Active Magnetic Bearing Interdisciplinary Design Modelling and Control Tool

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***Abstract*— This elaboration presents a modern approach in the field of active magnetic bearing design based on computations supported by partial differential equations (PDEs) and ordinary differential equations (ODEs). The magnetic field problems are solved using the finite element method (FEM), while the levitating rotor motion is calculated using ODEs. The novel Active Magnetic Bearing Interdisciplinary Design Modelling and Control (AMBIDMC) study tool was developed customising COMSOL Multiphysics and MATLAB software. This paper summarises the author's recent work in the field of integrated active magnetic levitation (AML) systems design and modelling including control and motion dynamics. A discussion of the features and limitations of the field of control systems is provided in this paper, showing how the developed model can be useful for controller studies. The discussion is illustrated by simulation data collected from working virtual prototypes.**

I. Introduction

An overview of the literature [29, 32, 35] focussed on the design and control of active magnetic levitation systems: suspensions and bearings shows different approaches and solutions related to AML system design, modelling, control studies and real-time control.

A control study for the AMB is a key point in AMB design. The controller is designed at the end of the prototyping stage, when the device is manufactured and identified. Subsequently, the modelling stage and controller study are activated. The open question is whether the identification supplies sufficient information for the controller study. It is rather difficult to investigate the rotor-AMB system in terms of all possible scenarios of control and measurement signals versus rotor displacement. With a complex model, an investigative experiment can be planned. It seems very practical to use a such model to identify cross couplings in the rotor-AMB system and to use them in the controller structure for optimal rotor control.

Nowadays, rapid prototyping methods and mechatronic devices with complex designs are becoming a reality; thus, the traditional approach of serial design needs to be modified.

A novel concept (see Fig. 1) of design, modelling and control study was proposed [19] in the field of control and active magnetic levitation. A simultaneous design, optimisation and control study is a desirable approach to prototyping new devices. Therefore, controller design and performance should be analysed at the design stage. A number of available software tools enable the design of so-called virtual prototypes (VPs), or computer models of the target device. The most advanced VPs are characterised by embedded dynamics. In the case of mechatronic systems, the controller is embedded to carry out dedicated tasks. Working with this type of VP enables verification of the concept, optimisation of design, and improvement of control quality.

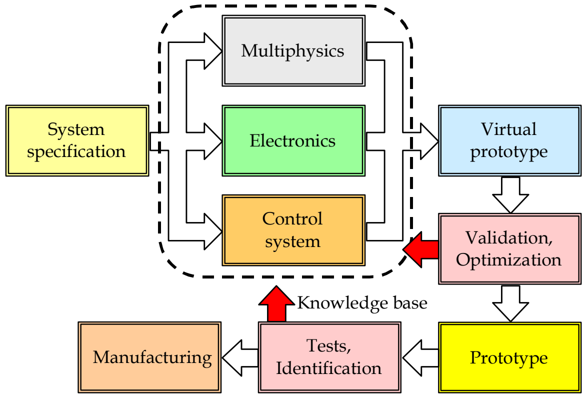


Figure 1. The proposed interdisciplinary design approach according to which the virtual prototype is being developed and studied

Typically, the active magnetic bearing control is designed on the basis of a mathematical model based in turn on ordinary differential equations (ODEs). The modelling stage is supported by the calculation of the electromagnetic foce characteristics on the baseis of the finite element methods (FEM). This method is very useful for the detailed analysis of magnetic circuits, mechanical features, thermal effects, etc. Finite element analysis can accurately account for the magnetic field which lies outside of the iron and thereby properly account for its effect on the actuator forces and electrical properties [15]. This method was succesfully applied to magnetic flux analysis [6, 7, 14, 17, 18, 34]. The finite element method was also applied to the analysis of eddy current losses in the thin surface layer of a laminated core [16]. The FEM calculations are very useful for the prototyping stage, optimization [5, 12, 16, 30]. The FEM method is used to calculate the shaft bending modes [2, 11, 12]. To perform a FEM analysis a wide range of software tools is used. One can find modelling supported by ANSYS [3, 14] , COMSOL [1, 9, 10, 13, 25, 26], COSMOS [12]. Recently, these calculations have been supported by the electromagnetic force characteristics obtained from FEM modelling [8,10, 31, 33, 35]. Very often, this stage is accomplished following a set of practical identification experiments. Typically, 2D analysis is used due to the computational effort and complexity of 3D modelling. However, the current trend is towards 3D modelling, in order to achieve a complex model of a rotor-AMB system.

