An Experimental Study on the Controllability of HTS Coils in MAGLEV Systems

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Abstract: An experimental system has been built to investigate the applicability of high temperature superconducting (HTS) electromagnets to MAGLEV systems. A two-order lead-lag compensator is designed for the experimental system. Based on the experiments, it is observed that the HTS electromagnet can be stably suspended, no matter a linear mode power amplifier (LMPA) or a switched mode power amplifier (SMPA) is utilized, even when the load has been significantly changed. Some dynamic characteristics of the HTS electromagnet have also been analyzed through frequency domain identification.

Key words: High temperature superconducting (HTS) coil, Magnetic suspension, Controllability, Robustness, Frequency domain system identification

1. Introduction

In recent years, magnetic suspension technologies are used extensively in many fields such as MAGLEV, active magnetic bearings. They are receiving increasing attentions as a means of eliminating friction due to mechanical contacts [1],[3],[5],[9]. Although various magnetic suspension technologies have been developed, suspension using controlled HTS electromagnets and attraction magnetic force has many appealing properties, such as the possibility of greatly increasing the suspension height, improving the ratio between magnetic force and weight, reducing the weight of the equipments, decreasing the maintenance costs and energy consumption, etc [4],[6],[8].

However, some previous researches declared that as the resistance and the inductance of an HTS electromagnet vary with frequencies, it might not be appropriate to use it in control applications [7]. With the advancements of HTS coil technologies and control theories, the current density has been significantly increased and a controller can be synthesized such that certain parametric variations can be tolerated. These advancements make it attractive and possible to develop an electromagnetically levitated system with HTS coils.

The purpose of this research is to experimentally investigate the applicability of HTS coils to MAGLEV systems. An experimental setup is built which mainly consists of an eddy current position sensor, a power amplifier and a digital signal processor, as well as an HTS electromagnet. In this paper, we focus on controller design and experimental results analysis, while the design issues of the HTS coil electromagnet are discussed in a companion paper [2].

For this experimental system, a two-order lead-lag controller is designed based on the linearized first principle plant model. Experiments show that the HTS electromagnet can be stably suspended, even when the load has been increased to almost 85% of the original one. Moreover, it has also been found that the HTS electromagnet works well with both LMPA and SMPA.

The rest of this paper is organized as follows. In section 2, the experimental system is briefly illustrated and a model based on physical principles is derived. In section 3, a controller is synthesized and closed-loop system properties are analyzed, while simulation and experimental results are presented in section 4. Finally, in section 5, some concluding remarks are given.

2. Experimental Setup and Modeling

The experimental system, which is shown in Figure 1, mainly consists of two parts. That is, the mechanical part and the control part. The mechanical part is constituted of an eddy current position sensor, a rigid iron beam as well as an HTS electromagnet. Levitation of the beam is achieved by attractive forces generated by the electromagnet attached at the right end of the beam, as shown schematically in Figure 2. The eddy current transducer is used to measure the air gap of the electromagnet and its output signal is feed into the controller. The control part is constituted of a power amplifier, a 32-bit Digital Signal Processor, a 12-bit A/D, D/A converter and some simple interface circuits. These circuits are used for adjusting voltage offsets. The system's physical parameters are given in Table 1.

