



# Influence of the boundary conditions on the dynamic behavior of large hydraulic machines

## Article-Based Thesis

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# ABSTRACT

Nowadays, hydropower plays an essential role in the energy market. With the massive entrance of new renewable sources such as wind or solar power, hydropower is the only renewable generating source that can provide fast response and regulation capacity to the electric grid. It can even store the surplus of energy when it is necessary using Reversible Pump-Turbine (RPT) power plants. However, this situation makes that hydraulic turbines are increasingly working at off-design conditions with a high number of start and stops in comparison with ten years ago. At these conditions, the forces and stresses over the structure are high, especially in the runner, documenting some failures along the time.

Therefore, it is of paramount importance to study the dynamic behavior of the runner under operation in order to avoid resonance conditions and fatigue problems. To study the dynamic behavior of the runner, both excitation and response have to be determined. Excitation forces have been studied for many years and they can be predicted with good accuracy through computational methods. However, the dynamic response of the runner still needs to be studied in detail. To define this dynamic response, natural frequencies, damping ratios and mode-shapes of the runner have to be estimated under operating conditions and for the different boundary conditions found in a hydraulic turbine.

In this thesis, the natural frequencies, damping ratios and mode-shapes of submerged structures under different boundary conditions are studied. As a hydraulic turbine runner is a complex structure where the boundary conditions are fixed, simplified models are used to study the influence of those boundary conditions on their dynamic response. Submerged and confined disks have been used to experimentally study the effects of axial and radial gaps to rigid walls, the effects of rotation and the effects of the acoustic modes of the surrounding fluid on their dynamic response. Moreover, experimental measurements in a large Pump-Turbine and a large Francis turbine prototype have been performed to confirm the knowledge acquired in the simplified models. Numerical models have been also developed and validated in the present work to study the dynamic response of hydraulic turbine runners.

This is an Article-Based Thesis, so it is based on three Journal Papers that have been published during the thesis duration. These three Journal Papers are based on the simplified models research, and they are attached and commented through the whole document of this thesis. Moreover, a summary of the findings of the research on hydraulic turbine prototypes is also included to extend the application of the knowledge acquired with the simplified models to actual hydraulic turbine prototypes.

# RESUM

Avui en dia l'energia hidràulica té un paper molt important en el mercat energètic. Amb l'entrada massiva de l'energia eòlica i solar, l'energia hidràulica és l'única energia renovable que és capaç de proporcionar una ràpida resposta i capacitat de regulació a la xarxa elèctrica. A més, pot inclús emmagatzemar l'energia sobrant quan és necessari utilitzant les centrals hidroelèctriques reversibles basades en bombes-turbines. Tanmateix, això fa que les turbines hidràuliques treballin en condicions fora de disseny, augmentant també el nombre de parades i arrencades en comparació amb deu anys enrere. En aquestes condicions, les forces i estressos que pateix l'estructura, especialment el rodet de la turbina hidràulica, són molt alts, fet que ja ha provocat importants avaries al llarg del temps.

Això fa que sigui molt important estudiar el comportament dinàmic del rodet en condicions d'operació per tal d'evitar possibles ressonàncies o problemes de fatiga. Per a estudiar el comportament dinàmic del rodet, s'han de conèixer en detall tant les possibles fonts d'excitació com la resposta dinàmica de la màquina. Les forces d'excitació han estat estudiades des de fa molts anys i actualment es poden determinar amb bona exactitud amb mètodes numèrics. En canvi, la resposta dinàmica de rodets necessita encara ser estudiada amb més detall. Per a fer això, les freqüències pròpies, l'amortiment i els modes propis del rodet han d'estimar-se sota les condicions d'operació de la màquina i per a les diferents condicions de contorn que es poden trobar en una turbina hidràulica.

En aquesta tesi s'estudien les freqüències pròpies, amortiment i modes propis d'estructures submergides i sota diferents condicions de contorn. Com que els rodets de les turbines hidràuliques són estructures complexes on les condicions de contorn són fixes, en aquest treball s'han utilitzat estructures més simples per tal d'avaluar la influència d'aquestes condicions de contorn en la seva resposta dinàmica. S'han utilitzat discos submergits i confinats en aigua per a demostrar experimentalment els efectes de les distàncies axials i radials a superfícies rígides i flexibles, els efectes de la rotació i els efectes dels modes acústics del medi fluid en el seu comportament dinàmic. També s'han realitzat mesures experimentals en una gran turbina-bomba i en una gran turbina Francis per a confirmar el coneixement

adquirit amb els models simples. A més, s'han desenvolupat i validat models numèrics que prediuen la resposta dinàmica dels rodets de turbines hidràuliques.

Aquesta tesi es presenta per compendi d'articles. Els articles que formen part de la tesi han estat publicats com a primer autor en revistes indexades al JCR per sobre del segon quartil. Aquests articles estan basats en la investigació sobre els models simplificats i estan adjuntats al final del document i comentats al llarg del mateix. En el document també s'explica la recerca que s'ha dut a terme en els diferents prototipus de turbines hidràuliques.

# RESUMEN

Hoy en día la energía hidráulica tiene un papel muy importante en el mercado energético. Con la entrada masiva de la energía eólica y solar, la energía hidráulica es la única energía renovable que es capaz de proporcionar una rápida respuesta y capacidad de regulación a la red eléctrica. Además, puede incluso almacenar la energía sobrante cuando es necesario utilizando las centrales hidroeléctricas reversibles basadas en bombas-turbinas. Aun así, esto hace que las turbinas hidráulicas trabajen en condiciones fuera de diseño, aumentando también el número de paradas y arranques en comparación con diez años atrás. En estas condiciones, las fuerzas y estreses que sufre la estructura, especialmente el rodete de la turbina hidráulica, son muy altos, hecho que ya ha provocado importantes averías a lo largo del tiempo.

Esto hace que sea muy importante estudiar el comportamiento dinámico del rodete en condiciones de operación para evitar posibles resonancias o problemas de fatiga. Para estudiar el comportamiento dinámico del rodete, se tienen que conocer en detalle tanto las posibles fuentes de excitación como la respuesta dinámica de la máquina. Las fuerzas de excitación han sido estudiadas desde hace muchos años y actualmente se pueden determinar con buena exactitud mediante modelos numéricos. En cambio, la respuesta dinámica de rodetes necesita todavía ser estudiada con más detalle. Para esto, las frecuencias propias, la amortiguación y los modos propios del rodete tienen que estimarse bajo las condiciones de operación de la máquina y para las diferentes condiciones de contorno que se pueden encontrar en una turbina hidráulica.

En esta tesis se estudian las frecuencias propias, amortiguación y modos propios de estructuras sumergidas y bajo diferentes condiciones de contorno. Cómo los rodetes de las turbinas hidráulicas son estructuras complejas donde las condiciones de contorno son fijas, en este trabajo se han utilizado estructuras más simples para evaluar la influencia de estas condiciones de contorno en su respuesta dinámica. Se han utilizado discos sumergidos y confinados en agua para demostrar experimentalmente los efectos de las distancias axiales y radiales a superficies rígidas y flexibles, los efectos de la rotación y los efectos de los modos acústicos del medio fluido en su comportamiento dinámico. También se han realizado

medidas experimentales en una gran turbina-bomba y en una gran turbina Francis para confirmar el conocimiento adquirido con los modelos simples. Además, se han desarrollado y validado modelos numéricos que predicen la respuesta dinámica de los rodets de turbinas hidráulicas.

Esta tesis se presenta por compendio de artículos. Los artículos que forman parte de la tesis han sido publicados como primer autor en revistas indexadas en el JCR por encima del segundo cuartil. Estos artículos están basados en la investigación sobre los modelos simplificados y están adjuntados al final del documento y comentados a lo largo del mismo. En el documento también se explica la investigación que se ha llevado a cabo en los diferentes prototipos de turbinas hidráulicas.



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# NOMENCLATURE

$c$	Speed of sound [m/s]
$f_n$	Natural frequency [Hz]
$n$	Number of nodal diameters
$m$	Number of nodal circles
$k$	Number of cross-sections
$\xi$	Damping ratio [%]

## Acronyms

BEP	Best Efficiency Point
CFD	Computational Fluid Dynamics
EMA	Experimental Modal Analysis
FEM	Finite Element Model
FSI	Fluid Structure Interaction
RSI	Rotor Stator Interaction
RPT	Reversible Pump-Turbine

# CHAPTER 1

## INTRODUCTION

The main purpose of this chapter is to explain the background and motivation of the topic of this thesis. First it shows why the topic of the thesis is important to be studied. Then, the state of the art in hydraulic turbines, as well as simpler structures such as disks. Moreover, it is also included what has been studied in the past by the research group and its research line. Finally, the outline of the present thesis is presented in a schematic way.

## 1.1. Background and interest of the topic

Hydropower is one of the main electricity generation sources in the world. In 2015, 13% of the electricity was generated by hydro resources (Fig. 1-1a). Moreover, fossil fuels and nuclear generating sources are less used every year due to their environment impact, being increased the use of renewable sources (see Fig. 1-1b). These renewables sources have grown drastically the last ten years (Fig. 1-2a), especially wind (Fig. 1-2b) and solar power, whilst hydropower electricity generation has remained almost constant along this period.

