Switching Stiffness Control of Lateral Motion in Magnetic Suspension System Using Lateral Displacement Detection with Hall Elements

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Abstract

The suppression of lateral vibration is investigated based on switching stiffness control strategy for partially active magnetic suspension system. In such magnetic suspension system, the motion in the normal direction of the suspended object (floator) is controlled actively while the motion in the lateral direction is passively supported. Therefore, it is often subject to vibration in the lateral direction. The application of switching stiffness control has been proposed to suppress such vibration by electromagnets placed in the normal direction. However, the conventional system used a displacement sensor in the lateral direction for detecting the lateral motion of the floator. It restricts the design of suspension system and causes high cost. In this work, it is proposed to detect the lateral motion of the floator with Hall elements instead of installing a sensor in the lateral of the floator. The proposed method of detecting the lateral motion is studied experimentally. The switching stiffness control is achieved based on the output of the fabricated detection device.

1 Introduction

Most of magnetic suspension systems use controlled DC electromagnets (Jayawant, 1981). In this magnetic suspension system, stable levitation is achieved by feedback control. The current flowing in the coil is increased when the suspended object (floator) moves to increase the gap between the electromagnet and the floator. In contrast, it is usually stable in the lateral directions due to the edge effects in the magnetic circuits. Such suspension is referred to as passive suspension. To achieve complete noncontact suspension with less cost and smaller size, passive suspension is often used in combination with active suspension. Such a system is referred to as *partially active magnetic suspension* *system*. One of the problems of partially active system is small damping in the passively suspended direction. Vibration is easily induced and hardly attenuated in this direction.

In active suspension system, two electromagnets operating differentially are often used to control a single degree of freedom of motion mainly because an electromagnet produces only attractive force for a ferromagnetic floator. This work focuses on such differentially operated magnetic suspension system. It has been proposed to suppress the lateral vibration by applying switching stiffness control to the electromagnets installed in the normal direction (Mizuno, Takasaki, & Ishino, 2016). The efficacy of the proposed strategy has been confirmed experimentally (Javed, et al., 2018).

However, an optical displacement sensor was installed in the lateral direction in the previous works (Mizuno, Takasaki, & Ishino, 2016) (Javed, et al., 2018). It caused the system to be large and costly. To detect the lateral displacement without any sensor in the lateral of the floator, it is proposed to install Hall elements beside the electromagnets in the stator. This configuration leads to several benefits:

- design flexibility
- lower cost
- reduction of size.

This paper organized as follows. First, the principle of switching stiffness control is explained in a differentially operated magnetic suspension. Second, the principle of detecting the lateral displacement with Hall elements is presented. Third, the switching stiffness controls is carried out based on the signals detected by the Hall elements to demonstrate the efficacy of the proposed detection method.

2 Principle of Switching Stiffness Control

Figure 1 shows a magnetic suspension system with a pair of electromagnets (E_1, E_2). This system is inherently unstable in the normal direction (z). Stable action can be achieved by an active control. In contrast, it can be stable in the lateral direction (x) due to the edge effects in the magnetic circuits. An example of the edge effects is shown in Figure 2. This is the same effect producing torque is reluctance motors (Boldea & Naser, 1997). Because restoring force is generated in the lateral direction, the system is modeled as shown by Figure 3 (Mizuno, Takasaki, & Ishino, 2016). The equation of motion is given by

$$m\ddot{x}(t) + kx(t) = 0, \tag{1}$$

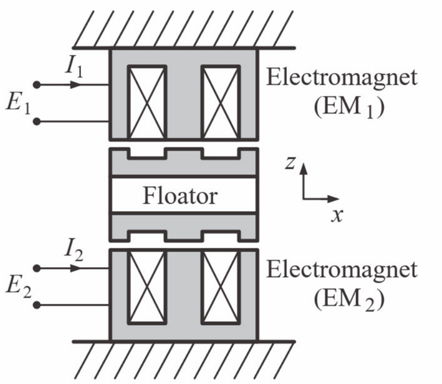


Figure 1 Differentially operated magnetic suspension system

where m : mass of the floator, k : effective stiffness of the system and x : displacement in the lateral direction. Figure 4 shows trajectories in the phase plane when (a) k is high, (b) k is low, and (c) k is switched according to the following control law (Winthrop, Baker, & Goob, 2005):

$$k = \begin{cases} k_0 + \Delta k & (x\dot{x} \geq 0) \\ k_0 & (x\dot{x} < 0) \end{cases} \tag{2}$$