One can find a number of different control strategies [32, 35]: linear, non-linear, and intelligent. The last-mentioned uses linear or non-linear models developed in a local (single electromagnet) or global case (complete AMB). Additionally, complete machine dynamics are modelled and simulated.

The aim of this research was to build complex dynamical models of the Active Magnetic Bearing. In a such model we wish to simulate: shaft levitation, controller action and electromagnetic forces acting on the shaft in a time domain.

In this research, which is focussed on a steered active magnetic bearing virtual prototype with truly levitating rotor motion solved in the time domain, the following questions can be addressed:

- *What are the main benefits of interdisciplinary design of AMB modelling, simulation and control?*
- *Is it possible to propose identification and control algorithms and test them with a virtual prototype?*
- *Is this kind of model/virtual prototype suitable for ODE-based modelling and controller studies?*

II. Active Magnetic Bearing Interdisciplinary Design Modelling and Control study (AMBIDMC) Tool

This research was motivated by the manual prototyping of active magnetic suspensions and bearings, [21] magnetic field analysis and geometric optimisation, [20] and a controller study [29] supported by a set of experimental studies including hard real-time control [23, 24, 29].

The main idea was to enable a complex study in the field of AML-based devices. Therefore, dedicated software had to be developed. To obtain a professional solution, the COMSOL and MATLAB packages were combined to take advantage of their best features. Software integration and customisation enabled a custom solution. This tool especially supports AMBs. It uses the COMSOL Multiphysics software as the core of the PDE and ODE calculations. Additionally, the MATLAB software is used to customise the design and carry out optimisation tasks, simulation, analysis and controller synthesis. The first application of the developed tool was an AMB shape generator [21]. Subsequently, the complexity was increased. Currently, the 2D modelling stage has been completed, and the completely functioning AMB-rotor VP is being simulated. The most important component, a controller, can be embedded either into the COMSOL model as internal mathematical formulas, or, alternatively, into m-coded functions and linked to the model.

The model is processed in the time domain in a parallel way, solving the magnetic field with the support of PDEs, computing rotor motion dynamics using ODEs, and solving controller equations. The applied method for the deformed mesh in time enables the rotor to be placed in true levitation mode in the AMB plane.

Using this tool, the user proceeds with the following steps:

- decision/concept stage: configuration, e.g. 3 or 4 electromagnets with a C-shaped core, solid or ring-type rotor, smooth or sharp poles [28],
- geometry design - dimensions of particular components,
- materials assignment: materials used in the model, such as air, copper, steel with or without B-H characteristics,
- definition of physics: assignment of magnetic field phenomena, coil regions, current- or voltage-driven coils with an RL equation,
- motion dynamics: formulas for rotor motion in the AMB plane,
- free-moving components: automatic assignment of the rotor properties available for motion in the AMB plane,
- time-dependent solver: time step and simulation time,
- analysis and post-processing: predefined post-processing quantities such as a 2D plot of magnetic flux density, rotor position, and control, coil current time diagrams, and a film representing rotor motion.

This tool is capable of performing a wide range of optimisation experiments, including: rotor unbalance, external vibrations and loads, material properties, heating, parameter perturbation, linear and non-linear control, forces, torque, mechanical stress, heat losses, eddy currents, etc. The range of analysis depends on the physical phenomena included in the model.

III. Rotor levitation in AMBs with Four and Three Electromagnets

Using the AMBIDMC tool, two AMB dynamical models were developed. Both operate with heteropolar configurations of 3 and 4 C-shape electromagnets. Both models were inspired by partly realised calculations and manufactured prototypes (see Figs. 2a and 5a).

