AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY

FIELD OF SCIENCE
ENGINEERING AND TECHNOLOGY

SCIENTIFIC DISCIPLINE
AUTOMATION, ELECTRONICS, ELECTRICAL ENGINEERING AND SPACE TECHNOLOGIES

SUMMARY OF DOCTORAL THESIS

Axial Active Magnetic Suspension Systems

Author: Bartłomiej Sikora M.Sc.Eng.

Supervisor: Adam Piłat Ph.D., D.Sc., prof. AGH

Completed in:
AGH University of Science and Technology
Faculty of Electrical Engineering, Automatics, Computer Science, and Biomedical Engineering
Department of Automatic Control and Robotics

Krakow, 2023

AGH

AKADEMIA GÓRNICZO-HUTNICZA IM. STANISŁAWA STASZICA W KRAKOWIE

DZIEDZINA
NAUK INŻYNIERYJNO-TECHNICZNYCH

DYSCYPLINA

AUTOMATYKA, ELEKTRONIKA, ELEKTROTECHNIKA I TECHNOLOGIE KOSMICZNE

AUTOREFERAT ROZPRAWY DOKTORSKIEJ

Osiowe aktywne systemy zawieszenia magnetycznego

Autor: mgr inż. Bartłomiej Sikora

Promotor rozprawy: dr hab. inż. Adam Piłat, prof. AGH

Praca wykonana:
Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie
Wydział Elektrotechniki, Automatyki, Informatyki i Inżynierii Biomedycznej
Katedra Automatyki i Robotyki

Kraków, 2023

Research motivation

The author of this dissertation during his PhD studies participated in a few projects, such as a high-power generator for hydroelectric plants or a prototype of an axial generator for low power wind turbines. In various studies the author has focused on the design of axial electric drives. These projects introduced numerous technological difficulties related to the design of the drive, the shape of the rotor, the magnetic circuit optimization, uneven distribution of peripheral forces or wobbling of the rotor. On the basis of these experiences, possible development trends were observed in the design and identification of axial actuators, together with their extended potential in magnetically levitated rotors. This constitutes the motivation for the doctoral dissertation, in which the author will tackle its subject in the course of an interdisciplinary approach, proposing a new solution for an axial actuator with a few pole pieces.

Aim of dissertation and main statement

The subject of the doctoral dissertation are **Axial Active Magnetic Suspension Systems**. The aim is the design, implementation and identification of the novel axial actuator with a few pole pieces, which operates as a levitation device capable of setting the tilt of the rotor and enabling control of the rotor position in the levitation space. The dissertation is interdisciplinary, referring to various issues of electromagnetic field theory, mechanical engineering, machine dynamics, control applications and material properties. This is in part due to the need to engage numerous fields of science to achieve the goals set for the dissertation, as well as the educational background of the author, who graduated from both Electrical Engineering, Mechanical and Material Engineering. The structure of the dissertation is modular, where each of the chapters sets out a unified thought devoted to a selected issue of designing axial magnetic suspension systems. Modularity allows for a comprehensive approach to the topic of the dissertation, presenting a consistent line of reasoning heading for the confirmation of the main statement, which is formulated as follows: **axial active magnetic bearing with a few pole pieces allows for setting the spatial orientation of the levitating object.**

Dissertation overview

Proving the main statement required extensive research, the effects of which are described in the twelve chapters of the dissertation. Below are brief descriptions of their content.

Chapter 2 contains research on a magnetic levitation system with two electromagnetic actuators in an E-shaped configuration, located opposite each other. The object of the levitation is a metal sphere. The influence of current and proportional–derivative (PD) controller settings on lateral motion of the sphere was considered. Simulation models in conjunction with experimental studies are validated with the help of image processing. The research carried out confirmed that the dynamical properties of the lateral motion can be configured by stretching control. The results were published in [3].

Chapter 3 considers thermal effects in the axial pot core actuator. This chapter focuses on the magnetic levitation thermal model and the effects associated with losses due to electromagnet heating. A slight change in the inductance of the electromagnet and its dynamics as a function of temperature were observed during the long-term stabilization of the sphere. An extension of these considerations, which will be included in the MAGLERS[1] team paper, is the nonlinear mathematical model of axial levitation with an E-type electromagnet, which takes into account the effect of temperature on the position of the levitating object.

