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INFLUENCE OF NON-RIGID SURFACES ON THE DYNAMIC RESPONSE OF A SUBMERGED AND CONFINED DISK

David VALENTIN*

Center for Industrial Diagnostics and Fluid Dynamics, Universitat Politècnica Catalunya (UPC), Barcelona, Spain.

Alex PRESAS

Center for Industrial Diagnostics and Fluid Dynamics, Universitat Politècnica Catalunya (UPC), Barcelona, Spain.

Eduard EGUSQUIZA

Center for Industrial Diagnostics and Fluid Dynamics, Universitat Politècnica Catalunya (UPC), Barcelona, Spain.

Carme VALERO

Center for Industrial Diagnostics and Fluid Dynamics, Universitat Politècnica Catalunya (UPC), Barcelona, Spain.

ABSTRACT

Determining the dynamic response of submerged and confined disk-like structures is of interest in the hydraulic turbines field. Disks present similar dynamic characteristics than hydraulic turbine runners, especially in the mode-shapes associated with each natural frequency. The dynamic response of submerged structures is heavily affected by the added mass and damping as well as the proximity of solid boundaries. In all studies the solid boundaries are commonly considered completely rigid, however in real cases this is not always true. This fact occurs in some hydraulic turbines where the casing is not completely stiff and it may have some dynamic response in the frequency range of the runner, which may affect its dynamic behavior.

To determine the influence of the casing stiffness on a vibrating disk submerged in water an experimental investigation has been carried out. A test rig consisting of a disk attached to a shaft inside a cylindrical tank closed with two different covers with different stiffness has been built up. The disk was impacted using a hammer and both disk and covers responses were measured with different accelerometers. Pressure sensors mounted on the covers have also been used. Natural frequencies of the disk have been obtained, compared and discussed for different disk to cover distances.

KEYWORDS

Added mass, natural frequency, non-rigid surface, dynamic response.

* *Corresponding author:* Center for Industrial Diagnostics and Fluid Dynamics, Universitat Politècnica Catalunya (UPC), Barcelona, Spain., phone: +34 934011738, email: david.valentin@mf.upc.edu

1. INTRODUCTION

Disks have been used in previous investigations to study the dynamic behavior of submerged structures. When a structure is submerged in a heavy fluid, such as water, its dynamic behavior drastically change in comparison with that in vacuum or in air. This dynamic behavior is commonly studied by analyzing the natural frequencies and damping ratio of each associated mode of vibration. Current analytical studies of natural frequencies and damping ratio of submerged structures are based on the added mass [1-3] and damping effect [4, 5]. The effect on natural frequencies of a submerged structure is the same as considering and additional mass. Therefore, the natural frequencies of submerged structures are lower than the natural frequencies of the same structure in air or in vacuum. The added mass theory also explains that the natural frequencies of submerged structures close to a rigid surface tend to decrease when the distance to this rigid surface also decreases [5-8]. Moreover, it is demonstrated that an added damping appears when the structure is submerged in water and this is even more important when nearby rigid surfaces are considered [4, 9, 10].

However, the case of a submerged structure that is close to another vibrating structure is not studied. Actually, only some studies with two identical disks coupled by a fluid are found [11-13], but in these papers the authors assume that both disks vibrate at the same natural frequency with the same mode-shape. This is not completely realistic in the case of hydraulic turbines, where the runner is a disk-like structure submerged in water and confined with other nearby structures, such as the head cover or the lower cover (see Fig. 1).