In Equation (2), $x\dot{x} > 0$ means that the floator moves away from the equilibrium position where the flux lines align. In contrast, $x\dot{x} < 0$ means that the floator approaches to the equilibrium position where the flux lines align. By this switching stiffness control, the displacement (x) and velocity ($\dot{x}$) of the floator converge to zero as shown by Figure 4(c). In the magnetic suspension system, the value of k increases as the coil current I increases. Therefore, Equation (2) is modified to Equation (3) (Mizuno, Takasaki, & Ishino, 2016):

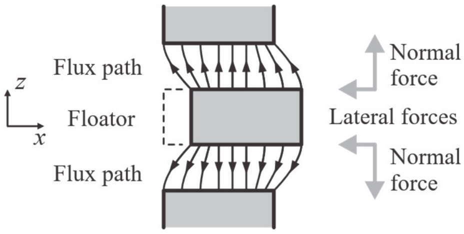


Figure 2 Edge effect

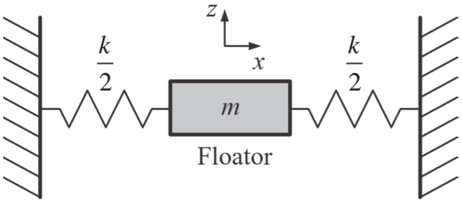
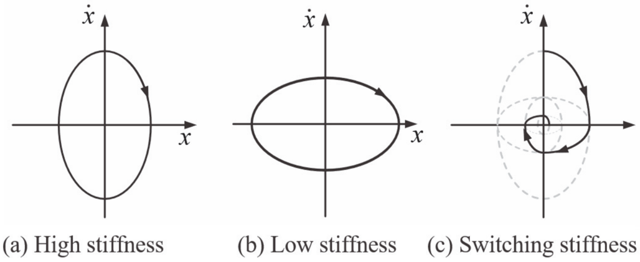


Figure 3 Model of magnetic suspension in the lateral direction



(a) High stiffness (b) Low stiffness (c) Switching stiffness

Figure 4 trajectories in the phase plane

$$I = \begin{cases} I_b + \Delta I & (x\dot{x} \geq 0) \\ I_b & (x\dot{x} < 0) \end{cases} \tag{3}$$

where I_b is a bias current and ΔI is a switching current. This is the principle of switching stiffness control in the differentially operated magnetic suspension system. It is to be noted that the forces in the normal (vertical) direction cancel each other out when the electromagnets are same in characteristics. Therefore, the vertical motion (z) will not be disturbed by the switching stiffness control.

3 Detection of Lateral Displacement

In the first work (Mizuno, Takasaki, & Ishino, 2016), a laser sensor was installed in the lateral direction of the floator to detect the displacement of the floator. However, it is preferable in applications to install nothing in the lateral direction of the floator. Then, another method of measuring the lateral displacement of the floator was introduced (Javed, et al., 2016). The measurement was based on the detection of force exerted by the floator to the electromagnets for suspension due to the magnetized force between them. In this method, however, the electromagnets in the stator were suspended by flexible joints for force detection. It led to some complexity in designing the stator.

In this work, Hall elements are introduced to detect the lateral motion. A Hall element is a sensor element that can detect the magnetic flux passing through the element. Figure 5 shows the flux lines between the electromagnet and the floator when the floator displaced from the equilibrium position. There is leakage flux on the edge of the electromagnet. This leakage flux is correlated with the lateral distance of the electromagnet and the floator. Therefore, Hall elements installed beside the electromagnet can detect the lateral displacement.

