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Using Look-up Tables to Model an Electromagnetic Suspension System

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Abstract: Problem statement: The aim of the study was to model an electromagnetic suspension system. The electromagnetic system consists of an electromagnet which was attracted an iron object which was freely suspended in air. **Approach:** Modelling a magnetic system requires modelling the magnetic force characteristics and the flux characteristics. The force characteristics were to be produced from a nonlinear flux characteristic-current. **Results:** The modelling of the system was accomplished and simulated using MATLAB/SIMULINK. **Conclusion:** Using look-up tables proves to give good results in modelling a magnetic suspension system.

Key words: Magnetic suspension, flux-current relation, saturation region, electromagnetic suspension system, flux-current relation, nonlinear characteristics

INTRODUCTION

The nonlinearity of the magnetic suspension system imposes some difficulty in modelling such a system. A diagrammatic view of the relationship between the flux linkage and the current, for a series of different airgaps is shown in Figure 1. A flux-current characteristic which is segmented into three regions; the first region is a linear relationship between flux linkage and current, the second region is a nonlinear relation between the flux linkage and current and the third region is the saturation region.

There are different approaches to model a magnetic suspension system with nonlinearity (Sun *et al*., 2008; Barie and Chiasson, 1996; Ali *et al*., 2010; Goethem and Henneberger, 2002; Lee *et al*., 2008; In-Gann *et al*., 1998).

Look-up tables are implemented at several occasions to model a magnetic suspension system. Examples of look-up tables implemented include; a 2D look-up table that relates the force to the applied voltage and the position (Lee *et al*., 2008), Current-force-position lookup table (Sun *et al*., 2008), inductance-position (Deshpande and Mathur, 2011; Noboa, 2010), force of current (Boeij and Lomonova, 2009), two lookup tables namely Position-flux linkage-current and Position-current-torque (Srinivas and Prasad, 2011) and force-torque to current lookup table (Berkelman and Dzadovsky, 2010). The approach followed in this study is similar to that presented in (Srinivas and Prasad, 2011) except that the type of motion here is vertical and not rotational.

Modelling flux-current characteristics: The equation which represents the flux-current relation in a magnetic suspension system is Eq. 1:

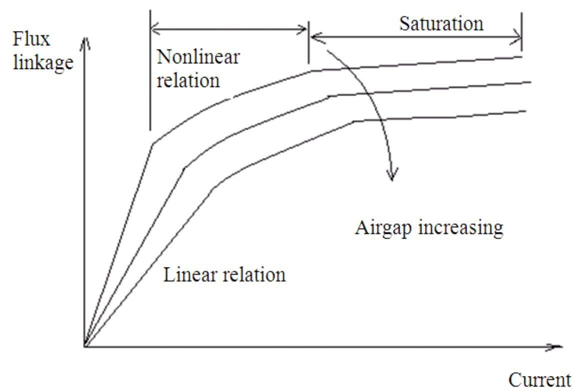

Fig.1: The relationship between flux linkage and current while airgap is changing

$$V = Ri + \frac{\partial\phi(i,z)}{\partial t} \quad (1)$$

To model the system using the previous equation, current-flux data has to be generated I (φ, z). The relation between current, airgap and flux linkage is non-linear relation, or in other words it is only linear in the first stage (at low current values). At this stage a linear relation will be assumed and later on it is going to be modified to include the nonlinearity. Thus the flux equation can be written as:

$$\phi = Li \quad (2)$$

The inductance-airgap relation can be expressed follows (Lee *et al*., 2008) Eq. 3:

$$L(x) = L_1 + L_0 e^{\frac{-z}{a}} \quad (3)$$

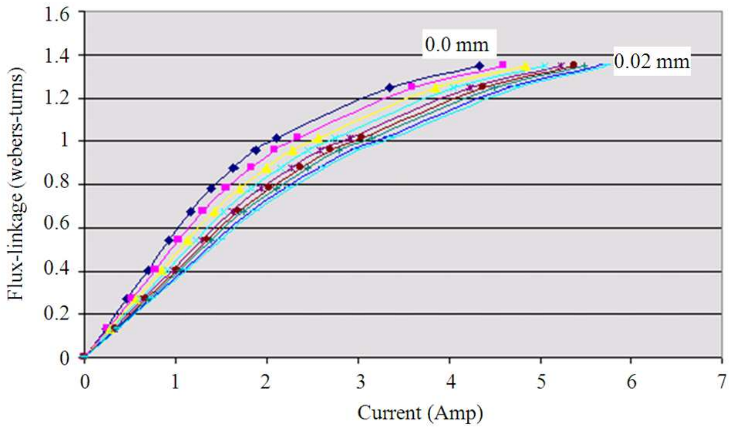

Fig. 2: Non-linear relationship between flux linkage and current (amp) while airgap is changing

