MATLAB-Based Tool for Teaching of Active Magnetic Bearing Design to Undergraduate Students

Vuojolainen Jouni, Nevaranta Niko, Jastrzebski Rafal, Pyrhönen Olli

DOI: 10.1109/EPEPEMC.2018.8521941

Please cite the publication as follows:

Vuojolainen, J., Nevaranta, N., Jastrzebski, R., Pyrhönen, O. (2018). MATLAB-Based Tool for Teaching of Active Magnetic Bearing Design to Undergraduate Students. 2018 IEEE 18th International Power Electronics and Motion Control Conference (PEMC). DOI: 10.1109/EPEPEMC.2018.8521941

MATLAB-based Tool for Teaching of Active Magnetic Bearing Design to Undergraduate Students

Jouni Vuojolainen*, Niko Nevaranta*, Rafal Jastrzebski* and Olli Pyrhonen*
*Dept. of Electrical Engineering
Lappeenranta University of Technology(LUT), Lappeenranta, Finland
Email: Jouni.Vuojolainen@lut.fi

***Abstract*—Visual educational tools are important in contributing to skills in the electrical engineering profession. This paper introduces an active magnetic bearing (AMB) design tool used to teach important skills in modern high-speed technology to undergraduate students. The proposed tool is based on MATLAB, and it has a visual and easy-to-understand graphical interface. The paper describes how to use the tool and gives a design example of an axial AMB. The tools provide an opportunity to import the design directly to a finite element method (FEM) software in order to enable further analysis. The tool is also discussed from the perspectives of research and education.**

***Index Terms*—active magnetic bearing (AMB), education, finite element method (FEM), simulation**

I. INTRODUCTION

Lappeenranta University of Technology (LUT) has a long tradition of research into active magnetic bearings (AMB) and high-speed machines. The research has resulted in numerous articles and dissertations in the field [1], [2], [3], [4], to name but a few. However, the electrical engineering courses currently held at LUT do not provide much information for undergraduate students about topical research activities or basic educational tools related to the high-speed technology. Enriching the teaching material with findings from recently completed and ongoing research projects is of great importance in order to enhance the quality of teaching, and more importantly, bridge the gap between theory and practice. Especially, it is important to provide the students with basic design skills if they should participate in research projects.

The AMBs apply electromagnets to magnetically levitate a rotor. The importance of teaching skills in the field of active magnetic levitation to undergraduate students was acknowledged in [5], [6], where courses focusing on the control design process were introduced. Similarly, [7] proposed a magnetic levitation system that can be used for advanced control education. An AMB laboratory environment, used as a learning environment, was studied in [8]. Yet another system was introduced in [9], where a magnetically levitated brushless DC motor with a magnetically levitated rotor was developed as a teaching tool for undergraduate students. However, these papers do not consider the field of high-speed motor applications, which represent a more complex problem of active magnetic levitation. When teaching active magnetic levitation, it is also important to provide the students with skills related to the design of AMBs.

The AMB design is an integral part of the AMB research. However, it is an iterative process, and the initial design is only the starting point. The design requires advanced knowledge of several scientific fields, such as electromagnetism and mechanical and material engineering. For beginners without any previous know-how, even the initial design can be difficult as the textbooks [10] in the field of AMBs usually only have a theoretical viewpoint. In order to facilitate the design of an active magnetic bearing, a MATLAB-based tool with an easy-to-understand graphical interface was developed. Visualization by a graphical interface supports both visual and situated learning [11], as the researcher or the teacher can participate in the design process by giving valuable comments and practical tips. With the tool discussed in this paper, the initial AMB design is a fast and simple process. The tool can also export the bearing geometry, and it can be directly imported to some finite element method (FEM) software such as ANSYS. By FEM simulations, more accurate and realistic dimensions of the AMB are achieved. Naturally, the student can learn important skills in electromagnetism by first analyzing the design by analytical equations (used in the tool) and after that, continue the design by FEM simulations.

This paper illustrates the AMB design tool for MATLAB. The paper focuses especially on the axial bearing design as this is a much simpler case than the radial bearing design. The authors' contribution to the design of the tool is proper documentation and modification of the axial bearing export code for the easier export to ANSYS. The paper is organized as follows. First, the AMB design tool is discussed in detail. Second, an example AMB design is provided with the tool, and FEM simulations are shown with ANSYS. The tool is also discussed both from the research and educational perspectives. Finally, conclusions are drawn.