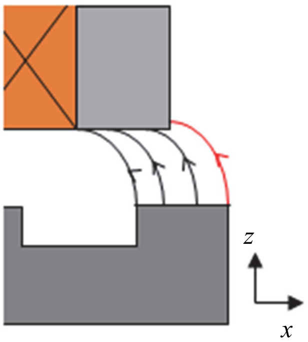


Figure 5 Flux lines when floator is displaced from the equilibrium position (x=0).

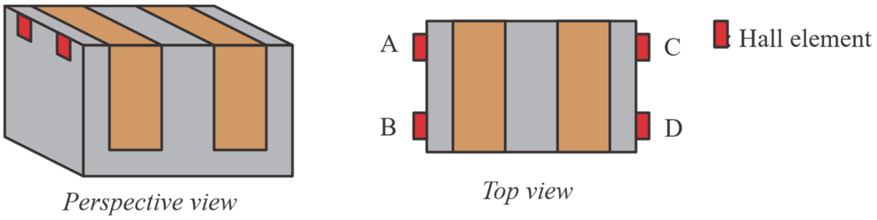


Figure 6 Arrangement of Hall elements on an electromagnet

In experiment, Hall elements are arranged as shown by Figure 6. To increase the sensibility of detection, two outputs in the same side are added. Then the difference between the two sums is calculated. The final output of the Hall-element detection circuit is

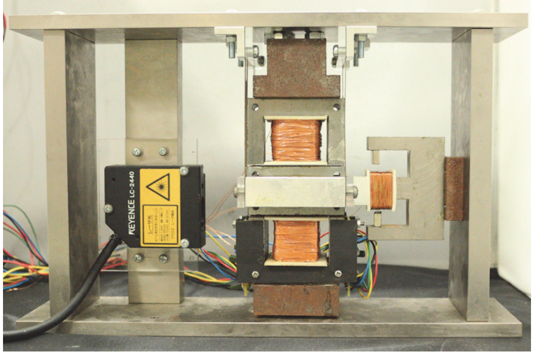
$$V_{\mathrm{H}} = (V_{\mathrm{C}} + V_{\mathrm{D}}) - (V_{\mathrm{A}} + V_{\mathrm{B}}) \tag{4}$$

where V_α is the output of the element α (α =A, B, C or D), and the lateral position of the floator is estimated from the value of V_{H}. This signal is referred to as the output of Hall-element sensor.

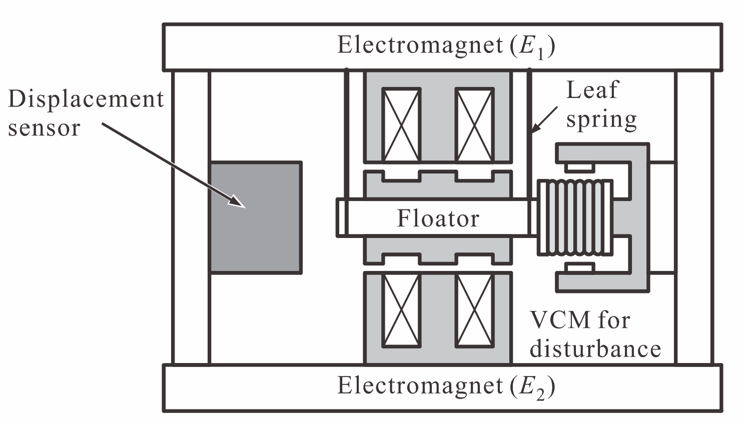
4 Experiment

4.1 Experimental apparatus

Figure 7 (a) shows a picture of the experimental apparatus and Figure 7(b) shows a schematic view of the experimental apparatus. Two electromagnets are arranged above and below the floator. The floator is suspended by four leaf springs to constrain the motion of the floator to a single-degree-of-freedom translation in the lateral direction. A laser displacement sensor is used to confirm the effect of



(a) Picture



(b) Schematic drawing

Figure 7 Experimental apparatus

vibration control. A voice coil motor (VCM) is used to generate a disturbance or adjust the initial position of the floator in the lateral direction. It is to be mentioned that these device in the lateral direction can be removed in practical situations.