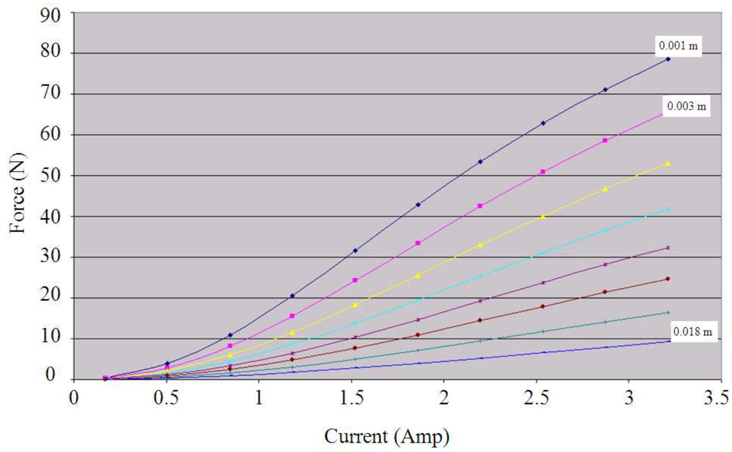

Fig. 3: Force-current characteristics of different airgap values generated using non-linear flux characteristics

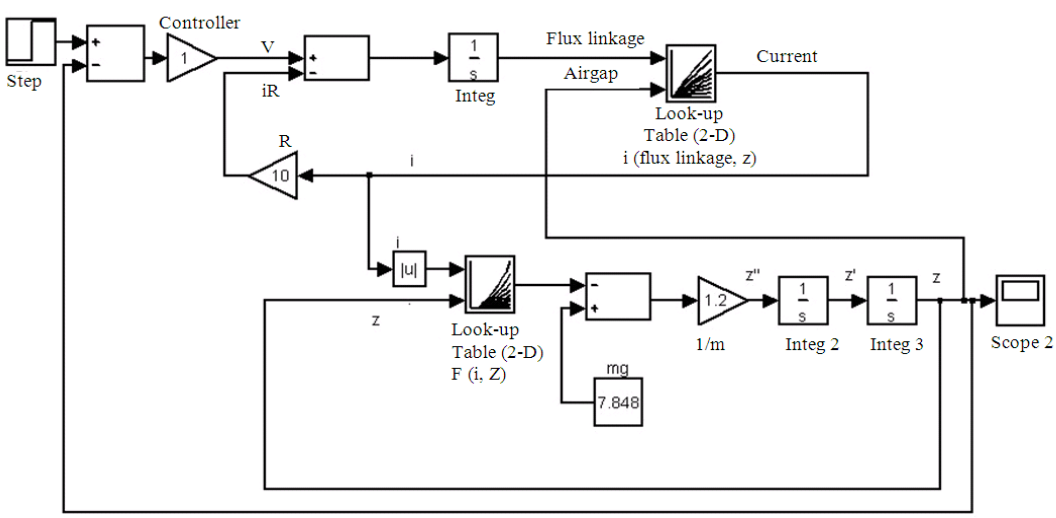

Fig. 4: Modelling electromagnetic suspension system using look-up tables

Therefore, Eq. 2 can be written as:

$$i = \frac{\phi}{L_1 + L_0 e^{\frac{-z}{a}}} \quad (4)$$

A fulx-current data was generated using Eq. 4. The data were generated around the nominal values (current = 1.69 Amp, airgap = 0.01 m and flux linkage = 0.676 Weber-turns). These nominal values are borrowed from the experimental kit for suspending a spherical ball (Nichol, 1998). Details about other parameters are given in Table 1.

Since the actual flux characteristics are nonlinear, the flux characteristics, obtained from Eq. 4, were modified to resemble nonlinear characteristics. Figure 2 shows the nonlinear characteristics as it has been produced.

Generating force characteristics using linear flux characteristics: Force characteristics can be produced from the flux characteristics by using the concept of energy. The mechanical energy is given by the area under the flux-current curve. While the electrical stored energy is given by the area above the flux-current curve. What is important for the production of the force is the mechanical energy and the following equation is used to calculate the mechanical energy:

$$\Delta W = \int_{i=0}^{i} \left[\phi(i,z) - \phi(i,\Delta z)\right] di \quad (5)$$

where, ΔW = change in mechanical energy. The force produced (for small airgap movement) can be calculated as the change of the mechanical energy over the change in the airgap as follows:

$$f\Big|_{\frac{z+\Delta z}{2}} = \frac{\Delta W}{\Delta z}\Big|_{i=\text{constant}} \quad (6)$$

where, f = magnetic force and Δz = Change in airgap

The force data was generated at different airgaps and current values using Eq. 5 and 6 around the same points which were used produce Fig. 2. It is worth mentioning that the force can be produced using the mechanical energy concept or the electrical stored energy because they are actually equal in the case of linear flux-current relation. But in the case of nonlinearity, these two energies are not equal. In fact the mechanical energy is higher in magnitude than the electrical stored energy.