A. Slim type AMB with four C shaped electromagnets and rotor stalibisation mode

Fig. 2a presents a slim-type AMB (10mm thick) called AMB4EM and ring-type rotor prototype; Fig. 2b is a schematic diagram with a smooth stator design [21].

A summary of the AMB4EM parameters is given in Table I with symbols corresponding to the AMB standard [4]. Due to the ring type rotor, the following properties were introduced: internal diameter ϕd_{int}, outer stator diameter D_{ext}, and W_{ext} representing the extended pole width.

TABLE I. AMB4EM Parameters

	Parameter	Value
D_{ext}	Outer diameter of radial stator core	90.0 mm
D	Inner diameter of radial stator core	50.0 mm
d	Outer diameter of radial rotor core	48.0 mm
d_{int}	Inner diameter of radial rotor core	40.0 mm
L	Effective radial bearing length	10.0 mm
W	Width of a magnetic pole	10.0 mm
W_{ext}	Width of a magnetic pole	12.0 mm

The numerical model was realised as current-driven. Rotor motion equations were added to translate the rotor in the AMB plane. The magnetic flux density at every pole was examined and the *XY* components of the electromagnetic force were calculated. The simulation results presented in Figs. 3 and 4 show the start-up and levitation of the rotor without the presence of gravity and without bias current. At the start-up, the rotor was located at the position of (150μm, -200μm), and other states to zero. The summary of AMB states calculated at the first time step is given in Table II. Two PD controllers operating in differential mode were applied for stabilisation, i.e. one for the X-axis and the other for the Y-axis.

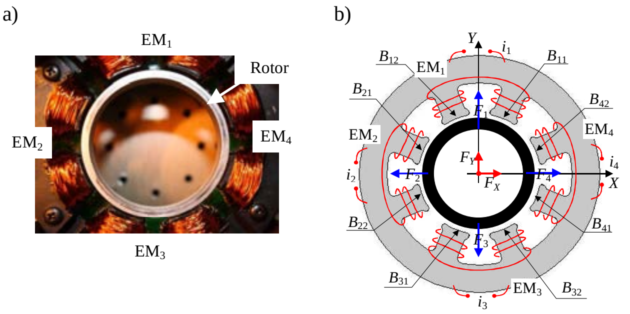
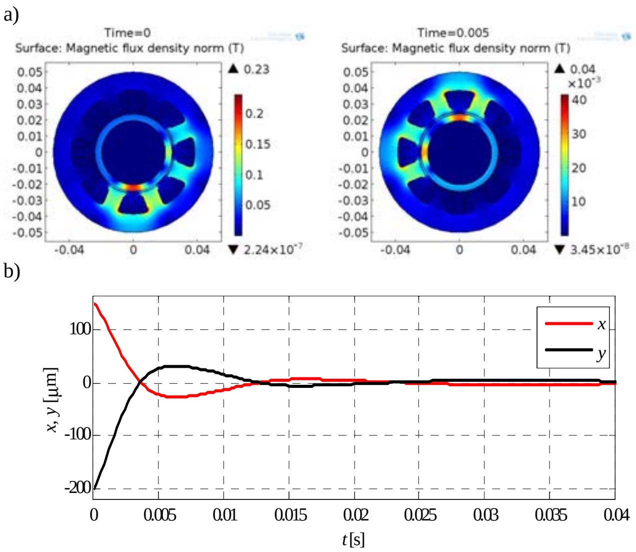


Figure 2. AMB with four actuators, smooth poles, and a ring-type rotor in the slim configuration: AMB and rotor thickness is 10mm

The simulation carried out with rotor planar motion represents control generated by the PD controllers attracting the rotor towards the bearing centre. The most interesting results are revealed in the magnetic flux density *Bij* where *i*-corresponds to the electromagnet i={1, 2,3, 4}, j represents the pole j={1, 2}. Thanks to this modelling approach, the differences in B values for every electromagnet are easily visible, which is crucial to the controller and observer studies. Moreover, the rotor displacement is visible in these signals indirectly, what allows to provide research towards self-sensing control.

