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Theoretical and experimental identification of the simultaneous occurrence of unbalance and shaft bow in a Laval rotor

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ABSTRACT

This paper discusses the theoretical and experimental identification of two of the most common faults that occur in rotating machines: unbalance and residual shaft bow. The identification procedure is based on the mathematical modeling system. The dynamic system was modeled using finite elements and the faults were identified using an approach based on correlation analysis that involves the rotor responses in the time domain. The identification equation derives from the Lyapunov matrix equation of the reduced system model, which contains only the measured degrees of freedom, and the fault parameters are identified by least-square fitting. The Differential Evolution (DE) optimization technique was used to identify the bearing physical properties as well as the coupling and rotor damping. The faults were identified theoretically, considering seven different cases of unbalance and bow locations, after which the rotor was subjected to four different unbalance situations in order to identify both the unbalance and the unknown shaft bow, based on experimental measurements. The proposed procedure proved consistent in identifying two faults that occur simultaneously and similar symptoms.

1. Introduction

Rotating machines, which are very common in technical plants, play a crucial role in machinery because they constitute one of the most important types of machines used in the industrial production chains that underpin every country's economy. Thus, safety, reliability, efficiency and performance are major concerns for rotating machines.

Pennacchi et al. [1] state that the dynamic behavior of rotors involves numerous topics of interest, and that ranking these topics is a difficult and subjective task. According to the authors, two possible criteria should be used for this purpose, the first economic and the second scientific and, considering these two criteria, fault identification in rotors is one of the most important topics. From the economic standpoint, early fault identification can reduce off-line times and maintenance stoppage, and prevent accidents. The scientific criterion attracts many researchers on all continents.

The most common fault is probably unbalance, since there is no such thing as a perfectly balanced machine. Errors of geometric dimensions, mounting, and raw material inhomogeneity make it difficult to have a perfectly balanced object, since they cause undesirable vibrations that can affect machine performance.

Markert, Platz and Seidler [2] propose an algorithm in time domain. The faults can be modeled as a set of equivalent forces and moments that generate the observed dynamic behavior. Least squares fitting and the concept of residuals, defined by the difference between the faulty and pre-faulty conditions, have been used to identify unbalance and rubbing, but the unmeasured degrees of

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freedom (DOF) should be estimated by modal expansion. Pennacchi et al. [1] adopt residuals and least squares fitting in the frequency domain, as well as the foundation model, to generate an identification algorithm.

Simultaneous faults commonly occur in rotating machines, and unbalance comes together with another fault. Therefore, numerous researches have focused on identifying multiple faults. Bachschmid, Pennacchi and Vania [3] modeled three types of faults: unbalance, misalignment and shaft bow occurring in a 320 MW turbo generator. Jalan and Mohanty [4] used the ideas of Markert et al. [2] to identify unbalance in the presence of misalignment. Sekhar [5] identified unbalance and cracking in the same algorithm.

Some techniques are able to identify not only the fault but also the bearing or foundation parameters. Sinha, Friswell and Lees [6] identified flexible foundation parameters and unbalance in a single run-down based on the system's dynamic stiffness matrix. Tiwari and Chakravarthy [7] developed two algorithms for the simultaneous estimation of residual unbalance and dynamic bearing parameters. The first algorithm uses the impulse responses of the shaft measured at the bearings and the second uses the synchronous unbalance response in the clockwise and counter-clockwise directions.

Another common fault in rotating machines, which may be permanent or temporary, is the shaft bow that occurs when the shaft sags due to gravity, thermal distortions caused by asymmetric heating or cooling, and mechanical bow due to unbalance, for example.

Nicholas, Gunter and Allaire [8] published one of the first works about shaft bow that is still cited today in shaft bow-related research. They demonstrated that the dynamic behavior of a bowed rotor differs from that caused by unbalance, and described the self balancing phenomenon that occurs when the shaft bow is 180° out of phase with the disk unbalance.