II. AXIAL ACTIVE MAGNETIC BEARING DESIGN

The axial active magnetic bearing is a type of AMB that suppresses the rotor movement in the axial (thrust) direction. A typical axial AMB structure is a disk added to the rotor to provide a surface for the magnetic flux generated in the axial AMB stator. The basic geometry of the axial AMB dimension is shown in Fig. 1.

The work has been cofunded by the Academy of Finland No. 270012, No. 304071 and 304784 as well as by Business Finland Dnro 1170/31/2016.

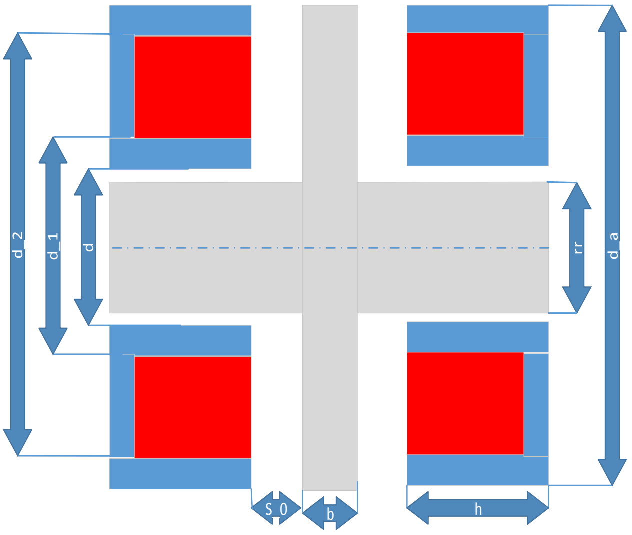


Fig. 1. Axial AMB with dimensions. rr is the rotor diameter, s_0 is the air gap, d is the inner diameter, d_1 is the inner winding diameter, d_2 is the outer winding diameter, d_a is the outer diameter, b is the thickness of the thrust disk, and h is the axial stator length.

The basic design of an axial AMB is presented in [10]. The pole area of the inner pole is

$$A_p = \frac{\pi(d_1^2 - d^2)}{4}, \tag{1}$$

where d_1 is the inner winding diameter and d is the inner diameter. Assuming no nonidealities, the balanced pole area can be achieved when

$$\frac{\pi(d_a^2 - d_2^2)}{4} = A_p, \tag{2}$$

where d_2 is the outer winding diameter and d_a is the outer diameter. The stator has to have a minimum area matching the pole faces

$$\frac{\pi d_1(l - b - 2h_n - 2s_0)}{2} = A_p, \tag{3}$$

and also a thrust disk

$$\frac{\pi d_1 b}{2} = \frac{\pi(d_1^2 - d^2)}{4}, \tag{4}$$

where l is the bearing total length, b is the disk thickness, h_n is the slot depth, and s_0 is the air gap. By meeting these constraints, the bearing force capacity depends on the pole area and the magnetic saturation density of the thrust disk or the stator. After selecting a reasonable saturation flux density B_{sat}, the maximum force of the bearing can be calculated by

$$f_{max} = \frac{B_{sat}^2 A_p}{\mu_0}, \tag{5}$$

where μ_0 is the permeability of vacuum.

III. ACTIVE MAGNETIC BEARING DESIGN TOOL

The bearing design of the tool is based on the maximum and average force constraints and the rotor radius. These are the basic parameters that are needed for the tool in order to get an insight into the dimensions of the design. Other parameters, such as material properties, are used to iterate the design to meet the specifications of the application. The example workflow of the radial bearing case can be found in [12].

As mentioned above, the tool was written in MATLAB and has an easy-to-use graphical user interface (GUI) for accessing it. The main view of the tool is shown in Fig. 2. On the left side we can see the input parameters for the tool. For the axial case they are: bearing design (type), air gap, mechanical gap, average force, force slew rate, maximum force, shaft radius, manufacturing tolerance, copper packaging factor, flux knee, iron ratio, maximum current density, and core material. Note that the values shown in Fig. 2 are default values shown when opening the tool. On the right side, the bearing obtained by the input values can be seen by clicking the ’calculate’ button in the tool row. From the tool row we can also export the bearing geometry to the FEM simulation software by clicking ’export’ and ’export geometry’. For quick demonstration, the default values will result in a bearing view shown in Fig. 3. It should be noted that this view is a side view from the axial bearing. Further, the tool provides two different options for the structure: the classical and E-core designs, which are useful especially when evaluating the structure of a radial bearing. The red color shows the coil area, and the axial stator is located around it, which, in reality, has a round shape. Thus, on the left side there is one axial stator and coil, and on the right side also one axial stator and coil.

