Lateral Vibration Attenuation by the Dynamic Adjustment of Bias Currents in Magnetic Suspension System

Takeshi Mizuno, Masaya Takasaki, Yuji Ishino
Department of Mechanical Engineering, Saitama University, Shimo-Okubo 255, Sakura-ku, Saitama 338-8570, Japan
mizar@mech.saitama-u.ac.jp

Abstract. Switching stiffness control is applied to attenuate vibration in the lateral directions in an active magnetic suspension system with electromagnets operated in differential mode. The magnetic suspension system using the attractive force between magnetized bodies is inherently unstable in the normal direction so that feedback control is necessary to achieve stable suspension. In contrast, it can be stable in the lateral directions due to the edge effects in the magnetic circuits. In several applications, such passive suspension is used in combination with the active one to reduce cost and space. However, damping in the lateral directions is generally small. As a result, induced vibrations in these directions are hardly attenuated. To suppress such vibration without any additional actuator (electromagnet), switching stiffness control is applied to an magnetic suspension system operated in the differential mode. The stiffness in the lateral direction is adjusted by varying the bias currents of an opposed pair of electromagnets located in the normal direction simultaneously according to the motion of the suspended object. When the varied bias currents are adjusted for the additive normal forces cancel each other, such control does not affect the suspension in the normal direction. The effectiveness of the proposed control methods is confirmed experimentally.

1. Introduction
Active magnetic suspension is a key technology in machines operated in vacuum and/or highly clean environments because of no mechanical contact and no necessity of lubricant [1]. This suspension technique has been used in various industrial fields such as Maglev system [2, 3] and active magnetic bearing (AMB) for complete contact-free suspension of a rotating object [1]. The most successful application is turbomolecular pump [1]. In this application, AMB-based instruments are dominant.

A typical suspension system consists of the following components (see Fig.1):
- object to be suspended (floator)
- electromagnet to produce suspension force
- sensor to detect the displacement of the floator
- electronic analog or digital controller
- power amplifier to feed current to the windings of the electromagnet

This system is inherently unstable in the normal (vertical in Fig.1) direction. Stable action can be achieved by sensing the position of the floator and controlling the force fields to prevent the floator from departing from its desired position with sufficient rapidity; increase the current when the air gap is too large, decrease the current when the air gap is too small. In contrast, it can be stable in the lateral
directions due to the edge effects in the magnetic circuits. To achieve complete noncontact suspension with less cost and space, partially active magnetic suspension system is used instead of totally active magnetic suspension system. However, such partially active systems inevitably suffer from small damping in the passive suspension [4]. Induced vibrations are hardly attenuated and resonances are easily excited in the lateral directions.

Another problem of the suspension system with a single electromagnet is that it relies on gravity to increase the gap because an electromagnet produces attractive force solely for a ferromagnetic floator. It limits the speed of response. In addition, such single-electromagnet configuration cannot be used in horizontal suspension. Therefore, a pair of electromagnets acting in opposition are commonly used to control a single-degree-of-freedom motion of the floator. This work focuses on magnetic suspension systems with such an opposed pair of electromagnets operated differentially.

In this work, a switching stiffness control is applied to reduce vibration in the lateral directions in active magnetic suspension system with electromagnets operated in the differential mode. Switchable and variable stiffness controls have been studied in the in the fields of vibration control [5-8]. It was shown that the vibration of a string can be suppressed by switching the tension [5]. A method for selecting and understanding the performance of variable stiffness devices was developed [6]. The application of an isolator with switchable stiffness to shock isolation was proposed and studied experimentally [7, 8].

Such controls are applicable to the lateral vibration control because the lateral stiffness varies with the bias current of an electromagnet placed in the normal direction. In addition, the normal forces cancel each other in the differential mode so that the motion in the normal direction is not affected by such controls. The effectiveness of the proposed controlled method is confirmed experimentally.

2. Principle of Lateral Vibration Control

2.1. Basic model of magnetic suspension systems

Figure 1 shows a basic model of magnetic suspension system using the attractive force of an electromagnet. This system is inherently unstable in the normal (vertical in Fig.1) direction. Stable action can be achieved by sensing the position of the rotor and controlling the force fields to prevent the rotor from departing from its desired position with sufficient rapidity; increase the current when the air gap is too large, decrease the current when the air gap is too small.

A problem of the suspension system with a single electromagnet is that it relies on gravity to increase the gap because an electromagnet produces attractive force solely for a ferromagnetic floator. It limits the speed of response. In addition, such single-electromagnet configuration cannot be used in horizontal suspension. Therefore, a pair of electromagnets acting in opposition are commonly used to control a single-degree-of-freedom motion of the floator. Figure 2 shows a basic model of magnetic suspension system operated in the differential mode. Two counteracting electromagnets EM$_1$ and EM$_2$...
are located above and below the floator. It is assumed for simplicity in the following that
(1) The floator moves only translationally in the vertical and horizontal directions.
(2) EM1 and EM2 have same characteristics and bias current ($I_b$).
(3) The effect of gravity is negligible.

In these conditions, the equilibrium position of the floator is just the middle of the electromagnets where the poles of the stator and the floator is aligned. The displacement from this position is denoted by $z$ in the normal (vertical) direction and $x$ in the lateral (horizontal) direction.