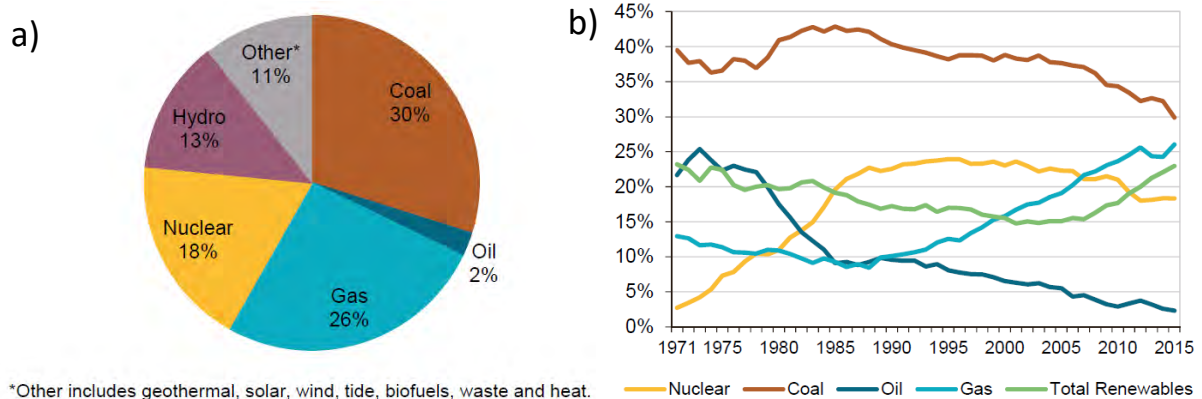


Fig. 1-1. a) World electricity generation mix in 2015. b) World electricity generation mix trend from 1971 to 2015. Sources from International Energy Agency (IEA) statistics [1].

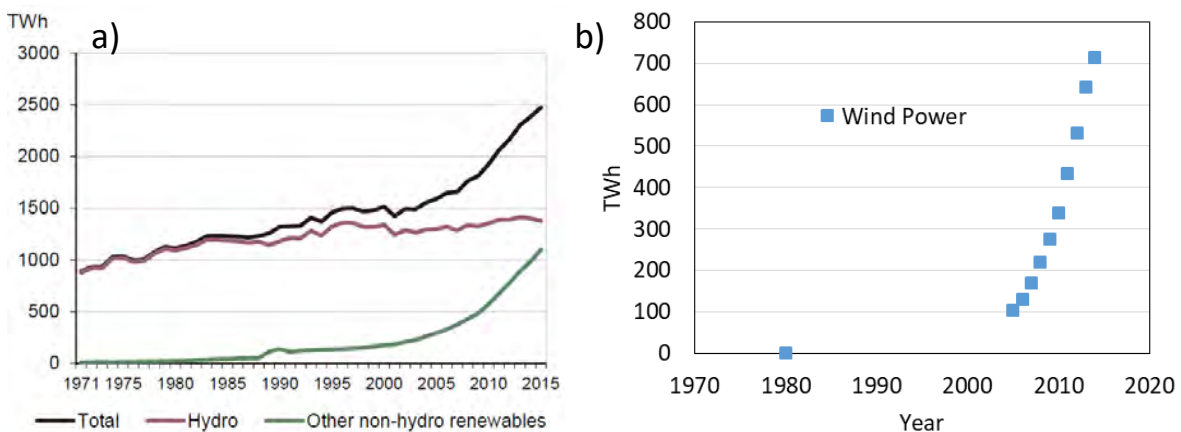


Fig. 1-2. a) World renewable sources trend for electricity generation (1971 to 2015). Data from International Energy Agency (IEA) [1]. b) World wind power electricity generation trend from 1980 to 2015). Data from Energy Information Administration (EIA) [2].

However, these new renewable energy sources, especially wind and solar power, strongly depend on weather, therefore their generation capacity cannot be constant. This fact

leads to require more regulation, flexibility and fast response to the other electricity generating sources in order to satisfy the energy demand. Hydropower is the only energy source that can provide wide range of power regulation (from 20 to 100% the maximum generating power) with a fast response (start up and stop and load changes in less than one minute). Moreover, it can storage large amounts of energy by using Reversible Pump-Turbine (RPT) power plants when there is a surplus of electricity in the grid.

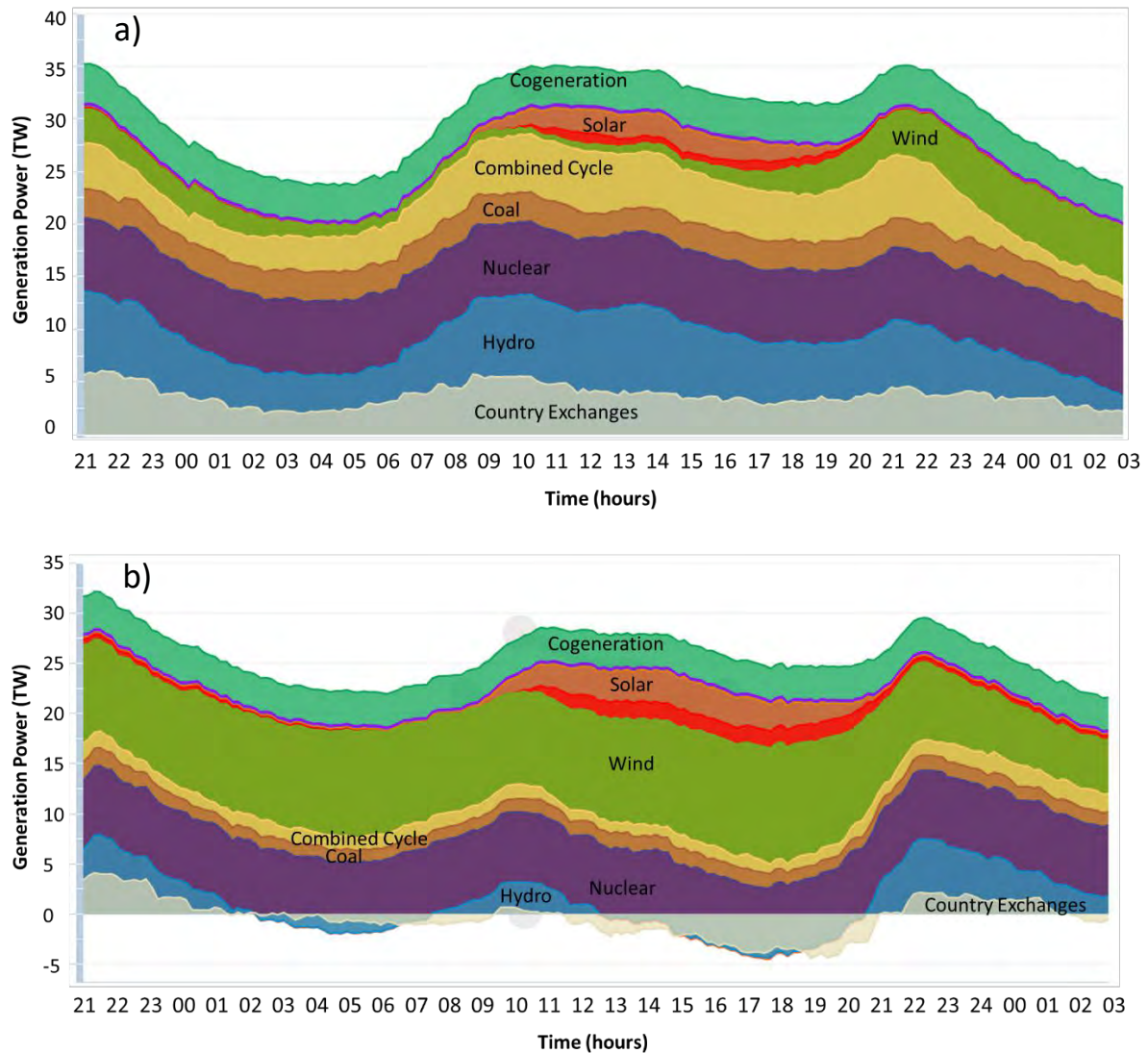


Fig. 1-3. Electricity generation mix in Spain along one day. a) Non-windy day. b) Windy day. Data from "Red Eléctrica [3]" (Spanish Electricity Generation Grid Supplier).

To illustrate this fact, Fig. 1-3 shows two different scenarios where hydropower plays a key role in the electricity generation mix. In this case, both cases are based on a summer day in Spain [3]. One (Fig. 1-3a) shows a non-windy day, where nuclear, coal, combined cycle and cogeneration remain constant during the day, and hydropower regulates the power according to the wind and solar generation. The other scenario (Fig. 1-3b) is a windy and sunny day,

where nuclear, coal, combined cycle and cogeneration remain constant as in the previous case, but hydropower covers the requirement of the energy demand according to the wind and solar power. In this case, hydropower goes from generating to pumping mode twice in the same day to compensate the surplus of energy generated by wind and solar power.

Under these circumstances, hydraulic turbines are therefore increasingly working in off-design conditions and they are subjected to transients events (start and stop and load changes) many more times in a day than ten years ago. In terms of life-time of the hydraulic turbine components, these situations are rather worse than in the best efficiency point (BEP). Fig. 1-4a shows an example of the dynamic stresses of a Francis turbine for different operating conditions. It is shown that for this machine, in the low loads and the transient events (startup), the dynamic stresses are much higher than at full power. This behavior is confirmed analyzing the damage that the runner suffers at every operating condition in comparison with a startup (see Fig. 1-4b).

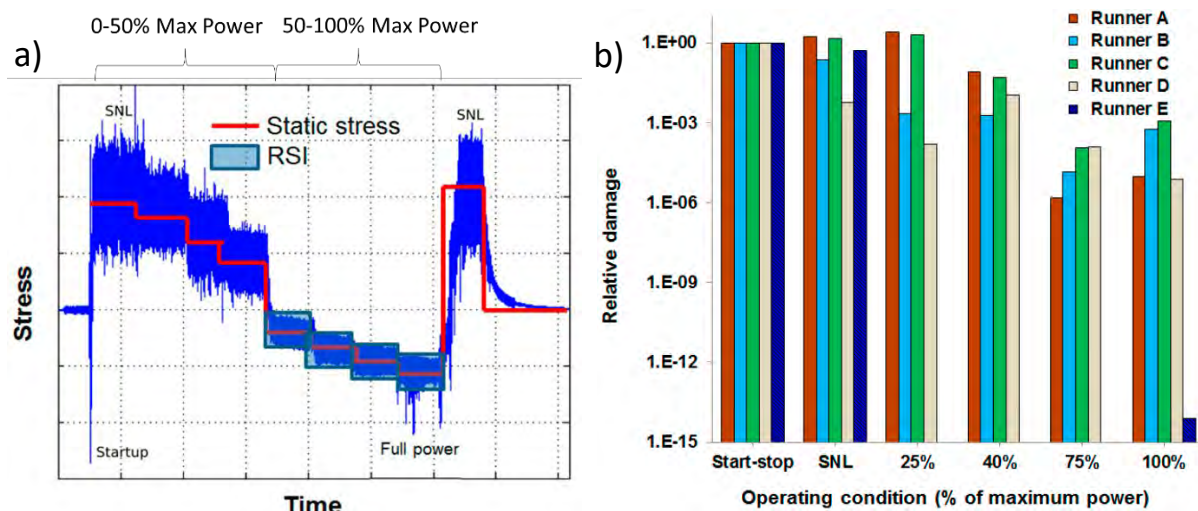


Fig. 1-4. a) Stress in a runner blade of a Francis turbine for different operating conditions. b) Relative damage to a start-up of different operating conditions and Francis runners. Source [4].