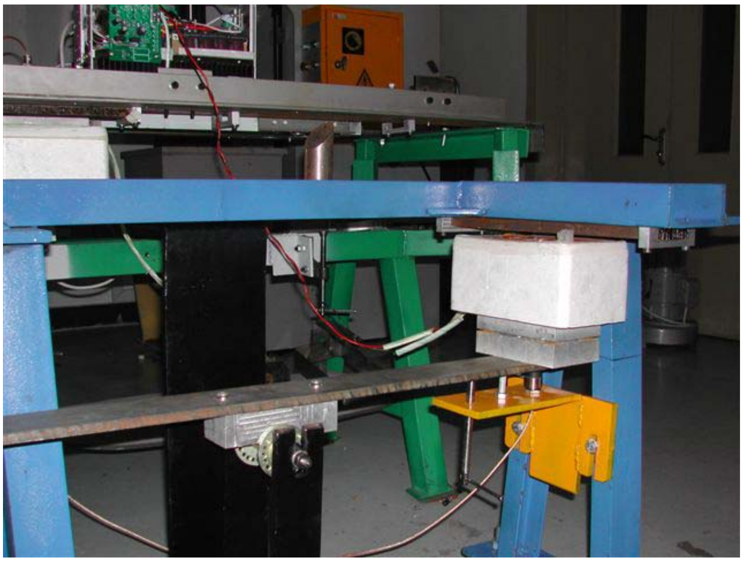

Figure 1.The experimental system

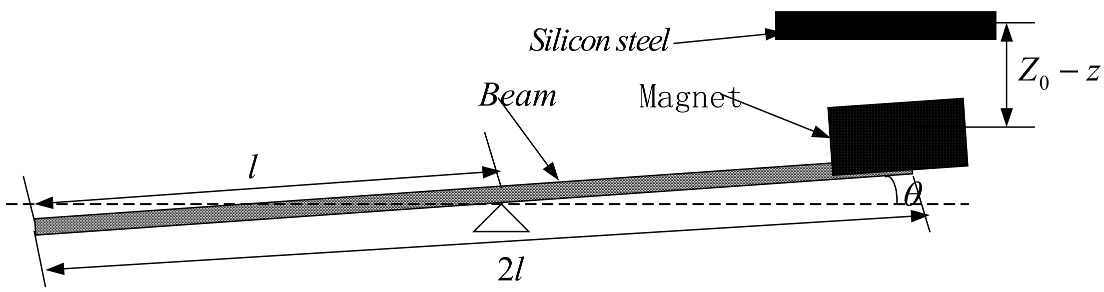

Figure 2. Schematic diagram of the experimental system

Table 1. Physical parameters of the experimental system

Mass of the magnet (including dewar and liquid nitrogen)(M)	7.5kg
Mass of the beam (m)	3.0kg
Distance between the geometry centers of the magnet and the beam (l)	0.43m
Constant air gap (Z_0)	5mm
Constant current (I_0)	3.33A
Rotary inertia of the beam and the electromagnet around the geometry center of the beam (J)	1.572kg • m^2
Electromagnetic constant of the magnets (k)	1.66×10^{-4}N • m^2/A^2
Input-output ratio of the power amplifier (k_{ui})	0.3542A/V

The following two assumptions are made in the derivation of the plant model. 1) The leakage flux of the coil is negligible; 2) the electromagnet constant can be regarded to be invariant constant around the equilibrium point, while the electromagnetic force to be a point force.

The dynamics of the system is of two kinds, viz, the beam's rotary motion and variation of the electromagnetic force.

The rotary motion of the beam can be expressed as

$$J\frac{d^2\theta}{dt^2} = Fl - Mgl\ , \qquad (1)$$

where J is the rotary inertia of the beam and the electromagnet around the geometry center of the beam; F the electromagnetic force; M the mass of the magnet; g the gravity acceleration; l the distance between the geometry centers of the electromagnet and the beam; θ the rotary angle of the beam.

The relation among the electromagnetic force, its current and its air gap is as follows.

$$F = k\frac{(I_0+i)^2}{(Z_0-z)^2}\ , \qquad (2)$$

where I_0 and Z_0 are respectively the constant current and air gap of the electromagnet, while k the electromagnetic constant. F, i and z represent respectively the electromagnetic force, the current change and the air gap change.

Note that when the beam is at its equilibrium, the following relation exists

$$Mg = k\frac{I_0^2}{Z_0^2} \quad . \tag{3}$$

In our experimental system, current feedback is adopted in the power amplifier in order to make the transfer function from the control voltage to the current of the electromagnet to be approximately a constant in a sufficiently wide frequency range. Direct measurements show that this relation is achieved from approximately 0Hz to 200Hz. And it is sufficiently wide, noting that closed-loop bandwidth of this experimental system is designed to be not greater than 20Hz. This implies that the transfer function between the current of the electromagnet and the control voltage can be approximated as

$$i = k_{ui}u \ . \tag{4}$$

On the other hand, note that $l >> Z_0$, and the beam is designed to be horizontal at its equilibrium. This means that the relation between the air gap change z and the rotary angle θ can be approximately as

$$\theta \doteq \frac{z}{l} . \tag{5}$$

Through linearizing Equation (2), a relation is built among the controlled electromagnetic force f, the control voltage u of the power amplifier and the air gap change z of the electromagnet

$$f = k_u u + k_z z \ , \tag{6}$$

in which, $k_u = 2k_{ui}k\frac{I_0}{Z_0^2}, k_z = 2k\frac{I_0^2}{Z_0^3}$.

