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Estimation of speed-dependent bearing dynamic parameters in rigid rotor systems levitated by electromagnetic bearings

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In the present work, an identification algorithm to estimate dynamic parameters (i.e., displacement stiffness and current stiffness) of active magnetic bearings (AMBs) and residual unbalances in a rigid rotor system levitated on AMBs has been developed. AMB dynamic parameters are considered to be dependent on the rotor speed and the run-up data could be used effectively in the present identification algorithm. To test the proposed algorithm, displacements and currents are generated with the help of a numerical simulation. For this purpose, a comprehensive four-degree-of-freedom model with a rigid rotor levitated on AMBs has been developed, which is also used for development of the identification algorithm. Then the estimation of parameters is performed based on least-squares fit technique in frequency domain. To check the robustness of the identification algorithm, modelling errors and measurement noises have been incorporated during the parameter estimation and deviation in estimated parameters is found to be reasonable.

1. Introduction

The most prominent problem in rotor dynamics is the dynamic balancing of rotors as even a small unbalance will cause excessive vibrations at high speeds, which may lead to catastrophic failures. Overall it reduces the efficiency of rotor-bearing systems and if this residual unbalance exceeds certain level will produce large amount of unbalance forces. This leads in vibrations that would prove to be fatal and causing failure to the entire rotor system [1–3]. Now-a-days there is a large usage of high-speed rotating machines; hence we require a control system integrated with the rotor system. Active magnetic bearings (AMBs) are such a choice, which are very much suitable to above requirements and also impart the contactless motion that helps in reducing the wear and tear of the rotor system. It is to be noted that the design of AMBs is very complex when compared to conventional bearings, as it includes the design of controllers, actuators and amplifiers, individually and simultaneously [4].

Vibrations in rotor systems can be reduced in principle actively and instantaneously by AMBs based on measured vibration responses from the system with the help of controllers, amplifiers and magnetic actuators. The several research efforts on AMBs have been performed on the control engineering. In synthesis of controllers, diverse control principles have been implemented to magnetic bearings from the traditional analogue controller to the modern digital ones [5, 6]. The modelling, simulation and control of the AMB system were studied by Binder et al. [7] with the PID and state space controllers.

AMBs do not aim in calculating residual unbalances in the system and try to remove it by applying additional magnetic force opposite to unbalance forces. However, it will be advantageous, if we reduce residual unbalances to minimum by physically balancing the rotor so that it will reduce the continuous effort of the controller and the power consumption in rotor systems that are levitated on AMBs. Zhou and Shi [8] studied the active control and balancing of rotating systems, and they concluded that active balancing

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suppresses vibrations due to unbalances as they eliminate residual unbalances, which is the cause for the vibration. Edwards et al. [9] used the finite element method to identify both residual unbalances and flexible support parameters of a rotor-foundation system. Sudhakar and Shekhar [10] have identified rotor unbalance while investigating model-based fault identification using vibration minimization methods. Tiwari et al. [11] identified inherent unbalances in a flexible rotor levitated on AMBs using an extended influence coefficient method, which correlates magnetic forces and applied unbalance forces with the help of trial unbalances.

The majority of work is related to the reduction of residual unbalance responses in the system and a very little effort is contributed for development of methods for the experimental estimation of AMB dynamic parameters without which one cannot analyse the rotor bearing-system properly. However, for conventional bearings several methodologies for experimental estimation of bearing dynamic parameters have been reported [12]. Qiu and Tieu [13] developed a method to determine dynamic coefficients of journal bearings from impulse responses using least-squares estimation and verified their work using the experimentally identified coefficients. Tiwari [14] proposed an identification algorithm for a four-degree of freedom conventional rigid-rotor flexible-bearing system and in addition to that he proposed different methods to improve the condition of proposed algorithm. Tiwari and Chakravarthy [15] developed an identification algorithm for the simultaneous estimation of speed-dependent bearing parameters and residual unbalances by using the impulse response measurement for a multi-degree of freedom flexible conventional rotor-bearing system.