Several failures and cracks have been documented in hydraulic turbines due to fatigue in the last years [5-8] (see Fig. 1-5). Some of them are related to a resonance phenomenon due to a coincidence of a hydraulic excitation frequency and a natural frequency of the structure, normally during a transient event or in a rough operating point. The hydraulic phenomena is well-known and it can be rather well predicted by using computational tools such as CFD (Computational Fluid Dynamics) or experimentally in model tests. However, the natural frequencies of the structures are much more complicated to be estimated, especially the ones of the runner, since they are strongly dependent on the boundary conditions.



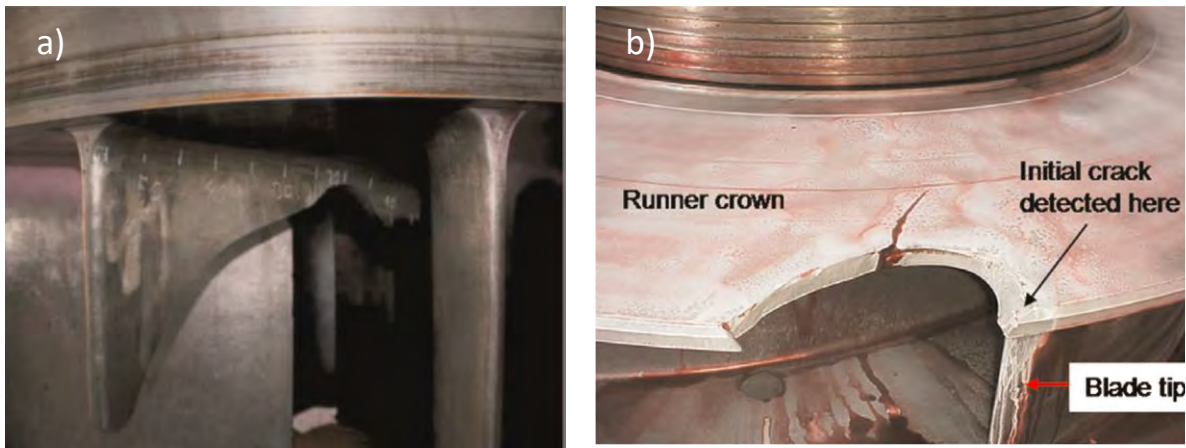


Fig. 1-5. a) Broken Francis runner [6]. b) Broken Pump-Turbine runner [5].

Hydraulic turbine runners, especially in reaction-type turbines, are submerged and confined rotating structures with small gaps to the stationary parts (Fig. 1-6). These stationary parts are other structures (head and lower covers basically) that depending on their fixation and stiffness, can vibrate at the same time than the runner. Moreover, the surrounding water have also its own dynamic behavior as a fluid cavity which has to be also taken into account. All these parameters are boundary conditions that affect the dynamic behavior of the runner, changing its natural frequencies, damping and mode-shapes.

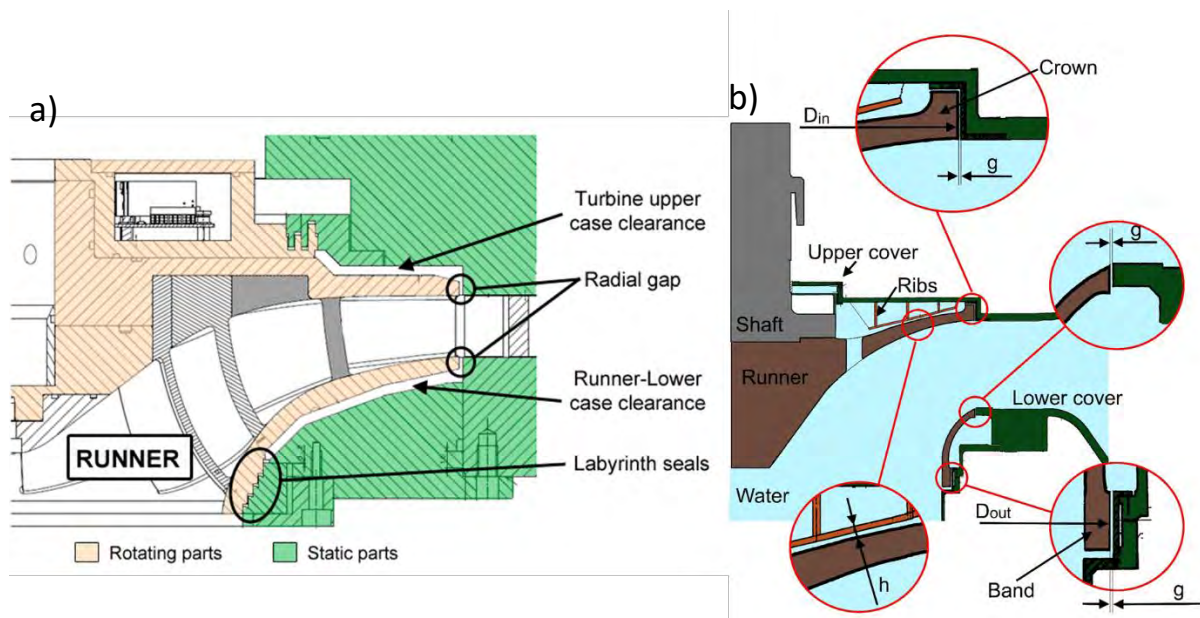


Fig. 1-6. Nearby rigid surfaces in prototype turbines. a) Pump-Turbine [9]. b) Francis Turbine [10].

In the present thesis, the aforementioned boundary conditions are studied in detail for simpler structures such as submerged disks and for real hydraulic turbine prototypes. In the real prototype these boundary conditions are fixed, but in a disk test rig they can be changed.

This fact let to experimentally evaluate the influence of the boundary conditions on the dynamic behavior of a submerged structure and to validate numerical models. The knowledge acquired with simpler models can be extrapolated to the prototype case, which with in addition to experimental results of different hydraulic turbine prototypes contribute to better understand the influence of the boundary conditions on the dynamic behavior of hydraulic machines.

## 1.2. State of the art

The state of the art related to the topic of study has been separated in two different sections. The first one is the state of the art of submerged simpler structures such as disks and the second one of prototype turbines.

### 1.2.1. *Research on disks*

#### *a) Free vibration of disks in air*

The dynamic behavior of disks have been extensively studied since the beginning of the 20<sup>th</sup> century. The natural frequencies and mode-shapes of disks vibrating in vacuum were determined analytically by Southwell [11] and Leissa [12]. According to these studies, the mode-shapes of a disk are defined by its number of nodal diameters and nodal circles ( $n, m$ ), which are related to the points that remain stationary in a deformation cycle. The value of the natural frequency is related to the geometrical characteristics of the disk (inner and outer diameter and thickness), the material properties (Young Modulus, Poisson Modulus and density), the fixation zone, and as mentioned before, also the number of nodal diameters and circles. This value is tabulated and could be easily calculated using the reference [13]. Due to the low density of the air, the natural frequencies in air are almost the same than in vacuum.

Having defined the natural frequencies and mode-shapes of a disk, the only parameter that has not been discussed of the dynamic behavior of disks is the damping. The damping is the mechanism to dissipate the energy of vibration. Usually this value is neglected in the analytical models to calculate natural frequencies of structures because its relevance in the natural frequency value is small and it complicates the formulas substantially [14]. For a disk in air, this value depends basically on the material properties and fixation characteristics. There is not a clear analytical way to calculate this value, so experimental data is necessary [15].

*b) Influence of the surrounding water*

There are many studies [16-18] that investigate the influence of submerging a disk in an infinite medium of water on its dynamic behavior. All of them conclude that the natural frequencies decrease in comparison with those in vacuum due to the called “Added Mass Effect” [19]. This effect can be understood as considering an additional mass (water) apart from the disk mass. The mode-shapes are not affected by the water but the influence of the added mass is smaller for mode-shapes with higher order. Depending on the disk mass, the influence of the water on the natural frequencies could be more or less important.

There is also an additional damping term due to the water called “Added damping [20]” or “Hydrodynamic damping [21, 22]” which, according to the studies, is directly related to the fluid velocity. All these studies affirm that the damping of a structure submerged in water is higher than in the air or vacuum. However, these studies are made for hydrofoils vibrating inside a flow water stream, the case of a disk vibrating inside a fluid in rest is not studied in detail.

*c) Influence of rotation*

The dynamic behavior of rotating disks in air has been also studied in the past [11, 23]. The influence of the rotation on the natural frequencies and mode-shapes for slow rotating speeds and from the rotating frame was almost negligible. However, when seeing from the stationary frame the problem, every natural frequency was split into two natural frequencies, corresponding to the same mode-shape than in stationary but one rotating in the same direction than the disk, and the other one in the opposite direction. The relationship between these two split natural frequencies in rotation and the one without rotation depend on the mode-shape and on the rotating speed.

However, when the disk is rotating and submerged in water, the behavior is different than in the air. Kubota and Ohashi [24] studied the problem analytically from the rotating frame but no experimental results were presented. This analytical model was provided only for the case of the disk submerged in one of the sides. The problem of the disk totally immersed in water and rotating have been studied experimentally by Presas [25] in his doctoral thesis. To study this problem of a rotating disk submerged in water by means of numerical simulations could be also interesting for hydraulic turbines. However, this topic has not been investigated by simulation in the past. In the present thesis this will be studied and compared with the experimental results presented in [25].