Combining Equations (1), (5) and (6), the transfer function between the air gap change z and the control voltage u is obtained as follows.

$$G_0(s) = \frac{z(s)}{u(s)} = \frac{k_u l^2}{Js^2 - k_z l^2} \ . \tag{7}$$

3. Controller Design

A corollary of Earnshaw's theorem is that systems using electromagnets without current control are inherently unstable [1],[3],[5]. In order to achieve stable suspension, it is necessary to introduce a mechanism to adjust the current of the electromagnets using position feedback. Its effect is to modify the force-distance relation such that the current and thus the attraction force decrease as the gap decreases and vice versa.

Multiplying Equation (7) by a constant resulting from sensor and interface circuit gains, we obtained the transfer function between the outputs of the position sensor and the controller as $G(s) = \frac{3075.3}{(s-58.81)(s+58.81)}$. Using the classical open-loop shaping based design techniques, a lead-lag compensator is constructed as $C(s) = 381\frac{(1+0.21s)(1+0.038s)}{(1+40s)(1+0.00058s)}$. Frequency characteristics of the plant G(s), the controller C(s), as well as the open-loop transfer function G(s)C(s) are shown in Figure 3, while those of the closed-loop transfer function in Figure 4.

From the above two figures, it could be seen that the bandwidth of the closed-loop system is about 20Hz, while its phase margin and gain margin are respectively more than 73 degrees and 6 dB. These imply that the designed closed-loop system may possibly have good response properties, as well as good robustness properties.

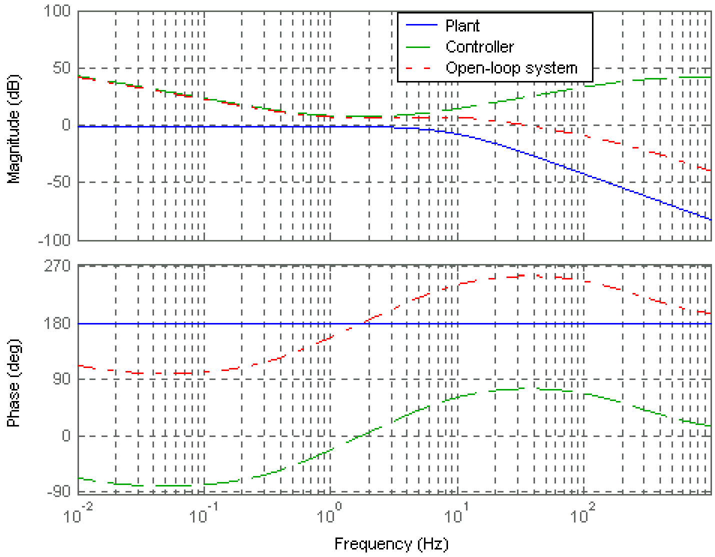

Figure 3 .Frequency characteristics of the plant, controller and open loop system

