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Simultaneous identification of unbalance and shaft bow in a two-disk rotor based on correlation analysis and the SEREP model order reduction method

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ABSTRACT

This paper focuses on a theoretical and experimental identification of two of the most common faults that occur in rotating machines, which exhibit similar problems: unbalance and residual shaft bow. Numerous studies deal with shaft bow, but only a few involve rotors containing many degrees of freedom and the simultaneous occurrence of these two faults. The identification procedure proposed here belongs to the techniques based on the mathematical model of rotors and faults. Finite elements were used to model the rotor, and the faults were identified using an approach based on correlation analysis, which involves only the rotor's responses in the time domain. The System Equivalent Reduction Expansion Process (SEREP) model reduction technique was employed in order to use only the disks' responses and avoid high computational costs. The identification equation derives from the Lyapunov matrix equation of the reduced system model and the fault parameters are identified by least-squares fitting, considering both magnitude and location. Since the shaft bow is considered constant, the faults were identified in two steps, which consider variations in the unbalance parameters: 1) theoretically, considering ten different cases of unbalance and subjected to the same shaft bow, and 2) experimentally, in which the same ten different cases are validated using experimental data from a laboratory test rig. The proposed procedure proved consistent in identifying two faults that occur simultaneously and exhibit similar symptoms.

1. Introduction

Fault detection in rotating machines is a classic topic in rotor dynamics and is still a topic of prolific research today, since the presence of any fault directly influences the performance of rotating machinery, leading to financial losses and safety implications. Any defect in rotors affects the vibration behavior, and the nature of this effect differs in each kind of fault the machine presents.

Fault identification techniques using vibration measurements follow two main approaches that use correlations of measurable symptoms to the faults [1,2]: the signal-based and model-based approach. In the first approach, qualitative

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information is used to identify the relationship between symptoms and faults and it is based on the experience of the analyst who will interpret the measured data. The vibration signal is combined with a statistical model of the expected fault, which is used when the physical model of the fault is difficult to obtain or when a statistical model suffices to give a good description of the fault [2].

Model based methods are used to identify the location and magnitude of the faults. This approach is quantitative and requires a reliable model of both the machine and the faults. Ref. [3] state that these techniques provide more accurate and faster information than conventional signal-based systems, since *a priori* information about the rotor is included in the identification process. These techniques are seen as more robust methods and the accuracy of the results they yield is strongly related to the accuracy of the model, which must be sufficiently simple to allow for fast on-line calculations but exact enough to reproduce the system's behavior.

Rotating machines have many faults that must be identified: unbalance, misalignments, shaft bow, gear faults, bearing faults, shaft cracks, rub and looseness, fluid-induced instability, etc. Similarly, there are several mathematical approaches to model system [4]. In general, rotor systems are modeled using finite elements and faults are modeled as equivalent external forces and moments.

This work focuses on unbalance and shaft bow, which are among the most common faults in rotating machines. Although these faults stem from completely different causes, they are both synchronous with the machine rotation and have similar symptoms, making it difficult for the analyst to make a correct diagnosis [5]. The bow and the eccentricity of the mass from the geometric center are usually in different angular locations and warped rotors behave somewhat differently from purely unbalanced rotors [6].

An important form of vibration to which rotating machinery is subject in a wide range of applications is vibration due to inherent unbalance caused by small manufacturing imperfections in forging, inhomogeneities in the material, slight errors in machining, etc. Simultaneous faults commonly occur in rotating machines, and unbalance is accompanied by another fault.

Lal and Tiwari [4] state that estimating unbalance is a long-standing problem, but research in this field is still active. Ref. [3] use least squares fitting in the time domain to identify unbalance and rubbing in a test rig. Ref. [7] adopted the methodology proposed by Ref. [3] in the theoretical estimation of unbalance and transverse fatigue cracking of the shaft, but these faults were considered separately. Ref. [8] used the same technique to identify unbalance in the presence of misalignment. Least squares fitting can also be used in frequency domain [1]: modeled three types of faults: unbalance, misalignment and shaft bow occurring in a 320 MW turbo generator. Ref. [4] developed an identification algorithm for the simultaneous estimation of dynamic bearing parameters, residual unbalances and misalignment of a rigid turbine-generator. Ref. [9] estimated the unbalance and the physical magnetic bearing parameters. Ref. [2] applied the Least Angle Regression (LAR) technique and compared the results with techniques in both time and frequency domains and LAR was performed. Their results were better than those reported by Refs. [1] and [3].

Some authors included the foundation in the rotor modeling: [10,11,12].

Shaft warping or static bending can be permanent or temporary due to some effects such as thermal distortion, gravity sag, mechanical bow from prior unbalance or shrink fits [6,13]. The literature about shaft bow is not as vast as that of unbalance. In general, references address the issue qualitatively. In other words, studies focus on changes in the rotor responses caused by the bow when the rotor already has another fault, such as unbalance or shaft crack. Changes in the amplitude and phase of rotor outputs are considered. Papers that use a quantitative approach in identifying bow parameters are less common than those that identify unbalance.

One of the pioneering works was performed by Ref. [13]. The authors conducted a systematic and extensive numerical study on the effect of shaft bow phase on the response of an unbalanced single mass flexible rotor supported by rigid bearings. The tests showed that, unlike conventional unbalance, the change in phase angle from rest up to the speed where maximum amplitude occurs is not 90°. Another interesting result occurs when the bow is 180° out of phase with the unbalance: there is always a speed at which the rotor amplitude is zero.

Ref. [14] demonstrated that the results obtained by Ref. [13] cannot be extrapolated to a rotor supported by fluid film bearings. Ref. [15] studied the effect of residual shaft bow on the dynamic response of a simply supported single disk rotor with disk skew and mass unbalances. The numerical results revealed the differences caused by disk skew on rotor responses compared to the rotor behavior presented by Ref. [13]. Ref. [6] carried out detailed studies of the influence of bow on rotor response phase. The author concluded that the response phase is more important than amplitude behavior when the bow is present. Ref. [16] employed a quantitative identification approach based on the best fit of a given objective function, enabling the identification of faults with similar symptoms, such as unbalance and shaft bow. Ref. [17] analyzed the effect of residual bow on the stiffness of the rotating cracked shaft, as well as changes in the dynamics of a cracked rotor. Ref. [18] investigated the dynamic characteristics of a geared rotor-bearing system mounted on viscoelastic supports subjected to gear faults and residual shaft bow. Ref. [19] simulated the influence of residual shaft bow on the longitudinal responses of the rotor in a test rig with multiple faults. Ref. [20] used the Ritz approach enriched with specific shape functions to identify bow, unbalance and roundness separately via optimization of the rotor orbital parameters.

As one can see, the great majority of the studies about shaft bow is performed qualitatively and so far few studies have focused on the identification of the unbalance and shaft bow when they occur simultaneously.

The complexity of rotor system models is increasing due to the need to understand the system's response in order to design predictable, low maintenance and cost-effective machines, which has led to complex large-order rotor models. The field of rotor dynamics utilizes several reduction methods and variations thereof from both structural mechanics and controls