Chapter 4 evaluates the concept of electromagnets with a porous core. The core was manufactured manually. The aim of this chapter is to provide an initial analysis of the proposed powder core together with the prototyping procedure, using a finite element method. The assessment of the convergence of the numerical model with the experimental data allowed for the estimation of the magnetic properties of the produced core. This chapter emphasizes the importance of careful material selection in the design of electromagnetic applications. The results were published in [7].

Chapter 5 implements from scratch the concept, design and prototype of hybrid axial magnetic bearing (HAMB). The numerical model was developed in COMSOL Multiphysics. The manufactured stator and rotor were tested on a laboratory test rig. Initial tests were carried out in differential mode with voltage control. The advantages of the hybrid actuator configuration and favorable force characteristics were demonstrated, as well as the need to develop a three-dimensional (3D) model taking into account the mutual coupling between its active and passive part. The results were published in [8].

Chapter 6 is the first to introduce six pole axial active magnetic bearing (6pAAMB). In principle, this configuration stabilizes the motion of the rotor in the axial direction and provides the possibility of

---

[1] Magnetic Levitation Reserach Systems; *http://www.maglev.agh.edu.pl/*

disc tilt control. The geometry of the actuator is presented with variants of coil connections. The features of the axial actuator are discussed.

Chapter 7 develops a numerical model of the axial magnetic bearing with six cylindrical poles. The model evaluates several configuration variants. The influence of changes in current and rotor position on force characteristics was investigated. The model confirms the possibility of controlling disc wobbling with the use of a few axial force components that are capable of actively compensating for the axial load. The chapter shows the advantage of striving to design a virtual prototype that allows for reliable multiparametric optimization of the system according to the criteria of cost, performance, operation or production. Before a real device is manufactured, the accurate numerical model will provide essential knowledge about the performance of the axial magnetic bearing. The results were published in [5].

Chapter 8 develops an original diagnostic method of the disc-type electromagnetic actuator by assessing the quality of its active surface. This chapter is an extension of the identification of axial active magnetic bearing (AAMB)s. The prototype manufactured on the basis of numerical analysis did not meet the operational requirements. A run-up experiment showed that 6pAAMB demands a quality test. The algorithm, which is used for actuator fault diagnosis, indicates differences between the heights of individual pole pieces with 50μm accuracy. The experimental results have been verified using the coordinate measuring machine. Finally, a scan of the actuator with a laser profiler is presented.

Chapter 9 describes several variants of laboratory test rig supported by two active magnetic bearings, the axial active magnetic bearing alone or in combination with radial passive magnetic bearing (RPMB). The concept of a slim-type AAMB with six cylindrical poles was tested and adapted to the vertical rotor-shaft configuration through an interdisciplinary approach to the design process. The results were published in [6]. Primarily, this chapter contains seemingly incomplete but immensely important research, which in the PhD timeline coincided with the pandemic. The prototypes of the test stands built at that time showed the overarching features of the proposed configuration of the axial actuator together with some limitations and further recommendations. In the next iteration of the research, a new prototype was described and implemented, current control was applied and the test stand was improved, including the measuring system and overall stability of the system.

Chapter 10 presents the second iteration of the novel six pole axial active magnetic bearing, which was manufactured and investigated experimentally. The developed analytical model utilizes the magnetic vector potential formulation and Schwarz–Christoffel mapping. The research covers in-depth deliberations on the end effect influence and the conjugate complex permeance function. The chapter guides the reader through the steps of mathematical analysis, discussing in detail the tools used to describe 6pAAMB. The main advantage of the proposed analytical model is the significantly shorter computation time compared to the numerical one, which is useful from the point of view of modeling and building controllers, especially in the case of optimization procedures. The results were published in [2].

Chapter 11 describes the consequences of combining the designed axial actuator with a radial passive magnetic bearing. The reliable operation of passive magnetic bearings depends on the properly adjusted force characteristics and mutual interactions between the active actuator and permanent magnets. In this chapter, several experiments have been designed to identify the rotor dynamics in the above-mentioned system. Finally, a proprietary magnetic coupling was used to accelerate the rotor to a speed of 4000 rpm in a full levitation mode.

