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Experimental observations in the shaft orbits of relatively flexible machines with different rotor related faults

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ABSTRACT

An experimental study on the shaft orbit response for different rotor related faults is presented in this paper. Similar previous studies in readily available literature were done considering a few fault conditions on different machines. Therefore, an opportunity exists to provide further insight to changes in the behaviour of a single machine when affected by a wider range of different rotor related faults. Experiments are done on a small laboratory ball bearing rig on which vibration displacement data are acquired for a baseline condition as well as six different fault conditions that are introduced separately at different subcritical steady state speeds. For each condition tested, orbit plots are generated and critically analysed. These orbits are also compared to those observed on a similarly configured rig with different dynamic characteristics on which the same experiments are done in order to assess any changes in the shaft orbit. The present work provides useful results for practical rotor fault diagnosis as well as worthwhile qualitative information to analytical studies related to the rotor faults observed here.

1. Introduction

The orbit plot is a two dimensional representation of the dynamic motion of the centre of a rotating shaft at a measurement plane [1], which presents a snapshot of the rotor actual motion at its centre [2]. Proper interpretation of the orbital paths or rotor lateral motion (rotor orbital and its direction) provides insight into the nature of the machinery fault [2] and the forcing functions acting on a shaft [1]. Unsurprisingly, since its introduction at least some forty years ago (Bently, 1974 cited in [3], p. 12) the orbit plot is widely utilised in theoretical studies aimed at gathering insight to the nature or effects of different rotor fault conditions such as: bow [4–6], crack [4,7–15], looseness [16,17], misalignment [18–20], rub [5,6,12,16,19,21–25] and unbalance [5,11,13,19,26,27]. Though these theoretical studies have been highly relevant to revealing the intricacies of machinery faults, it was generally observed that they are often attempted with several assumptions and simplifications that may produce results or features that may not be useful in practice [13,28]. It is therefore apparent that the validation of theoretical models with experimental or practical field acquired results is important [2,3]. Needless to say, both theoretical and experimental studies should co-exist in a continuously improving symbiotic relationship in order to advance the knowledge of the nature of failures and the understanding of diagnostic tools such as the orbit plot. That said, relatively lesser experimental works have been attempted than theoretical ones.

In an attempt to characterise the presence of a crack on an overhung rotor, Adewusi and Al-Bedoor [29] extracted different vibration features from different techniques including the orbit plot analysis. During crack propagation at a steady state speed on an experimental rig with

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self-lubricated sleeve bearings, the rotor tracked a smooth inner looped orbit which became distorted, due to wobbling, on increasing the bending moment acting on the overhung rotor. Both Darpe et al. [7] and Sinou [30] experimentally identified a similar inner looped orbit which changes size around half of the first critical speed for a transverse crack due to the presence of a dominant second harmonic. Whilst Darpe et al. [7] used experiments on a self-aligning ball bearing rig to validate results obtained from the analysis of a Jeffcott rotor passing through subcritical resonances with a transverse breathing crack, Sinou [30] presented a comprehensive experimental study using a rig with bush bearings and slotted rotors that represented rotors with open cracks. Darpe et al. [7] concluded that the change of orientation of the inner looped orbit on passing through "subcritical resonances" could be a crack diagnostic indicator. Sinou [30] added that the inner loop size is proportional to slot depth. Interestingly, Bai et al. [27] also reported an inner looped orbit for a ball-bearing rotor system, but not for a cracked rotor condition. Instead, that orbit shape was "provoked" by subharmonic resonance which occurred when the rotating speed of a small ball bearing rig under an unbalance load was around twice its critical speed.