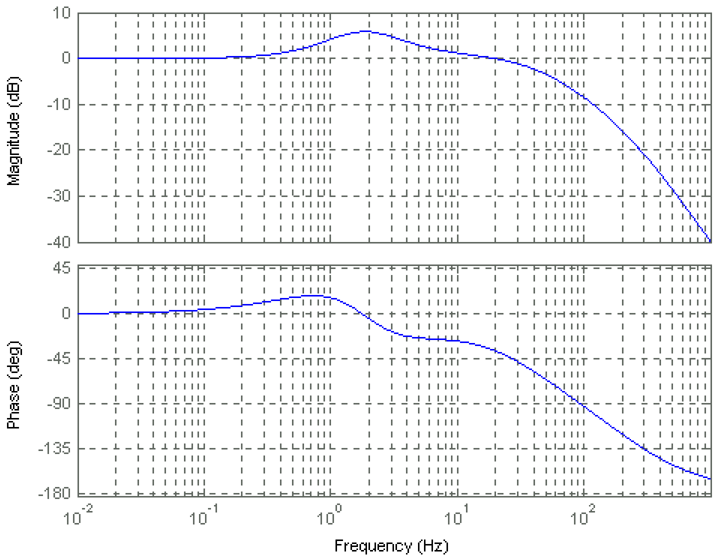

Figure 4. Frequency characteristics of the closed-loop system

4. Simulation and Experimental Results

The designed controller is discretised through the Tustin transformation with a sampling period T=1ms, and implemented by a TMS320C32 digital signal processor (DSP). This DSP can perform 32-bit floating multiplications. Compared with the bandwidth of the closed-loop, 1ms is very short. Therefore, the degradations of the closed-loop system's performance caused by discretization and the time delay due to the calculation of the DSP, are negligible.

The HTS electromagnet is stably suspended using the designed controller. To verify the performances of the closed-loop system, a step form disturbance is added to the controller output with a magnitude of 3.36 volts, and the position of the electromagnet is measured when the load has been changed. Some typical responses of the system are shown in Figure 5, as well as the simulated results. In these experiments, a LMPA is used. From this figure, it is clear that the designed controller is really robust against the load variations, noting that the weight of the nominal system is 7.5 kg. Moreover, the transient response of the designed closed-loop system is also satisfactory, which means that the overshoot of the response, the steady error, as well as the response time, are all acceptable.

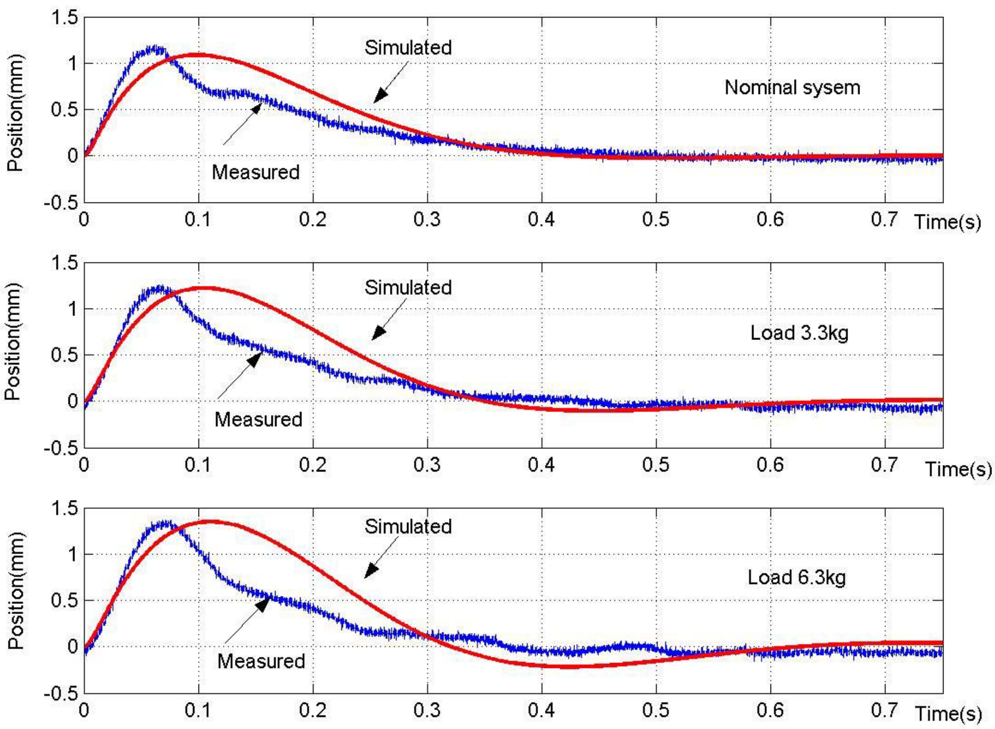

Figure 5. Simulated and measured position response to a step form disturbance

In Figure 6, the closed-loop system's performances are compared when the LMPA is replaced by a SMPA that has almost the same frequency response characteristics as those of the LMPA in the frequency range 0Hz-200Hz. In this comparison, we also add a 3.36 volts step form disturbance (at the controller output) to the system and measure the position of the electromagnet. It can be seen from this figure that from a control view of point, a SMPA works almost as well as a LMPA. Moreover, the robustness of the control system has also been confirmed through changing the load when a SMPA is used. Due to space limitations, the details are omitted.