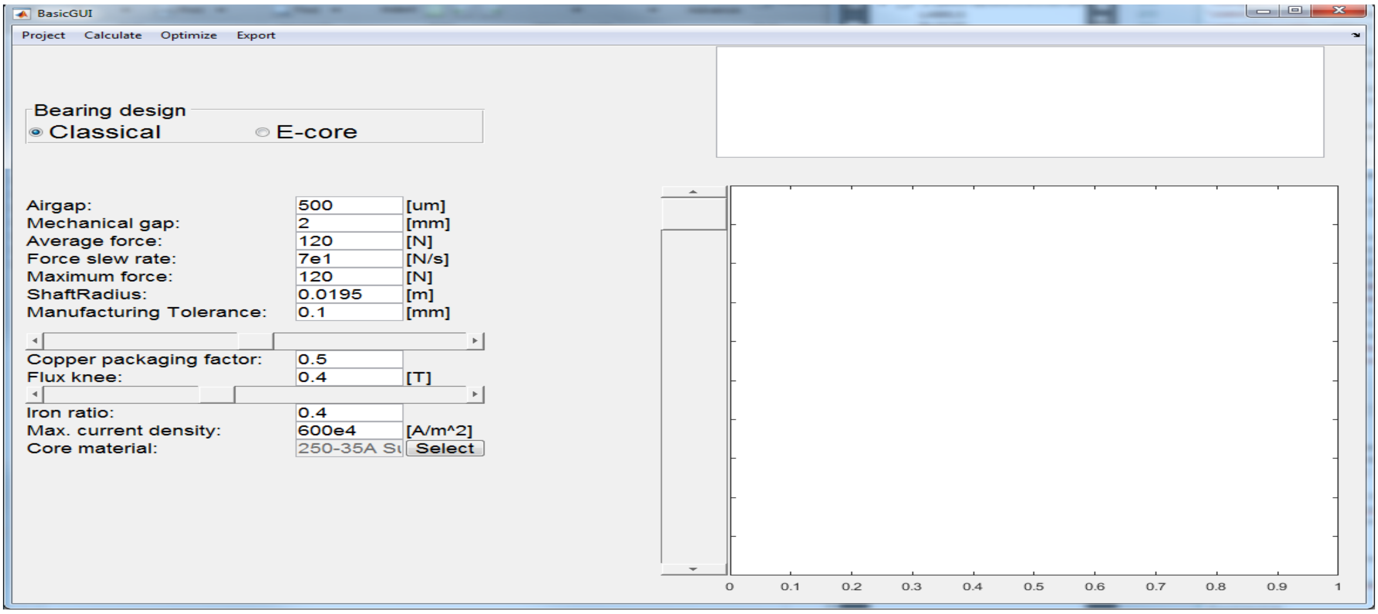
From the educational perspective, for undergraduate students, the tool with an interactive GUI is easy to understand as only a few design parameters are needed to design the bearing. The students can test different iron material properties by changing the magnetic properties, and determine the practical limitations of AMB manufacture, for instance the limitations related to the winding configuration, by testing different copper filling factors.

IV. DESIGN EXAMPLE OBTAINED BY USING THE TOOL

To show the basic principle of the design tool, an example of the axial bearing design is shown. Thus, the students have an opportunity to use the design parameters presented here as a reference design to learn the AMB design. The basic design is obtained by using the AMB tool with the values given in Table I, and when the initial design has been analyzed, it can be directly imported to ANSYS for more detailed FEM simulations. Thus, the students have an opportunity to learn AMB design based on both analytical equations and FEM analysis.