The majority of works on the estimation of magnetic forces and stiffness parameters of AMBs have been performed by the FEM formulation of the bearing magnetic field. To evaluate the force and the stiffness of radial AMBs, the linear magnetic circuit theory was utilized [16]. In a canned motor pump, the conformity of measurement was observed to be sensible at small eccentricities. Using finite element techniques a magnetic bearing actuator force was studied [17]. A nonlinear finite element technique was utilized to establish the force of a radial magnetic bearing [18] through Maxwell's stress tensor technique. A non-linear two-dimensional finite element method is performed to calculate the effectiveness of radial magnetic bearings [19]. Linearized variables for the dynamic model of AMBs at diverse process conditions were obtained. Due to actual test conditions at bearing locations (magnetic flux leakage losses, effect of non-uniform temperature on magnetic material properties, etc.) are difficult to access practically, hence; even when theoretical analysis procedure is accurate, but does not estimate acceptable values. This encourages estimating these variables by experimentation in genuine test situation. On the evaluation of dynamic parameters of active magnetic bearings advances of the experimental method are exceptional.

The AMB force magnitude on a rotor levitated by AMBs could be predictable indirectly by either measuring the magnetic flux density with imbedded Hall sensors into the air gap or by measuring actuator winding currents and shaft displacements [20, 4]. By application of calibrated forces on the rotor the effectiveness of these methods was compared by Aenis et al. [20]. They observed that the flux based procedure is more precise in comparison to the current–displacement method. However, accommodating Hall sensors in the AMB air gap is a real practical problem. To estimate the forces applied by an AMB through the FEM formulation an effort was made in [21]. A multi-point technique for the force estimation in AMBs was proposed by Kasarda et al. [22], in which they concluded that it was a more precise method than traditional force measuring methods. Tiwari and Chougale [23] developed an identification algorithm for the simultaneous estimation of speed-independent AMB parameters and residual unbalances for a rigid rotor system fully levitated on AMBs. Tiwari and Chougale [24] also developed the identification algorithm for the speed-independent AMB parameters using flexible rotor fully levitated on AMBs and validated their work with experimental data. Wang et al. [25] concluded in their work that both stiffness and damping of AMB system are complex functions of the frequency, and they also provided relations of the stiffness and damping performances with reference to the frequency. Hence, our focus lies on the development of methodology for the estimation AMB dynamic parameters along with residual unbalances in which AMB dynamic parameters have been considered to be dependent on the rotor speed, especially methodology suitable to be used with the help of measurements during the run-up data of a rotor system. This gives difficulty because the number of AMB parameters increases with the number of speeds of interest. So identification algorithm deviates as compared to the previous works on AMBs.

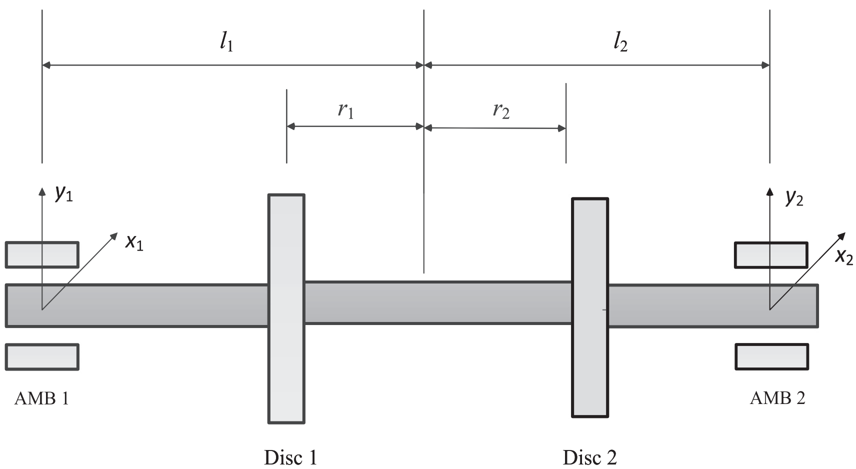

Fig. 1. Rigid rotor fully levitated on AMBs.