

# Features and Limitations of 2D Active Magnetic Levitation Systems Modeling in COMSOL Multiphysics

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**Abstract:** This elaboration presents the Active Magnetic Suspension (AMS) and radial Active Magnetic Bearing (AMB) as a representatives of the Active Magnetic Levitation Systems (AMLS). The laboratory test rigs are analyzed in the 2D space to simplify calculations. The control algorithm as well as the motion dynamics are implemented directly in the COMSOL Multiphysics. The discussion on features and limitations is provided to show an overview of the considered problems.

**Keywords:** active, magnetic, levitation, suspension, bearing, control, electromagnetic force, moving mesh, geometry, ODE

## 1. Introduction

Nowadays, the prototyping stage of complex devices require an interdisciplinary approach.

The Active Magnetic Levitation Systems are classified as mechatronic devices that are very complex and require the synergy of knowledge and technology. Today, the application of the COMSOL Multiphysics [1] software opens a new way to advanced design and test of modern devices where active levitation technology is applied. The prototyping costs are minimized thanks to the computer simulations. Although, it is required to have an adequate model of some prototypes to compare and verify modeling techniques. It seems that the COMSOL Multiphysics is an universal tool that can be used in the AMLS design. During the past years some research has been done in this field [7, 9, 11] and a number additional software tools were designed [5, 6, 7] to support the modeling and simulation stage.

## 2. Active Magnetic Levitation Systems

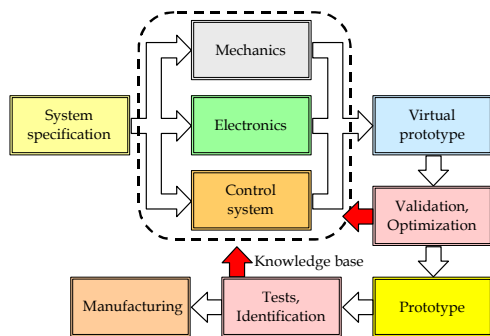
The AMLS consists of electromagnet or a set of electromagnets that are supplied from steered power actuators, ferromagnetic object to be levitated, and the control system. The control

formulas vary with respect to the operating mode properties and device functionality.

The main issue to use the COMSOL Multiphysics software for modeling and simulation purposes was to have a numerical model similar to the experimental test-rig. The AMLS devices are modeled with precision adequate to the manufacturing possibilities that depend on machining process and costs [5]. For the presented devices the precision is set in the range of  $10 \div 100$  micrometers. In the case of AMLS it is especially important to have geometry as exist due to the magnetic field distribution and variable levitation gap.

The AMLS dynamics is modeled using PDE and ODE modes. The electromagnetic force is calculated for the applied electromagnet geometry and material properties. This force is used in the equation of motion of the levitated object to compensate the gravity force or other counteracting forces. The control signal is directly introduced into the model by the calculated current density to achieve stable levitation mode.

One of the most important features in the proposed interdisciplinary [8] approach is the availability to apply material properties and especially magnetization curve. Moreover, the device is studied using the geometry as the basis for modeling tasks. In the case of AMLS systems the geometry plays a crucial role for magnetic force distribution and device functionality. The application of many physical phenomena and cross-couplings makes availability to have a virtual prototype closer to the real product. The COMSOL Multiphysics environment fulfills requirement of the proposed prototyping scheme. A number of user defined add-ons is required for the device specific geometry and operational modes (e.g. controller application) to obtain a full functionality of the virtual prototype.



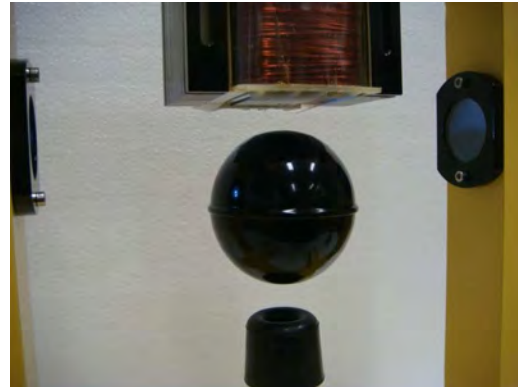
**Figure 1.** The proposed interdisciplinary Design Approach where virtual prototype is being developed and studied.

The parameterized and automatically generated geometry [9] allows to provide an optimization of the AMLS components. The optimization stage was applied to maximize the force and minimize AMB core losses [6]. The developed construction generator allows to prototype a new devices and model existing ones. The main feature is that e.g. the coil area could be adapted to match the real one.

