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Dynamics of a misaligned Kaplan turbine with blade-to-stator contacts

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ABSTRACT

Rotor-to-stator contacts can occur in hydropower systems due to mechanical and electrical misalignment as well as high unbalance forces. It can result in high impact forces and damages in case of malfunction of the machine. As a result, a real hydropower rotor is studied to evaluate the different types of dynamic motion due to multiple impacts when it is initially misaligned. In this paper, the simplicity of its blade rubbing modelling allows us to evaluate in a fast and efficient way the dynamics of this system as a function of several design parameters. It is observed that the global dynamics of the system are similar to simple bladed Jeffcott rotors when scaled with the number of blades. Since the rotor runs at its operating point, the contact forces are also evaluated at nominal speed. A parametric study – as a function of contact stiffness and damping – is performed and results are given in terms of Poincaré sections, bifurcation diagrams and maximum displacements at steady state. These simulations are used to determine if the system is safe to operate. It can be used to design hydropower rotors by choosing the operating speed in a suitable range, or to analyse if the machine can be stopped before a catastrophe occurs.

1. Introduction

Rubbing in rotating machines is known to produce high impact forces and can lead to catastrophic failures in the worst case scenario. In recent years, studies have been more focused on blade-to-stator contacts. The severity of these kinds of system is due to the intermittent contacts between the blades and the casing. Due to the modelling complexity of contact systems, it becomes tedious to find analytical solutions for blade rubbing problems, and the first expectations of the system's behavior can be discredited by numerical simulations.

Rotor to stator contacts have usually been studied assuming cylinder to cylinder contact. Simple models have been developed and analyzed extensively. For instance, Karpenko et al. developed a model of Jeffcott rotor with preloaded snubber ring. The experimental model validates the results found numerically [1,2]. Popprath and Ecker [3] studied the behavior of a suspended rotor contacting a dynamic stator as a function of the normalized speed and mass ratio. Gonsalves et al. [4] developed a model of discontinuous Jeffcott rotor subjected to mass-unbalance forces and found a good agreement between numerical simulations and experimental tests. Qin et al. [5] investigated the contact of an overhung rotor as function of rotating speed, unbalance and external damping using the transfer matrix method. Most of these models are simplified but they can be evaluated as function of several parameters. However, Behzad et al. [6] have developed a model of rigid rotor contacting a discretized stator using the Lagrange multiplier technique to solve the constraint equation during contact. In a similar way, Ma et al. [7] evaluated the rubbing between an elastic rod and a disk using the augmented Lagrangian method. They showed that the contact stiffness and gap have a strong influence on collision rebounds. Blade–tip rub interaction usually concerns detailed models studied for a fixed set of parameters. Padovan and Choy [8] developed a blade to stator contact model with large linear kinematics. They investigated the influence of several parameters such as unbalance, friction and blade stiffness. Sinha [9] studied the transient response of a decelerating rotor where blade rubbing occurs close to resonance. Roques et al. [10] also investigated blade rubbing caused by accidental imbalance using a Lagrange multiplier approach and prediction–correction marching procedure. Using a complex model, Legrand et al. [11] evaluated contacts due to modal interaction and small clearances. They also developed a three-dimensional model of the contact phenomena using the Lagrange multiplier and B-splines of the contact surface. More details of rotor-stator interaction can be found in Jacquet-Richardet et al. [12].

In most of these articles, the contact modelling has been performed using a detailed finite element formulation in the case of blade contacts. It is of interest to use these models to obtain reliable contact forces during rubbing. However, the drawback of highly accurate models is the simulation time. It does not allow in

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Nomenclature

Roman Symbols

c_{ij}	damping coefficients
c_r	runner damping
E	Young's modulus
e	unbalance eccentricity
$f_{\max}$	maximum force
f_s	standard alternating-current
J_d, J_p	moment of inertia
k_{UMP}	magnetic pull stiffness
k_c	contact stiffness
k_{ij}	stiffness coefficients
L	blade length
m	added mass
p	pair of poles
R	casing radius
R_0	cylinder radius
$r_{\max}$	maximum amplitude
v_{c_k}	contact velocity
x	displacement in x-direction
y	displacement in y-direction
y_0	misalignment

