Mechanical Systems and Signal Processing 23 (2009) 2205–2227

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/jnlabr/ymssp

Light and short arc rubs in rotating machines: Experimental tests and modelling

P. Pennacchi *, N. Bachschmid, E. Tanzi

Politecnico di Milano, Department of Mechanical Engineering, Via La Masa 1, I-20156, Milan, Italy

ARTICLE INFO

Article history:
Received 11 November 2008
Received in revised form
17 March 2009
Accepted 21 March 2009
Available online 5 April 2009

Keywords:
Rotordynamics
Rub
Experimental tests
Modelling

ABSTRACT

Rotor-to-stator rub is a non-linear phenomenon which has been analyzed many times in rotordynamics literature, but very often these studies are devoted simply to highlight non-linearities, using very simple rotors, rather than to present reliable models. However, rotor-to-stator rub is actually one of the most common faults during the operation of rotating machinery. The frequency of its occurrence is increasing due to the trend of reducing the radial clearance between the seal and the rotor in modern turbine units, pumps and compressors in order to increase efficiency. Often the rub occurs between rotor and seals and the analysis of the phenomenon cannot set aside the consideration of the different relative stiffness. This paper presents some experimental results obtained by means of a test rig in which rub conditions of real machines are reproduced. In particular short arc rubs are considered and the shaft is stiffer than the obstacle. Then a model, suitable to be employed for real rotating machinery, is presented and the simulations obtained are compared with the experimental results. The model is able to reproduce the behaviour of the test rig.

1. Introduction

Rotor-to-stator rub in industrial rotating machinery can occur in different sections of the machine and can have different degrees of severity. In this paper, the interest is focused on rub that occurs between parts that have different stiffness, in particular when the rotor is stiffer than the stator or, more precisely, than the parts where the contact happens. This fact, which can appear unrealistic when thinking about massive casings, is on the contrary very frequent, when a working fluid is present. In order to increase machine efficiency, there is a trend to reduce the gap between the rotor and the fluid seals. Considering that rotating machinery can cross some critical speeds during the run-ups and the run-downs, the rotor can interfere with the seals in case of incorrect design, excessive imbalance, misalignment, bad assembly or other causes. Due to their specific function, these seals are often of labyrinth type and in this case the stiffness of the threads is less than that of the rotor. Fig. 1 shows the effect of rub on a seal: threads are practically destroyed and the functionality of the seal is heavily damaged.

Several experimental cases have been documented in literature about rub occurred during operation or commissioning of real rotating machinery. Some of them are related to rub diagnostics and employ model-based fault identification applied to vibration measurements (see [1–3]). Curami et al. [4] present the experimental evidence of a heavy rub in a

* Corresponding author. Tel.: +39 02 2399 8440; fax: +39 02 2399 8492.
E-mail addresses: paolo.pennacchi@polimi.it (P. Pennacchi), nicolo.bachschmid@polimi.it (N. Bachschmid), ezio.tanzi@mecc.polimi.it (E. Tanzi).

0888-3270/$ - see front matter
doi:10.1016/j.ymssp.2009.03.008

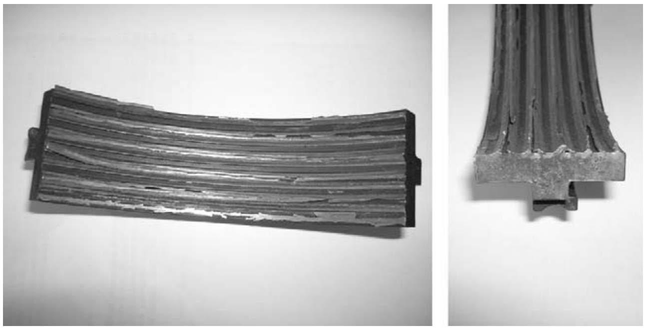

Fig. 1. Effect of the rub on a labyrinth seal.

320 MW steam turbine and analyze the possible parametric instability due to the periodic radial stiffness variation of the rotor, concluding that this phenomenon is unlikely in real machines.