The outputs of the laser sensor and the Hall-element sensor are inputted to a DSP-based controller. The controller determines the commands to two power amplifiers according to Equation (3). Each power amplifier energizes the connected electromagnet.

4.2 Detecting lateral displacement by Hall elements

First, the performances of the fabricated sensor device are studied experimentally. Figure 8 compares the output of the laser sensor (reference) and that of the Hall-element sensor. They agree well with each other. It indicates that the lateral displacement of the floator can be detected with the device with Hall elements.

4.3 Vibration control with switching stiffness control

Figure 9 shows a block diagram of the switching stiffness control in the following experiments. Experimental procedures are as follows. First, the floator is set to an initial position (x=0.8mm) with the VCM. Second, the VCM is powered off and the lateral displacement is observed during switching stiffness control. Figure 10 shows the time histories of the output of the Hall-element sensor and the

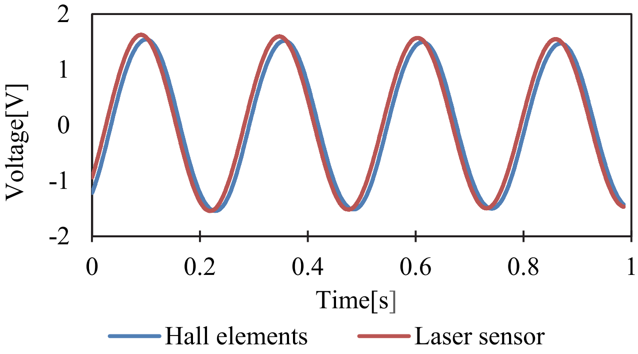


Figure 8 Comparison of the laser sensor and the Hall-element sensor

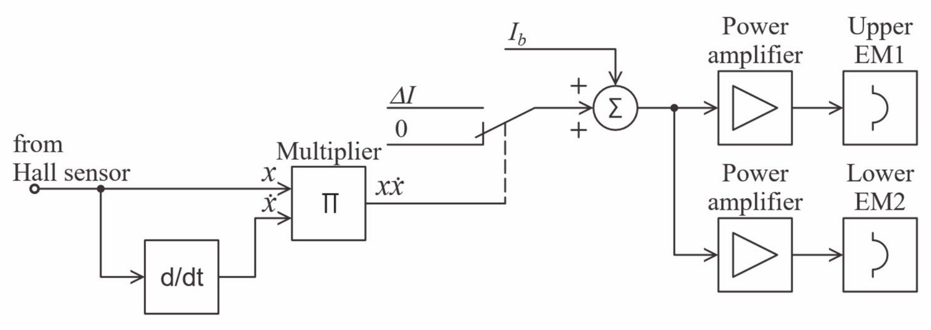
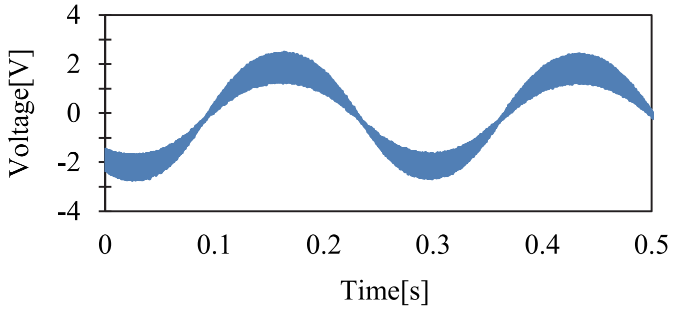
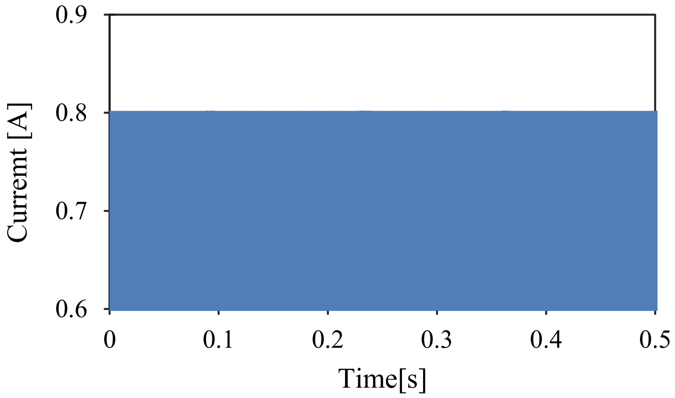