*d) Influence of nearby rigid walls*

Few works study the influence of nearby rigid surfaces on the dynamic behavior of disks. However, for cantilever plates some studies are found. Rodriguez et al. [26] investigated the added mass effect for different distances to a rigid wall, as well as Naik et al. [27], who also presented results about damping. Both papers concluded that the natural frequencies decrease when decreasing the distance to a rigid wall. Moreover, Naik et al. [27] also indicated that damping tend to be higher for smaller distances to the rigid wall.

In the case of submerged disks close to a rigid surface, Kubota and Suzuki [19] and Askari et al. [28] developed an analytical model to calculate the natural frequencies of a disk close to an axial surface. Results presented the same conclusions than in the case of cantilever plates. Nevertheless, experimental results were not presented and neither the influence of the radial gap on the dynamic behavior of the disk was studied.

*e) Influence of the non-completely rigid walls*

The case of a disk vibrating inside water near another vibrating structure has been never studied. This case is interesting because could be similar to a hydraulic turbine runner vibrating near the head cover, which is not completely rigid. Only works of two identical disks coupled by a fluid and vibrating at the same time are found [29-31]. However, the case of two different structures with different dimensional characteristics, as is the case of a disk and a cover, affecting their dynamic behavior each other is not studied.

*f) Influence of acoustic modes*

All the studies mentioned before about disks submerged in water consider that the water is an incompressible fluid, therefore the speed of sound value is not considered in the formulation. If the speed of sound is taken into account, the fluid cavity has its own natural frequencies and mode-shapes which are commonly named as acoustic natural frequencies and acoustic mode-shapes [13]. This acoustic natural frequencies are basically dependent on the fluid cavity dimensions and the speed of sound.

In the case of a disk, due to its small scale size, the natural frequencies of the disk are by far smaller than the acoustic natural frequencies of the fluid cavity for a realistic value of speed of sound. This is why the dynamics of the fluid have been never taken into account in the case of submerged disks. However, in the case of real prototypes, due to its large dimensions, both acoustical natural frequencies of the fluid cavity and the disk natural frequencies can be of the

same order. In this case they may affect each other. Nevertheless, this case has not been studied in detail.

### 1.2.2. *Research on prototype turbines*

#### a) *Free vibrations on prototype turbines in air*

The hydraulic turbine prototypes selected for study in the present thesis are Francis turbines and Pump-Turbines. The runner of these turbines has similar dynamic characteristics than a disk and it is also submerged and confined with very small axial and radial clearances.

Several studies are found about the mode-shapes and natural frequencies of Francis turbines runners in air, most of them are based in the reduced scale model [32-35]. They discuss how the mode-shapes of a Francis turbine runner are. The main mode-shapes of this kind of structures are also formed by different number of nodal diameters. However, the big difference in comparison to a disk is that the maximum deformation is mainly in the radial direction, instead in the axial as in a disk. Moreover, this maximum deformation is located in the band for the first group of mode-shapes and in the blades for the second group of mode-shapes.

The mode-shapes of Pump-Turbines runners are also formed by different number of nodal diameters and in this case the deformation is mainly in the axial direction as it is also the case in a disk. Tanaka [36], Liang [37] and Egusquiza et al. [38, 39] classified the mode-shapes of Pump-Turbines runners according to the amplitude and phase of the crown and band deformation. For this type of turbines, there is a first zone of natural frequencies where the deformation of the crown and band is of the same order of magnitude and another zone where the deformation is higher in the crown than in the band or vice versa. The mode-shapes of the first zone are the ones that are more similar to the ones of a disk.

#### b) *Influence of surrounding water*

The same studies that classified the mode-shapes of Francis turbines runners [32-35] also consider the effect of the added mass when submerging the runner in an infinite medium of water. As mentioned before, these studies were performed with reduced scale models. It was observed that the natural frequencies decrease between 20-40% of the natural frequency in air depending on the mode-shape. The mode-shapes with higher number of nodal diameters have more affectation in the natural frequency value, unlike the case of a disk, where the behavior was the opposite.

In the case of Pump-Turbine runners submerged in infinite medium of water, the reduction behavior of the natural frequencies is similar than in Francis turbine runners [37-39]. The higher is the number of nodal diameters, the bigger is the reduction of the natural frequencies. Moreover, mode-shapes with a relative motion between crown and band have the largest added mass effect.

*c) Influence of boundary conditions*

There are few works that study the influence of nearby rigid surfaces in prototypes. Tanaka [36] was one of the first authors who investigated this topic in Pump-Turbines. He concluded that confining the runner with nearby rigid surfaces decreases the natural frequency about 50% the natural frequency in air, which was more significant than in infinite water. He also introduced the need of study this influence experimentally with a disk. These conclusions were also reached by Liang in its doctoral thesis [37] for Francis turbine and Pump-Turbine prototypes. Mao and Wang [40] also studied the influence of the clearances on the natural frequencies of a high-head Francis turbine, observing in this case a reduction of 30-40% in the natural frequency with respect to the natural frequency in air depending on the mode-shape. However, these works presented only the results for the few first mode-shapes and there is a lack of experimental data.

In all of these works, the authors considered always the boundaries as completely rigid. However, in a real prototype this is not always true. Head and lower covers that confine the runner have their own dynamic behavior, which may affect the dynamic behavior of the runner. Presas et al. [41] observed in their investigation with a Pump-Turbine reduced scale model that the nearby boundaries may not behave as completely rigid and that fact could affect the dynamic behavior of the runner. However this phenomenon could not be studied in detail. Huang [42] investigated numerically and experimentally the natural frequencies and mode-shapes of the head cover of a Pump-Turbine prototype, confirming that its dynamic response is complex and has to be considered when studying natural frequencies of prototype runners.

*d) Influence of acoustic modes*

As mentioned in section 1.2.1f, acoustic modes are especially important in large size dimensions as it is the case of the great majority of prototype turbines. For certain dimensions, the acoustic mode-shapes of the fluid cavities (spiral casing, wicket gates water passage, runner water passages and draft tube) are of the same order than the natural frequencies of

the runner. These acoustic mode-shapes have been studied in the past [43] but with the goal of better understanding the hydraulic excitation due to Rotor Stator Interaction (RSI). However the influence of them on the dynamic behavior of the runner has not been investigated.

### **1.3. Research line**

The main research line of the Fluid Mechanics Department and the Center for Industrial Diagnostics and Fluid Dynamics (CDIF) is based on the dynamic behavior of hydraulic turbines. Since 2005, several theses were presented related to the topic of dynamic behavior of prototype turbines [37, 42, 44-46]. These theses addressed the topic of natural frequencies of prototype turbine runners. However, they do not study all the parameters that can affect the dynamic behavior of prototype turbines due to the complexity of the problem.

Therefore, it was decided to perform also a basic research on simplified models to better understand the phenomena. Inside this topic, another thesis was presented [25] contributing to the knowledge on the influence of the rotation on the natural frequencies of submerged structures. The present thesis continues the work done in [25] and it deals also with basic research on simplified models and at the same time with its application to prototype turbines.

### **1.4. Objectives**

The main objective of this doctoral thesis is to evaluate the influence of different boundary conditions on the dynamic response of hydraulic machines. To do so, a basic research on simplified models and an experimental and numerical research on two different prototype turbines have been carried out. Therefore, the objectives can be separated in two parts, the ones of the basic research and the ones related to the study in prototypes:

-Objectives of the research on simplified models:

- To experimentally study the dynamic behavior (natural frequencies, mode-shapes and damping ratio) of submerged disks under different boundary conditions (nearby rigid and non-rigid boundary conditions).
- To evaluate the influence of acoustic mode-shapes on the dynamic behavior of submerged and confined disks.

- To validate numerical models with the experimental data obtained with the disks test rigs.

-Objectives of the research on hydraulic turbine prototypes:

- To apply the knowledge obtained with simpler models to real prototypes.
- To experimentally determine the dynamic response of different hydraulic turbine prototypes in mounted conditions and under operation.
- To study the same boundary conditions than in simplified models but in prototypes.

## 1.5. Outline of the thesis

The present thesis has been structured chronologically during the five years of its duration (see Fig. 1-7). Approximately, each chapter of the thesis belongs to one year of work:

-Before 2013: Previously to the start of the thesis, the author had a specific training in CFD with a contribution of two journal papers [47, 48].

-Year 2013: The first period of the thesis was dedicated to perform a preliminary work on the state of the art. During this period the author did also a basic training on Experimental and Numerical Modal Analysis with a contribution of a conference paper [49]. This period correspond to Chapter 1 of the thesis.

-Year 2014: During the first period, the author performed an experimental investigation on simplified models (standing disk and rotating disk), at the same time than an experimental investigation on a Pump-Turbine Prototype. As a contribution of this period, the author published one Journal Paper [9] and one conference paper [50] as first author and collaborated in another Journal Paper [51] and conference paper [52]. This period correspond to Chapter 2 of the thesis.

-Year 2015: In this period the author carried out numerical investigations on the simplified models (standing disk and rotating disk) as well as in a Pump-Turbine Prototype and a Francis Turbine Prototype. As a result of this period of investigation, the author published one Journal Paper [53] and one conference paper [54] as a first author and collaborated in another three Journal Papers [55-57] and one conference paper [58]. This period correspond to Chapter 3 of the thesis.



-Year 2016: This period was dedicated to investigate experimentally the influence of the cover stiffness on simplified models and also in prototype turbines. As a contribution of this period, the author published one Journal Paper [59] and one conference paper [10] as first author and also collaborated with another Journal Paper [60] and two conference papers [61, 62]. Moreover, the investigations carried out since the start of the thesis in a Pump-Turbine Prototype contributed to a part of the collaborative project with VOITH® [63]. This period correspond to Chapter 4 of the thesis.

-Year 2017: During this period the author did experimental research on the Francis turbine prototype and collaborated in a numerical investigation about the influence of the acoustic modes on simplified models and prototype. As a result, one conference paper [64] was presented as first author and two Journal Papers [65, 66] and three conference papers [67-69] as collaboration. Moreover, the research carried out on the Francis turbine prototype since the start of the thesis contributed to a part of the European Project HYPERBOLE [70]. This Period correspond to Chapter 5 of the thesis.

