refers to the 60% average attenuation for a rectangular profile immersed in water, relative to the modal natural frequency, as per Kůrečka and Habán [1], whose values obtained for different vibrating modes varied between 68% and 80%. For more complex profiles, these values can be lower. For studies focused on water intake gratings, this value reaches levels between 60% and 70%, according to Nascimento et al. [2]. The evaluation is performed for each of the directions (in the global coordinate system), and for these values to be representative, it is essential that the parameter Cumulative Effective Mass Fraction (CEMF) reaches a plateau of at least 80%, and that each analysis frequency reaches at least 1% of the ratio between the effective mass (of the vibration mode) in relation to the total mass of the structure. Such criteria are adopted for general structure analyses, according to Ahmad et al. [3], Jaen-Sola et al. [4], Arcuri [5], Priestley et al. [6], Martinez [7]. Figure 6 shows a plot with the frequencies of the vibrating modes and their contribution to the total effective mass of the structure.

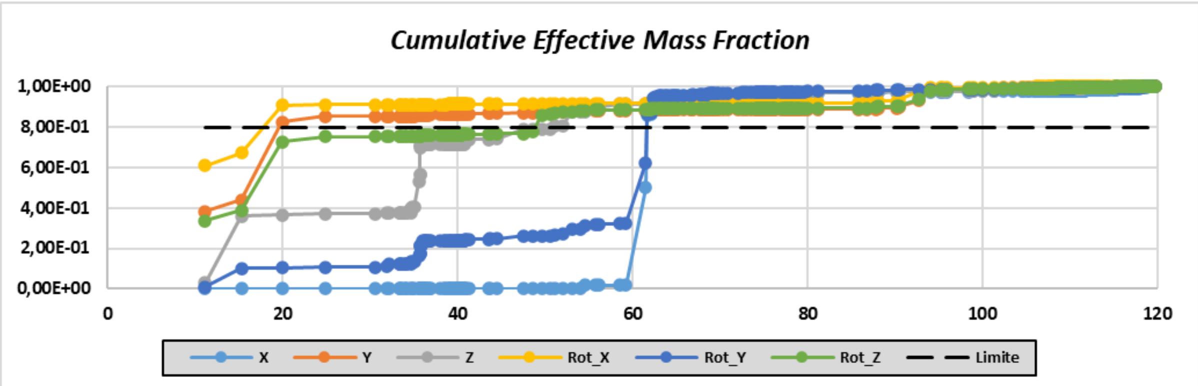

Figure 6. Plot summarizing the various natural frequencies of the structure (abscissa) and the ratio of the effective mass of each mode to the total mass of the structure (ordinate).

Remark 2: Structural and Harmonic Analysis. The structural analysis of the rack panel components also goes by the static and harmonic structural analysis of the equipment, being aware that the main efforts submitted to the rack panels during operation come from the contact between the panels, impacts, and by the oscillatory load generated by the water flow. An example of the structural analysis is shown in Fig. 7.

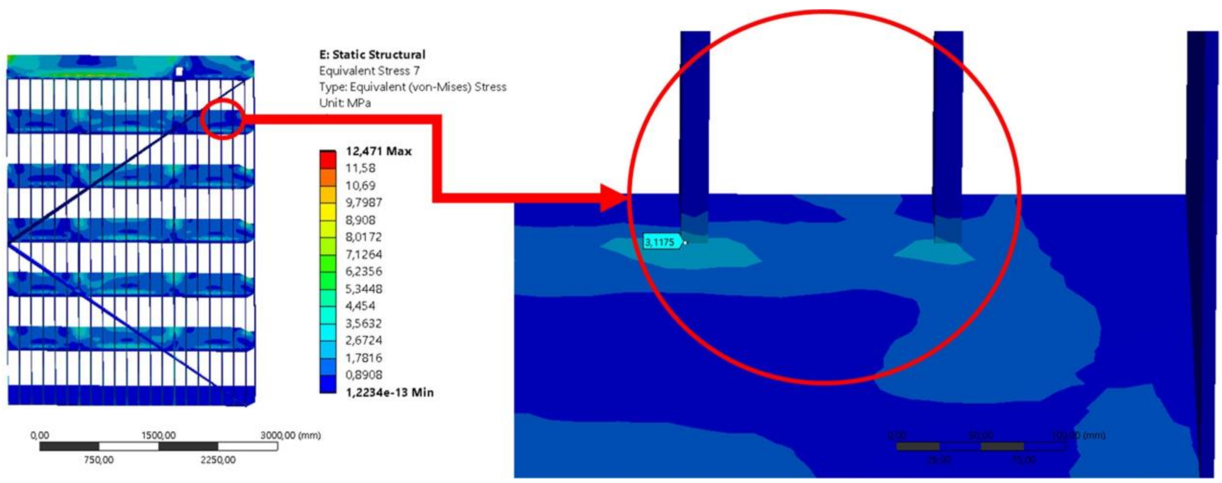

Figure 7. Result (mechanical stress) obtained by applying a weight force to the panel installed on the base plate. Partial result, prior to superposition with the stresses obtained by harmonic loading analysis.

Remark 3: Comparison with Eurocode 3. After obtaining the equivalent stress data (von Mises) for the grating panels, the results of the static and harmonic structural analysis are compared to their respective limits. For the first case, the material strength limit is evaluated (yielding stress), and for the second case, there is a comparison between the data obtained by the harmonic response and the maximum strength for the welded regions. When applied to low carbon steels, for an infinite fatigue life, the calculated numerical results are compared to the tabulated data by Eurocode 3 (EN 1993-1-9) [8]. For each type of welded joint there is a "Detail Category", to which constants are applied to obtain the Cut-off limit, that is used as the maximum allowable limit stress (disregarding safety factors) as shown in Fig. 8.