The produced force characteristics obtained from the non-linear flux characteristics is shown in Fig. 4. The curves turn to flatten as the current value increases and that corresponds to the flattening in the actual nonlinear flux-current curves.

Modelling of the magnetic suspension system: Using Fig. 2 and 3, the magnetic suspension system can be modelled using MATLAB/SIMULINK as shown in Fig. 4.

A 2D look-up table was used to represent the current as a function of the airgap and the flux linkage. Another 2D look-up table was used to represent the electromagnetic force as a function of the current and the airgap. The inputs to the first 2D look-up table are the flux linkage and airgap value while the inputs to the second 2D look-up table are the current and the airgap. The first 2D look-up table reads out the current value corresponding to the given position and flux inputs, while the 2D look-up table reads out the electromagnetic force corresponding to the given position and current inputs.

The previous model contains no form of controller as it can be seen from the simulation model that the controller is unity proportional gain. The position is fed back and compared to a reference position (nominal position) to form the error and the error signal is used to derive the system.

The model was run in MATLAB/SIMULINK and when applying a step response to the system, the graph which represents the airgap position turns to increase dramatically as shown in Fig. 5 and that indicates the instability of the system. The parameters used in the previous model (to suspend a metallic object) are given in Table. 1. Instead of entering the numeric data manually into the model, an M-file was generated to store the data. In the case of the flux-current characteristics, 546 points were used with 26 flux linkage values against 21 airgap positions. The flux model was tested using intermediate airgaps and flux linkages to be compared with the exact calculated values. Errors were found to be almost zero. On the other hand, the force-current characteristics were generated using 31 values of current and 21 airgap positions.

To investigate the validity of the model representation, a nominal airgap position and flux linkage (Nichol, 1998) was applied to the model as shown in Fig. 6 using MATLAB/SIMULINK.

By looking at the final force produced which is 10.98 N, it is obvious that this value is very close to the expected value which is 10.96 N (the weight of the 0.2 kg metallic object (Nichol, 1998).

Table 1: values of variables used in the simulation (Nichol, 1998)

Quantity	Value
Number of turns, N	250
Measured system resistance, R	10 Ω
Pole face area, A	0.003136 m^2
Primary magnetic constant, μ_o	1.257×10^{-6} H/m
Object mass, m	0.2 Kg
Gravity, g	9.80665 m/s^2

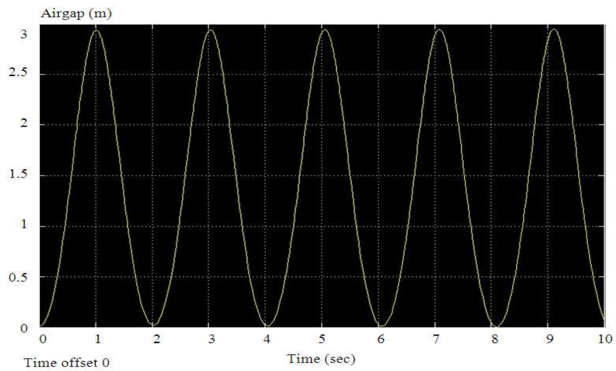

Fig. 5: Simulation results of modelling the suspension system

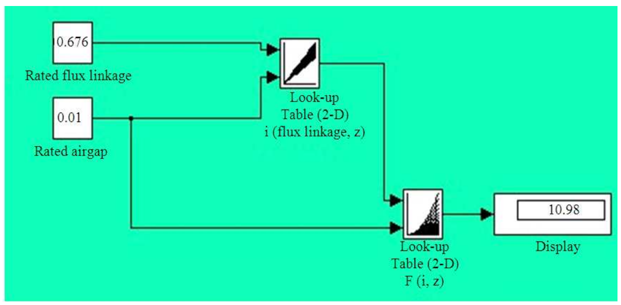

Fig. 6: Calculating the nominal electromagnetic force

CONCLUSION

A magnetic suspension system model using look-up tables was presented. The electromagnetic force was generated from non-linear flux-current characteristics. The proposed model was validated with the nominal airgap and the flux linkage values. The simulated model is clearly unstable since no form of controller was implemented. One limitation which was encountered, was the linear interpolation of the look-up tables.

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