Modeling, Simulation and Control of Dual Electromagnet Active Magnetic Levitation

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Abstract: This paper presents the simulation of the dual electromagnet Active Magnetic Levitation System realized in the COMSOL Multiphysics software. The mixed mode of Partial Differential and Ordinary Differential Equations is used to realize the levitated object motion. Two control scenarios are given as illustrative example of the working model.

Keywords: active magnetic levitation**,** active magnetic bearing, control, modeling, simulation.

1. Introduction

The dual electromagnet configuration of Active Magnetic Levitation system (AML) where the electromagnets are locate opposite to each other, constitutes and single axis of the Active Magnetic Bearing [4, 5, 10, 13]. The same configuration can be used to test the single electromagnet AML controller [9]. A single electromagnet AML system was already modeled and simulated with COMSOL Multiphysics [11].

This research was motivated by the control research and real-time experiments realized for the designed dual electromagnet active magnetic levitation (MLS2EM) test-rig [2]. This elaboration is devoted to the cylindrical electromagnets applied for the AML task. The interdisciplinary modeling, simulation and control approach [5] is a key component of this research. The modeling and simulation of the AML configuration is required when a new devices are designed or existing one are modeled for the verification and controller synthesis purposes. In both cases there is a request to add the control feedback to keep the levitated object at the desired position. Therefore, the model must be extended with the motion dynamics and controller formula. The COMSOL Multiphysics features allows to combine a few physical and mathematical aspects in a single model [1, 3, 11].

2. Dual Electromagnet AML system

An example of the dual electromagnet AML system is the prototyped MLS2EM laboratory test-rig [2]. It of two electromagnets located apart to each other (Fig. 1). They generate the electromagnetic force used for the levitation. The control system adjusts the force value to stabilize the levitated object with a desired stiffness and damping properties [6, 12].

The electromagnetic force produced by the electromagnets depend on the actuator construction, the control signal and the levitated object distance. Considering the current driven coil, the levitated object dynamics is described by the equation (1).

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= (-F_1 + F_2 + Fg)\cdot m^{-1} \end{aligned} \tag{1}$$

where: x_1 - position, x_2 - velocity, F_1, F_2- force generated by upper and lower electromagnet respectively, F_g - gravity force, m - object's mass. The equation (1) can be used for many control tasks depending on the gravity field interaction and control of one or two electromagnets. Typically, it is described by (2) when the electromagnet constant K_{em} is used.

$$F = K_{EM} \cdot i \cdot x_1^{-2} \tag{2}$$

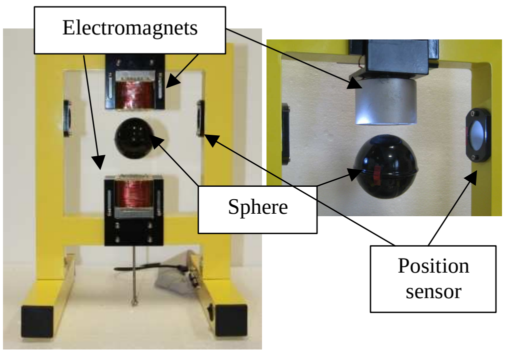

Figure 1. Single axis dual electromagnet Active Magnetic Levitation system (MLS2EM) and modified version with cylindrical electromagnet.

To achieve stable levitation and control the dynamical properties the state-feedback controller is used. For the control purposes the state error $e = x_d$-x is calculated. For the stable operation x_d vector elements: x_{1d} corresponds to the desired levitation level and x_{2d} to the zero velocity. When the voltage driven coil is considered the equation (1) is expanded by two electrical equations corresponding to the actuator dynamics [4, 7, 9].

3. Use of COMSOL Multiphysics

Modeling with support of COMSOL Multiphysics is well suitable for educational and research purposes. In the past version (COMSOL 3.3) there was a possibility to embed the model into MATLAB/Simulink. It was a great solution for the controller design and dynamic simulation. At this moment the connection is available via MATLAB link with the MATLAB package only. In this case the controller design and closed loop simulation can be realized in two ways:

a) directly in COMSOL Multiphysics – this require to embed the motion dynamics and controller equations into the COMSOL package,
b) supported with MATLAB package – using the COMSOL model m-file to solve the model.

Focusing on the levitation task the COMSOL Multiphysics software is useful due to many features like:

a) common multiphysics modeling,
b) moving mesh option,
c) ODE solver,
d) possibility to embed linear and nonlinear controller formula,
e) modeling in 2D, 3D and axisymmetry modes,
f) availability to include electric circuit.