Finally, Chapter 6 summarizes all the conclusions reached during the thesis, Chapter 7 includes a copy of the three papers that are part of the present Article-Based thesis and the last chapter shows the bibliographic references. All the detailed information about the outline of the thesis is shown in a schematic way in Fig. 1-7. The contributions of Journal Papers are summarized in Table 1-1 and of conference papers in Table 1-2.

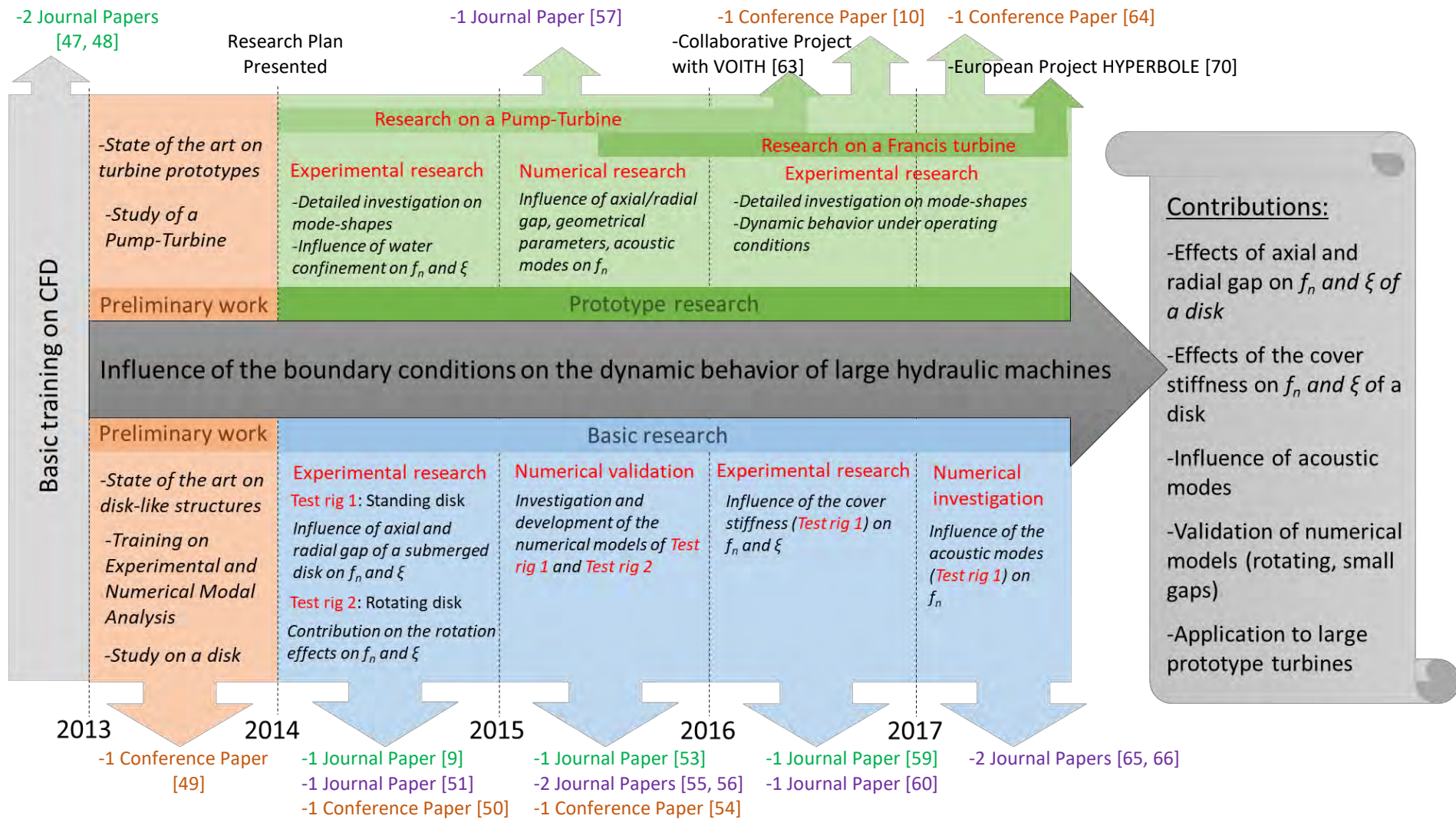


Fig. 1-7. Schematic view of the outline of the thesis.

*Table 1-1. Journal Paper Publications.*

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**First Author**

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- [47] Use of Coandă nozzles for double glazed façades forced ventilation. *Energy and Buildings*, 2013. 62: p. 605-614.
- [48] Assessment of the economic and environmental impact of double glazed façade ventilation systems in Mediterranean climates. *Energies*, 2013. 6(10): p. 5069-5087.
- [9] Experimental study on the added mass and damping of a disk submerged in a partially fluid-filled tank with small radial confinement. *Journal of Fluids and Structures*, 2014. 50(0): p. 1-17.
- [53] On the Capability of Structural–Acoustical Fluid–Structure Interaction Simulations to Predict Natural Frequencies of Rotating Disklike Structures Submerged in a Heavy Fluid. *Journal of Vibration and Acoustics*, 2016. 138(3): p. 034502-034502.
- [59] Experimental Study of a Vibrating Disk Submerged in a Fluid-Filled Tank and Confined With a Nonrigid Cover. *Journal of Vibration and Acoustics*, 2017. 139(2): p. 021005.

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**Collaborations**

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- [51] Feasibility of Using PZT Actuators to Study the Dynamic Behavior of a Rotating Disk due to Rotor-Stator Interaction. *Sensors*, 2014. 14(7): p. 11919-11942.
- [55] Influence of the rotation on the natural frequencies of a submerged-confined disk in water. *Journal of Sound and Vibration*, 2015. 337(0): p. 161-180.
- [56] On the detection of natural frequencies and mode shapes of submerged rotating disk-like structures from the casing. *Mechanical Systems and Signal Processing*, 2015. 60–61: p. 547-570.
- [57] Condition monitoring of pump-turbines. New challenges. *Measurement*, 2015. 67: p. 151-163.
- [60] Dynamic response of a rotating disk submerged and confined. Influence of the axial gap. *Journal of Fluids and Structures*, 2016. 62: p. 332-349.

- [65] Accurate Determination of the Frequency Response Function of Submerged and Confined Structures by Using PZT-Patches. *Sensors*, 2017. 17(3): p. 660.
- [66] Numerical study on the influence of acoustic natural frequencies on the dynamic behaviour of submerged and confined disk-like structures. *Journal of Fluids and Structures*, 2017. 73: p. 53-69.

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*Table 1-2. Conferences Papers.*

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First Author

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- [49] Influence of nearby rigid surfaces on natural frequencies in a submerged disk, in 5th IAHR International Workshop on Cavitation and Dynamic Problems in Hydraulic Machinery. 2013: Laussane, Switzerland.
- [50] Influence of the added mass effect and boundary conditions on the dynamic response of submerged and confined structures. *IOP Conference Series: Earth and Environmental Science*, 2014. 22(3): p. 032042. 27th IAHR Symposium on Hydraulic Machinery and Systems, Montreal, Canada.
- [54] Influence of non-rigid surfaces on the dynamic response of a submerged and confined disk. 6th IAHR meeting of the Working Group, IAHRWG 2015: Ljubljana, Slovenia, September 9-11, 2015: Proceedings. 2015.
- [10] Influence of the boundary conditions on the natural frequencies of a Francis turbine. in *IOP Conference Series: Earth and Environmental Science*. 2016. IOP Publishing. 27th IAHR Symposium on Hydraulic Machinery and Systems, Grenoble, France.
- [64] Dynamic response of the MICA runner. Experiment and simulation. *Journal of Physics: Conference Series*. 2017. IOP Publishing. HYPERBOLE Conference, Porto 2017.

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Collaborations

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- [52] Experimental analysis of the dynamic behavior of a rotating disk submerged in water. *IOP Conference Series: Earth and Environmental Science*, 2014. 22(3): p.

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032043. 27th IAHR Symposium on Hydraulic Machinery and Systems, Montreal, Canada.
- [58] ON THE EXCITATION OF A SUBMERGED DISK-LIKE STRUCTURE WITH RSI PATTERNS, 6th IAHR meeting of the Working Group, IAHRWG 2015: Ljubljana, Slovenia, September 9-11, 2015: Proceedings. 2015.
- [61] Natural frequencies of rotating disk-like structures submerged viewed from the stationary frame. 2016, 27th IAHR Symposium on Hydraulic Machinery and Systems, Grenoble, France.
- [67] Detection and analysis of part load and full load instabilities in a real Francis turbine prototype. in *Journal of Physics: Conference Series*. 2017. IOP Publishing. HYPERBOLE Conference, Porto 2017.
- [68] Overview of the experimental tests in prototype. in *Journal of Physics: Conference Series*. 2017. IOP Publishing. HYPERBOLE Conference, Porto 2017.
- [69] Condition monitoring of a prototype turbine. Description of the system and main results. in *Journal of Physics: Conference Series*. 2017. IOP Publishing. HYPERBOLE Conference, Porto 2017.
- [62] Effects of extended operating conditions in pump-turbines. in *14th IMEKO TC10 Workshop on Technical Diagnostics 2016: New Perspectives in Measurements, Tools and Techniques for Systems Reliability, Maintainability and Safety*. 2016.
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## **CHAPTER 2**

# **EFFECTS OF NEARBY RIGID SURFACES**

In this chapter the influence of nearby rigid surfaces on the dynamic response of submerged structures is evaluated. First, an experimental research on a standing disk test rig is discussed. Natural frequencies, damping ratios and mode-shapes are obtained for different configurations of axial and radial distances to nearby rigid walls. Then, the same investigation but with two different hydraulic turbine prototypes is presented by means of numerical simulations.

