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Nonlinear dynamic characteristics analysis of active magnetic bearing system based on cell mapping method with a case study

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ABSTRACT

Active magnetic bearings (AMBs) are widely applied in high-speed rotating machinery, especially those in special environments. In the designing and adjusting an AMB system, the mathematical model of the system plays an important role. An AMB system is essentially nonlinear, thus the widely applied linear model cannot fully reflect the system characteristics in some cases. Cell mapping (CM) method is a global analysis method for nonlinear dynamic systems, which can obtain the global structure of a nonlinear system and the influences of varying parameters on it. In this paper, a CM type method is applied to analyze the nonlinear characteristics of the AMB system. Operational data from an actual AMB system is analyzed. During the on-site commissioning experiment, this system was unstable under specific conditions and was stabilized after modifying the controller. Analysis based on CM method reveals that the main cause of the instability is the bifurcation due to the nonlinearity of the system and the on-site treatment was valid.

1. Introduction

Compared with conventional bearings, active magnetic bearings (AMBs) [1,2] possess several attractive advantages, such as no friction, no need of lubrication, and the ability of long-term high speed running. Therefore AMBs are widely applied to support high-speed rotating machinery, especially those in special environments. A typical AMB system includes the following parts: a rotor, bearings, sensors, a power amplifier and a controller. The displacement of the rotor is measured by the sensors. The controller computes the current commands thereby. The power amplifier generates the current accordingly and the bearings generate the restoring force to maintain the position of the rotor.

Nevertheless, for each application case, the AMB system should be specifically designed, installed and adjusted. This procedure is quite expensive and time-consuming. The mathematical model of an AMB system plays an important role in designing and adjusting the whole system. In practice, the linear models are commonly adopted to describe AMB systems. Based on the linear models, identification [3–5] and controller design [1,2] techniques were developed. However, an AMB system is essentially nonlinear, so that the linear model cannot fully describe the system characteristics in some cases. The main nonlinearities in an AMB system include the force-current-displacement relationship, current and voltage

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limitations of the power amplifier, nonlinear dynamics of the complex rotating parts. In addition, the sophisticated nonlinear ferromagnetic characteristics including nonlinear magnetization, saturation, and hysteresis make the nonlinearity in AMB system more complicated. Therefore, the nonlinear phenomena, such as jumping, bifurcation, multi-solution, sensitivity to initial conditions, even chaos, are not rare in AMB systems [6]. Otherwise, the nonlinear models of the AMB systems were necessary to analyze the systems in many situations. For example, the contact between the rotor and the touchdown bearings occurred in some special operating situations [7–9]. When the contact appeared, the nonlinear contact forces made the system more complicated. Refs. [7–9] presented several approaches to recover the contact-free levitation from the auxiliary bearings (also called as "touchdown bearings" or "backup bearings") and the dynamic behaviors of the systems with these approaches were illustrated. Ref. [10] presented a comprehensive analysis of the drop of an AMB-levitated vertical rotor onto auxiliary bearings. In these papers, the dynamic behaviors of the AMB systems subjected to nonlinear contact forces were analyzed. It can be seen from the literature that the dynamics of AMB systems under some operating conditions were so complicated. Ref. [11] redesigned a new linear feedback law of the AMB system based on the optimization problem formulated in linear matrix inequality form and extended the operating region from the linear region into the nonlinear region. The nonlinear dynamics of AMB system is so sophisticated that the stability analysis conclusions based on linear models are not sufficiently accurate [12]. Thus analyzing the nonlinear characteristics in AMB systems is necessary to attain more precise and comprehensive models of the system.

Many achievements in the field of the nonlinear analysis of the rotor-AMB systems were reported. Some works focused on the modeling of nonlinear characteristics and analysis of the dynamic behaviors in time-domain [13,14]. Some researchers discussed the dependence of system characteristics and parameters in the parameter-domain from the perspective of nonlinear vibration. Refs. [15,16] utilized numerical simulation methods to analyze the bifurcation phenomena in AMB systems. Orbit plot, bifurcation diagram, power spectrum and Poincaré mapping were used in [15] to identify the main factors affecting the dynamic characteristics of an AMB system. Nonlinear phenomena like period-doubling, quasi-periodic motion, and chaos in the presence of geometrical coupling were observed in [17] with numerical simulation. Approximate analytical method was applied in [17] to investigate the nonlinear vibration of the rigid rotor-AMB system considering the delay of control force. The effects of parameters in AMB systems on system response were analyzed and the proposed method was validated by experiments. Ref. [6] constructed a multiple scales solution for a rotor-AMB system that was subjected to primary resonance excitations at the presence of 1:1 internal resonance and shown the consistency between the approximate analytical solution and the numerical result. Asymptotical perturbation method [18] and the multiple scales method [19] were used to study the dynamical response of the rotor-AMB system with time-varying stiffness.

Cell mapping (CM) method is a global analysis method for nonlinear dynamic systems, which mainly focuses on the global structure of the phase plain of a nonlinear system, including the positions of attractors and their domains of attraction, the unstable and stable manifolds of unstable solutions, and the influences of varying parameters on the global structure. The basic idea of CM type methods can be described as follows: firstly the original spatially continuous state space is converted to discrete cell space with a lot of cell units (CUs) and the set of (infinitely many) state transfers is reduced to a finite cell transfer set thereby. Then the global analysis can be performed on the finite cell mapping system. In general, in numerical simulation methods, the behaviors of a nonlinear system under various initial states are treated separately. On the contrary, CM methods provide a systematical method to construct a global structure of the state transition relationship by combining the information [20–22]. Compared with numerical simulation methods, the computational efficiency is significantly improved and the global characteristics of a nonlinear system can be attained by CM methods.

CM method was originated by Hsu in 1980 [20]. In [20] the basic theories of the CM method were proposed and the CM method was applied to systems described by point mapping and differential equation. In addition, the general procedure of global analysis was introduced. Ref. [23] introduced the theory and basic concept of the cell mapping and illuminated the basic ideas, algorithm realization of simple and generalized cell mapping methods and other methods based on the two.

In simple cell mapping (SCM) method, the global characteristics such as the periodic solutions and attraction domains of stable solutions can be evaluated. Refs. [24,25] had generalized SCM method to generalized cell mapping (GCM) method. In SCM method, there is only one image CU associated with a CU. Unlike this, in GCM method a CU can be transferred to several image CUs, in other words, there can be several orbits which start from the same CU. Markov chain model and probabilistic description of the evolutional behavior of the system were introduced to replace the deterministic description in the SCM method. GCM method is especially suitable to analyze stochastic nonlinear dynamic systems in that comprehensive qualitative and quantitative global analysis can be performed [26,27]. This analysis is in general quite difficult for traditional methods. Theories of graph and partially ordered sets were introduced in [28]. More effective analysis methods were proposed to attain the information about unstable solutions of the system. Ref. [29] had proved the correspondence between GCM of dynamic systems and directed graph and had proposed the generalized cell mapping digraph (GCMD) method. Based on this method, the transient CUs can be classified topologically and more information of transient CUs can be extracted. Many improved CM methods including interpolated CM method, Poincaré-like CM method and so on were proposed [30–34].

As for the application of CM type methods, in [29] the GCMD method was applied to the forced Duffing system. Attractors, basins (namely attraction domains), basin boundaries and unstable solutions were obtained with low computational cost, and a boundary crisis was studied. GCMD method was further utilized to investigate the discontinuous bifurcations of chaotic attractors [35]. The principle of discontinuous bifurcations was discussed and the validity of GCMD method was verified. The global dynamic behavior of a physical pendulum system with rotation and vertical vibration was studied by an improved