Stegemann et al. [5] describe long lasting tests on a 100 MW steam turbine with about 500 cases of rub, investigated by means of the combined use of vibration and acoustic emission. Hall and Mba [6] present a successful case of rub diagnosis on a 500 MW steam turbine using acoustic emission. These last studies highlight the presence of high-frequency components in the measured noise.

Intense research activity has been also performed on test rigs. Due to the relative small scale of the rigs employed, rotor-to-stator rub phenomenon can be studied with more accuracy and in the controlled environment of the laboratory. However, in some cases, test rigs are so small and simple, with very flexible shafts that can hardly reproduce the behaviour of real rotating machinery. Hall and Mba [7] have tuned up their method using a test rig in which partial rub is reproduced between a multi-disk rotor and several types of steel and brass fixture, reproducing seals. Anyhow the contact occurs as a consequence of the non-circular section of the shaft in correspondence of the seal, rather than of the rotor whirling.

Several experimental tests are also documented by Chu et al. [8–11] for a rather small test rig. Starting from the experimental observation that the so-called transient natural frequencies change once the rub-impact occurs, they analyze the increase of the transient stiffness of the rotor as the consequence of the interaction with the obstacle. The transient stiffness increasing is used to locate the position of the rub [8] and some test, aimed to identify it, are presented in [11], indicating that transient stiffness keeps on increasing with the rub-impact and aggravating when the speed is increasing. The study of the stiffness increasing is also presented by Fumagalli and Schweitzer [12] by means of a test rig, in which magnetic bearings are used as both exciters and sensors and the obstacle is rather stiff. The results obtained are similar to those of Chu and Lu [11], even if the concept of transient stiffness is not introduced. Magnetic bearings are also used to prevent physical interaction between rotor and stator laminations by Keogh and Cole [13,14].

Keeping in mind the aspects related to the contact, Choi [15] discuss the combined effect of the rotor dynamical behaviour (i.e. rotor whirling) and of the relative speed between the rotor and the obstacle on the friction coefficient. From these results, it appears that the friction coefficient varies considerably from reference values when the rotating speed is close to the critical speed of the small test rig employed in the experiments. Other studies of the same author are focused on partial rub during speed transients, with the analysis of the rotor forward and backward whirling [16,17]. Experimental tests on partial arc rub are presented and discussed by Muszyńska and Goldman [18] and Muszyńska [19], which observed that frequency behaviour patterns of the rotor response were systematically repeatable, but the specific orbits appeared quite unstable, especially when the rotor-to-stator normal forces are higher (i.e. when the interference between the rotor and the obstacle is higher) and the contact lasted longer. Authors share the explanation given to this: friction-related surface wear causes continual changes in clearance. Anyhow a deeper analysis is cumbersome: in case of real machinery, seals are relatively less stiff than the rotor and this cause not only wear but also seal plastic deformation. Consequently the transient stiffness varies sensibly. This notwithstanding plastic deformation is reduced in case of light rub and can be considered as a second-order effect. The possibility to forecast the experimental chaotic motion of a test rig using a fitting technique is presented by Hu and Wen [20].

The precession and the effects of the friction force, especially with regard to dry-friction whirl and whip, are also analyzed repeatedly by Childs [21–23]. Bently et al. study the same problem, focusing on mechanical seals and on full-annular rub: experimental results obtained by using a small test rig are presented [24] and a mathematical model aimed to study the stability, but not to reconstruct experimental results, is introduced [25]. Stability analysis is the topic of several papers in literature: Jiang and Ulbrich [26,27] use a Jeffcott rotor model to perform the stability analysis of the full-annular rub. A similar topic is studied by Muszyńska [28]. Also Ehehalt et al. [29–31] study the stability thresholds by means of a Jeffcott rotor. Cole and Keogh [32] use a Jeffcott rotor model to analyze the stability of the rotor-to-stator contact of a test rig. Anyhow stability thresholds show that the interference should be so severe that rarely can occur in real machines without a catastrophic result and all these results appear not verified by experimental studies by Curami et al. [4]. Thus this paper is not focused on so severe rub and considers only short arc rubs.