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Identification of bearing dynamic parameters and unbalance states in a flexible rotor system fully levitated on active magnetic bearings

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ABSTRACT

An identification algorithm for the estimation of dynamic parameters of Active Magnetic Bearings (AMBs) and rotor residual unbalances has been presented for a flexible rotor system. The proposed algorithm is suitable for the state of the art rotors that are fully levitated on AMBs. Due to a partial attenuation of unbalance responses by AMBs, difficulty arises in getting the correct estimations from unbalance responses alone, which is not the case with the conventional bearings. For latter bearings responses do reflect real effects of unbalances. Thus, the present algorithm is based both on the measured AMB controlling currents and rotor unbalance responses, and uses these to identify AMB dynamic parameters of each AMB and residual unbalances in flexible rotors at predefined balancing planes. The algorithm is based on the least-squares fit technique in frequency domain. AMB dynamic parameters consist of the force–displacement and the force–current coefficients in two orthogonal transverse directions for each AMB. The finite element method has been used to obtain a unified model of the flexible rotor fully levitated with AMBs for the numerical study, in which the PID controller is used. Numerical simulations have been performed to illustrate the reliability of proposed algorithm. The algorithm is also tested against the measurement noise and modelling errors to investigate its robustness. The proposed algorithm has been finally applied to an experimental data (from Technical University of Darmstadt, Germany) from a fully levitated five-disc flexible rotor test rig with the help of two AMBs. Estimates of AMB dynamic parameters are found to be in close range with that of theoretical values.

1. Introduction

In the present day industries rotating machines are very common, thus analyses of its characteristics and performance has become a foremost focus for practicing engineers and researchers. Associated with this the most frequent faults related to rotating machines are unbalances, misalignments, fatigue cracks, the wear and tear of various moving and stationary components, and faults related to components of gears, bearings, couplings, blades, vanes, and seals [1–3]. Now several active devices are being used in rotors to tackle the problem of fault detection and diagnosis. With the industrial requirement of very high-speed rotating machinery, the recent trend is to use Active Magnetic Bearings (AMBs), which provide contactless motion of rotors to reduce friction and eliminate the lubrication system. This has posed several new challenges to *rotordynamicsts* and encouraged them to switch over their role as *rotortronists* [4,5].

Amongst a variety of faults, the most frequent fault is the residual unbalance in machineries, which occurs due to the manufacturing inaccuracy (fits and tolerances), material in-homogeneity, thermal deformation, wear and tear during operation, and residual stresses. Even a well balanced rotor may deteriorate its balance state due to many causes like the wear, abrasion, acquiring some mass in the form of dirt, breakage of its element parts and during its repairs. Hence, any operational rotor requires inspection and balancing at regular intervals. Residual unbalances beyond certain level produces excess of unbalance forces thus generating large vibrations which may prove to be fatal causing failure of the entire rotor system. Many balancing methods have been developed to avoid excessive vibrations of rotors [2,3,6–8]. However, the focus is now on getting the estimation with minimum number of test runs and fewer number of measurements because downtime is very expensive and also there is a limitation on the accessibility of rotor for the measurement.

Zhou and Shi [9] reviewed the active control and balancing of rotating systems. They classified active control into two parts namely the *direct active control* and *active balancing techniques*. It was concluded that active balancing suppresses the vibrations

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due to unbalance; as they eliminate the cause of vibration, i.e. the residual unbalance directly. Now as AMBs are being used gradually, the balancing of flexible rotors fully levitated on AMBs have posed a great challenge. AMBs have a characteristic to suppress both steady-state unbalance responses and other transient responses [5]. Lee et al. [10] developed an active balancing program. He used influence coefficient method and electromagnetic balancing device for the balancing of high-speed spindle system.

The majority of the work on AMBs has been done on the control system. In design of controllers various control laws have been applied to magnetic bearings from classical PD controller to even robust and nonlinear ones [11,12]. Groom and Bloodgood [13] proposed a model by adding leakage to the ideal models. Binder et al. [14] dealt with the modelling, simulation and control of AMB system, where the PID and state space controllers were used. Vibrations in rotor systems levitated on AMBs can be controlled by actively controlling controller parameters; hence, very little effort has been given on finding the actual residual unbalance. However, it is advantageous to reduce residual unbalances to minimum in rotors that are levitated on AMBs because this reduces the effort on controller and also reduces the power consumption in the form of a continuous controlling current to be supplied to attenuate rotor vibrations [15].