TABLE II. AMB4EM STATES CALCULATED AT THE FIRST TIME STEP

	Parameter	Value
x, y	rotor X , Y position	150.0 µm,-200.0 µm
i_1, i_2, i_3, i_4,	EM 1÷4 coil current	0.00 A, 0.00 A, 1.59 A, 1.59 A,
Fx	*Electromagnetic force in X, Y axis*	2.73 N, -5.03 N
B_{11}, B_{12}	Magnetic inductance at EM 1	0.72 mT, 0.23mT
B_{21}, B_{22}	Magnetic inductance at EM 2	0.23 mT, 0.94 mT
B_{31}, B_{32}	Magnetic inductance at EM 3	77.00 mT, 83.97 mT
B_{41}, B_{42}	Magnetic inductance at EM 4	62.12 mT, 55.44mT



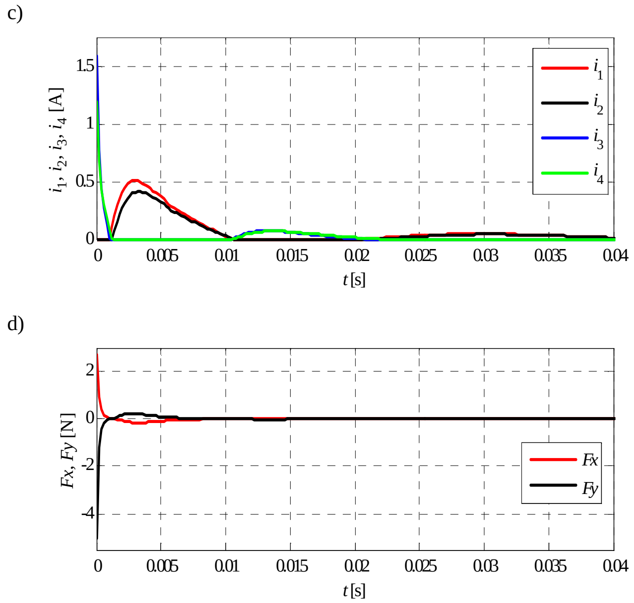


Figure 3. The simulation results of the stabilisation task - distribution of magnetic flux density (a); rotor displacement (b); coil curerents (c) and electromagnetic force components (d).

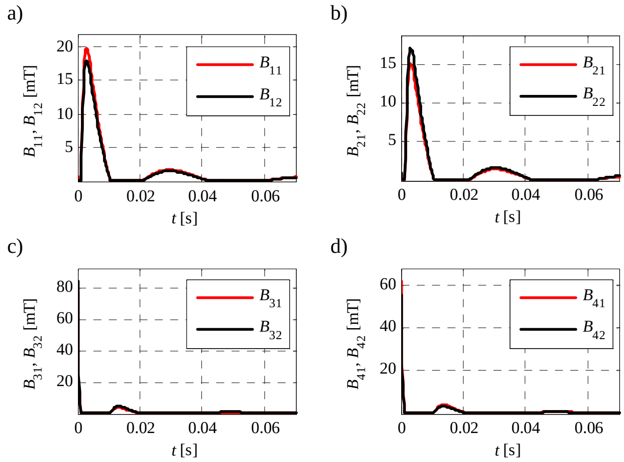


Figure 4. Magnetic flux desity measured at every AMB pole (refer to Fig. 2) in the stabilisation task (Fig. 3).

B. AMB with three C shaped electromagnets: rotor stabilisation and rotations

The second configuration to be considered is an AMB with three electromagnets (AMB3EM) [26]. A summary of the AMB3EM parameters is given in Table III. Symbols correspond to the AMB standard [4] extended with a few new properties due to the ring type rotor: internal diameter ϕd_{int}, outer stator diameter D_{ext}, and W_{ext} representing the extended pole width. The irregular displacement of electromagnets and smooth stator poles are the main features differentiating this configuration from standard ones. For this configuration, the motion dynamics in the AMB plane are modelled by a set of two differential equations [22, 26].