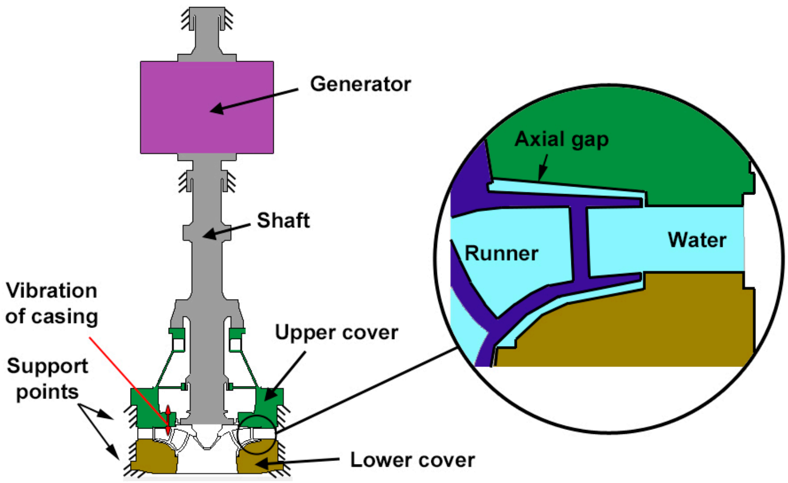

Fig. 1. *Runner nearby structures in a pump-turbine.*

Head covers of hydraulic turbines are structures that can vibrate at the same time than the runner if they are not very stiff. This fact could alter the expected dynamic behaviour of the whole machine and especially of the runner. In these machines, the axial and radial gaps of the runner and the covers are rather small, less than 3 or 4 millimetres in most of the cases. These boundaries are usually modelled as rigid surfaces in the numerical models used for the natural frequencies estimation as Jacquet-Richardet and Dal-Ferro [14], Lais, Liang, Henggeler, Weiss, Escaler and Egusquiza [15] and Hübner, Seidel and Roth [16] confirmed in their studies, hence the vibration of nearby structures is usually neglected.

To evaluate the influence of non-completely nearby rigid surfaces on a submerged structure, a test rig has been built up. This test rig consists of a stainless steel disk attached to a shaft and confined inside an aluminium tank closed with two different covers. These covers have different thickness and so different mass and stiffness, resulting in different natural frequencies. Disk natural frequencies and damping ratios have been estimated experimentally for different distances to both covers. Accelerometers and pressure sensors installed on the disk and casings have been used. Moreover, structural-acoustical numerical simulations are performed and compared with experimental results.

2. EXPERIMENTAL INVESTIGATION

2.1 Test rig description

The test rig used in the present work comprises a stainless steel disk coupled to a shaft and confined with water in an aluminum tank (see Fig. 2). This aluminum tank is closed using two different covers, one thin with natural frequencies in the same range than the disk, and the other cover used is thick with natural frequencies separated with those ones of the disk. Both covers are made of the same aluminum than the tank. The tank has a large thickness and mass to simulate rigid surfaces around the disk. The disk can be moved up and down along the shaft in order to evaluate the influence of the nearby rigid bottom surface (H_2) and the influence of the distance between disk and cover (H_1). Between the disk and the tank there is a small radial gap (G) (0.35±0.05 mm). The radial gap is selected as 0.35 in order to represent the same order of magnitude that there is in a hydraulic turbine runner against its radius $\left(\frac{G}{R_D} \approx 10^{-3}\right)$. The influence of this radial gap was evaluated in previous works [4, 5].

