Design and Dynamic Analysis of Electromagnets for Magnetic Suspension Systems based on 3-D FEM

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Abstract— This paper deals with design and dynamic analysis of electromagnets for magnetic suspension systems. On the basis of an equivalent magnetic circuit (EMC) method and a 3-D finite element analysis (FEA) model, initial and detailed design of an electromagnet are performed. By performing various tests, the validity of the design is confirmed. And then, by employing a closed-loop PID control algorithm, the dynamic behavior of electromagnets is also investigated experimentally. In particular, by estimating exact control parameters taking into account delay due to first-order lag element, the exact air-gap maintenance control can be acheieved without reference to increase of winding temperature and saturation of electromagnets.

I. INTRODUCTION

The magnetic levitation (Maglev) train is one of the best candidates for new-generation transportation system [1-2]. Therefore, the study on propulsion, levitation and guidance system for the Maglev train has been developed. Typically, there are three types of levitation technologies: an electromagnetic suspension (EMS), an electro-dynamic suspension (EDS), a hybrid electromagnetic suspension (HEMS). EMS is easier than EDS technically and it is able to levitate by itself in zero or low speeds. Also, EMS requires a much smaller variation of the current's amplitude as compared with HEMS because the permeability of permanent magnet (PM) is unity [3-4]. Especially, in order to improve their reliability, particular attention to design and control of the suspension systems has been increased.

Therefore, this paper deals with design and dynamic analysis of electromagnets for suspension applications. First, by using EMC method, initial design for electromagnets is performed. And then, on the basis of the initial design results and 3-D FEA model, its detailed design is also accomplished. Test results such as levitation force measurements according to current under fixed air-gap are given to confirm the validity of design. Then, by using PID control algorithm, dynamic tests of the electromagnets are also performed. In particular, in order to consider influence of winding temperature on suspension control, the transfer function of first-order lag element is introduced. Finally, despite the variation of resistance and inductance due to increase of winding temperature and saturation of electromagnets, respectively, exact air-gap length control under a rated load weight can be accomplished.

II. DESIGN PROCEDURES AND RESULTS

The design of electromagnets is performed as following steps:

i) Under constant current density and restricted dimensions, by changing C-core thickness, namely, d and h shown in Fig. 1, the slot area ($l*(m-h)$) and pole-face area ($d*w$) are calculated.

ii) From calculated slot area, the number of turns and current of a coil is determined by changing a coil diameter.

iii) By using turns (N), current (i), pole-face area (A), the force is calculated.

iv) By the iteration of i)~iii), we can obtain the results shown in Fig. 2(b) and can find the C-core thickness which makes the suspension force have the maximum.

v) However, an EMC method cannot consider the saturation and detailed shape of the electromagnets. So, as shown in Fig. 2(c), we perform the detailed design considering saturation and exact shape by using 3-D FEM. Here side view of the exact shape is trapezoidal shape which provides some advantages in terms of winding works and weight of electromagnets.

Finally, using design results obtained from procedures stated above, the electromagnet shown in Fig. 3 can be manufactured.

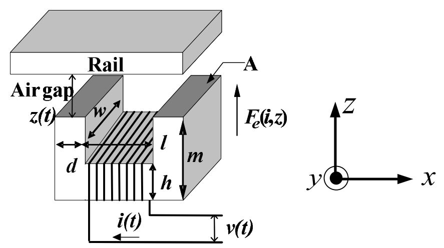

Fig. 1. Analysis model for the design of electromagnets.

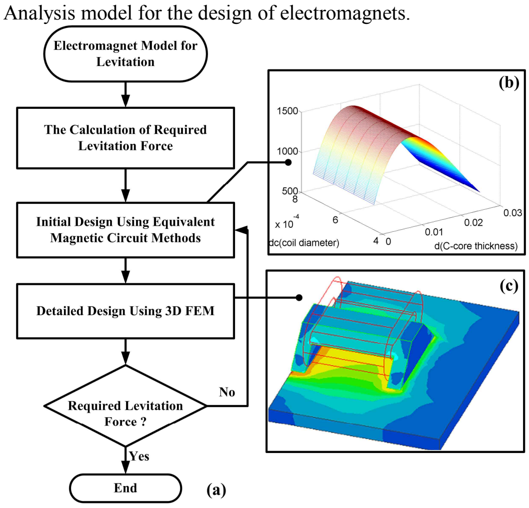

Fig. 2. Design of electromagnets: (a) design procedures, (b) initial design and (c) detailed design using 3-D FEM.

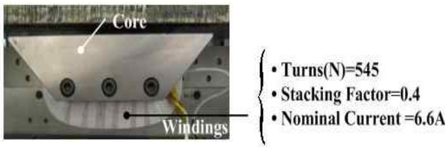

Fig. 3. Actual manufactured electromagnets.