Research has been carried out on the estimation of magnetic forces and stiffness parameters of AMBs but most of the work has been done by FEM formulation of bearing magnetic field. Imlach et al. [16] used linear magnetic circuit theory to estimate the force and stiffness of radial AMB's. Measurements were done with AMB's installed in a canned motor pump. The agreement was found to be reasonable at low eccentricities. Knight et al. [17] used linear finite element techniques to study a magnetic bearing actuator. The virtual work method was used in his work. Hsiao and Lee [18] used a nonlinear finite element technique to determine the force of a radial magnetic bearing. They presented a study on two types of radial magnetic bearings and effects of geometric parameters. The force of an AMB was calculated by using the Maxwell's stress tensor method. Lee et al. [19] studied a permanent magnet bias system with a magnetic circuit model. The static characteristics of a prototype were tested and compared with the estimated ones in the linear region. Antila et al. [20] used a nonlinear 2-dimesional finite element method to predict the performance of radial magnetic bearings. Linearised parameters for the dynamic model of AMBs at different operation points were determined by FEM. Even though these theoretical models are accurate, however, these fail to predict the reliable estimate of magnetic bearing forces and its dynamic parameters because of the lack of actual test conditions at bearing locations (magnetic flux leakage losses, effect of temperature, etc.). Hence, estimation of these parameters through experiments in actual test conditions is an alternative. However, development of experimental methodology is rare on estimation of dynamic parameters of the magnetic bearings. It has been observed from the literature survey [21,22] that though many algorithms have been proposed for the estimation of conventional bearing parameters and residual unbalances through forced responses of the system, hardly such work has been carried out for rotors levitated with AMBs.

The force acting on a rotor supported in an AMB can be measured by either measuring the magnetic flux density by integrating Hall sensors into the air gap or by measuring coil currents and rotor displacements [23,5]. Aenis et al. [23] compared the effectiveness of these methods by applying known forces on the rotor. They concluded that the flux based method is more accurate compared to current–displacement method. However, the air gap of the AMB has to be enlarged to accommodate Hall sensors. This decreases load capacity of bearings and common actuators does not have enough room to hold Hall sensors. Both the flux method and current–displacement method use analytical formulae to calculate the force. Polajzer et al. [24] made an attempt to calculate the forces exerted by an AMB using the FEM formulation. Kasarda et al. [25] used a multi-point method in contrast to a single point method for the force measurement in AMBs. This is altogether a different complicated approach, but asserts to be more accurate than conventional force measuring techniques.

In the present work, a methodology is proposed to estimate AMB dynamic parameters along with inherent unbalances in a flexible rotor that is fully levitated by AMBs. It is based on measured controlling currents of AMBs and unbalance responses at AMB locations. Numerical examples are used to illustrate the developed algorithm in which numerically simulated unbalance responses and current information is used for the estimation. The numerical model consists of discs mounted on a flexible rotor that is fully levitated with AMBs. The identification algorithm is based on least-squares fit and estimates are found to be excellent even with the addition of measurement noise and model parameter bias errors. The proposed methodology is applied to an experimental setup and estimates are compared with those from the closed form theoretical formulae.

2. System modelling

In the present section assumptions regarding the model considered are stated. The finite element formulation of the unified rotor-AMB model is carried out to obtain equations of motion. These are then used to develop the identification algorithm to estimate the residual unbalances and AMB dynamic parameters.

2.1. Basic assumptions and model description

A flexible rotor-train system levitated on AMBs, as shown in Fig. 1, is considered for the study. It is composed of flexible shafts on which rigid discs are mounted and shafts are connected by couplings. Rigid discs are mounted on the flexile beam either by shrink fit or by other mechanical means. Practically, a rigid disc model represents flywheels, turbine blades, cranks, rotary wings, couplings, disc brakes, impellers, rolling bearings, etc. The whole rotor is levitated with the help of AMBs at different locations. The rotor is driven by a motor through a flexible coupling. Standard Timoshenko beam theory with gyroscopic effects has been considered in finite element modelling of the rotor system. The proportional damping has been considered for the shaft. AMBs are considered to have the linearised displacement and current stiffnesses in two orthogonal transverse directions. The rotor can have discrete unbalances at disc locations, distributed unbalance along the length of the shaft or a combination of both is also possible. In this case, discs are assumed to be balancing planes to estimate residual unbalances in these planes. The number of balancing planes would be based on the operating speed of the rotor. A PID controller is used for AMB and effects of sensors and amplifiers are ignored in the present study for brevity.

2.2. Finite element model formulation

The finite element method involves the discretization of a continuous structure and has been used successfully in the design and analysis of practical rotors with the complex and irregular shapes [3]. The considered model is composed of flexible rotor, rigid discs and AMBs on which the whole rotor is levitated. The total model is discretized into smaller models for simplicity i.e. the shaft model, disc model, and AMB model. Then each individual model is considered separately and equations of motion for that model are presented. All such equations from each sub-model are then reassembled to get the global equations of motion so that boundary/support conditions could be applied.