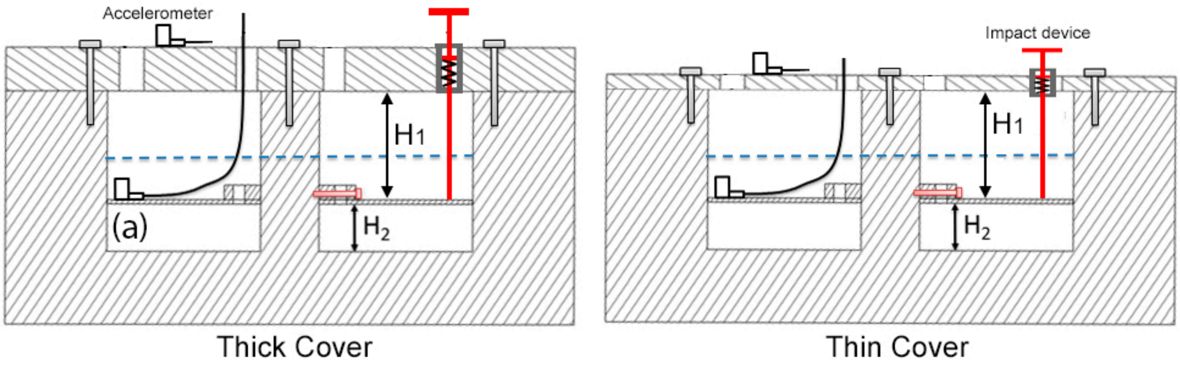

Fig. 2. *Test rig cross section.*

2.2 Instrumentation

The natural frequencies and mode-shapes of the disk and cover were determined making use of experimental modal analysis (EMA). The force over the structure was applied using an instrumented hammer (Kistler 9722, 2.25 mV/N). For the natural frequencies estimation of the cover, impacts were applied directly over the cover surface, however, to calculate the natural frequencies of the disk, this was impacted using an impact device based on a bar coupled to a spring (see Fig. 2). The response of both structures due to the impact excitation was measured using submersible accelerometers (Dytran 3006A, 100 mV/g). Two of these accelerometers were installed on the disk separated 90 degrees and another two in the same position but in the cover. Moreover, two pressure sensors (Kistler RAG50A20BC) were installed on the cover to measure the pressure variations due to the disk vibration. Signals of hammer, accelerometers and pressure sensors were computed and monitored using an acquisition system (Brüel & Kjaer Type 3036-B-120).

2.3 Procedure

As a first stage, natural frequencies of the disk and cover were estimated in the air. The frequency response function (FRF), which is the ratio between the vibration and the force that produces that vibration, was computed to perform EMA. The average of 5 different impacts was selected to perform the FRF of each accelerometer. FRFs were computed using the commercial software PULSE Reflex® [17] from Brüel & Kjaer. A frequency range of 0-3200 Hz and a frequency resolution of 0.25 Hz was selected to calculate FRFs.

The procedure when the disk was in water was practically the same than in air. In this case, two pressure sensors separated 90 degress were also available also during these impacts. This procedure was repeated for different positions of the disk along the shaft and for the two different covers. Moreover, both covers were impacted also for each configuration tested to evaluate their dynamic response.

3. RESULTS

3.1 Mode-shapes

The mode-shapes of a disk are defined with its number of number of nodal diameters (n) and nodal circles (m) [18]. Fig. 3 shows the natural frequencies and mode-shapes found within the frequency band studied in air and in water for the configuration where the added mass effect has less influence (H_1=47 mm and H_2=60 mm). This is the configuration where natural frequencies are more similar for both covers. It is appreciated that natural frequencies decrease in water in comparison with those in the vacuum, while damping is higher in the case of water.

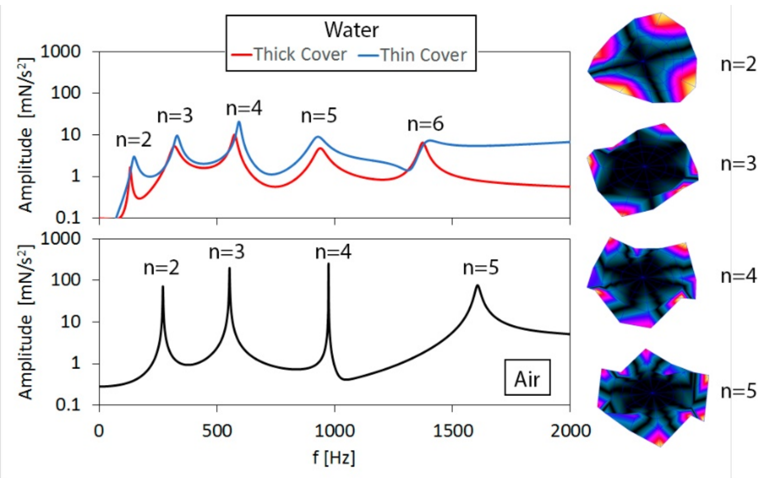

Fig. 3. *Disk mode-shapes.*

The mode-shapes of the cover are rather similar to those of the disk, having the difference that the cover is a circular plate clamped in its exterior diameter, therefore mode-shapes are more focused on the center of the structure [18]. As the cover had many instruments installed over its surface (accelerometers, pressure sensors, impact device, water inlet and waterproof gland connectors for the wires), its mode-shapes were not completely symmetric because the mass of the cover was not symmetrically distributed. This fact implied the response of the cover to be complicated as is shown in Fig. 4. The more important thing in the cover mode-shapes estimation is that, as seen in Fig. 4, the thick cover did not have a high response in the same frequency band than the disk but the thin cover has some natural frequencies in this zone.