The dual electromagnets AML model was realized in the axis symmetry mode due to the modified construction of the real laboratory test rig (MLS2EM). Two cylindrical electromagnets were designed and the spherical ferromagnetic object is levitating between them. The object's position is sensed by the optical sensor. The model of such system contains:

a) components geometry, actuators properties – identical as exists in the real system,
b) motion dynamics described by the ODE,
c) control action for a single and/or both electromagnets to achieve the levitation under external excitation, differential control mode and independent control mode.

The realized model in COMSOL Multiphysics is presented in Fig. 2.

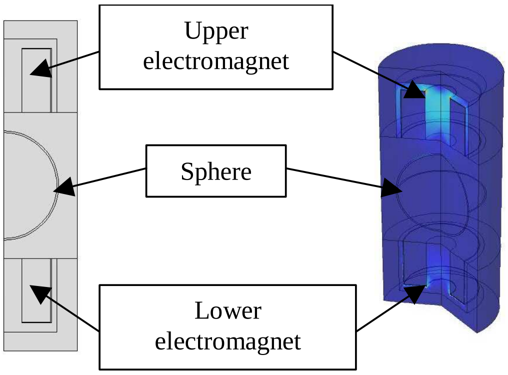

Figure 2. Axisymmetric model of dual electromagnet AML system developed with COMSOL Multiphysics.

4. Simulation

The 0.056kg ferromagnetic sphere was located at initial position, and the simulation experiments were realized. The model was simulated in two variants.

4.1 Levitation in the gravity field at external excitation.

The excitation signal is generated by the lower electromagnet to test the levitation controller working with upper electromagnet. The closed-loop properties are determined using the levitated object state. This experiment is very useful to validate the designed controller. Such approach was practically implemented using MLS2EM Active Magnetic Suspension test-rig [7, 9]. The coil current signals are specified by the equation (3)

$$\begin{aligned} i_1 &= -k_1 e_1 - k_2 e_2 \\ i_2 &= f(t) \end{aligned} \tag{3}$$

where: k_1, k_2 represent the controller parameters, and $f(t)$ represents the excitation signal. The system responses are presented in Fig. 3. This simulation experiment shows the nonlinear properties of the AML system, steered by the linear controller. One can find the difference in the system response. The closed loop properties vary with respect to the ball position. The ball motion has a higher velocity in the motion towards upper electromagnet resulting in the overshoot of the ball position.

The same properties of the closed loop system are observed during real-time experiments [6].

4.2 Levitation by contraction without gravity

The second approach is devoted to the control in the differential mode, without presence of the gravity ($F_g = 0$ in (1)). Such approach can be used, when the mechanical construction allows to neglect the gravity or generated forces are much higher than the levitated object load. Such, dual AML configuration represents the axial AMB or a single axis of the radial AMB. The control current signals are described by equation (4). The control signal i is calculated using the state feedback form (as before).

$$\begin{aligned} i_1 &= i_0 + i \\ i_2 &= i_0 - i \end{aligned} \tag{4}$$

Both actuators counteracts to each other. The generated force compensates any object displacements from the desired steady-state. The steady-state current i_0 and controller parameters corresponds to the stiffness and damping properties.

7. Conclusions

The application of COMSOL Multiphysics for dual AML system allows to provide a number of control experiments in the simulation mode. The application of multi-turn allows to specify real electromagnet properties better than coil controlled directly by the current density. The simulation is provided in conditions similar to the experimental one. In this case the developed controller can be simulated before embedding into the hardware layer. The designed model and controller can be optimized [8] for the target application on the base of simulation results. The provided research can be applied in the levitation based devices like radial AMB, axial AMB, single or dual electromagnet AML. The next stage in the research process is to verify the modeling results with experimental ones. Moreover, the created model will be extended towards voltage driven coil and electronic steering circuit structure and properties.