A. Design specifications

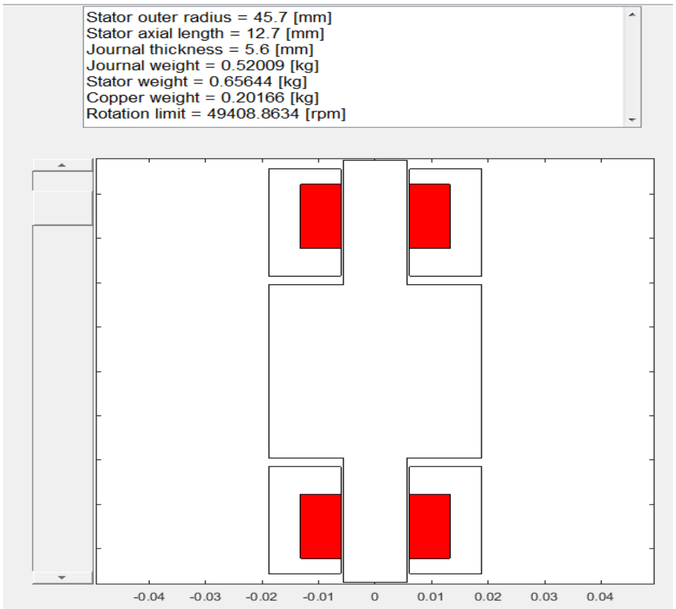
Depending on the high-speed motor design, the AMBs have different properties, dimensions, and materials. Table I shows



Bearing design
● Classical ○ E-core

Airgap: 500 [um]
Mechanical gap: 2 [mm]
Average force: 120 [N]
Force slew rate: 7e1 [N/s]
Maximum force: 120 [N]
ShaftRadius: 0.0195 [m]
Manufacturing Tolerance: 0.1 [mm]
Copper packaging factor: 0.5
Flux knee: 0.4 [T]
Iron ratio: 0.4
Max. current density: 600e4 [A/m^2]
Core material: 250-35A St

Fig. 2. Screenshot of the design tool. The tool has a graphical user interface (GUI) that is easy to understand, and the design can be changed by design parameters. The initial design can be imported to the FEM software to iterate the final design.



```
Stator outer radius = 45.7 [mm]
Stator axial length = 12.7 [mm]
Journal thickness = 5.6 [mm]
Journal weight = 0.52009 [kg]
Stator weight = 0.65644 [kg]
Copper weight = 0.20166 [kg]
Rotation limit = 49408.8634 [rpm]
```

Fig. 3. Example of a bearing obtained with the default values of the tool depicted in Fig. 2.

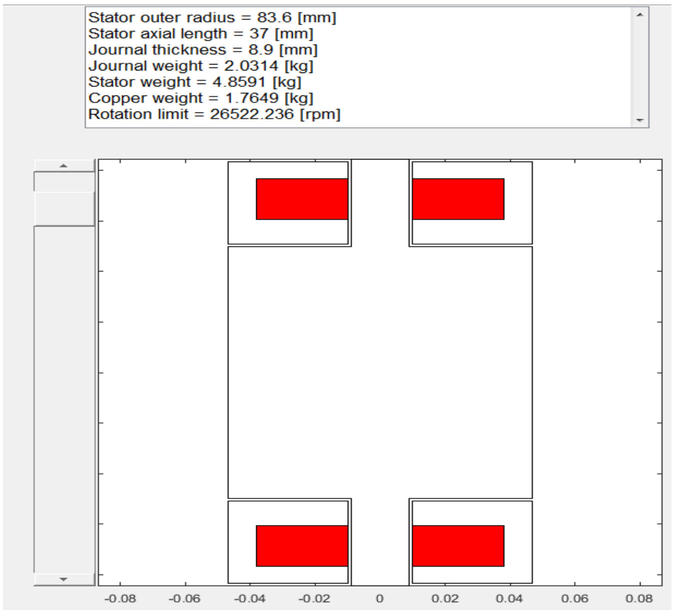
the design specifications used in this paper to demonstrate the tool. The values given in the table are example design parameters for an industrial project. The initial design parameters given by the industrial partner were the force requirement and the air gap length. The rest of the parameters have been chosen by the designer.

B. Application of the tool with the specifications

When designing an AMB, the basic information required for the initial design is related to the force production of the AMB (see average and maximum forces in Fig. 2) and physical dimensions such as the air gap length. Especially, radial AMB designs should be optimized so that the axial length of the machine is not increased by the design as subcritical rotor dynamics is often preferred [13]. In the AMB design, a compact structure is usually desired, and therefore, the material used in the AMB stator and the disk has to be selected accordingly. The material properties can be analyzed with the tool by changing the magnetic properties, that is, by varying the flux knee value. In this paper, the axial bearing design is used as an illustrative example. With the specifications provided in Table I, we obtain the bearing shown in Fig. 4. This geometry is used for the FEM simulations. By using these results as a reference, the students can evaluate their design and vary the design parameters to understand the influence of different parameters and the importance of the iterative design process.