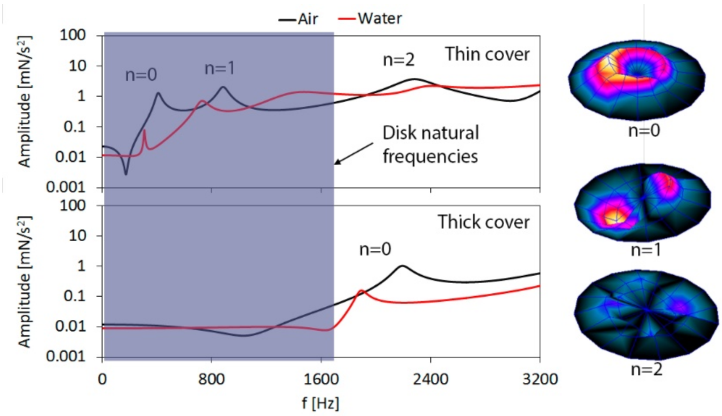

Fig. 4. *Cover mode-shapes.*

3.2 Natural frequencies

Natural frequencies associated with the mode-shapes commented above were estimated experimentally for different configurations of H_1 and H_2 and for the thick and thin covers. Fig. 5 shows the experimental results obtained for both covers. Distances have been normalized using the disk thickness (h_D). It is observed that the trend of natural frequencies when the disk is close to the thick cover is the same than when it is close to the bottom rigid surface for modes n=2-5: the closer to the rigid surface, the lower natural frequencies values presented the disk (Fig. 5a). This behavior is the same as expected and studied by many authors [4, 7, 8, 19]. However, the mode n=6, did not experimentally present the same behavior when the disk was near the thick cover. The natural frequency of this mode was in the region of 1200-1600 Hz, close to a natural frequency of the thick cover. In this case, the thick cover was vibrating near a natural frequency with a high amplitude and therefore it could not be considered as a rigid surface.

For the thin cover case (Fig. 5), which had a high response and natural frequencies in the same range than the disk (Fig. 4), results are completely different in comparison with those obtained with the thick cover . When the disk was near the thin cover, the trend of disk natural frequencies was not to decrease as in the case of the rigid surface, in this case, natural frequencies seemed to increase. When the disk was far from the cover and near the bottom rigid surface, the natural frequencies were as expected for a rigid surface.

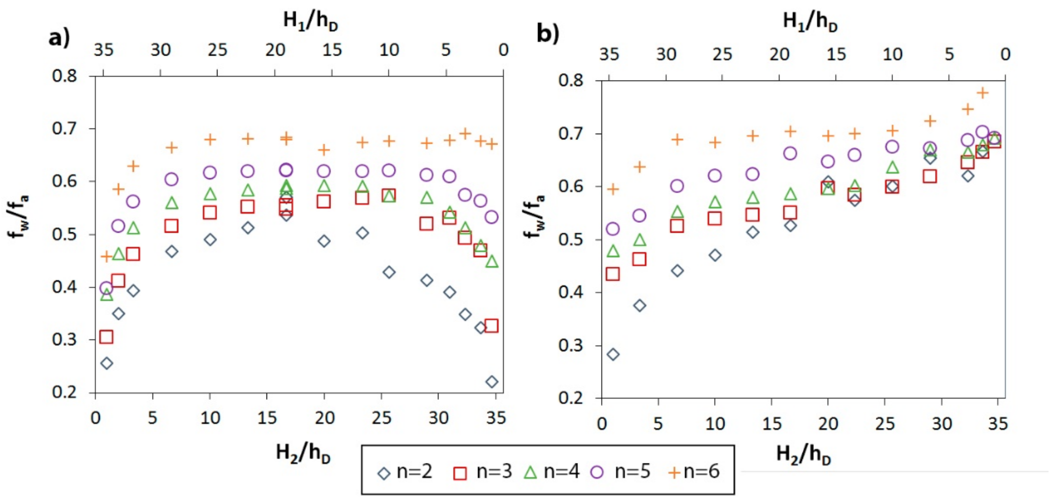

Fig. 5. *Natural frequency in water (fw) over the natural frequency in air (fa) for different distances to the cover. a) Thick cover. b) Thin cover.*