TABLE III. AMB3EM PARAMETERS

	Parameter	Value
D_{ext}	Outer diameter of radial stator core	95.0 mm
D	Inner diameter of radial stator core	51.8 mm
d	Outer diameter of radial rotor core	48.8 mm
d_{int}	Inner diameter of radial rotor core	42.0 mm
L	Effective radial bearing length	25.0 mm
W	Width of a magnetic pole	10.0 mm
W_{ext}	Width of a magnetic pole	13.0 mm

The shaft stiffness and damping coefficients were set to zero and, instead of standard electromagnetic force formulas, the electromagnetic force *X* and *Y* components were applied to both equations appropriately. The rotor imbalance was set to zero, but the rotations were enforced to drive the rotor via the transformation of the external coordinates. In this case the rotations operate as a disturbance for the stabilisation task. The rotation profile was set as a desired speed-up curve. Three local PD controllers were applied to stabilise the rotor at the bearing centre. These controllers operated on the basis of local distances between the rotor and electromagnet axis, calculated on the basis of geometrical rotor position. The bias current value was set at 0.1A. The summary of AMB states calculated at the first time step is given in Table IV. These simulations show that the basic PD controller is able to stabilise the rotor over a wide range of rotational speeds, although it is not robust for variable speed. However, using the proposed modelling approach, a number of modifications (including gain scheduling, adaptive or robust) to control methods can be proposed and validated.

TABLE IV. AMB3EM STATES CALCULATED AT THE FIRST TIME STEP

	Parameter	Value
x	rotor *X* position	-150.0 µm
y	rotor *Y* position	-300.0 µm
i_1, i_2, i_3	EM 1÷3 coil current	659.8mA, 0.0 A, 140.2mA
F_X, F_Y	*Electromagnetic force in X, Y axis*	-83.1 mN, -52.7 mN
B_{11}, B_{12}	Magnetic inductance at EM 1	6.24 mT, 8.24 mT
B_{21}, B_{22}	Magnetic inductance at EM 2	0.28 mT, 0.29 mT
B_{31}, B_{32}	Magnetic inductance at EM 3	28.29 mT, 25.74 mT

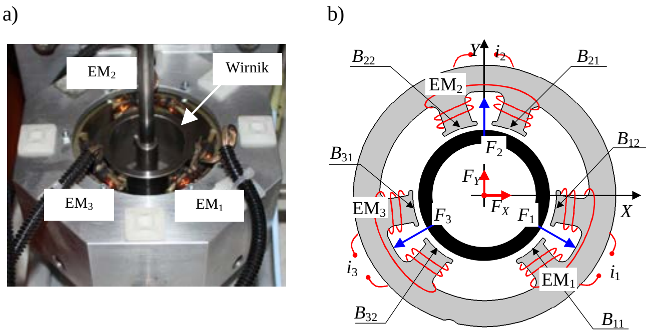


Figure 5. AMB with three electromagnets: a) prototype; b) model.

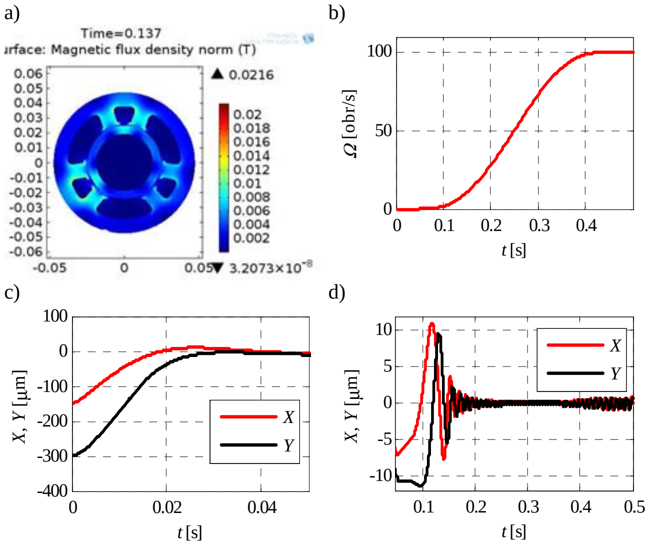


Figure 6. Dstribution of magnetic flux density (a); rotor velocity profile (b) and rotor displacement (c) time diagrams: start-up (d) and stabilisation phase at rotations (e).