Figure 9 Block diagram

current command to the two electromagnets. As shown by Figure 10 (a), the output of the Hall-element sensor oscillates, and the switching's occur rapidly. The noises generated by a current switching cause



(a) Output of Hall sensor



(b) Current command

Figure 10 Time histories when switching stiffness control works

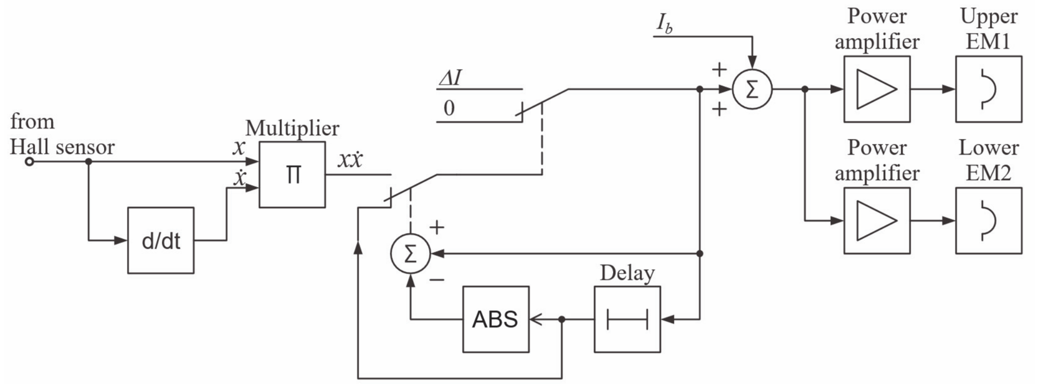


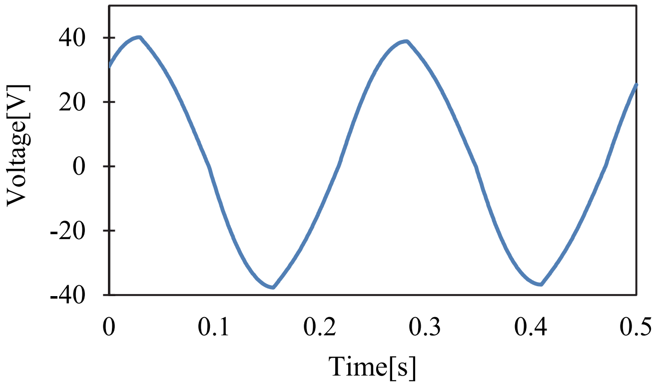
Figure 11 Block diagram

the next current switching and this process repeats. Therefore, the output of the Hall-element sensor oscillates, and the current is switched continuously. It makes the vibration control ineffective.

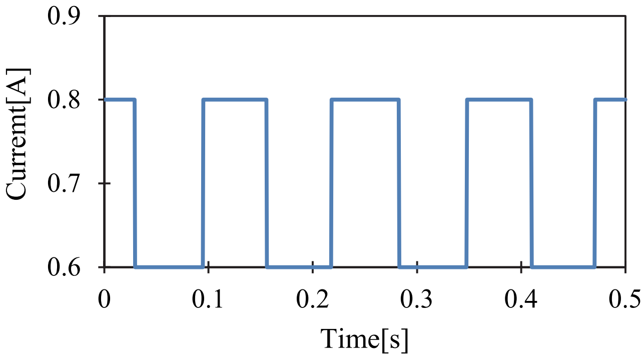
The control system is modified to avoid such mis-switching's. Figure 11 shows a block diagram of the modified control system. When the currents of the two electromagnets are switched, the previous value is maintained to determine switching in the next sampling. By this modified process, repeating current switching's caused by switching noises can be removed. Therefore, the noises in the output of the Hall-element sensor decrease.