TABLE I
AMB DESIGN PARAMETERS

Parameter	***Value***	***Unit***
Bearing design	classical	
Air gap	1000	[μm]
Mechanical gap	1	[mm]
Average force	1500	[N]
Force slew	7e1	[N/s]
Maximum force	1700	[N]
Shaft radius	0.05	[m]
Manufacturing tolerance	0.1	[mm]
Copper packaging factor	0.5	
Flux knee	0.8	[T]
Iron ratio	0.5	
Max. current density	500e4	[A/m^2]
Core material	250-35A	



```
Stator outer radius = 83.6 [mm]
Stator axial length = 37 [mm]
Journal thickness = 8.9 [mm]
Journal weight = 2.0314 [kg]
Stator weight = 4.8591 [kg]
Copper weight = 1.7649 [kg]
Rotation limit = 26522.236 [rpm]
```

Fig. 4. Bearing obtained with the design specifications given in Table I.

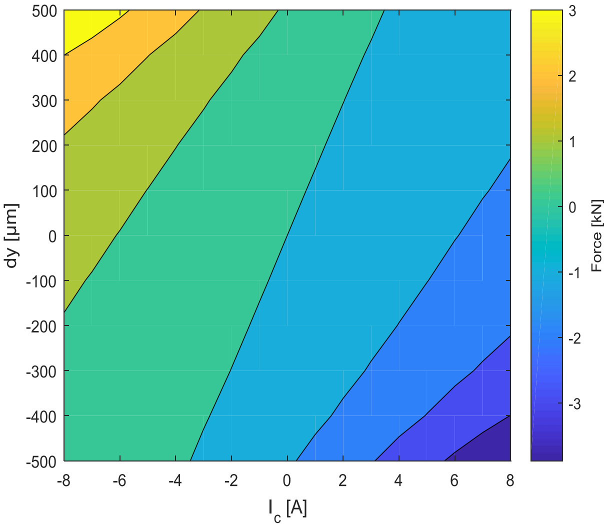


Fig. 5. Force contour plot obtained from the FEM software.

C. FEM simulations

The geometry used for the FEM simulations is shown in Fig. 4, and it is exported from the tool to ANSYS used for the FEM simulations. Now, we also have to specify the maximum coil current I_{max}, the bias current I_b, the coil control current I_c, and the number of coil turns N. The bias current I_b is used to linearize the force production of the AMB. The currents for the left- and right-side coils are obtained from

$$I_{left} = I_b + I_c \tag{6}$$

$$I_{right} = I_b - I_c. \tag{7}$$

Naturally, the current of the coil must be positive, and it cannot exceed the maximum coil current.

In this case, the maximum coil current I_{max} is selected to be 16 A, the bias current I_b is 8 A (half of the maximum current, typical selection), and the control current I_c is 8 A in order to have the maximum current in the left coil. The number of coil turns N can be calculated by

$$N = \frac{Bg_0}{\mu_0 I_{max}}, \tag{8}$$

where B is the flux density (flux knee), g_0 is the air gap, μ_0 is the permeability of vacuum, and I_{max} is the maximum coil current. In this case, the number of coil turns N is 40. The material used for the rotor and axial stator parts is steel 1008. With this information, the simulation can be carried out in the FEM.

First, the bearing is simulated with the maximum coil current in order to see how much maximum force the FEM-simulated bearing can produce. In this case, the maximum force is 1300 N. This is slightly lower than the specified force (Table I) and could be increased for example by increasing the number of turns in the coil or by redesigning the bearing. As this design is for demonstration purposes only, the value of N is kept at 40.

Next, the bearing is simulated with a 2-D sweep, where the coil control current I_c is varied from -8 A to 8 A in 1 A steps and the rotor position dy from -500 μm to 500 μm in 100 μm steps. In this case, the rotor position movement is in the axial direction (left-right movement in Fig. 3). The bearing force and the inductance of either the left- or the right-side coil is measured (they should be symmetrical). This information can be used later to simulate the bearing for example with SIMULINK. The resulting force contour plot is shown in Fig. 5, and the inductance contour plot in Fig. 6.