Chapter 12 elaborates a comprehensive approach to identify the parameters of the novel six-pole axial active magnetic bearing actuator with current-driven electromagnets. The reader can explore a number of identification methods that provide a holistic view of the actuator. This research emphasizes the accessible in situ identification of 6pAAMB using various measurement methods to obtain a complete description of the actuator with uncertainties in its parameters. In general, the proposed mechatronic actuator is capable of increasing the stability range of rigid or flexible rotors and is characterized by favorable dynamic properties. The results were published in [1].

Chapter 13 summarizes the interdisciplinary design of the 6pAAMB . Stabilization experiments were performed in a control system consisting of three local proportional–integral–derivative (PID) controllers, obtaining a set of equilibrium points and transient states of the rotor with satisfactory repeatability. Raw experimental data were used in numerical calculations to formulate model equations that describe the rotor in steady state. A detailed analysis of the electromagnetic force and torque distribution was provided. The tilt of the rotor around the x axis with variable PD settings illustrates the influence of the controller on the dynamics of the spatial orientation of the rotor. This chapter is the closure of the presented scientific course to confirm the main statement of the dissertation.

In the course of developing the scientific research included in the following dissertation, 9 articles have been published. The author also participated in 5 conferences and technical workshops. The result of completed experimental studies is more than 10 various test stands, HAMB prototype, 2 versions of 6pAAMB prototype and various RPMB variants. During prototyping, 3D printing technology, computerized numerical control (CNC) machining and laser cutting were utilized. Approximately 15 rolls of filament were printed during the more than 1500 hours of the 3D printer Zortrax M200. The dissertation refers to nearly 150 literature items, a large part of which are the latest achievements in the field of magnetic levitation. The interdisciplinary scope of research required the use of tools from many fields of science, i.e. computer aided design (CAD), development of numerical models using finite element method (FEM) methods, extended mathematical calculations and advanced measurement methods, which required the use of more than 20 different computer applications. The dissertation is well illustrated for a better overview, guiding the reader along the main line of reasoning. All charts and illustrations were prepared almost entirely by the author. It is also worth mentioning that during his doctoral studies, the author completed the KIC InnoEnergy PhD School program, participating in 7 international business trainings and conferences throughout Europe, focused on networking and pioneering changes in sustainable green energy toward innovation and business. The author completed a 4-month internship at Uppsala University, developing numerical models for a high-power hydrogenerator.

Summary of results

In this doctoral dissertation, the author presented an innovative concept of an axial active magnetic bearing with six pole pieces. The proposed solution has application potential as a modern automation actuator. As a result of scientific research, the main statement was confirmed, showing the exclusive feature of 6pAAMB, which is the possibility of spatial positioning of the levitating object. The completed research that comprised this dissertation required an interdisciplinary approach to actuator design. Its scope covered numerous fields of science around the author's interests, the effect of which is the presented coherent line of reasoning leading from the application need and idea, through testing and verification of various concepts, to the design procedure, including numerical modeling, analytical calculations, manufacturing, quality check, identification and control application. A roadmap to prove the main statement of the dissertation led through a wide range of research, the effects of which were described in twelve modular chapters. Each of them was a separate milestone to achieve the set goal. The most important results in relation to the individual chapters are briefly presented below.

Investigation of lateral motion in levitation system with opposite electromagnets

- This chapter demonstrated the possibility of minimizing an active magnetic levitation to the configuration with two electromagnets if the stretching forces are sufficient to stabilize the levitating object under external disturbances.
- The simplified single axis active magnetic bearing (AMB) allows to influence to some extent the position of the levitating object in the inactive axes.
- It is recommended to develop AAMB that can control the dynamics of axial motion to the extent that it can support the task of radial stabilization in a more controlled way.

Axial active magnetic levitation extended by heat transfer

- Long-term experiments indicated that increasing the temperature of the electromagnet causes a decrease in the value of the magnetic induction and the electromagnetic force, which, in consequence, influences the dynamic properties of the system.

- Understanding the influence of temperature on the dynamics of the system in connection with its geometry and electromagnet parameters provides important suggestions for improvements during the actuator design stage.
- The influence of the actuator core temperature on the inductance value was observed. The issue requires a separate analysis to draw verified conclusions.
- For the correct description of thermal effects in the electromagnetic actuator, a higher-order nonlinear model is required, introducing state variables in the form of coil, core and ambient temperature depending on the geometrical parameters of the actuator.

