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On the non-linear behaviour and orbit patterns of rotor/stator contact with a non-conventional containment bearing

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ABSTRACT

The present work is a numerical study with experimental validation of the non-linear behaviour of a rotor interacting with a non-conventional back-up bearing. When the rotor's movement in the (x,y) plane reaches an undesirable amplitude, such movement is restrained by the new bearing, composed by pins. These pins receive all the impacts, working as a containment bearing. This work presents a numerical study of the rotor impacting on the pins and later compares it with experimental data extracted from a vertical rotor test rig. While conducting numerical simulations, the results show the different characteristics of the rotor orbit, depending on the applied torque. The steady state trajectories formed singular geometries, different from each other. A set of data was collected, showing this interesting rotor/stator interaction due to impacts with the pins. The results include various non-linear features, such as bifurcations and chaos. Furthermore an experimental test rig is mounted and the position of the rotor inside the modified safety bearing is measured and the result is compared to the simulation presented.

1. Introduction

Rotor/stator contact is one of the most serious malfunctions occurring in rotating machinery. Specifically, rotor rub against a seal may cause a catastrophic failure of the machine in a very short time. The rotor/stator rub may manifest itself in the form of a full annular rub, when the contact between the rotor and stator is continuously maintained. The rub occurs due to high friction-related wear and damage may occur quite rapidly. Among the first authors to deal with this topic we find the works of Johnson [2] and Black [3] analysing the possible contact with the stator, through a clearance, of a whirling rotor. The topic of full annular rub and dry whip recently gained more attention, following an increasing number of applications of machines with active magnetic bearings, usually equipped by retainer bearings [1].

Retainer bearings (also called *back-up*, *auxiliary* or *safety* bearings) have become standard 'back-up' elements in rotor machinery applications. They provide support for the machine rotor during start-ups and shut-downs. Recently, retainer bearings have been used not only for these functions, which are auxiliary to the machine main operation, but also in 'load-sharing' applications. In these uses, while not interfering with the rotor during normal machine operation, retainer bearings provide added, often just temporary, support to the rotor in critical situations. Sudden imbalance or bearing failure give rise to transient short- or long-term overloads, which would lead to increased lateral static or dynamic displacements of the rotor. The use of retainer bearings as an additional load-sharing support of the rotor during all abnormal conditions must ensure safe, effective, and consistent operation of the machine.

The dynamic phenomena occurring when the rotor is forced into contact with the retainer bearings are very similar to the rotor full annular rubs in mechanical seals and/or other stationary contacting parts with circumferential surfaces. The regime of self-excited dry whip of a rotor dropped onto retainer bearings is certainly very unwelcome, and can be devastating [4].

Impacts and rubbing are also a major concern for magnetic bearings machines, which a sudden failure or due to a non-robust control is considered a critical issue as the rotor looses its levitation support. Magnetic bearing designs are described by Schweitzer [5] and Ulbrich et al. [6] and since then it has become a device with great importance and industrial interest. Therefore, the eventual drop of a rotor on the bearing and ways to avoid contact on the structure are densely researched. Schmied and Pradetto [8] used a one ton compressor and dropped it on a rolling retainer bearing to study its vibrational behaviour in a case of failure of the magnetic bearing. Ishii and Kirk [9] simulated numerically a flexible rotor transient from the shutdown to the contact state with the back-up bearing. Their results showed that backwards whirl movement happens and the contact force magnitudes were considered high. In the work of Fumagalli [10] the

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performance of the auxiliary bearing due to the dynamics of the rotor sliding on it was investigated, identifying the effects of the parameter variation on the motion, force and energy dissipation. Then he investigated different contact models and analysed the contact force on the bearing measuring acceleration on the vertical plane. In the works of Wiercigroch [11], he presents an algorithm on solving dynamical systems with discontinues in parameters, and secondly considers a continuous function approximation for the discontinuities as a smooth function. Different dynamics models are presented, including that for a Jeffcot/DeLaval rotor.

Many researchers try to avoid the contact by applying active control techniques to the systems. Ginzinger et al. [14] and Keogh [15] undertook this control strategy by considering the auxiliary bearing as an active element. Actually the majority of industrial applications use the rolling bearing concept for retainer bearings. Recent publications from Wilkes et al. [12] and Wilkes and Allison [13] make a thorough investigation by modelling a rolling bearing drop test with experimental transient tests.

While the rotor/retainer bearing dynamic behaviour was addressed in several publications (e.g., [7–16]), the aspect of designed load-sharing feature of these bearings during normal operations only recently became the subject of research. Retainer bearings with pins inside the structure were developed for this purpose.