Finally, the current stiffness k_i and the position stiffness k_x can be obtained from the results in Fig. 5. The AMB is linearized in the dy = 0 μm, I_c = 0 A operating point. In the current stiffness case, the control is altered and the rotor position is kept at a constant dy = 0 μm. This results in a value of 163 N/A for k_i. The linearization accuracy is depicted in Fig. 7, where the real force and the linearized force are shown for the zero rotor position. In a typical case, the linearization accuracy for the current stiffness is very good. Next, in the position stiffness case, the rotor position is altered and the control current is kept at a constant I_c = 0 A. This results in a value of 1115000 N/m for k_x. The linearization accuracy is shown in Fig. 8 where the real force and the linearized force are illustrated for the zero control current. The accuracy is good when the operation point is close to the zero rotor position, but otherwise, the accuracy is not that good. However, behavior of this kind can be expected as the applied bias current I_b linearizes the force current relation but not the force position relation. Note that when building a model with SIMULINK for controller design validation purposes it is important to use these values to take into account the nonlinear

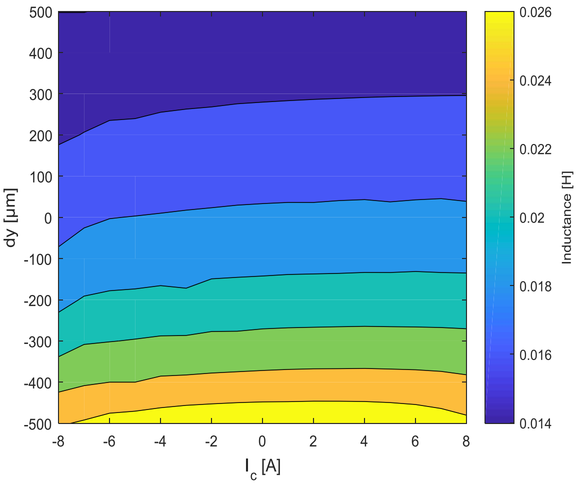


Fig. 6. Inductance contour plot.

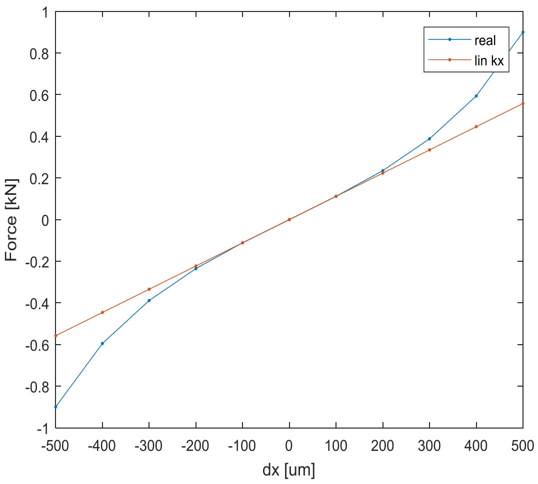


Fig. 8. Linearized force compared with the real force production real force when I_c = 0 A.

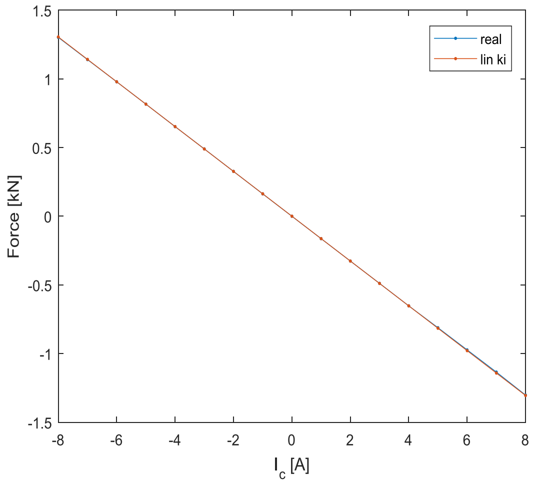


Fig. 7. Linearized force compared with the real force production when dy = 0 μm.

dynamics of the bearing force production. The results from the FEM design are typically used to build look-up-table-based models to represent the AMB dynamics in the simulation environment.