Porous core electromagnet design for levitation applications

- An original method was implemented for the rapid prototyping of the AAMB powder core.
- The manufactured electromagnet did not meet the expected requirements as a result of no access to industrial facilities that enable the powder core manufacturing process to be optimized.
- The efficiency of the powder core magnetic circuit depends on the degree of packing of the iron filings and the type of bonding agent.

Hybrid axial active magnetic bearing

- Power consumption was reduced using the permanent magnets (PMs)-biased configuration in the implemented concept of AAMB. At the same time, significant magnetic forces from PMs caused frequent disc tilting; thus, the task of radial stabilization requires the support of an active magnetic radial bearing.
- The appropriate configuration of PMs can provide close to linear characteristics of the axial electromagnetic force in a narrow range of axial levitation. The magnetic flux path of HAMB was adjusted to compensate for the gravity load at the desired operating point.
- two-dimensional (2D) numerical models do not cover all the phenomena that occur in machines with axial magnetic flux flow, which is why it is recommended to develop the 3D numerical models.

Concept of axial active magnetic bearing with six poles

- The undoubted achievement presented in this chapter is the prototype of the actuator with six pole pieces manufactured in several iterations over the PhD timeline.
- A distinguished feature of the described prototype is the configuration of six pole pieces that allow the arrangement of at least three electromagnets generating separate vectors of the axial electromagnetic force.

Numerical model of axial magnetic bearing with six cylindrical poles

- The effect of this chapter was a virtual twin of 6pAAMB, from which the user can collect various characteristics.
- The numerical model consists of numerous elements, such as parameterized geometry, selected materials, meshing, solver configuration and study type. During the development of the model, material tests were performed to determine the magnetization curve of the utilized steel, which was then imported into the model. The model is a useful tool in the optimization and verification process of the actuator design. It is recommended to continue numerical research towards multidisciplinary models.

Quality performance of the axial magnetic bearing

- A tool was developed to detect defects in the assembly or operation of axial machines in situ.
- The open-ended procedure for semiautomatic identification of the axial actuator has been proposed. Current trends in the design of control and measurement systems for electromagnetic actuators are oriented toward self-monitoring or diagnostic systems.
- The quality assessment of the manufactured actuator was carried out using a proprietary algorithm, a coordinate measuring machine and a laser profiler, presenting and comparing the capabilities of selected tools.

Axial active magnetic bearing in rotor system

- A reconfigurable magnetic bearing system was set up for flexible shaft machinery.
- Experimental scenarios were developed to assess cross-coupling between individual electromagnets in the actuator with several pole pieces.
- Considerations undertaken at that time and preliminary research on axial active magnetic bearing with six cylindrical poles resulted in the development of the latest actuator iteration.

Analytical modeling and experimental validation of six pole axial magnetic bearing

- The validated 6pAAMB analytical model was obtained, which is convergent with experiments and numerical simulation.
- Schwarz-Christoffel transformation was utilized in the study of the actuator end effect.
- The 3D complex permeance function, which represents the stator pole pieces, was provided and can be utilized to optimize the geometry of the slot or select a suitable location of the sensing element for identification or control feedback purposes.
- The computational time of the analytical model was significantly shorter than the numerical one.

- The mathematical model provides explicit formulae, which contribute valuable information about the magnetic field distribution in the 6pAAMB air gap.

Radial passive magnetic bearing in configuration with axial active magnetic suspension

- The developed RPMB prototype achieved its task of supporting the stabilization of the rotor in the x-y plane and can be extensively modified and miniaturized due to its simplicity.
- passive magnetic bearing (PMB), depending on the position of the rotating part in relation to the stationary part, can generate a negative or positive axial electromagnetic force component.
- It is a key issue and, at the same time, a nontrivial task to propose integrated force and dynamic characteristics for active magnetic suspension (AMS) with PMBs.
- The proprietary noncontact magnetic gear was developed to accelerate the rotor to a speed of 4000 rpm. As a result, a rotational motion of a fully levitated 6-degrees of freedom (DoF) rotor was observed.