## 2.1. Research on simplified models

This section is based on the experimental research on a standing disk test rig. This disk is submerged in water with axial and radial confinement. The dynamic response of the disk, i.e. natural frequencies, damping and mode-shapes, has been determined for different axial and radial gap configurations. This experimental research is explained in the Journal Paper [9] which is one of the three papers that is part of the present Article-Based Thesis. This Journal Paper can also be seen in Chapter 7.

As a first step, the natural frequencies, damping and mode-shapes of the disk were experimentally determined with the disk hung in the air and attached to the shaft. To do so, the disk was impacted in different points and its response was measured with one accelerometer. This method is called Roving Hammer Method. The mode-shapes of the disk were formed by nodal diameters ( $n$ ) and nodal circles ( $m$ ), but in this study only diametrical modes (mode shapes with no nodal circles,  $m=0$ ) are considered. Results show that for diametrical modes no big difference in frequency was appreciated for the cases of the disk hung in the air and attached to the shaft (see Fig. 7. of [9] or Chapter 7).

After determining the dynamic response of the disk in air, the disk was submerged in water and the same procedure than in air was repeated. Different tests were done to see the influence of the free surface distance (distance of the water depth above the disk) but its effect was rather small in terms of natural frequencies and damping (see Fig. 8 of [9] or Chapter 7). To see the effects of the axial gap on the natural frequencies and damping ratios of the disk, the distance of the disk to the bottom of the tank was changed. Moreover, to evaluate the influence of the radial gap, two tests with and without water in the radial gap were performed.

### 2.1.1. *Effects of axial gap*

The effects of the axial gap on the natural frequencies were significant. The smaller was the axial gap to the nearby rigid distance, the smaller was the natural frequency value. However this affectation was smaller for higher order of diametrical mode-shapes. These results are shown in Fig. 9 of [9] or Chapter 7. The reduction of the natural frequency was of about 30-50% the natural frequency in air for the smallest gap tested. These results confirm the theoretical models presented by Kubota and Suzuki [19] and Askari et. [28].

The behavior of the damping ratio was the opposite than the behavior of the natural frequencies. The smaller was the axial gap to the rigid wall, the higher was the damping ratio (see Fig. 10 of [9] or Chapter 7). The damping ratio is related to the kinetic energy and the work done by the fluid to the structure [21, 27]. This kinetic energy is higher for smaller gaps because the water velocity due to the disk velocity is higher, therefore the damping ratio is also higher for smaller gaps. In comparison to the damping of the disk in air, which is directly related to the material damping, the damping in water was almost 10 times higher. To confirm that the damping ratio is related to the work done by the fluid to the structure, different liquids with different viscosities were also tested. Results show that liquids with higher viscosities present also higher damping ratios (see Fig. 14 of [9] or Chapter 7).

### *2.1.2. Effects of radial gap*

Different tests with and without water in the radial gap were carried out. The natural frequencies were smaller for the configuration with water in the radial gap (see Fig. 12 of [9] or Chapter 7). Moreover, numerical simulations confirmed that decreasing the size of this radial gap also decreased the natural frequency values (see Fig. 13 of [9] or Chapter 7).

The behavior of the damping ratio was again the opposite than the natural frequencies. The damping ratio was higher for the configuration with water in the radial gap (see Fig. 12 of [9] or Chapter 7). This damping ratio increased 10-20% having water in the radial gap with respect to the empty radial gap case. Therefore, the radial gap is an important parameter that has to be considered when analyzing the dynamic response of submerged structures.

## **2.2. Research on prototype**

The effects of nearby rigid surfaces are studied in two different hydraulic turbine prototypes. The influence of the axial gap is evaluated in a large Pump-Turbine prototype which was object of study inside the frame of a collaborative project with VOITH [63]. The effects of the radial gap are studied in a large Francis Turbine prototype in the frame of the European Project "HYPERBOLE" [70]. The axial gap has been studied in a Pump-Turbine because the runner's mode-shapes have basically axial displacement as it is the case of a disk, and the radial gap has been studied in a Francis Turbine runner because its mode-shapes have basically radial displacement (this was previously comment in the State of the art section).



### 2.2.1. *Effects of axial gap*

In the prototype the axial distance of the runner to the head cover is fixed, however this can be different depending on the prototype. To evaluate the influence of this distance on the dynamic response of a Pump-Turbine runner, different numerical simulations with different axial gap runner-head cover were performed. In this case the runner was still confined in water, without rotation. The type of numerical simulations used and their validation are explained in Chapter 3.

For the case of the Pump-Turbine studied, the axial distance to the head cover was changed from 0.3 times the nominal distance (the one existing in the prototype) to 1.3 times. The natural frequencies decreased when decreasing the distance to the head cover, as it is the case of the standing disk. The added mass effect of confining the structure with water was stronger for higher order mode-shapes (higher diametrical modes), contrary to the case of the disk. The mode-shapes of Pump-Turbine runners are more dominated by the crown or band deformation when increasing its order, this is why the added mass effect is stronger for those modes. This phenomenon was previously discussed in [38]. The reduction of frequency was of about 20-30% depending on the mode-shape between the configuration with larger axial gap (1.3 times the nominal distance) and the one with lower axial gap (0.3 times the nominal distance). These results are presented in the collaborative project report [63].

### 2.2.2. *Effects of radial gap*

In hydraulic turbine prototypes there are small radial gaps near the crown, the band and in the labyrinth seals (see Fig. 1-6). These gaps can be really small, usually they are of between  $10^{-3}$  and  $10^{-4}$  times the diameter of the runner. To evaluate the influence of the radial gap on the dynamic response of a hydraulic turbine runner, a Francis turbine was selected for study. The radial gap between band/crown to the stationary parts were changed by means of numerical simulations from  $4 \cdot 10^{-4}$  to  $10^{-2}$  times the runner diameter. The runner was still in water without rotation in the numerical model. Further details are found in the conference paper [10].

Results showed that for the smallest radial gap tested ( $4 \cdot 10^{-4}$  times the runner diameter), the natural frequency decrease about 10-20% in comparison to a big radial gap ( $10^{-2}$  times the runner diameter). This affectation is higher for lower order modes, as it was also the case of the disk. These results can be seen in [10].

Therefore, the importance of considering the axial and radial gap for the natural frequencies calculation of prototype turbines have been demonstrated in this chapter.

## **CHAPTER 3**

# **VALIDATION OF NUMERICAL MODELS**

In this chapter the validation of numerical models with experimental results is presented. First, numerical models for simplified structures are validated with experimental data. For the case of standing disks, the numerical model results have been compared with the experimental results discussed in Chapter 2. Moreover, to study the effects of rotation on submerged structures a numerical model has also been developed. Finally, the numerical models of two different hydraulic prototype turbines are also presented.

### 3.1. Numerical model for simplified structures

FEM (Finite Element Method) models are widely used to perform modal analysis of structures. For structures submerged in water, the water is considered as an acoustic fluid which interacts with the structure. This type of simulations are called structural-acoustical FSI (Fluid Structure Interaction) simulations.

#### 3.1.1. *Standing submerged structures*

The numerical model for standing submerged structures has been validated by many authors in the past [26, 33]. This model is based on structural elements connected to acoustical elements by a FSI Interface. With this kind of numerical models, the natural frequencies of submerged structures can be estimated with a good accuracy. However, the hydrodynamic damping due to the water cannot be obtained with this kind of numerical models since the fluid is considered as an inviscid and incompressible acoustic fluid without mean flow.

For the case of the standing disk presented in this thesis, results using a structural-acoustical FSI numerical model were also presented in the Journal Paper [9]. Natural frequencies were obtained with a very good accuracy in comparison with experimental results for all the configurations of radial and axial gap tested. The maximum error obtained between simulation and experiment was of about 5%. Results of numerical simulations are compared with experimental results in Fig. 7,8,9 and 12 of [9] or Chapter 7.

#### 3.1.2. *Rotating submerged structures*

The effects of the rotation on the natural frequencies of a submerged structure by means of numerical simulations have not been studied before. In this section, a numerical model for rotating disk-like structures is developed and discussed in detail. This numerical investigation is explained in the Journal Paper [53], which is one of the three papers that is part of the present Article-Based Thesis. This Journal Paper can also be seen in Chapter 7.

In this paper all the limitations that the actual numerical models present for rotating structures are listed and it is explained how to overcome them to obtain the natural frequencies of rotating disk-like structures. This numerical model is based on the standard structural-acoustical FSI method but considering rotation. In this case, this method has been

applied to a rotating disk case and validated with the experimental results obtained in the doctoral thesis [25].

When applying rotation to a structure submerged in water, different aspects have to be considered. First, as the water is modeled as an acoustic fluid, it cannot rotate, therefore there will be rotating and static components in the same model. This fact implies that the simulation has to use the stationary frame formulation, because in the rotating frame formulation is mandatory that all the components rotate. However, when using the stationary frame formulation, the rotating structure has to be axisymmetric around its rotation axis, something that is accomplished by a disk but not by a prototype runner. Therefore, this numerical model is only valid for rotating disk-like structures.

The only structure that rotates in the numerical model is the disk, so the water remains standing. However, in the real case, the water is drawn by the disk and it also rotates as a rigid solid but with different velocity. Therefore, this means that the results obtained with the numerical model are shown from the fluid's reference frame. In the Journal Paper [53], a formula to change the natural frequency values from the fluid's reference frame to the stationary frame (outside the disk) or the disk's reference frame. This formula is related with the disk rotation and the water rotation, which according to some studies [71, 72] is always 0.4 times the disk rotation.

Results obtained with the numerical model accurately agree with experimental results. Table 1 of [53] or Chapter 7 shows the comparison of the numerical and experimental results of the natural frequencies of the rotating disk. As found by Presas [25], every natural frequency of the disk without rotation is split into two different natural frequencies with rotation. From the stationary frame, the lowest natural frequency found correspond to a mode-shape travelling in the opposite direction than the disk rotation (backward travelling wave) and the highest natural frequency found correspond to a mode-shape travelling in the same direction than the disk (forward travelling wave). A clear visualization of this phenomenon is seen in Fig. 6 of [53] or Chapter 7.

This investigation has contributed to a better knowledge of the limitations and possibilities of structural-acoustical FSI numerical models for rotating structures.