V. CONCLUSIONS

The design of an AMB is an iterative process, and it requires advanced knowledge of several scientific fields. For beginners such as undergraduate students, it can be a very difficult process. To facilitate learning, a MATLAB tool with an easy-to-use GUI was presented. This tool is used at LUT to obtain an initial design for AMB-supported high-speed machines, but it is also introduced to undergraduate students so that they can learn skills related to the AMB design. In this paper, an example axial bearing design was shown and the parameters for the design were given. The proposed design can be used as a reference design when the students begin to make their own designs. The tool also provides an opportunity to import the model directly to the FEM software, thereby allowing the students to study electromagnetic design by FEM simulations. In this paper, simple FEM simulations with ANSYS were shown to obtain the inductance and force matrices, the current stiffness k_i, and the position stiffness k_x. These values are important especially from the perspective of control design; with them, the students can proceed in the learning process and make a nonlinear AMB model by building a look-up-table of the data for control analysis purposes in Simulink. Thus, the tool can be used to provide the students with skills in various research fields that are an important part of high-speed machine design.

This paper provided guidelines to use the AMB tool for axial bearing design. By using the parameters given in the paper, the undergraduate students can learn the design procedure by analyzing the results they obtain with the tool. The future development of the teaching material could focus on modification of the tool based on user feedback. Naturally, radial bearings are also needed in the high-speed motor application, and thus, an example of a radial AMB design should be added to the educational material.

REFERENCES

[1] R. P. Jastrzebski, "Design and implementation of FPGA-based LQ control of active magnetic bearings," Doctoral dissertation, Dept. Elect. Eng., Lappeenranta Univ., Lappeenranta, Finland, 2007.

[2] K. Hynynen, ”Broadband excitation in the system identification of active magnetic bearing rotor systems,” Doctoral dissertation, Dept. Elect. Eng., Lappeenranta Univ., Lappeenranta, Finland, 2011.

[3] A. Smirnov, ”AMB system for high-speed motors using automatic commissioning,” Doctoral dissertation, Dept. Elect. Eng., Lappeenranta Univ., Lappeenranta, Finland, 2012.

[4] N. Uzhegov, ”Design and material selection of high-speed rotating electrical machines,” Doctoral dissertation, Dept. Elect. Eng., Lappeenranta Univ., Lappeenranta, Finland, 2016.

[5] J.M. Watkins, and G.E Piper., ”An undergraduate course in active magnetic levitation: Bridging the gap,” in *Proc. of 35th Southeastern Symp. on System Theory*, Morgantown WV, USA, 2003 pp. 313–316.

[6] T. H. Wong, ”Design of a magnetic levitation control system – An undergraduate project,” *IEEE Trans. on Education*, vol. 29, no. 4, pp. 196–200, Nov. 1986.

[7] W. Yu, and X. Li., ”A magnetic levitation system for advanced control education,” in *Proc. of 19th World Congress of IFAC* , Cape Town, Africa, Aug. 2014 pp. 9032–9037.

[8] S.C Mukhopadhyay, C. Gooneratne, and G. Sen Gupta, ”Magnetic bearing: An integrated platform for teaching and learning,” in *Proc. of 2nd Int. Conf. on Autonomous Robots and Agents*, Palmerston North, New Zealand, Dec. 2094 pp. 283–288.

[9] M.Raab, A. Kazi, and D.L. Trumper, ”Magnetically levitated BLDC motoras a modular teaching tool,” In *Proc. of 16th Int. Conf. on Research and Education in Mechatronics*, Bochum, Germany, Nov. 2015, pp. 1–8.

[10] G. Schweitzer, et al., ”Magnetic Bearings Theory, Design, and Application to Rotating Machinery,” London, Springer, 2009.

[11] A. Johri, and B.M Olds, ”Situated Engineering Learning: Bridging Engineering Education Research and the Learning Sciences,” *Jour. of Eng. Education*, vol. 100, no. 1, pp. 155–185, Jan. 2011.

[12] R. P. Jastrzebski, et al., ”Automated design of AMB rotor systems with standard drive, control software and hardware technologies,” in *Proc. of 15th Int. Symp. on Mag. Bear.*, Japan, 2016 pp. 78–85.

[13] N. Uzhegov, A. Smirnov, C. H. Park, J. H. Ahn, J. Heikkinen, and J. Pyrhönen, ”Design Aspects of High-Speed Electrical Machines With Active Magnetic Bearings for Compressor Applications,” *IEEE Trans. on Ind. Electron.*, vol. 65, no. 11, Nov. 2017, pp. 8427–8436.