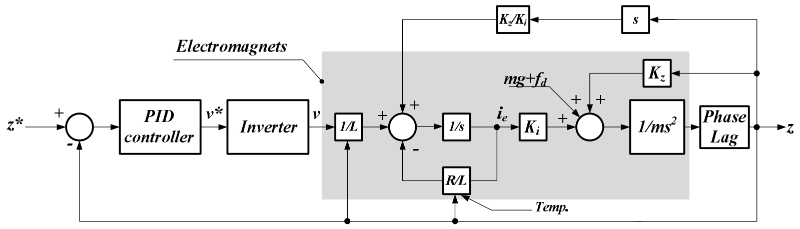

Fig. 4. Block diagram for the closed-loop control of a suspension system with electromagnets.

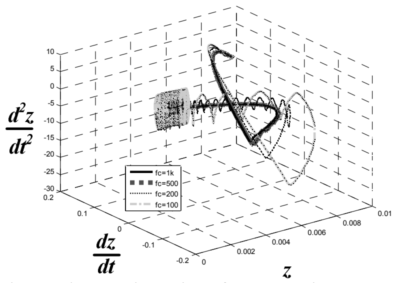

Fig. 5. Phase trajectories of a suspension system.

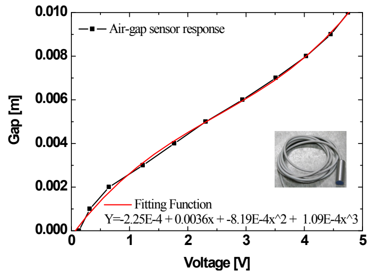

Fig. 6. Measured gap sensor response.

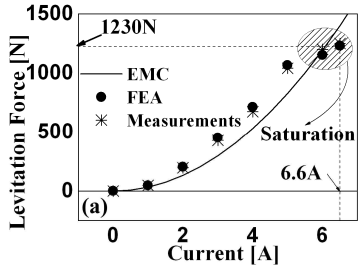

Fig. 7. Levitation force variation with current.

III. Dynamic Model

Figure 4 shows the block diagram for closed-loop control of a suspension system with electromagnets obtained from voltage and balance equation. The position z of an electromagnet is detected and amplified by a displacement sensor and then compared with the position reference z^*. An error between z and z* is amplified by a PID controller and generates the reference signal (v^*) for PWM voltage (v) of the inverter. And then, a current i_e produced by PWM voltage is fed to the electromagnet [5].

In linear system, it is possible to analyze the stability of the system with linear algebra. However, in nonlinear system, it is necessary to confirm that phase trajectory of state variables converges to a nominal point. To do this, low pass filter is commonly used to remove noises from gap sensor. To define bandwidth of low pass filter, the value of cut off frequency (fc) for sensor input should be investigated. Thus, in our work, using the second order Butter-worth filter as low pass filter, it is confirmed from Fig. 5 that the system stability can be achieved when the bandwidth of filter to eliminate noises of gap sensor is over 500Hz. On the other hand, the air gap sensor has nonlinear characteristics against air-gap. Therefore, the sensors are calibrated and we are find curve fit function of 3rd order polynomial to suspension control. The air-gap sensor response and curve fit function are shown in Fig. 6.

IV. Results and Discussion

Fig. 7 shows the comparison of results predicted by the EMC method with 3-D FE and experimental results for the variation of levitation force according to current under fixed nominal air-gap. It can be seen that for the case when current exceeds 6A, the saturation begins to occur in the C-core of electromagnets. Despite the saturation, since the levitation force (1230N) at nominal current (6.6A) is satisfied with the required specifications, the validity of design procedures and results presented in this paper are confirmed. Since a simple equation for inductance obtained by the EMC method is employed for an inductance block used in Fig. 4, the influence of saturation on inductance is not considered. So, The necessity of first-order lag element in our system is proven. Fig. 8 shows the measured results for winding temperature, current and maintained air-gap of the electromagnet under rated load conditions (load weight 120kg and self-load 7kg). It can be observed that despite an increase of winding temperature and saturation of the electromagnet (because current is about 6.5A), levitation control of the electromagnets is achieved stably.

The more detailed analysis results, discussion, mathematical expressions related to the EMC method and experimental method for a levitation control will be given in the final paper.

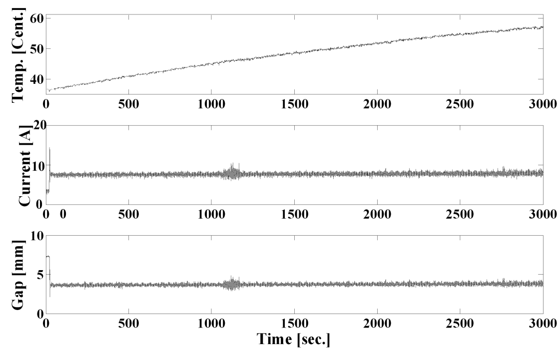

Figure 8. Measured results for winding temperature, current of the electromagnet and maintained air-gap in levitation system under rated load.

V. References

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