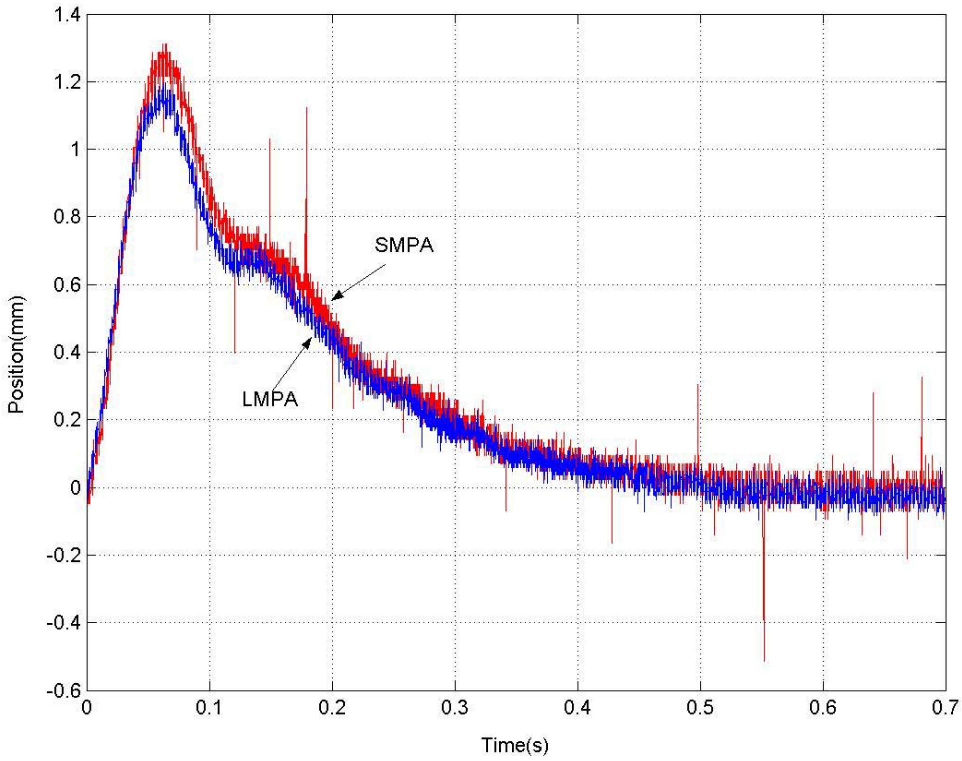

Figure 6. Position response to a step form disturbance when SMPA and LMPA are utilized

On the other hand, the dynamic characteristics of the HTS electromagnet have also been primarily analyzed based on frequency domain closed-loop identification technique. Moreover, a comparison has been made between HTS electromagnets and copper electromagnets. It is observed that while their dynamic properties are quite similar, there do exist some slight differences. The theoretical reasons behind these differences, as well as their influences on controller design, are not very clear, yet.

5. Conclusions

From this experimental study, it can be concluded that through an appropriate hardware configuration, HTS coils can be applied to magnetic suspensions. Moreover, the suspension systems can be designed to have not only good performances in robustness against the load variations, but also good performances in response characteristics. On the basis of this research, a four-axis HTS coil based Maglev vehicle has been successfully suspended at the Applied Superconductivity Research Center of Tsinghua University in May 2004. This verifies again the conclusions that HTS coils can be applied to magnetic suspensions. The experimental results are under further investigations and the details may be reported elsewhere. On the other hand, we are now planning to develop a more energy efficient suspension system in order to make full use of the attractive properties of HTS coils.

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