3.3 Pressure sensors

For all the tests performed two pressure sensors were intalled in both covers in order to measure the dynamic pressure produced by the impact. With these pressure sensors, disk natural frequencies could also be found. Analyzing the amplitude of each natural frequency, a clear trend was found for all mode-shapes and different distances to the cover. According the the theory [7], higher values of dynamic pressure lead to lower natural frequencies values, therefore for a rigid configuration it is known that pressure increase when the distance to the rigid distance decrease. This can be seen in Fig. 6a. However, for a non-rigid configuration (Fig. 6b), as in the case of the thin cover, it is appreciated that for closer distances to the cover, pressure decreases instead of increasing, following the behaviour of natural frequencies. In Fig. 6 pressure is normalized against the maximum value in all distances configurations of each cover.

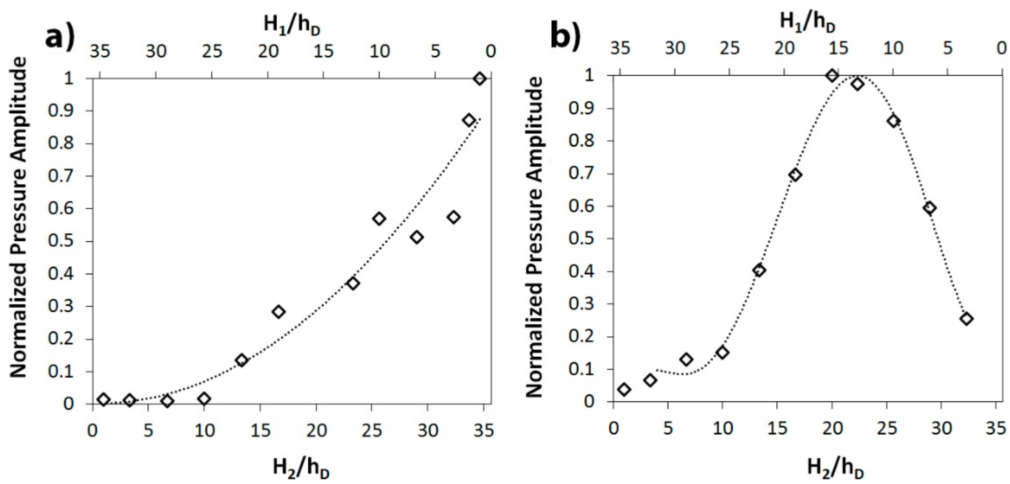

Fig. 6. Normalized pressure amplitude for a n=2 and different distances to the covers. a) Thick cover. b) Thin cover.

4. CONCLUSION

The influence of non-totally rigid surfaces on the dynamic response of a submerged and confined disk has been studied. This study is especially of interest when the distance between the disk and the casing is small like in some hydraulic machinery runners.

An experimental investigation in a test rig with a disk confined using two different covers with different stiffness has been carried out. Accelerometers mounted on the disk and on the cover as well as pressure sensors have been used. Natural frequencies have been calculated using EMA.

Experimental results show that disk natural frequencies are affected by the cover stiffness. When the natural frequencies of the casing are much higher than the ones of the disk, the behavior is like a completely rigid boundary. However, when the natural frequencies of casing and disk are in the same frequency range, they are affected especially when the distance between disk and cover is small. For the rigid case, natural frequencies decrease when the disk is near the cover, whereas for the non-rigid case the behavior is the opposite.

5. ACKNOWLEDGEMENTS

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