Bold symbols

$\mathbf{C}$	damping matrix
$\mathbf{F}_n, \mathbf{F}_t$	contact forces
$\mathbf{f}_{\text{contact}}$	contact forces
$\mathbf{f}_{\text{unb}}$	unbalance forces
$\mathbf{G}$	gyroscopic matrix
$\mathbf{i}, \mathbf{j}$	unit vectors in fixed coordinate system
$\mathbf{K}$	stiffness matrix
$\mathbf{M}$	mass matrix
$\mathbf{n}, \mathbf{t}$	unit vectors in rotating coordinate system
$\mathbf{r}$	blade tip position vector
$\mathbf{T}, \mathbf{S}$	transformation matrix

Greek symbols

β	blade angle
δ	clearance
$\mathbf{\Omega}_{nom}$	Nominal speed
μ	friction coefficient
ν	Poisson's ratio
ω, Ω	rotating speed
ρ	density
θ_p	Poincare phase
φ_k	blade phase
ζ	damping ratio

Subscripts

IRS	Improved Reduction System
m	master node
s	slave node
UMP	Unbalance Magnetic Pull

a reasonable computational time to evaluate the global properties of the system as a function of one or several design parameters. In this paper, the dynamics of rubbing is simplified and modeled as an unilateral contact between rigid blades and a flexible casing. In our case, the blade contact interaction is investigated in a 10 MW Kaplan turbine. Since the clearance is small in this type of machine – around 0.1% of the hub diameter – contact might occur between the runner blades and the turbine chamber due to high unbalance forces and fluid forces. A previous study on a general hydropower machine has been performed by Gustavsson and Aidanpää [13]. It was assumed that the angle of the blades was set to 0°, making the contact similar to cylinder-to-cylinder rubbing. In our model, it is assumed that contact of all blades can occur during operation. A first study is performed to verify the global dynamic properties when the rotor is initially misaligned and compare the results with simplified Jeffcott models [14,15]. Then a complementary study of the contact model is performed at operating speed as function of the contact stiffness and damping induced by fluid–structure interaction.

2. Model description

2.1. Overview of the system

The model of the 10 MW Kaplan turbine is composed of 46 nodes and described by Timoshenko beam elements with shear, rotary inertia, gyroscopic effects and consistent mass matrix. The rotor is hollow with an inner diameter of 0.15 m. The three bearing positions are shown in Fig. 1(a), with the first one for the upper guide bearing at node 6, the second one for the lower guide bearing at node 16, and the third one at node 41 for the turbine guide bearing (from top to bottom). The stiffness and damping properties of the bearings are constant (no rotational speed dependency) and anisotropic. Additional masses and inertia are set at node 1 for the exciter, 11 for the generator and 46 for the runner. These values are shown in Table 1. The Unbalance Magnetic Pull (UMP) between the rotor and the generator is modeled as a constant negative stiffness k_{UMP}.

2.2. Contact model

In this simplified model, the 6 Kaplan blades in Fig. 1(a–c) are considered to be extremely stiff due their thickness and material properties. On the runner, pivots allow us to change the angle β of the blades as seen in Fig. 1(b). When $\beta = 0°$, the contact model can be assimilated to cylinder rubbing [13]. On the contrary, our study focuses on the extreme case where the blades are open as much as possible. Two main assumptions have been adopted when deriving the equations of motion that are specific to hydropower machines. First of all, the blades are assumed to be rigid in comparison with the draft tube that defines the surrounding structure. Moreover, their mass is neglected when compared with the runner total mass. As a result, the study will focus on the dynamics of the system due to unilateral contacts only since stiffening effects for the blades will not have any influence, especially when the rotor runs at low speed. In addition, their will be no parametric excitation induced by the blades rotation. Hence this unilateral contact model cannot be applied to machines such as gas turbines or steam turbines and is more specific to hydropower rotors (or similar machines) having a low operating speed.

The contact forces during blade impacts are derived in the fixed coordinate system in Fig. 2 ($\mathbf{O}, \mathbf{i}, \mathbf{j}$). The rotor is initially misaligned in the y direction with an eccentricity y_0. When a contact occur for the kth blade, a restoring force $\mathbf{F}_n^{(k)}$ is applied to the rotor where