Rao [9] points out that phase angle measurements are necessary to make an unequivocal diagnosis of a warped rotor, since rotor responses exhibit a particular behavior only when the bow is out of phase with the unbalance. The author discusses several cases, considering variations of the amplitude and phase of the rotor bow relative to the unbalance. The phase behavior in each case is completely different from a pure unbalanced rotor.

Shiau and Lee [10] showed that disk skew changes the dynamic behavior of the rotor described by Nicholas et al. [8]. Darpe, Gupta and Chawla [11] analyzed the effect of residual bow on the stiffness of the rotating cracked shaft and changes in the dynamics of a cracked rotor. Kang et al. [12] investigated the dynamic behavior of a gear-rotor system with viscoelastic supports under the effects of gear eccentricity, the transmission error of gear mesh and the residual shaft bow. Song, Yang and Wang [13] simulated the influence of residual shaft bow on the longitudinal responses of the rotor in different cases. A test rig with multiple faults was built and the experimental signals were collected. The fault features were extracted using wavelets and nonlinear manifold learning. The shaft bow signal was isolated from the other faults by means of principal component analysis, and the proposed equation of the rotor considering sensor installation error was validated experimentally.

Most of the studies that have investigated shaft bow are qualitative. In other words, they describe the effect of bow on the rotor's dynamic responses, mainly in the presence of other faults such as unbalance, crack, and misalignment. Few studies have identified shaft bow in quantitative terms, unlike the unbalance identified for the performance of balance procedures. Pennacchi and Vania [14] and Vania, Pennacchi and Chatterton [15] used statistics and mathematical models to locate and identify thermal bow in power unit turbines. The aforementioned works describe a methodology to identify the most likely fault by means of the best fitting of a given objective function, enabling the identification of faults with similar symptoms, such as unbalance and shaft bow. However, no studies have focused on the identification of these faults that occur simultaneously.

Correlation analysis is the basis to generate the algorithm for fault identification. This approach was proposed theoretically by Pederiva [16] to identify physical parameters of the rotor by means of random excitation. The advantage of this methodology is the use of correlation matrices, which take into account only the responses measured at different time instants, precluding the need for direct measurements of the excitation forces. Sanches and Pederiva [17] identified unbalance and shaft bow theoretically for a two-piece disk rotor, using a simple mathematical model of the rotor based on the lumped mass matrix. The first experimental validation of this methodology was done by Sanches and Pederiva [18], considering only the identification of unbalance without the presence of shaft bow and using a more complete mathematical model of the rotor based on finite elements, residuals and model order reduction.

This paper identifies the magnitude and location (phase) of unbalance and shaft bow that occur simultaneously. The identification is done first theoretically, considering variations in the unbalance position relative to a specific reference that coincides with a specific point on the shaft, so the location of unbalance varies in relation to the shaft bow. Experimental validation is also performed in a test rig, considering four different changes in the location of unbalance, allowing for the verification of different combinations of unbalance angular positions and the shaft bow.

The identification algorithm is performed in the time domain and is based on the mathematical modeling of the rotor and the faults, which are determined using only the rotor responses without trial runs. The Guyan reduction is applied to reduce the order of the rotor model, so that the responses of proximity probes can be used in the disk position.

2. Mathematical modeling

The rotor, which is excited by both unbalance and shaft bow, is modeled as a stable linear time-invariant system. Thus, the dynamic system can be described by a matrix differential equation with n degrees of freedom:

$$[M]\left\{\ddot{\xi}(t)\right\} + [P]\left\{\dot{\xi}(t)\right\} + [K]\{\xi(t)\} = [H]\{n_{un}(t)\} + [B]\{n_b(t)\} \quad (1)$$

where $[M]$ is the mass matrix, $[P]$ is the force proportional to velocity matrix, which contains the damping and gyroscopic matrices, and $[K]$ is the force proportional to displacement matrix; all previously mentioned matrices have order (g,g). $\{\ddot{\xi}(t)\}, \{\dot{\xi}(t)\}$