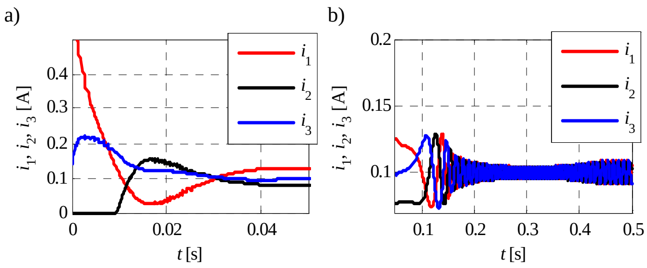


Figure 7. Control signals (coil currents) applied at the start-up and stabilisation phases under external rotary excitations

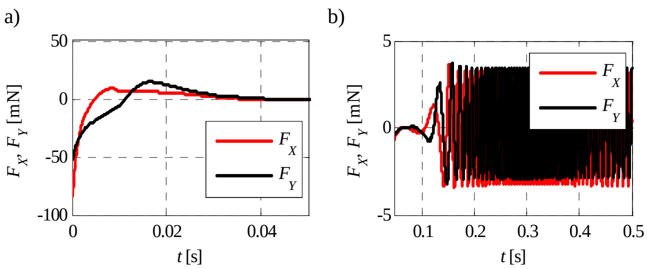


Figure 8. Caclulated electromagnetic forces obtained at the start-up (a) and stabilisation (b) phases under external rotary excitations

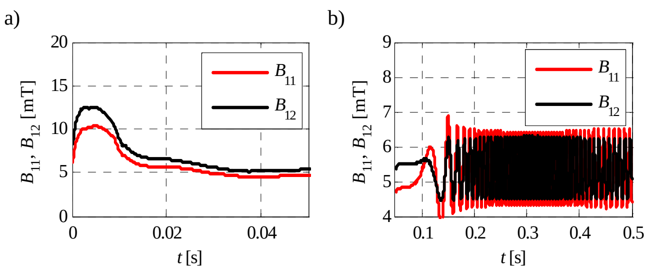


Figure 9. Measured magnetic flux density at EM1 poles, collected at the start-up (a) and stabilisation (b) phases under external rotary excitations

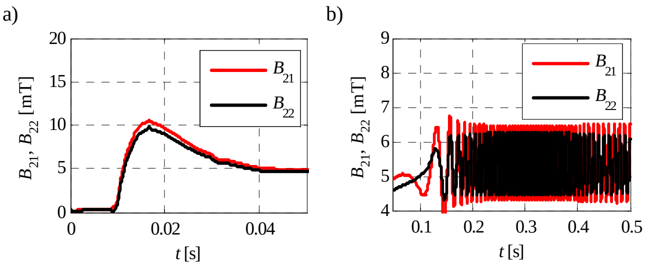


Figure 10. Measured magnetic flux density at EM2 poles - collected at the start-up (a) and stabilisation (b) phases under external rotary excitations.

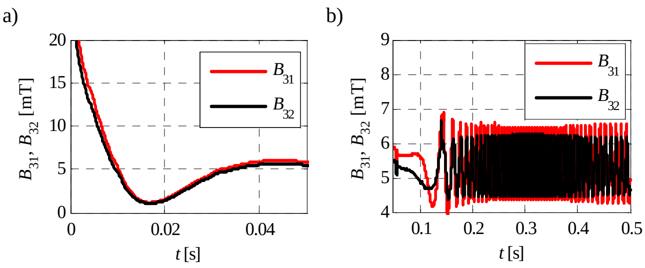


Figure 11. Measured magnetic flux density at EM3 poles - collected at the start-up (a) and stabilisation (b) phases under external rotary excitations.

Again, for the AMB3EM the magnetic flux density measured at the front of poles, allows to estimate the rotor position. Thus, the developed model is well suitable for a nonlinear controller synthesis, observers design and research towards self-sensing control. All these aspects will be considered in further research.