## 3.2. Numerical model of prototypes

In order to estimate the natural frequencies of the two different hydraulic prototypes studied, structural-acoustical FSI numerical models have been developed for both prototypes. This type of simulations are the same than for the simplified models without rotation (section 3.1.1). In both cases, Pump-Turbine and Francis Turbine prototypes, the whole rotating train of the machine has been considered in the numerical model. This includes the generator, the shaft and the runner. Moreover, the surrounding water with the actual nearby rigid distances (axial gaps, radial gaps and simplified labyrinth seals have been also included in the simulations.

### 3.2.1. *Pump-Turbine numerical model*

For the Pump-Turbine prototype, the simulations started considering only the runner hung in the air and then the runner hung but submerged in infinite water. After that, the shaft was attached to the runner, and finally, the runner was simulated in mounting conditions with the surrounding water with nearby rigid surfaces. Moreover, the head cover and lower cover were also included in the simulation to better simulate the dynamic response of the whole machine.

The numerical simulation of the runner hung in the air was validated with a complete EMA of the runner done onsite in the power plant. The runner was impacted in 35 different points in the crown, band and eye periphery and its response was measured with different accelerometers. The first 25 natural frequencies and mode-shapes accurately match for numerical and experimental results. The numerical simulation of the runner hung in infinite water was also validated with an experimental analysis presented in [38]. In this case, the numerical simulation also matched with good accuracy the available experimental data.

The case of the runner attached to the shaft in air were previously studied in [39]. The numerical model again estimated the natural frequencies with good accuracy in comparison with the experimental data measured onsite in the power plant. These experimental tests are explained in [39]. In this numerical model a sensitivity analysis of the bearing stiffness was needed to obtain the natural frequencies with small error, especially for the mode-shapes where the shaft was involved.

For the runner submerged in water in mounting conditions, the experimental tests were more complicated to be carried out because the inaccessibility of the runner. For this purpose, an especial device was designed to impact the runner from a head cover hole. Moreover, two accelerometers were also installed directly on the runner with their corresponding especial devices through another two holes in the head cover. Furthermore, other sensors such as pressure sensors, hydrophone, LDV (Laser Doppler Vibrometer) or proximity probes were also used to better understand experimentally the dynamic response of the runner in mounting conditions. After several experimental tests in the prototype some runner natural frequencies were estimated with the runner in mounting conditions. These natural frequencies presented some discrepancies with the ones obtained with the numerical model.

Experimental results showed that some acoustic modes of the surrounding fluid cavities were affecting the dynamic response of the runner (hydrophone and pressure sensors confirmed this evidence), therefore an investigation on these acoustic modes was necessary in order to include their effects also in the numerical model. These investigations are commented in Chapter 5, section 5.2. After considering these effects, the numerical results presented good results in comparison with the experimental ones.

All the conclusions commented in this section are based on the results presented in the collaborative project report [63]. The experimental results and their comparison with the numerical models are shown in this report.

### 3.2.2. *Francis-Turbine numerical model*

The process to simulate the Francis turbine prototype was the same than for the Pump-Turbine prototype. First, the runner was simulated hung in the air and then submerged in infinite water. After that, the runner was attached to the shaft in air considering also the generator, and finally the surrounding water with the nearby radial and axial gaps was included. The mesh used for this simulation can be seen in [10].

The numerical model was experimentally validated for the runner attached to the shaft in air. For the EMA, the runner was impacted in 16 different points of the band outlet and in 16 different points in the blades and its response was measured with different accelerometers located in the band outlet and inlet and in the crown. Mode-shapes were classified according their band and blades deformation and the number of nodal diameters. These mode-shapes and their natural frequencies were accurately obtained by means of the numerical model,

with a maximum error of 5% (see [64] for further details of the experimental-numerical comparison).

The case of the runner in mounting conditions could not be validated with experimental results since in this case the runner was not accessible to be impacted.



## **CHAPTER 4**

# **EFFECTS OF NON-RIGID SURFACES**

In this chapter the influence of non-completely nearby rigid surfaces on the dynamic response of submerged structures is evaluated. First, an experimental research on the standing disk test rig is presented. In this case, the disk has been approached to two different covers with different stiffness and mass. The natural frequencies, mode-shapes and damping of the disk are discussed for both covers tested. A research on prototype about the influence of head cover on the runner natural frequencies is also presented in this chapter.

## 4.1. Research on simplified models

This section is based on the experimental research on the standing disk test rig confined with two different covers. The test rig is the same than the one presented in section 2.1 but covered with a thick cover or with a thin cover. The thick cover has its natural frequencies at a higher range than the disk and the thin cover in the same range. The dynamic response of the disk, i.e. natural frequencies, damping and mode-shapes, has been determined for different axial distances to the cover. This experimental research is explained in the Journal Paper [59] which is one of the three papers that is part of the present Article-Based Thesis. This Journal Paper can also be seen in Chapter 7.

The procedure to obtain the natural frequencies was the same that explained in section 2.1. However, this time the disk had to be impacted through a hole in the cover with a especial device based on a rod with a spring (see Fig. 5 of [59] or Chapter 7). This procedure was repeated for different distances to both thin and thick covers. Moreover, the dynamic response of the cover was also obtained for every configuration in order to see how the disk and the cover interacted between each other.

The EMA of both covers showed that, in the case of the thick cover, it has its natural frequencies far away from the natural frequencies of the disk corresponding to the first five nodal diameters. The natural frequency of the disk corresponding to the sixth nodal diameter was near the first natural frequency of the thick cover. However, in the case of the thin cover, it has its natural frequencies in the same range than the disk. Therefore, the response of the thin cover is rather higher than the response of the thick cover in the range of the natural frequencies of the disk. These results are shown in Fig. 7 of [59] or Chapter 7.

When approaching the disk to a rigid wall, its natural frequencies decrease and its damping ratios increased as shown in section 2.1. However, now the cover is not a rigid wall because it has its own dynamic response in the same zone than the disk. In this case, when approaching the disk to the thick cover, the natural frequencies corresponding to the first five nodal diameters behave as in the rigid case, they decrease when the distance to the cover also decrease. However, the natural frequency of the sixth nodal diameter is almost constant when the distance to the thick cover decrease. In this zone, the thick cover has its first natural frequency, so the relative deformation between the disk and the cover is higher than for the

other modes of the disk found at lower frequencies. These results are shown in Fig. 9a of [59] or Chapter 7.

For the thin cover case, the behavior when approaching the disk is different. In this case, the natural frequencies of the disk tend to slightly increase when decreasing the distance to the cover (see Fig. 9b of [59] or Chapter 7). The relative amplitude of vibration between the cover and the disk shows that the cover cannot be considered as rigid, so its dynamic response is affecting to the dynamic response of the disk (see Fig. 8 of [59] or Chapter 7). This means that if the nearby surface is not rigid enough, the results can be different than as expected if it was rigid. This is an important conclusion for the case of hydraulic turbine prototypes.

The trend of the damping is to increase when approaching to a rigid wall, as commented in section 2.1. In this case, this behavior is the same when the cover can be considered as rigid (thick cover for the first five nodal diameters). However, when the cover vibrates at the same time than the disk with an important amplitude (this is the case of the thick cover for the sixth nodal diameter of the disk and the case of the thin cover), the damping does not follow any trend. Results are shown in Fig. 12 of [59] or Chapter 7. Therefore, when both structures cover and disk are strongly coupled, the dynamic response of the disk depend also on the dynamic response of the cover and they become difficult to be estimated.

## 4.2. Research on prototype

The influence of non-rigid surfaces has been experimentally studied in the Pump-Turbine prototype. In this case, the runner vibrates near the head cover, which is not completely rigid. To see if the dynamic response of the head cover affects the dynamic response of the runner when it is in mounted conditions, an experimental research was conducted. The head cover was instrumented with several accelerometers to estimate its dynamic response. Impacts were done in the runner and in the head cover. In that way, some natural frequencies of the runner and the head cover were determined.

Results show that the first natural frequency of the head cover was a 0 nodal diameter mode-shape and it was near (40 Hz approximately) the 2 nodal diameter mode-shape of the runner. The relative vibration between the head cover and the runner was not as high as in the case of the simplified model, but it is possible that they were affected each other. The value of the natural frequency of the 2 nodal diameter mode-shape of the runner was slightly

higher than in simulation, where the nearby surfaces are considered as completely rigid. This fact could lead to think that the head cover slightly affects the value of this mode-shape of the runner, as it was the case of the simplified model. For higher mode-shapes of the runner the affectation of the head cover could not be confirmed.

All the results commented in this section are presented in the report of the collaborative project with VOITH® [63].

## **CHAPTER 5**

# **EFFECTS OF ACOUSTIC MODE- SHAPES**

In this chapter, the acoustic modes of the surrounding fluid of submerged structures are studied. First, a numerical investigation on a submerged and confined disk is performed. In this research, all the parameters that affect the acoustic mode-shapes are studied, as well as their affectation on the natural frequencies of the disk. Then, the same investigation is presented but applied in the case of prototype turbines.

## 5.1. Research on simplified model

Fluid cavities have their own natural frequencies and mode-shapes which are called acoustic natural frequencies and acoustic mode-shapes [13]. Acoustic natural frequencies are basically dependent on the geometrical dimensions of the cavity and the speed of sound. For certain values of geometrical dimensions and speed of sound, these acoustic natural frequencies can be in the same range than the natural frequencies of the submerged structure in the fluid cavity. In this case, both acoustic and structure natural frequencies may affect each other, so this should be studied in detail because it can be very important especially in the case of prototype turbines.

The research summarized in this chapter is based on the Journal Paper [66]. This Journal Paper is not part of the present Article-Based Thesis, but it is a collaboration in the research on the topic of acoustic modes. In this paper, the acoustic and structural natural frequencies of a submerged disk in a cylindrical fluid cavity is studied. First, the structural natural frequencies of submerged disks are studied for different geometrical characteristics of the disk and different axial and radial gaps to nearby rigid walls. Then, the main parameters that affect the acoustic-mode shapes of the fluid cavity are identified. Finally, the affection of acoustic natural frequencies on the natural frequencies of the disk is quantified also for different geometrical dimensions of disk and fluid cavity.