2. The new safety bearing design

The idea of using pins to reduce the rotor amplitude was primarily investigated by graduate students in the Dynamics and Vibration Laboratory at PUC-Rio. The ongoing cooperation with DTU (Denmark Technical University) lead to the results presented by Lahriri et al. [21,22] and Fonseca et al. [17]. They conducted numerical and experimental analyses of a rotor system with the presence of the pins in safety bearings. One main purpose of that retainer bearing design is to prevent the whirling effect on the rotor interacting with the stator. Such phenomenon, especially if a backward whirl arises, is hazardous, leading to shaft fatigue and bearing or rotor failure. The idea behind the presence of the pins is that they act as elements to support impacts. In [17], a controlled but rather simplified concept of a bearing design using pins showed that this safety bearing design could help the rotor to surpass its critical speed. The controller acts by advancing the pins into the bearing clearance during critical situations, such as the rotor reaching resonance or rotor amplitudes high enough that impacts on the bearing wall may occur. When the rotor returns to a low vibration condition or no other indication of rotor instability exists, the pins are retracted, and the rotor resumes its normal operation. The simulations, combined with experimental validation, showed that it is possible to overcome the rotor critical speed with the help of this new safety bearing. Nevertheless, the torque must be greater than the minimum torque [24] necessary to overcome this operation point.

The impact behaviour of the disk was previously analysed in the work of Isaksson [20], which identifies stable regions by various parameters. In Chavez et al. [26], a vibration control strategy was created using active auxiliary bearings. Recently, numerical investigations using finite elements were presented by Ma et al. [25]. In the work of Simon [23] there were presented and analysed different geometries for safety bearings. However, it is believed that single-shaped structure designs are more efficient to work as containment bearings when the rotor passes through resonance. An idealized concept to prevent any impact on the bearing structure is to leave the exact free space for the rotor to move without the possibility of hitting the stator wall. Fig. 1(a) illustrates this condition. The shadowed area is the space where the rotor centre is able to move, which will be called the rotor's *workspace*. In the limit case, shown in Fig. 1(a), the workspace corners are the only points where the rotor really hits the structure of the bearing. As it will be shown the lengths of the pin are calculated in a way that such contacts with the bearing will not occur.

In this work a numerical study takes place to investigate the shape of the orbits and the impact force magnitudes during the rotor start up, under different motor torque values (even lower than the minimum torque). Due to the presence of the strong non-linearity caused by the impacts, the mechanical system presents unique orbit shapes, even under the slightest variations of the applied torque. Bifurcations and chaotic behaviours are also observed by mapping the impact forces magnitudes and the disk centre position in time. Due to the strong non-linearity caused by the impacts at the steady state, a slight increase or decrease in the motor torque can result in a different form of the trajectory of the disk centre. Also, the forces on the pins at each impact are calculated and the next steps include a comparison of these numerical studies with experimental results (prototype of safety bearing shown in Fig. 1(b)). The non-linear analysis used here are based on the work Strogatz [27].

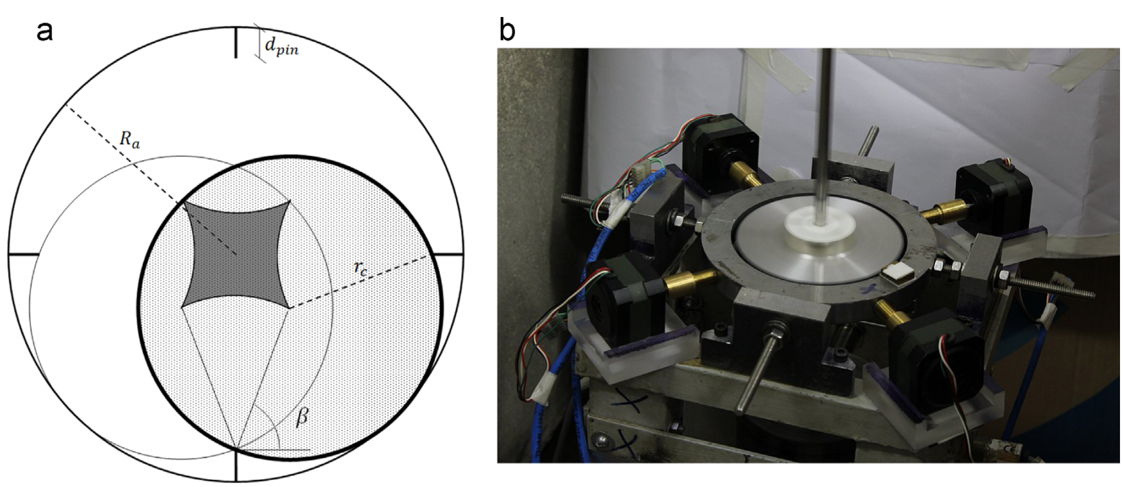

Fig. 1. (a) Sketch of the safety bearing design using impact pins to avoid rubbing. The grey area is the rotor centre free area, or workspace. (b) Prototype of the safety bearing on the rotor machinery test rig.