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On the detection of natural frequencies and mode shapes of submerged rotating disk-like structures from the casing

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ABSTRACT

To avoid resonance problems in rotating turbomachinery components such as impellers, it is of paramount importance to determine the natural frequencies of these parts when they are under operation. Nevertheless, most of these rotating structures are inaccessible and in some cases submerged and confined. To measure the natural frequencies of submerged impellers from the rotating frame is complicated, because sensors have to be well fixed, withstand with large pressure and centrifugal forces. Furthermore, the signals have to be transmitted to the stationary frame. For this reason it may be advantageous to measure the natural frequencies with sensors placed on the casing.

In this paper, the analysis of rotating disk-like structures submerged and confined has been performed from the stationary frame. Previously, an analytical model to determine the natural frequencies and mode shapes of the disk from the rotating frame is presented. Once natural frequencies and mode shapes are obtained in the rotating frame, the transmission to the stationary frame has been deduced.

A rotating disk test rig has been used for the experimental study. It consist of a rotating disk that has been excited from the rotating frame with a piezoelectric patch and it response has been measured from both rotating and stationary frame. Results shows that for rotating submerged structures in heavy fluids such as water, not only the structural modes of the rotating part are different than for rotating structures in air, but also the transmission from the rotating to the stationary frame.

1. Introduction

The vibration of rotating disk-like structures has been studied extensively in the last years due to their relevance in real engineering applications such as circular saws, cutters, hard disks or turbomachinery components. Particularly in hydraulic turbomachinery, some types of runners are disk-like structures which are submerged and confined rotating in water. When they are in operation the interaction between the stationary guide vanes and rotating blades produces an excitation (rotor stator interaction) that may causes resonance problems which lead to fatigue damages or critical failures on the rotating

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structure [1–5]. The similarity between the mode shapes of runners and disks, especially for the first modes of vibration, has been commented in many studies [1–10]. Particularly, the first modes of some kind of hydraulic runners are characterized by the number of nodal diameters, which characterize also the mode shapes of a simple disk.

Many studies deal with the topic of rotating disk-like structures, rotating in air [11–18]. The effect of rotation in the dynamic behavior of the disk was first studied by Lamb and Southwell [11]. Campbell [12] introduced the term critical speed, at which a standing wave appears on the disk. Southwell [13] studied the vibration of circular disks clamped at its center, which is in practice, the most used configuration. Later researches, studied more complex structures such as bladed disks [14,15]. In [14] Ewins compared the stress levels of a perfect bladed disk and a mistuned bladed disk under operation. El-Bayoumy and Srinivasan [15] studied the stress levels of turbine and compressor blades of mistuned bladed structures. Newer studies [16–18] determined other effects using numerical simulation. In [16] Heo and Chung studied the effect of misalignment in the natural frequencies of the disk. Bauer and Eidel [17] studied the effect of the attachment to the stationary part. Pust and Pesek [18] studied a bladed disk with imperfections. All these researches give a good knowledge of different effects that are relevant for the dynamic response of rotating disks, nevertheless these studies did not consider the interaction of the disk with the surrounding media.

The surrounding fluid has a relevant effect on the natural frequencies of the structure if its density is high, because the added mass effect. The added mass effect of water in static structures that are surrounded by water has been studied in many cases [19–22]. Lamb [19] studied the added mass effect of water in the vibration of a thin plate. Recently, Kwak in [20] and Amabili and Kwak in [21] reviewed the problem of Lamb, emphasizing the added virtual mass incremental factors (AVMI) for each mode of the disk. Some studies have been also performed where the disk is totally confined, for example [22,23]. Although the added mass effect of water is well characterized in these studies for static structures, the effect of a rotating structure that induces a relative motion between the structure and the surrounding fluid is not studied in these cases.

The study of rotating disks submerged in water or water that rotates with respect to the disk has been considered in few cases [3,24,25]. Kubota and Ohashi [3] provided an analytical model for a stationary disk and water that rotates with respect to the disk. Nevertheless, no experimental results were given. Hengstler [24] provide experimental results for a submerged and confined disk, with rotating water on the lower surface. In both cases, the water was rotating with respect to the disk, but the disk was standing. Only Presas et al. in [25] studied a disk that is forced to rotate inside a tank full of water. Nevertheless the analysis of the natural frequencies was performed from the rotating frame.

Analyzing the problem from the stationary frame can be advantageous in case of real turbomachines. In this case, rotating parts are usually inaccessible and in hydraulic turbomachinery, also submerged. Furthermore, sensors installed on the rotating frame have to withstand with high centrifugal forces and pressure fluctuations and the signals have to be transmitted to the stationary frame. For all these reasons, it could be easier to install sensors on the casing (stationary frame) to detect natural frequencies and mode shapes of the rotating frame. Nevertheless, the frequency content of the signals acquired from the stationary frame is more difficult to be interpreted, due to the difference within measured (rotating) and instrumentation frame (stationary).

For disks that rotate in air, the correlation between natural frequencies in the rotating frame and in the stationary frame is well known. This relation depends on the rotating speed of the impeller and also on the mode shape as deduced mathematically and proven experimentally in [26,27]. Nevertheless, no experimental or analytical studies have been found with the measurement of the natural frequencies of submerged rotating disks in water from the stationary frame (casing).

In this paper the detection of the natural frequencies and mode shapes of a submerged rotating disk-like structure from the stationary frame is studied in detail. First, this transmission is studied analytically. The natural frequencies of a submerged and rotating disk are determined from the stationary reference frame. To analyze the transmission experimentally a rotating disk test rig has been used. It consists of a disk that is excited from the rotating frame with a piezoelectric patch and its response measured from the rotating and stationary frame simultaneously. Therefore, measurements on the rotating and on the stationary frame have been compared and all the conclusions of the analytical model have been validated with experimental results.

2. Analytical model

2.1. Natural frequencies and mode shapes of a rotating disk considering the surrounding fluid

The model developed by Kubota [3] is used to study the natural frequencies and mode shapes of a rotating disk considering the surrounding fluid. In this paper, this model has been particularized for a totally confined disk (Fig. 1).

As shown in Fig. 1 cylindrical coordinates are used to describe the problem. The disk rotates at a constant speed Ω_{disk} with respect to the stationary frame. This induces a motion of the surrounding fluid, which has an average speed Ω_{fluid}, with respect to the stationary frame. Both are positive definite in the direction shown in Fig. 1. Therefore the following relations can be deduced for the angular coordinate θ:

$$\begin{cases} \theta_{disk} = \theta_{casing} + \Omega_{disk} \times t \\ \theta_{fluid-up} = \theta_{casing} + \Omega_{fluid-up} \times t \\ \theta_{fluid-down} = \theta_{casing} + \Omega_{fluid-down} \times t \\ \Omega_{fluid/disk} = \Omega_{disk} - \Omega_{fluid} \end{cases} \tag{1}$$