The effect of axial and radial gaps on the natural frequencies of submerged disk have been studied in the present thesis in Chapter 2. Due to the geometrical characteristics of the disk studied experimentally, the acoustic natural frequencies of the fluid cavity were far enough from the natural frequencies of the disk, so they were not affected. The first part of the Journal Paper [66] repeat this study numerically but considering a wide range of geometrical dimensions of the disk and fluid cavity. Results are presented in a dimensionless way, so they permit to estimate the natural frequencies of any kind of submerged disk with different axial and radial gaps.

The second part of the Journal Paper [66] studies the acoustic mode-shapes and the acoustic natural frequencies of cylindrical fluid cavities. The mode-shapes of cylindrical cavities are formed by nodal diameters ( $n$ ), nodal circles ( $m$ ), and number of cross sections ( $k$ ). The value of the acoustic natural frequencies of cylindrical cavities are dependent on the

mode-shape  $(n,m,k)$ , linearly dependent on the speed of sound  $(c)$ , and inversely dependent on the cavity diameter and cavity height. The first acoustical natural frequencies and mode-shapes found in cylindrical cavities are nodal diameters  $(n)$  with no nodal circles  $(m=0)$  and no cross sections  $(k=0)$ . These mode-shapes have been called as “Global Mode-Shapes”. Moreover, in the study [66] is demonstrated that those mode-shapes are only affected by the cavity diameter, and radial and axial gaps and cavity height do not affect their natural frequency value. This is an important conclusion because only knowing the diameter and the speed of sound, it is possible to determine if the acoustic natural frequency will be in the same range than the natural frequency of the disk.

To see the influence of those global acoustic modes on the dynamic response of the disk, several acoustic-structural FSI numerical simulations were done changing the speed of sound value. For certain speed of sound value, the acoustic natural frequencies of the fluid cavity are in the same range that the natural frequencies of the disk. In this case, the natural frequencies of the disk tend to approach to the acoustic natural frequencies instead of remaining constant as it was the case when they were far away from the acoustic natural frequencies. There is a point where the natural frequencies of the disk become the same than the acoustic natural frequencies. This behavior can be seen in Fig. 10 of [66]. Moreover, this behavior only occurs for acoustic and structural mode-shapes with the same nodal diameter number. For example, the acoustic mode-shape  $n=2$  only affects the natural frequency of the disk of the mode-shape  $n=2$ .

This study has been made for the case of a submerged disk with small geometrical dimensions, so the zone where the acoustical natural frequencies affect the natural frequencies of the disk is found at a very low value of speed of sound. This is not a realistic case since the speed of sound in prototype turbines range normally from 1000-1400 m/s. However, as the results of this study are presented in a dimensionless way, there is a certain diameter where acoustic natural frequencies and natural frequencies of the disk are of the same order and for that range of realistic speed of sound values. This diameter is about 3-4 m, the size of some of the large existing prototype turbines.

## 5.2. Research on prototype

The same study than for the simplified model has been made for the case of the Pump-Turbine prototype. For that case, the speed of sound was changed from 600 m/s to 1400 m/s and the influence of the acoustic modes on the dynamic response of the runner was evaluated. In the simulation, the fluid cavity considered the water passage through the runner blades and the small clearances to the rigid walls. Results showed the same trend than the ones obtained on the simplified model. The natural frequency of the runner decreased when it was near an acoustical natural frequency whose mode-shapes had the same number of nodal diameters. These results are presented in the collaborative project report [63].

However, this study only considered the water inside the runner and in the clearances. Further studies were performed including also the spiral casing, the wicket gates and the draft tube. The mode-shapes of the draft tube cavity practically do not affect the ones of the runner, however, the mode-shapes of the spiral casing and wicket gates cavities also had an effect on the runner mode-shapes. The most remarkable point was a  $n=2$  acoustic mode-shape of the spiral casing found near the  $n=2$  mode-shape of the runner for a realistic value of speed of sound. This mode-shapes was also found experimentally in the tests carried out in the Pump-Turbine prototype explained before in Chapter 3, section 3.2.1.

In those experimental tests, two different situations were tested: one with pressure in the runner and other one without pressure. In the first situation, the runner was under the pressure of the lower reservoir level with the wicket gates open and the spiral casing full of water with the valve at its inlet closed. In the second situation, the runner was under atmospheric pressure because the gate at the draft tube outlet was closed and air was injected through the spiral casing removing water and so pressure from a draft tube hole. Therefore, the spiral casing was half-filled with water with free surface at certain level and the runner was submerged without pressure.

Results of natural frequencies of the runner were different for these two situations. With the runner under pressure, two different  $n=2$  mode-shapes were found separated few hertz between them. However, with the runner without pressure, only the second  $n=2$  was found. In the first situation, the first  $n=2$  mode-shapes was clearly detected with the hydrophone installed. With this information and the one obtained by simulation, this first



mode-shape was identified as an acoustic mode-shape of the spiral casing and the second one was identified as the structural mode-shape of the runner. Moreover, as they both are near in frequency, they can be affecting each other, presenting a strongly coupled situation between acoustic and structural modes. These results are also shown in the collaborative project report [63].

Therefore, affectation of acoustic mode-shapes in real prototype were experimentally and numerically demonstrated with this study. The effect of the acoustic mode-shapes of the fluid cavities (spiral casing, wicket gates water passage, runner water passage and draft tube) on the dynamic response of the runner could be important and should be considered for the calculation of the natural frequencies of the runner.

# CHAPTER 6

## CONCLUSIONS

In this chapter the major conclusions of this thesis are summarized. First, the main conclusions of the studies performed on simplified models are summarized and its application to prototypes is pointed out. Finally, the conclusions obtained in both prototypes turbines are also included.

Summing up all the investigations performed in this thesis and the obtained results, several conclusions and contributions have been achieved:

- **Effects of nearby rigid surfaces were evaluated.**

Experimental investigations on a submerged disk were carried out and the influence of axial and radial gaps to rigid surfaces on the natural frequencies, damping ratio and mode-shapes was studied. The same investigation but by means of numerical simulations were carried out in two different large hydraulic turbine prototypes, one Pump-Turbine and another Francis turbine. With this study the influence of the axial gap was studied for a Pump-Turbine runner and the influence of the radial gap was studied for a Francis turbine runner. For both, the change in natural frequencies according the nearby rigid surface is important and should be always considered.

- **Effects of nearby non-rigid surface were estimated.**

An experimental research on a submerged disk confined with two different covers was carried out. With this investigation, the influence of the cover stiffness on the natural frequencies, damping and mode-shapes of a submerged disk was evaluated. This research is useful in the field of hydraulic turbines because runners are also submerged structures confined with head and lower covers, which are not totally rigid. Some experimental investigations have been also conducted on a Pump-Turbine prototype analyzing the dynamic response of the head cover and runner at the same time.

- **Effects of acoustic mode-shapes were evaluated.**

A numerical investigation on a submerged disk to study the influence of the acoustic-mode-shapes of the surrounding fluid on the natural frequencies of the disk was performed. The natural frequencies and mode-shapes of the disk and the natural frequencies and mode-shapes of the fluid cavity were studied separately for different geometrical dimensions. Once the influence of all the geometrical parameters was evaluated in both dynamic responses of disk and fluid cavity, the coupled case was studied in detail. In this case, the influence of the acoustic mode-shapes on the dynamic response of the disk was studied and its affectation was obtained.

This study is useful especially in the hydraulic turbine prototypes, because due to its large dimensions, the acoustic natural frequencies of the surrounding fluid and the natural frequencies of the runner are of the same order. The behavior found with the simplified model has been confirmed also in the case of a Pump-Turbine prototype. A numerical and

experimental investigation was carried out in a Pump-Turbine prototype and the affectation of acoustic mode-shapes on the dynamic response of the runner was confirmed.

- **Numerical models have been validated.**

All the experiments performed in this thesis have been simulated also using numerical models. These numerical models presented good results in comparison with the experimental data, so they were validated. Once validated, these numerical models were used to study, confirm and complete the knowledge about the dynamic response of large hydraulic turbine prototypes.

As a general conclusion, this thesis has contributed to a better knowledge of the influence of some boundary conditions on the dynamic behavior of hydraulic turbine runners. This has been achieved by means of experimental and numerical research on simplified models, as well as with experimental and numerical research in a large Pump-Turbine and in a large Francis turbine. These investigations have contributed to several publications in indexed Journals Papers (see Table 1-1) and to several presentations in congresses related with the topic (see Table 1-2). Moreover, they are also part of two important research projects: “Dynamic response of pump-turbine impeller in operation [63]” in collaboration with VOITH® and “HYPERBOLE [70]” European Project.

# CHAPTER 7

## COPY OF THE JOURNAL PAPERS

In this chapter the copy of the three Journal Papers that are part of the present Article-Based thesis is included. The first paper is entitled “*Experimental study on the added mass and damping of a disk submerged in a partially fluid-filled tank with small radial confinement*” and it is published in the Journal of Fluids and Structures (Q1, 2014, Impact Factor 2.021). The second one is “*On the Capability of Structural–Acoustical Fluid–Structure Interaction Simulations to Predict Natural Frequencies of Rotating Disklike Structures Submerged in a Heavy Fluid*” published in the Journal of Vibration and Acoustics (Q2, 2016, Impact Factor 1.692). The third Journal Paper is “*Experimental Study of a Vibrating Disk Submerged in a Fluid-Filled Tank and Confined With a Nonrigid Cover*” published also in the Journal of Vibration and Acoustics (Q2, 2016, Impact Factor 1.692).

All these papers are non-open access papers, so here a copy of them is included with a digital watermark of “Confidential”.

### ATTENTION ;

Pages 46 to 80 of the thesis, containing the texts mentioned above, should be consulted on the web pages of the respective editors:

<https://www.sciencedirect.com/science/article/pii/S0889974614001248>  
<http://vibrationacoustics.asmedigitalcollection.asme.org/article.aspx?articleid=2492698>  
<http://vibrationacoustics.asmedigitalcollection.asme.org/article.aspx?articleid=2579990>

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