In the AMLS, the coil winding has many turns from several to hundreds. In this case the coil model is simplified to a single component represented in rectangular, polygon or user-defined shape [5]. This simplification is not adequate to cases where the actuator is controlled by the frequently changed signals (e.g. PWM) due to the skin effect. The modeling of the exact coil makes the geometry complicated and increases numerical effort.

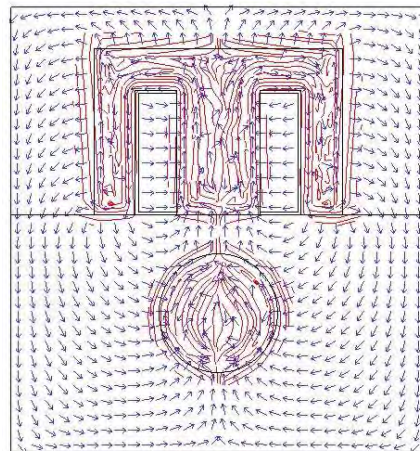
### 2.1 MLS with E-shape cuboid electromagnet

The MLS1EM (Fig. 2) contains a single E shape electromagnet and the ferromagnetic sphere as levitated object. The electromagnet core has a E form of the cross section. The coil is wound at the central part of the core. Because of the spherical ball shape the AMLS could be modeled in the 2D in the form of the middle cross-section only. But such modeling is not very precise due to the spherical shape of the levitated object. Although, this modeling allows to observe and analyze the magnetic field properties and forces acting on the object. In this case the simplification is done to a single electrical steel sheet and the ferromagnetic sphere cross-section, both 0.5mm thick.



**Figure 2.** Magnetic levitation system MLS1EM [2] in action.

Figure 3 presents the magnetization and magnetic field in the form of streamlines and arrows respectively. One can find that the levitated object is self centered with respect to the actuator geometry and the iron based components are magnetized.



**Figure 3.** Cross-section model of the MLS1EM.

### 2.2 MLS with cylindrical electromagnet

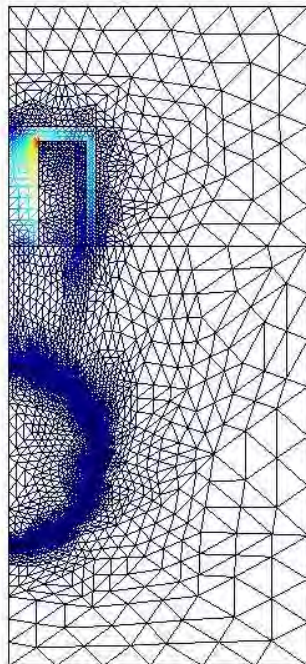
Modifying the MLS1EM or MLS2EM by the replacement of the electromagnetic actuator to the cylindrical form a new AMLS is obtained. Figure 4 presents the reconfigured MLS2EM with the levitated sphere to collect the experimental data.

The levitated object is a ferromagnetic sphere, while the electromagnet is cylindrical with a E-shape cross-section. Thus the

application of axial symmetry mode is possible and allows to simplify modeling stage. The analyzed construction of the MLS is given in Fig. 5.



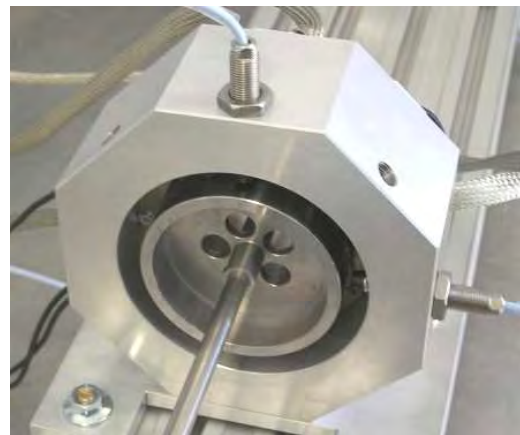
**Figure 4.** MLS2EM [3] - upper electromagnet replaced with cylindrical one.



**Figure 5.** Magnetic flux density represented in the wire frame mode.

### 3.1 AMB with 3 electromagnets

The prototyped construction of the AMB consists of 3 electromagnets in the C form. The simplified AMB modeling in the 2D plane is possible and well applicable due to the specified width of the AMB and rotor. The AMB stator is made as a set of laminated electrical steel sheets usually, that can be treated as a single one, package or as a solid block. It depends on the required analysis – for example if the eddy currents can be neglected or not. In the case of this AMB construction 3 control signals are required to supply electromagnetic actuators. The measurement coordinates remains the same as in the experimental one. The modeling stage will be used for the prototype verification purposes. At this moment the axial motion of the rotor was realized and simulated. The state-feedback controller [12] has been applied as a set of equations embedded in the COMSOL environment. The AMB modeling process is very sophisticated due to the relatively small levitation gap with respect to the stator and rotor size. This research will be reported separately.