5. References

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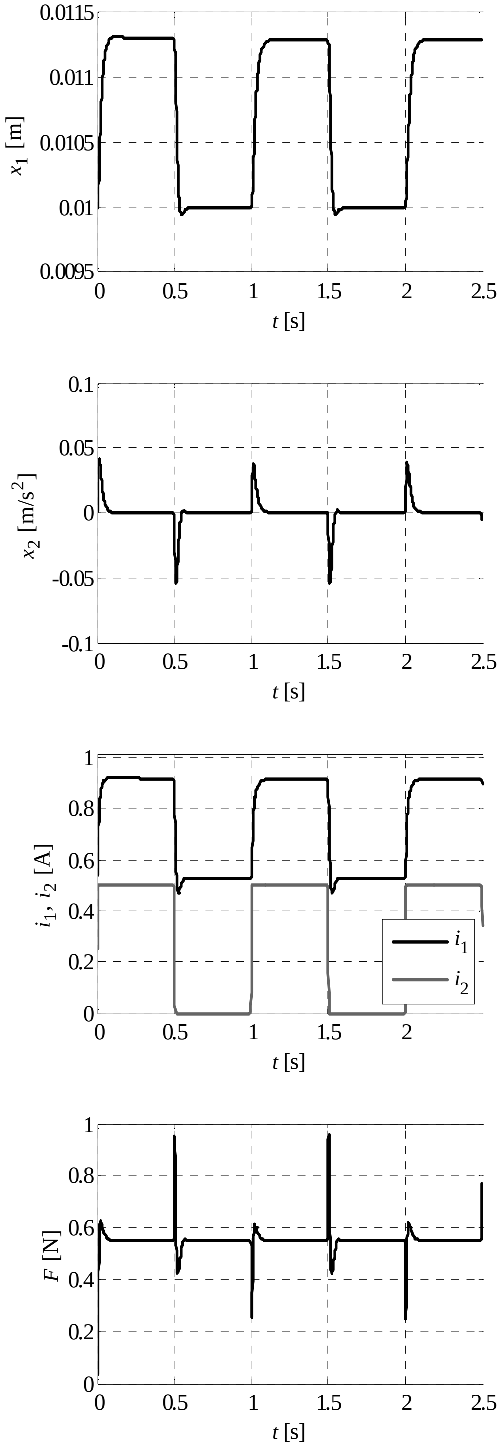

Figure 3. Levitated object stabilization at external square form excitation force.

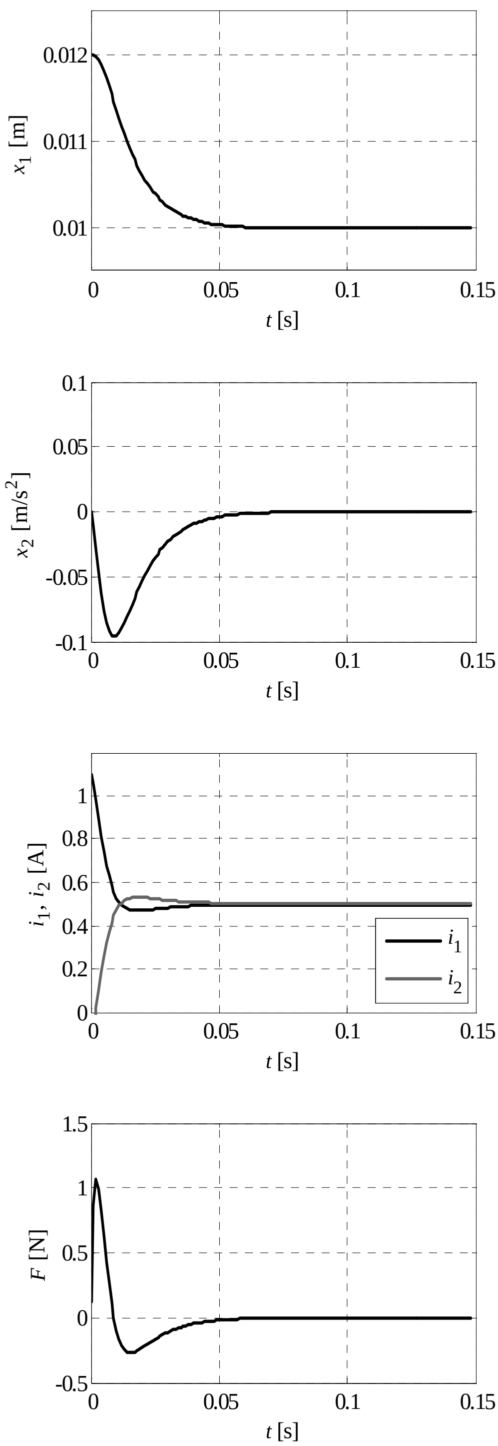

Figure 4. Levitated object control in the differential mode without presence of the gravity field.