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Numerical and experimental study of a double physical pendulum with magnetic interaction

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ABSTRACT

Chaotic and regular behavior of the system consisting of a double physical pendulum with two repulsive permanent magnets is studied. We are focused on mathematical modelling, numerical simulations, experimental measurements and in particular on a novel magnetic interaction modelling. System parameters are identified by matching the output signals from experiments and numerical solutions to the developed mathematical model governed by a strongly non-linear set of two second order ODEs including the friction and the magnetic interaction torques. Considered system shows chaotic and periodic dynamics. Few chaotic zones have been detected numerically and confirmed experimentally. Scenarios of transition from regular to chaotic motion and vice versa, as well as the bifurcation diagrams are illustrated and discussed. Good agreement between the numerical simulation and experimental measurement is achieved.

1. Introduction

A rapid development of science and technology requires their matching and mutual feedback for detection and understanding of real-world non-linear phenomena and to guarantee the useful application of non-linear behavior aimed at improving the quality and safety of the numerous engineering processes. Complexity of evolution of real-world non-linear processes requires novel methodological approaches spanned by interdisciplinary exchange of ideas, combining different sciences (mechanics, physics, applied mathematics, electrical and electronical engineering) and developing dedicated approaches aimed at accurate modelling of the studied phenomena.

Our approach which is presented in this paper is focused on mathematical modelling, numerical and experimental investigation of a mechanical system (double pendulum) subjected to influence of magnetic and electric fields. The carried out research fills the gaps in insufficient knowledge and uncertainties between mechanics, mechatronics and applied physics spanned by non-linear phenomena.

It is well known and documented that even simple configuration of the pendula may exhibit almost all features of non-linear phenomena detected and reported so far, in the field of non-linear dynamical systems [1–12]. The carried out overview of the up to date research devoting to mathematical modelling based on fundamental mechanical-electro-magnetic laws and meticulous experimental validations highlights a need to refresh and extend the initiated investigations of vibrations of the pendulum-type systems with and account of the magnetic, electric and mechanic fields.

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On the other hand, the magneto-electro-mechanical pendulum-type systems may serve as archetypical members in the engineering systems including mechanisms and machines construction, space exploration, manufacturing estimation, control and automation, robotics, sensors and servo-motor construction and fabrication, as well as numerous MEMS and NEMS devices (including sensors and gyroscopes).

In what follows we briefly describe state-of-the-art of research results in this field embracing a group of comprehensive and up to date accounts of non-linear vibrations of the mechanical systems under the magnetic and electric fields.

Nana et al. [13] carried out both theoretical and experimental study of an electromechanical system composed of a physical pendulum with repulsive magnets and a DC motor. The employed analytical/numerical prediction has been validated by modelling, simulation and experimental investigation of the introduced mathematical model. A few novel non-linear features have been illustrated and discussed including hysteresis, chaotic and regular dynamics, as well as jump phenomena.

Schmidt and Childers [14] studied first- and second-order phase transitions and tri-critical points exhibited by a magnetic pendulum controlled by the currents. Siahmakoun et al. [15] reported regular and chaotic behavior, as well as amplitude jumps, hysteresis and bistable states of a sinusoidally driven pendulum embedded into a repulsive magnetic field. Fradkov et al. [16] investigated more complex laboratory rig including mechanical and electromagnetic devices and consisting of two similar subsystems, where each of them consists of two coupled pendula.

Dannagain and Rasskazov [17] reported numerical investigation of the modified Duffing oscillator modelling a periodically driven iron pendulum embedded into a non-uniform magnetic field. In particular, the Preisach nonlinearity to model magnetization effects have been used and the hysteretic/chaotic effects have been illustrated. Experimental investigations with a magnetically controlled pendulum modified by positive/negative feedback with an emphasis on the chaotic vibrations and data acquisition system have been considered by Kraftmakher [18]. Energy-based criterion to predict escapes for either externally forced or parametrically excited bistable magnetic pendulum has been proposed by Mann [19].

Kitio Kwuimy et al. [20] considered the effect of tilted harmonic excitation and parametric damping on chaotic vibrations of an asymmetric magnetic pendulum. Both regular and fractal shapes of the basin of attraction have been employed to validate the Melnikov-type analytical prediction. It has been illustrated how increase of the tilt angle of the excitation yields increase of the lower part of chaotic domain. It has been also demonstrated that the parametric damping may enhance or suppress chaos. Lima et al. [21] analyzed the impact behavior of an embarked pendulum in a vibro-impact electromechanical system. A continuous contact dynamic model has been proposed, whereas the impact has been modeled by the spring-dashpot system. The maximum entropy principle has been employed to derive the probability model, and the Monte Carlo simulations have been carried out to validate the confidence interval of the pendulum displacements and the angular speed of the motor shaft. Tran et al. [22] predicted and studied the behavior of the chaotic physical-magnetic pendulum with variable interaction potential. Standard tools of theory of non-linear dynamical systems have been used and it has been illustrated that the large scale system dynamics encompassing different attractors can be predicted by employing only a single region of chaotic behavior.

Skubov and Vavilov [23] considered dynamics of the conductivity bodies of pendulum types under alternating magnetic field. Kadjie and Woafo [24] investigated an energy harvester consisting of an electromechanical pendulum supported by non-linear springs. It has been illustrated by an appropriate choice of the springs, that output power attains higher magnitudes than in the case without springs. A simple instance of the electro-mechanical system (EMS) is considered in Ref. [25]. The paper contains an analysis of a dynamical system with a pendulum, an AC electromagnet and a permanent magnet. The magnet is mounted at the end of the pendulum and determines its bob. The coexistence and relative relations between chaos and parametric resonances are studied. Analytical results are compared against numerical simulations and experimental studies.

Over the past three decades, a great attention has been paid to modelling, theoretical, numerical and experimental investigations of the active magnetic bearing employed to support rotating machinery and rotors in particular, due to their advantages including much lesser friction, absent lubrication and high rotating speeds. Ji [26,27] studied both theoretically and experimentally non-linear dynamic phenomena exhibited by a Jeffcott rotor-magnetic bearing system with time delays. Zhang and Zhan [28] investigated regular and chaotic dynamics of a rotor active magnetic bearings with non-linear terms and time-varying stiffness, and with 8-pole legs. Zhang et al. [29] carried out investigations of multi-pulse Shilnikov-type chaotic vibrations of a rotor-acting magnetic bearing system with time-varying stiffness. Chen and Hegazy [30] reported non-linear dynamics of a rotor active magnetic bearing, whereas Kamel and Bauomy [31] analyzed non-linear behavior of a rotor under active magnetic bearing with multi-parameter excitations. More recently, Fang et al. [32] proposed an active vibration control of rotor imbalance in active magnetic bearing system, whereas Yang et al. [33] implemented control of elliptic motions of rotors suspended in active magnetic bearings. Chen et al. [34] employed a recurrent wavelet fuzzy-neural network to the positioning control of a magnetic-bearing mechanisms. In 1996 Hansen et al. [35] studied oscillations of two nearly identical resonant series of LC circuits, where two coaxial coils were placed nearby and when one of them was fixed and the other one was movable. New electromagnetic phenomena associated with induction and magnetic hysteresis have been detected and studied including estimation of the Lyapunov exponent based on reference [36]. Foerster et al. [37] considered mechanical vibrations of the gradient coil system during readout in echo-planar imaging under the magnetic field distribution during functional magnetic resonance imaging. The frequency drift correction method has been proposed. Pulse-modulated control law for both synchronized and non-synchronized vibrations has been employed based on the speed-gradient method. The simulation and laboratory experiments showed a good coincidence.

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