Interdisciplinary identification of six pole axial active magnetic bearing prototype

- Research demonstrated a complete identification inspired by real system imperfections, leading to the verified model of the single-axis axial active magnetic bearing.
- The problem of eccentricity was emphasized during the levitation of the tilted disc, which has a consequence on its chaotic motion.
- The dynamic properties of the system in a broad frequency range were examined using a shaker with external harmonic excitation. The adjusted PD controller for 6pAAMB shows the desirable features of the magnetic levitation system in terms of the amplitude-phase characteristic.
- In general, the 6pAAMB actuator could extend the stabilization range of rigid and flexible rotors.

Disc spatial orientation in six pole axial active magnetic bearing

- The chapter guided the reader through the analysis of an extensive set of experimental data supporting the main statement, describing the rotor steady states as functions of various parameters.
- Despite the assembly inaccuracies and the difference in the actuator electromagnet parameters, the repeatability of the rotor steady state in the inactive axes was confirmed.
- Extended numerical verification of the experimental data was carried out in COMSOL Multiphysics to provide a reliable description of the distribution of electromagnetic forces and torques in the 6pAAMB active space. The steady states measured from the levitating rotor were imported into the developed 6pAAMB numerical model.
- A global formula of the axial electromagnetic force requires precisely calculated air gap volumes.

- The 5-DoF actuator model was developed for steady states obtained experimentally and numerically verified. The model shows convergence with the experiment for the axial position and tilt angles of the rotor, whereas the equations of the lateral forces in steady state do not reflect their real dynamics due to the nonperiodic, chaotic or statistically unrepeatable nature of the 6pAAMB lateral motion.
- The possibility of arbitrarily orienting the rotor in the 6pAAMB levitation space was demonstrated.
- Analysis of the rotor dynamics in the control system with three local regulators indicates the need for a compromise between stability in the z axis and damping of lateral vibrations.

The issues presented in the above dissertation summarize the interdisciplinary course of designing, manufacturing, identifying and controlling the levitation object by means of an axial active magnetic bearing with six pole pieces. The reader may consider the above as the blueprint for the design of an axial actuator with a few pole pieces. Individual chapters outline the struggle with the subsequent stages of the 6pAAMB design and implementation procedure. Perhaps the key end result of the author's research is the motivation, inspiration and knowledge necessary to propose an industrial application of the developed actuator. Low-power wind farms, pumps, centrifuges and energy storage facilities are among the considered options.

List of publications

[1] B. Sikora and A. Piłat, “Interdisciplinary identification of the six-pole axial active magnetic bearing prototype,” *Mechatronics*, vol. 92, p. 102 982, 2023. DOI: *https://doi.org/10.1016/j.mechatronics.2023.102982*.

[2] B. Sikora and A. Piłat, “Analytical modeling and experimental validation of the six pole axial active magnetic bearing,” *Applied Mathematical Modelling*, vol. 104, no. 1, pp. 50–66, Jun. 2022. DOI: *https://doi.org/10.1016/j.apm.2021.10.024*.

[3] A. Piłat, B. Sikora, and J. Źrebiec, “Investigation of lateral stiffness and damping in levitation system with opposite electromagnets*,” in *2019 12th Asian Control Conf.*, vol. 2029, Jun. 2019, pp. 1210–1215. DOI: *10.1063/1.5066519*.

[4] A. Piłat, J. Źrebiec, and B. Sikora, “Neural velocity observer trained with experimental data supporting stabilization of magnetically levitating sphere,” in *2019 12th Asian Control Conference (ASCC)*, 2019, pp. 214–219.

[5] B. Sikora and A. Piłat, “Numerical model of the axial magnetic bearing with six cylindrical poles,” *Archives of Electrical Engineering*, vol. 68, no. 1, pp. 195–208, Jun. 2019. DOI: *10.24425/aee.2019.125990*.

[6] A. Piłat, B. Sikora, J. Klocek, *et al.*, “Set-up of active magnetic bearings for control of flexible shaft,” *AIP Conference Proceedings*, vol. 2029, no. 1, p. 020 058, Jun. 2018. DOI: *10.1063/1.5066520*.

[7] A. Piłat and B. Sikora, “Design and initial study of porous core electromagnet for levitation applications,” *AIP Conference Proceedings*, vol. 2029, no. 1, p. 020 057, 2018. DOI: *10.1063/1.5066519*.

[8] B. Sikora and A. Piłat, “Hybrid axial active magnetic bearing - design, modelling and prototype,” Aug. 2018.