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Crack identification for rotating machines based on a nonlinear approach

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A B S T R A C T

In a previous contribution, a crack identification methodology based on a nonlinear approach was proposed. The technique uses external applied diagnostic forces at certain frequencies attaining combinational resonances, together with a pseudo-random optimization code, known as Differential Evolution, in order to characterize the signatures of the crack in the spectral responses of the flexible rotor. The conditions under which combinational resonances appear were determined by using the method of multiple scales. In real conditions, the breathing phenomenon arises from the stress and strain distribution on the cross-sectional area of the crack. This mechanism behavior follows the static and dynamic loads acting on the rotor. Therefore, the breathing crack can be simulated according to the Mayes' model, in which the crack transition from fully opened to fully closed is described by a cosine function. However, many contributions try to represent the crack behavior by machining a small notch on the shaft instead of the fatigue process. In this paper, the open and breathing crack models are compared regarding their dynamic behavior and the efficiency of the proposed identification technique. The additional flexibility introduced by the crack is calculated by using the linear fracture mechanics theory (LFM). The open crack model is based on LFM and the breathing crack model corresponds to the Mayes' model, which combines LFM with a given breathing mechanism. For illustration purposes, a rotor composed by a horizontal flexible shaft, two rigid discs, and two self-aligning ball bearings is used to compose a finite element model of the system. Then, numerical simulation is performed to determine the dynamic behavior of the rotor. Finally, the results of the inverse problem conveyed show that the methodology is a reliable tool that is able to estimate satisfactorily the location and depth of the crack.

1. Introduction

Visual examination, ultrasonic tests, and dye penetrant inspection are some examples of nondestructive techniques widely used for crack detection in rotors. These methods have proved to be costly, since satisfactory results rely on detailed and periodic inspections. Significant research effort has been directed in recent years to online monitoring techniques, i.e., based on vibration

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signals measured during rotor operation for the detection or identification of cracks location and severity (size and depth of cracks) [1–3]. The techniques based on vibration measurements are recognized as promising SHM tools (Structural Health Monitoring). According to Dimarogonas [4], over 500 papers were published on this subject between the 1980s and 1990s and this number is still very significant in the present days.

There are several Structural Health Monitoring techniques, the so-called SHM techniques, proposed in the literature for crack detection in rotating machines. Among them, the ones based on vibration measurements are recognized as useful tools because they lead to satisfactory results even when the damage location is not accessible or even unknown [5]. About these techniques, two accepted rules are employed for detecting a crack. The first one is based on the monitoring of the synchronous vibration amplitude and phase. According to [6], changes in 1X amplitude and phase are the primary indicators of crack presence. The second rule relies on 2X vibrations, where [6] states that if a cracked rotor has a steady unidirectional radial load, then a strong 2X response may appear when the rotor is turning at half of any balance resonance speed. However, although widely used in industry, when applied in non-ideal conditions such techniques can detect cracks that eventually have already spread significantly by the cross section of the shaft, usually above 40% of its diameter. Therefore, currently, the researchers' attention is turning to more sophisticated methods capable of identifying incipient cracks (cracks that spread up to 25% of shaft diameter), which represent a type of damage that are hardly observable in vibration analysis [7–9].

Based on previous simulations, [10] and [11] have experimentally detected a crack by applying a specified harmonic force on the rotor by means of a single magnetic bearing. The rotor used in the work is composed of a shaft supported by two active magnetic bearings and one disc located at the shaft middle span. In the analyses, a small notch was cut by using a wire electric discharge machine close to the disc in order to obtain a behavior similar to the breathing crack mechanism. The presence of the damage led to spectral responses with additional peaks at frequencies that are combinations of the rotor speed, its critical speed, and the frequency of the diagnostic force. The method of multiple scales was used to determine the conditions required to create the combinational resonance. In [12], a preliminary experimental application of a crack identification methodology based on combinational resonances was proposed (i.e., technique based on [10,11,13]). The technique uses external applied diagnostic forces at combinational frequencies, together with a pseudo-random optimization code known as Differential Evolution, in order to characterize the signatures of the crack in the spectral responses of the flexible rotor. The rotor used is composed by a horizontal flexible shaft, two rigid discs, and two roller bearings. A small notch was also cut on the shaft in order to obtain breathing crack behavior. The methodology proposed by this work (i.e. preliminary experimental application) proved to be an interesting tool to detect, locate and estimate the depth of transverse cracks in shafts of rotors.

Regarding the crack simulation, two models are currently used to represent the breathing behavior with weight dominance, namely the models proposed by Gasch [14] and Mayes and Davies [15]. In both, the mechanism for opening and closing the crack is described by simple mathematical functions. The Gasch's model considers the crack opening and closing abruptly, while the Mayes' model allows for a smooth transition between the fully opened and fully closed crack. It is worth mentioning that when static loads prevail over the dynamic ones (i.e. in a heavy horizontal shaft with relatively low unbalance) the crack opens and closes gradually every revolution of the system. Thus, the breathing assumes weight dominance. Although lead to reliable results, there are other models that can accurately represent the breathing phenomenon. Among them are the 3D model (developed at the research center of EDF) and the FLEX model [7]. However, the computational cost of the Mayes' model is significantly smaller than the FLEX. In [16], an analytical method devoted to the modeling the crack behavior was carried out (i.e., finite shaft element with transverse crack). In [17], the authors present a number of different simplified approaches to modeling cracks in rotating shafts. The influence of the crack models on the dynamic response of a Jeffcott rotor is demonstrated by using the method of harmonic balance. New breathing functions are proposed by [18] in order to formulate the time-varying stiffness matrix of the cracked finite element. The results were compared with typical formulas for representing the breathing mechanism. According to the authors, the proposed functions give more accurate results regarding the dynamic behavior of the cracked rotor. Additionally, [19] proposes a new mathematical model for the cracked rotating shaft based on the rigid finite element method. The crack is represented as a set of spring-damping elements connecting the crack faces. The proposed model is validated by numerical and experimental evaluations.

In this context, the present contribution comprises the numerical application of a SHM technique previously proposed by [12]. The open and breathing crack models are compared regarding its dynamic behavior and the efficiency of the proposed identification technique. Based on the nonlinear behavior introduced by transverse cracks in rotating shafts (i.e., the combinational resonance), the crack presence, location, and severity is identified by using an evolutionary optimization method combined with the mathematical models encompassing the rotor and the open crack. Additionally, the dynamic response of the rotating shaft considering the breathing crack is compared with the results obtained from the open crack model (i.e., the small notch used to represent the crack behavior). Therefore, the Fourier expansion of the periodic stiffness matrix truncated at the third harmonic component is performed on the crack finite element.

According to [20], cracks where firstly found in shafts of some steam turbines around the 1950s. Thus, research on the vibration behavior of cracked rotating shafts began to be reported in order to prevent major accidents and to develop diagnostic systems. Simultaneously, a few scientific works on nonlinear subharmonic resonances due to ball bearings were published. However, the nonlinear treatment dedicated to cracked rotors is more recent. Research conducted by [10], and other experts, shows an interesting similarity between experimental and numerical results. Thus, it is expected that the methodology proposed here (i.e.