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Model based identification of crack and bearing dynamic parameters in flexible rotor systems supported with an auxiliary active magnetic bearing

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ABSTRACT

In this paper, possibility of identification of a crack appearing in flexible rotor systems supported with active magnetic bearing has been investigated. A cracked rotor with active magnetic bearing (AMB) support in auxiliary bearing configuration has been analysed for identification of crack and end support bearing stiffness. Presence of AMB in an auxiliary bearing configuration provides additional damping to the rotor system, thus attenuates the vibrations induced by rotor flaws. Identification strategies based on vibration responses of such a rotor may not produce correct results. However, loss of diagnostic information due to attenuation of the vibration signal could be compensated for, by supplementing the vibration signal with the AMB control current history. With inclusion of the control current history, the crack force and other parameters could be identified. A cracked rotor with multiple discs has been modelled by standard finite elements method, with consideration of gyroscopic effect due to rigid discs. Breathing behaviour of the crack has been modelled with a switching crack excitation function, containing multiple harmonics of both forward and backward nature. Full spectrum of the frequency domain of the response is utilised to develop the identification algorithms. This algorithm identifies the crack force in form of additive crack stiffness and simultaneously estimates the disc unbalances, end support bearing stiffness and active magnetic bearing dynamic parameters as well. The algorithm has been tested in a simple rotor system for the measurement noise and bias errors in system parameters, and found robust.

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1. Introduction

Active magnetic bearings (AMB) are mechatronics product that find wide applications in rotating machines. These bearings are capable of continuously manipulating the force between the fixed magnetic poles and the rotor, such that the rotor is maintained spinning around its predetermined position. Design of smart machines, capable of adapting to the changes in the working and ambient conditions has been envisioned and research is active in this field [1]. AMB used to support the rotor or used as auxiliary bearing, brings in the possibility of smart machine concept into rotating machines application.

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More so, AMB has applications in field of condition monitoring of rotating machines since diagnosis and prognosis of faults, particularly of the rotor, is key factor deciding their reliability and dependability.

While, allowable vibration, stability and other technical issues in design and implementation of AMB has been documented in standards, particularly those originating from ISO [2–4], issues in their application in rotating machine applications has been dealt in detail in [5,6]. The principal benefit of AMB application in rotor support system rests on the fact that the shaft load is not born by any metallic or fluid contact (as in rolling element and hydrostatic or hydrodynamic bearings), but by the magnetic force between the stationary poles and the spinning rotor. This makes AMB a bearing of choice in vacuum and high temperature ambiance environment, where conventional bearings cannot be put into service. It's suitable for applications where lubrication is prohibitive or unmanageable, like pharmaceutical appliances, diffusion pumps and space applications [6]. In main stream industrial application, usage and review of performance of AMB in crude oil pumps has been reported in [7]. AMBs find newer applications due to their contactless (hence silent) and smooth operation.

Research on AMB supported rotors focuses on two important issues: first – the AMB as a technology product is full of challenges to be overcome in terms of improvement in performance and second – utilising the AMB for newer and innovative applications. On the first count, research is focused on reducing the size of the ensemble of components that complements an AMB implementation in the way of development of improved solid state components and design of better control strategy. While solid state components dictate the size and information processing capability of the device, the control strategy has a direct impact on the dynamics of the rotor [8]. For a successful AMB implementation, the control strategy should be adequate enough to maintain stability in the event of occurrence of rotor flaw and ensure rotor motion with reduced vibrations - as before occurrence of the flaw. On the second front of AMB related research – AMBs are used for non-contact forcing/excitation for the purpose of detection of crack in the rotors [9].

Crack identification in rotors has been conventionally accomplished with model based methods. These methods utilize analytical or numerical models to simulate the behaviour of cracked rotors and attempt is made to correlate the simulated vibration history with the presence of cracks at designated locations on the rotors [10]. In this method, the effect of crack is modelled as an equivalent force applied in the intact system. Many researchers, such as Sekhar [11], Pennacchi et al. [12] and Lees et al. [13] have utilized this to identify the location and depth of cracks in rotors. Some other model-based methods have also been reported, like Söffker et al. [14] compared a model-based technique based on a proportional-integral observer with a signal-based technique based on the support vector machine using features extracted from wavelets to identify a crack in an operating rotor.

Of a multitude of faults like mass unbalance, rotor-stator rub, shaft bow and misalignment, crack, and rotor asymmetry; the appearance of a transverse crack is the most detrimental event in operation of a rotating machine. Appearance of transverse crack exposes the machine and the operator at the risk of lost production and risk of life, respectively, if not identified and attended upon in early stage. Among the researchers in the field of diagnostics and condition monitoring of machines, rotors in particular, modelling of cracked rotors for analysis and identification has been a field of interest. Rotor with AMB support has added difficulty to attend to – due to the inherent nature of the AMB of keeping the rotor close to its predefined position; the operational vibration due to appearance of a crack on such rotor are weaker as compared to rotor without active support. For this reason, any crack identification program based on operational vibrations alone may not yield correct results in presence of AMB support. For a fruitful identification program, the model should replicate the actual set up as closely as possible and all the source of information should be utilised. AMB control current can be used as a diagnostic signal, which compensates for the loss of information on account of vibration attenuation.

The authors analysed a simple model of a Jeffcott rotor with a crack and AMB support for the purpose of crack identification [15] and extended the analysis for an offset Jeffcott configuration [16]. The identification algorithm used in these works was based on observation of vibration displacement and AMB control current. Since an AMB implementation already has provision for these measurements as part of its hardware component, identification of crack and other system parameters could be performed without any additional measurements. Due to assumption of a simplified model, many aspects of rotor-AMB system dynamics, like unbalance effect on multiple planes and end support bearing stiffness could neither be incorporated nor identified in the previous models.

In this paper, dynamics of the cracked rotor – AMB system has been modelled in a more realistic way, by means of finite elements. The work reported in this paper deals with identification of the crack and the end support bearing stiffness. The AMB current and displacement stiffness and the magnitude of residual unbalance are also identified.

2. System configuration

A schematic representation of the rotor configuration considered for this work is presented in Fig. 1. The rotor supported on conventional bearings and AMB, carries p number of discs. The rotor is composed of rigid discs mounted on a flexible shaft containing a single transverse crack. The rigid disc model in analysis suits best for components like flywheels, turbine and fan impellers, brake and clutch discs, and cranks from the practical application point of view. The rotor has support of m number of AMBs at different locations. The rotor is driven by a motor through a flexible coupling outside the end support bearing. The end support bearings have been characterized by stiffness and damping along the orthogonal transverse directions. Properties of the left and right bearings are considered different. The dynamics of the prime mover and the flexible coupling are not included in this analysis.

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