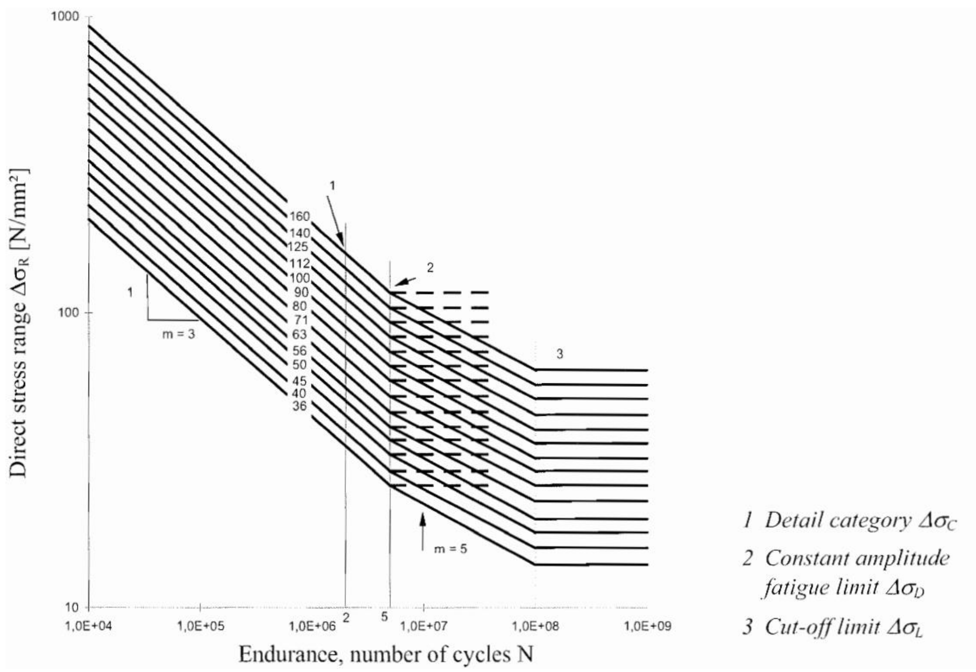

Figure 8. Direct stress range (MPa) as presented in Eurocode 3 for typical cases of welded joints.

3 Conclusions

Computational fluid dynamics simulations and finite element analysis can be used to evaluate the structural integrity of rack panels, as well as several other structures and assets for electric power generation. In this case study, it was demonstrated that the use of virtual prototyping, which uses computational fluid dynamics simulations (CFD) and finite element analysis (FEA), in an integration of results by fluid-structure interaction (FSI). The main steps for the definition of an integrity structural analysis of a water intake rack panel are presented, passing by the understanding of the flow to which a rack is subjected; and carrying out optimizations related to the minimization of the head loss. With the information of the pressure and velocity field, it is possible to relate them to the static and dynamic mechanical forces, through empirical modal analysis and numerical analysis, so that the maximum stresses obtained in the structures, for any operational conditions, can be assessed. These maximum stresses are compared with design codes and standards, verifying the service life and safety factors of such structures. Subsequently, instrumentations can be performed on the designed intake rack panels, so that validations of the virtual prototype can be made. Among the case studies analyzed, the maximum errors obtained from the virtual prototype were 5% for the flow velocity field, and 10% for the maximum mechanical stresses.

Acknowledgements. We thank the companies and teams of COPEL GeT and ENGIE for the extensive support in data collection, analysis, studies, design, and validation activities, which enabled the development of methodologies for validating the structural integrity of water intake grids, through data collection, virtual prototyping, and further field data validation.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] J. KŮREČKA and V. HABÁN. "Experimental and acoustic modal analysis of the submerged steel plate in water". *AIP Conference Proceedings*, v. 2000, p. 1–5, 2018.
[2] L. P. NASCIMENTO, J. B. C. SILVA and V. DI GIUNTA, "Damage of hydroelectric power plant trash-racks due to fluid-dynamic exciting frequencies". *Latin American Journal of Solids and Structures*, v. 3, n. 3, p. 223–243, 2006.
[3] M. S. AHMAD, M. JAMIL, J. IQBAL, "Modal analysis of ship's mast structure using effective mass participation factor". *Indian Journal of Science and Technology*, v. 9, n. 21, p. 1–5, 2016
[4] P. JAEN-SOLA, A. S. MCDONALD and E. OTERKUS, "Dynamic structural design of offshore direct-drive wind turbine electrical generators". *Ocean Engineering*, v. 161, p. 1–19, 2018.
[5] G. ARCURI, "Automatic Test Equipment structure's mass reduction through topology optimization processes", Master of Science Thesis, 2019.
[6] M. J. N. PRIESTLEY, F. SEIBLE, G. M. CALVI, "Seismic Design and Retrofit of Bridges". *Seismic Design and Retrofit of Bridges*, 1996.
[7] J. MARTÍNEZ, "Understanding the Mass Participation Factor". Available in: <https://engineerjau.wordpress.com /2013/05/11/understanding-the-mass-participation-factor/>
[8] EUROPEAN STANDARD, "Eurocode 3: Design of Steel Structures – Part 1-9: Fatigue", 2005.