C. *Discussion on simulation results*

The completed simulations (see also [25, 26, 27, 28]) show that the electromagnetic force F_{Em} calculated on the basis of the standard formula (1) is a simplification and does not cover geometrical and magnetic properties; nor is it truly rotor-dependent.

$$F_{\mathrm{Em}}(a,i) = -\frac{K_{\mathrm{Em}}}{4}\frac{i^2}{a^2}, \text{ or }, F_{\mathrm{Em}}(B) = -\frac{A}{\mu_0}B^2 \qquad (1)$$

where: K_{Em} - electromagnet constant, i - coil current, A - area of electromagnet cross-section, a - distance between the levitated object and electromagnet pole, B - magnetic flux density. The magnetic flux density measured at both poles of the electromagnets varies; therefore it must be considered in the identification and magnetic flux density based controllers and observers. The implemented rotor motion in the AMB plane enables testing of the controller. The structural rotor imbalance can be computed on the basis of rotor geometry and used in the simulation model.

Simulated models correspond to existing prototypes, but the comparison and convergence discussion on the simulation and experimental results is planned to be executed. This requires the proposal and identification of scenarios in which both variants can be realised.

IV. Modelling aspects towards controller study

The developed AMB model using the AMBIDMC tool makes it possible to conduct a set of studies:

- This type of synergistic model enables an unlimited number of experiments and dependencies existing in levitation systems. As the most impressive results, the author cites the complete dynamics solved in the time domain, including rotor displacement and its influence.
- Identification of electromagnetic force. Thanks to the complexity of the model, the rotor position and the coil current can be adjusted statically or dynamically, thus making it possible to achieve static and dynamic characteristics. Direct identification in the AMB plane is a difficult task and requires the use of a special apparatus, but gives a overview of the true force characteristics.
- Identification of the actuator properties. Using the AMBIDMC tool, magnetic flux density vs coil current and rotor position can be analysed. Additionally, coil current vs supply control signal can be analysed when the model is extended with a RL circuit representing the electromagnet winding.
- Admissible sets can be achieved for a study of control signals and rotor displacements in the region of levitation. This enables the study of the static and dynamic properties of the complete solution with embedded control.
- The magnetic flux density is a valuable quantity for magnetic-flux-based feedback controllers and rotor position observers.
- All quantities can be analysed statically, in the time and frequency domains.
- Other quantities corresponding to mechanical and thermal properties are available for analysis. Mechanical strain can be achieved under the rotor load of the electromagnetic forces. For the electromagnet windings, core and surrounding elements, thermal analysis can be accomplished on the basis of resistive heating of coils.
- The study, focussed on the influence of material properties on AMB dynamics and operation, can easily be used for the definition of constants or characteristics.
- The linear and non-linear controller formulas can be embedded in the form of equations, including integration or derivative calculations. The controller embedded in the model and its parameters can be easily tuned using the optimisation stage for defined control quality criteria.
- For those wishing to calculate the controller analytically, the developed model can be a source of data for ODE model tuning. In this case there is no need to build the prototype initially and perform a number of expensive tests, some of which cannot be carried out due to specific apparatus requirements, e.g. magnetic flux density, electromagnetic force value for every rotor position and any control signal. Certain electromagnetic force investigations and thermal analyses were conducted [29].

With the proposed model, carrying out identification schemes is much more flexible. Please note that simulation models offer much more than just experiments. However, it is obvious that the models (including material properties, physical phenomena, and real controller implementation) ought to be verified on the basis of experimental results. Thus, the AMBIDMC tool can be used to verify the identification concepts behind practical experiments.

V. Colnclusions

The synergistic dynamical models of the active magnetic bearings were realised and allow to provide time domain simulations. The developed AMBIDMC tool can be helpful in the analysis of existing AMB configurations as well for new designs. It helps designers to check and validate the device concept at the simulation stage, thanks to the full functionality of the virtual prototype. Model verification is available and convergence analysis is required on the basis of experimental investigations. It appears that the complex model gives a better overview of physical quantities than mathematical approximations based only on identification data. The complex model enables the collection of much more information and many more dependencies due to an unlimited number of possible identification scenarios. Finally, such a complex numerical model is well suited for controller design, tuning and tests. The tool is conducive to the addition of new features and will be expanded in the direction of 3D modelling and complex machine design.

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