Lee and Lee [18] validated a theoretical model for a misaligned rotor bearing system at different steady state speeds near the first critical speed of a laboratory test rig supported by deep groove ball-bearings. It was shown that with increasing angular misalignment, the orbit tends to collapse from a circular shape to an ellipse; due to an increase in the anisotropic nature of the bearing stiffness. The major axis of this ellipse was perpendicular to the misalignment direction below the critical speed, but was aligned to the misalignment direction after passing through the critical speed (that is, a 90° rotating of the elliptical orbit). The orbits for parallel misalignment were, however, unperturbed relative the healthy orbit due to the effect of a very flexible coupling element. Similarly, Pennacchi and Vania [31] also reported a collapsed 1× filtered orbit for an angular coupling misalignment case on an experimental study of a real turbo-generator train with lemon shaped oil-film bearings. The fault symptoms were analysed in the field, modelled and then experimentally verified for identification. Both Lee and Lee [18] and Pennacchi and Vania [31] conducted experiments in the vicinity of the first critical speed of the system explored. As earlier demonstrated by similar findings by Lee and Lee [18], Pennacchi and Vania [31] reiterated that their observations were applicable to machines supported by ball bearings, but was exacerbated for machines on oil-film journal bearings because of lower bearing stiffness and hence possible higher rotor deflections in the latter case.

Patel and Darpe [32] studied the whirl nature of higher frequency components of the vibration response due to coupling misalignment at or near different "sub-harmonic resonances" on experimental rig supported by single-row ball bearings. It was noted that regardless of the type of misalignment, rotor orbits are stretched in the direction of the plane of the misalignment due to an increase in the effective stiffness, and consequent suppression of vibration response, in the direction perpendicular to the plane of the misalignment. It was further added that rotors with angular misalignment reveal outer loops, whereas those from parallel misalignment might exhibit inner looped orbits. Further to this, with the aim of identifying features which are better able to discriminate faults with similar spectral features, such as crack and misalignment, Patel and Darpe [33] presented experimental investigations on crack, misalignment and rub from steady-state vibration response at sub-critical rotational speeds on two different laboratory rigs supported by ball bearings. The results show that misalignment generates a backward whirling outer loop orbit which is stretched in the direction orthogonal to the misalignment direction as compared to a forward whirling inner loop of a crack. The inner looped orbit for crack fault was consistent with aforementioned findings [7,29,30].

With the intent to ascertain which pattern of vibrations represents steady state processes and to identify what are the most sensitive parameters affecting changes in said steady state regions, Muszynska and Goldman [16] examined the dynamic behaviour of unbalanced rotor rolling element bearing systems with a loose bearing pedestal or rotor–stator rubs using different experimental rigs respectively. Results from a local impact model were compared to results from experiments that were presented in the orbit plot, amongst others, to mainly provide insight to the dynamics of rotor–stator rub. It was observed that at higher machines speeds during partial rotor–stator rubbing, orbits contain distinct reverse-procession loops due to the rub-related tangential force which opposes the direction of rotation. It was also shown that the rotor support anisotropy resulted in a "butterfly" (sideways 8) effect for a rotor operating at twice its first balance resonance speed under the influence of a partial rub.

The nature of rotor/seal full annular rub was demonstrated with orbit plots by Yu et al. [21], which conducted experiments on an "annular rub test rig" supported by two brass bushing bearings. The authors made a clear distinction between reverse procession full annular rub, which had a very smooth orbital pattern and "multicontact intermittent rub" which had a "bounce pattern". The difference in the mentioned rub patterns depended on friction between contacting surfaces during the rub. Aided by the tracking of the evolution of the orbit around the first natural frequency, it was concluded that reverse procession (dry whip) can occur without external disturbances for small rotor/seal clearances. Chu and Lu [34] explored the dynamic effects of partial and full rotor–stator rub on a small experimental rig with rolling element bearings in order to aid rub fault diagnosis. The authors were able to correlate the different types of rubs with the different rotor orbits from responses that contained 1/2 and 1/3 fractional harmonics as well as super harmonic components. Pennacchi et al. [23] analysed the effects of light rub between rotor and seal strips by comparing experimental results from a rig supported by two lemon shaped oil-filmed bearings with simulations from a mathematical model. At both sub-critical and super-critical speeds, it was noted that the shape of the rotor orbit is strongly dependent on the interference between the seal and rotor. Cong et al. [35] validated an earlier proposed rub-impact model with