**Figure 6.** 3EM Active Magnetic Bearing [13].

### 3. Enabling control strategy in AMLS models

To stabilize an object in the AMLS the controller must be used. The control strategy depend on the target application of the device. Therefore, it is required to simulate the whole device with a control algorithms implemented at the designing stage. The control structure can be

very simple - from a few separated gains up to nonlinear cross-coupled forms. From the control system designer point of view it is required to have a model that represents the real system. Such model could be used for the control system development and analysis of the device operation, test and optimization.

The control design is usually done in the following ways: math calculations and final formulas coded in the programming language, formulas transferred to the object oriented form and programmed with graphical environments like MATLAB/Simulink, LabView, and SciLab/SciCos and others, control concepts done with optimization and intelligent controller strategies realized with support of many control tools. As the result the controller with its functionality is executed on the dedicated hardware where is ported directly from the written code or automatically generated from the object based diagrams (e.g. using code generation techniques). The final version of the controller is executed in the real-time.

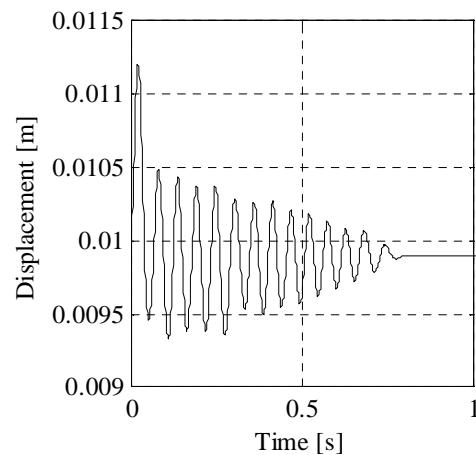
Using COMSOL Multiphysics up to version 3.5a the link between COMSOL and Simulink was very useful from the control design point of view. The embedded dynamics in to the Simulink block was used together with controller configurations tested in the real-time. Such configuration allowed to design controllers with all properties coming from the real-time hardware implementations. The control loop includes signal processing path like scaling, quantization, multitasking as they were implemented.

At this moment there is an Live link do MATLAB that allows scripting realization of similar tasks only.

The controller implementation in the equation form directly embedded into COMSOL/Multiphysics environment takes time and limits the application of advanced strategies or makes them very complex to implement. It is additional and unnecessary time-consuming task. Nowadays, there is an only one external way to put advanced formulas, direct coding the m-file and using available exporting the controller to the MEX files and use them via MATLAB/Live link or directly from MATLAB.

To test the behavior of the designed models the minimal requirements for the stable operation of the levitation system were fulfilled using the PD controller. It's parameters can be tuned up to

obtain over-damped, critically-damped or under-damped properties of the closed loop system [10]. Such controller has been embedded in the mathematical form in to the COMSOL environment. Thanks to the ALE mode the motion of the levitated object has been realized. Figure 7 presents the stabilization of the levitated sphere in the axis symmetric mode under the PD controller parameters tuned for oscillatory damped vibrations of the closed loop system.



**Figure 7.** Position of the levitated object steered by the PD controlled – both implemented in COMSOL Multiphysics.

The AMLS are representatives of the dynamical systems with programmable dynamics. Their properties can be set by the appropriate construction design and controller architecture. Depending on the construction and dynamical properties the control system reaction time should be in the range of micro up to milliseconds. It makes the that the AMLS control systems are time critical and require very sophisticated control tools and methods. Such small control periods eliminates the multiphysics modeling from the real-time application. Even the optimal selection of the mesh [4], simplification of the simulation mode and powerful computer (Intel i7 975, 8GB RAM) is not able to solve the model in the real-time. Only in the case of 2D axis symmetry and levitated sphere under the controller supervision with 500Hz sampling frequency is possible. This fact eliminates a few interesting control applications of the interdisciplinary model.

## 7. Conclusions

Thanks to the COMSOL Multiphysics many physical phenomena could be modeled and analyzed together. In the case of ALMS in the point of interest are thermal effects caused by the resistive coil heating, strain and stress effect caused by the thermal and electromagnetic force expansion. They can be easily coupled with presented models. The described modeling and simulation methodology allowed to extend the knowledge base on Active Magnetic Levitation Systems. Moreover, having an interdisciplinary model it is possible to develop a new construction, control strategies and test them in the virtual prototype form.

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## 9. Acknowledgements

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