Figure 12 show the time histories of the output of the Hall element sensor and the current command to the power amplifiers, respectively. As shown from Figure 12(a), the output of the Hall-element sensor includes less noises. In addition, Figure (b) shows that the current is switched properly according to the value of $x\dot{x}$.

Vibration control with the modified control system is conducted. Figure 13 shows the time histories of the lateral displacement of the floator (a) without switching stiffness control and (b) with switching stiffness control (b), respectively. The comparison of Figure 13 (b) with Figure 13 (a) demonstrates the effectiveness of the switching stiffness control for attenuating the vibration in the lateral direction.

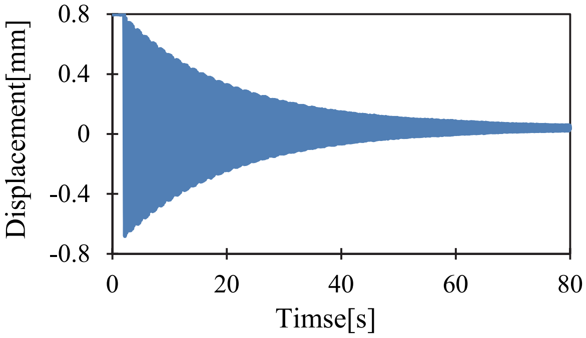


(a) Output of Hall sensor

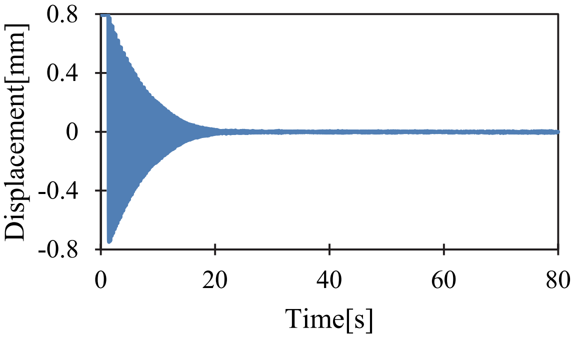


(b) Current command

Figure 12 Time histories when modified switching stiffness control works



(a) Without switching stiffness control



(b) With switching stiffness control

Figure 13 Effects of switching stiffness control

5 Conclusions

A method of detecting the lateral displacement with Hall elements was proposed. The method is characterized by locating Hall elements besides the stator electromagnets. The signal detected with the fabricated device with Hall elements included some noises due to current switching. It caused mis-switching's. Then the controller was modified to use the pre-sampled value to determine the control current. The modified control system succeeded to suppress the lateral vibration.

References

Boldea, I., & Naser, S. A. (1997). *Linear Electric Actuators and Generators.* Cambridge University Press.

Javed, A., Mizuno, T., Takasaki, M., Ishino, Y., Hara, M., & Yamaguchi, D. (2016). Proposal of Lateral Vibration Control Based on Force Detection in Magnetic Suspension System. *International Journal of Applied Electromagnetics and Mechanics, 52*, 223-229. doi:10.3233/JAE-162064

Javed, A., Mizuno, T., Takasaki, M., Ishino, Y., Hara, M., & Yamaguchi, D. (2018). Lateral Vibration Suppression by Varying Stiffness Control in a Vertically Active Magnetic Suspension System. *Actuators, 7*, 21. doi:10.3390/act7020021

Jayawant, B. (1981). *Electromagnetic Levitation and Suspension Technique.* London: Edward Arnold.

Mizuno, T., Takasaki, M., & Ishino, Y. (2016). Lateral Vibration Attenuation by the Dynamic Adjustment of Bias Currents in Magnetic Suspension System. *Journal of Physics: Conference Series 744: MOVIC2016 & RASID2016*, 012005. doi:10.1088/1742-6596/744/1/012005

Winthrop, M., Baker, W., & Goob, R. (2005). A variable stiffness device selection and design tool for lightly damped structures. *Journal of Sound and Vibration, 287*(4-5), 667-782.