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Analysis of the dynamic response of pump-turbine impellers. Influence of the rotor

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ABSTRACT

This paper deals with the dynamic response of pump-turbine impellers. A pump-turbine impeller is a complex structure attached to a rotor and rotating inside a casing full of water with very small clearances between the rotating and the stationary parts. The dynamic response of this type of structures is very complex and it is very much affected by the connection to the rotor as well as by the added mass and boundary conditions. As a consequence its calculation presents several uncertainties.

First, the dynamic response of pump-turbine impellers is introduced. Second an experimental investigation in a real impeller attached to the rotor and inside the machine was carried out. For this investigation, the impeller of an existing pump-turbine unit with an installed power of 110 MW and a diameter of 2.87 m was studied. For a better analysis of the experimental results a numerical model using FEM was also built-up. Frequencies and mode-shapes were identified numerically and experimentally and the characteristics of the structural response analyzed.

To determine the influence of the rotor and supporting structures on the impeller response the results were compared with the ones obtained with the same impeller but suspended (non-connected to the rotor). Experimental and numerical simulation were also used for this case. The changes in the dynamic response due to the rotor connection were determined.

Finally the results obtained are compared with the results from other pump-turbine impellers of different designs and general conclusions about the dynamics of this type of structures are given.

1. Introduction

With the increase of new renewables (wind, solar, and marine energy), pump-storage power plants are becoming more and more important for grid control. These power plants are used for the storage of the surplus of energy produced by other power plants when energy demand is low so that consumption and generation is always matched. The stored energy can be

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delivered again to the electrical grid when demand is high. The future of renewables is tied directly to pump-storage which is the most effective technology for the storage of large amounts of energy.

Pump-storage power plants use pump-turbines which are reversible machines that can be operated as a pump and as a turbine. The impeller of a pump-turbine is a complex structure, very stiff and rotating inside a casing full of water with very small clearances between the impeller and the casing. Under these conditions the dynamic response of the impeller is very complex because it is affected by the added mass and damping of water, by the rotor to which it is connected and by the proximity of the casing walls. The hydrodynamic added mass and damping effects modify the natural frequencies and mode-shapes. The effects of all these parameters on the natural frequencies should be known at design stage in order to avoid operation at resonance conditions which would generate excessive stresses and fatigue damage.

With the trends to increase power concentration (head per stage), the pressure fluctuation induced by the rotor–stator interaction during the operation of the machine is large resulting in large dynamic forces on the impeller. If resonance occurs, damage can appear in the impeller and in fact, damage in this type of impellers was reported by several authors [1–3]. To avoid this kind of problem, it is of paramount importance to have an accurate understanding of the dynamic response of the impeller, especially when it is submerged in water.

For a structure with a complex geometry, such as a hydraulic turbine impeller, there is a limited number of studies available, performed in Francis impellers in air and in water but with simplified boundary conditions [4]. Other publications have presented detailed experimental and numerical analysis considering the effect of surrounding mass of water [5–7] but in a reduced scale model and without taking into account the boundary conditions of the casing. Other publications about dynamic behavior in Francis turbines [8] do not give details about the impeller response.

A pump-turbine impeller has a quite different design than a Francis turbine impeller. There are even fewer references available for this type of impeller, especially for a prototype. Some results in reduced-scale models and prototypes are available in air and water but without casing [9,10]. The frequency response of prototype impellers is shown in [11] but no details about the influence of boundary conditions are indicated. A reference publication in this field [12] gives a general view on the dynamic behavior of a prototype impeller but the impeller response shown is only in air. Detailed measurements of the dynamic response of pump-turbine impellers with real mounting conditions (connected to the rotor and inside the casing) have never been published.

In this paper the dynamic response of actual pump-turbine impellers is investigated. After introducing the general characteristics of a impeller response, an experimental investigation is carried out with the impeller in real mounting conditions, connected to the rotor and inside the casing. To determine the influence of the rotor connection the natural frequencies and mode-shapes obtained are compared with the ones of the same impeller but suspended (without the influence of the rotor). Numerical models were built-up and the numerical results were compared with the experimental data. In the paper a comprehensive analysis of the impeller dynamic characteristics is indicated showing the evolution of natural frequencies and mode-shapes. Finally the results are compared with the results obtained in other impellers and general conclusions are given. The paper is limited to the dynamic response of the impeller and the shaft response is not included. Rotating effects are not included either.

2. Dynamics of a pump-turbine impeller

2.1. Modal behavior of disk-like structures

The vibration modes of a cyclic symmetric structure can be classified according to the numbers of harmonic index (k), nodal diameters (N_D) and nodal circles (N_C). The harmonic index (k) is an integer that determines the variation in the value of a single degree of freedom (DOF) at points spaced at a circumferential angle equal to the sector angle. The following equation represents the relationship between the harmonic index k and nodal diameter N_D for a model consisting of N sectors

$$k = \begin{cases} N/2, & N \text{ is even number} \\ (N-1)/2, & N \text{ is odd number} \end{cases} \tag{1}$$

$$N_d = mN \pm k; m = 0, 1, 2, 3\ldots\infty. \tag{2}$$

$$\phi = \pi/(2d) \tag{3}$$

Defined by the condition $k=0$, the modes are singlet. These modes are independent of the angular coordinate θ. The modes with $k \neq 0$ are doublet; they have a pair of mode shapes with the same natural frequency. Each member of such a pair has either sinusoidal or cosinusoidal θ-dependent mode shape. The only difference between them is a spatial phase shift of ϕ. Another parameter is the nodal circle N_c that represents the number of circles with zero out-of-plane displacement in the structure [13,14].

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