First, we discuss on the motion in the normal direction. The suspension system is inherently unstable in this direction. For stabilization, it is necessary to vary the coil currents $I_1$ and $I_2$ rapidly according to the motion of the floator. For example, when the floator displaces downward, $I_1$ must be increased while $I_2$ must be decreased. Such a relation is represented by

$$\begin{cases} I_1 = I_b + i \\ I_2 = I_b - i \end{cases}$$  

(1)

where $I_b$ is the bias current and $i$ is the control current. The most fundamental control law is PD control which is represented by

$$i(t) = -(p_d z(t) + p_v \dot{z}(t))$$  

(2)

where $p_d$ is the feedback gain of displacement and $p_v$ is that of velocity. The stiffness and damping of suspension can be adjusted with these gains. It is one of the advantages of active magnetic suspension.

![Fig. 2 Magnetic suspension system with a pair of electromagnets operated in the differential mode](image1)

![Fig. 3 Edge effects](image2)
Next, we discuss on the lateral motion and the edge effects of a magnetic circuit. An example of the edge effects is shown in Fig.3. This is the same effect producing torque in reluctance motors [9]. The forces on the ferromagnetic pieces cause them to align with the flux lines, thus shortening the magnetic flux path and reducing the reluctance. In the suspension system, restoring force acts on the floator when it displaced from the equilibrium position where the edges of the floator align with the edges of the stator. As a result, the suspension system becomes stable in the lateral direction without active control. This effect is utilized to achieve complete noncontact suspension with less cost and space. Examples are found in a miniaturized magnetic bearing [4] and a solar magnetic suspension system [10]. Such partially active magnetic suspension systems are used instead of totally active magnetic suspension system when high-performance suspension is not necessary in all directions. However, passive suspension inevitably suffers from small damping. Induced vibrations are hardly attenuated and resonances are easily excited in the passively supported direction(s).

2.2. Switching Stiffness Control
In the fields of vibration control, several switchable and variable stiffness strategies have been investigated [5-8]. The most fundamental principle of switching stiffness control is explained based on the model shown by Fig.4. A mass $m$ is suspended by a spring $k$ without damping. The equation of motion is given by

$$m\ddot{z}(t) + k\dot{z}(t) = 0$$

A free vibration is induced for a non-zero initial displacement. Phase plane plots are shown for a high stiffness $k_0 + \Delta k$ in Fig.5(a) and for a lower stiffness $k_0$ in Fig.5(b). A typical switching stiffness control strategy is

$$k = \begin{cases} 
  k_0 + \Delta k & \ddot{z} > 0 \\
  k_0 & \ddot{z} \leq 0
\end{cases}$$

Fig.4 Switching stiffness

Fig.5 Principle of reducing vibration by switching stiffness
Then, the phase plane plot changes as shown by Fig.5(c). It demonstrates that the vibration decreases despite no damping. This is the principle of vibration control by switching stiffness.

2.3. *Lateral vibration control by switching stiffness*

The switching stiffness control is applied to magnetic suspension systems operated in the differential mode to reduce vibration in the lateral direction(s). The principle is explained based on Fig.6. The restoring force is approximately represented by $k_x x$ where $k_x$ is the stiffness in the lateral direction (lateral stiffness). The lateral stiffness becomes larger as $I_b$ increases. Therefore, it can be switched to $k_x + \Delta k_x$ by adding a constant current $\Delta I$ to the bias current. The proposed control strategy is

$$I_1 = I_2 = \begin{cases} I_b + \Delta I & \text{if } x \ddot{x} > 0 \\ I_b & \text{if } x \ddot{x} \leq 0 \end{cases}$$

(5)

It is to be mentioned that the vertical (normal) forces cancel each other so that the vertical motion of the floator is not affected by such control in principle.

3. *Experiment*

3.1. *Experimental apparatus*

Figure 7 shows a schematic drawing of the fabricated apparatus for experimental study. The aim of the...
The experiment is to evaluate the performance of the proposed lateral vibration control using switching stiffness. Thus, the floator is suspended by a pair of leaf springs to restrict the motion in the lateral direction solely. Two electromagnets are placed above and below the floator. A voice coil motor (VCM) is installed in the lateral direction to add disturbance to the floator. An optical displacement sensor is also installed in the lateral direction to measure the lateral displacement of the floator. The detected signal is inputted to a digital controller DS1103 manufactured by dSPACE\textsuperscript{TM}. The designed control algorithms are implemented with this controller. The control period is 100\,\mu s. The power amplifiers have an output of current.

3.2. Experimental results

First, to examine the efficacy of the proposed control, the responses to an impulse disturbance produced by the VCM were measured when

- (a) $I_0 = 0\,[\text{A}]$, $\Delta I = 0\,[\text{A}]$ (Low stiffness),
- (b) $I_0 = 1\,[\text{A}]$, $\Delta I = 0\,[\text{A}]$ (High stiffness),
- (c) $I_0 = 0\,[\text{A}]$, $\Delta I = 1\,[\text{A}]$ (Switching stiffness).

![Graphs showing displacement over time for different stiffness levels](image)

(a) Low stiffness

(b) High stiffness

(c) Switching stiffness

Fig. 8 Effect of switching stiffness control.
Figure 8 shows the measured responses. Comparing the response (a) with response (b), we find that the frequency of vibration in the response (b) is 0.8 Hz higher than that in the response. From this result, the increased stiffness is estimated to be approximately 44%, that is, $\Delta k_x / k_x = 0.44$. In contrast, the vibration attenuates more rapidly in the response (c). The settling time $t_s$, at which the peak of response decreases to 5% of the initial peak, is measured as

(a) $\Delta I = 0.5$ [A], $t_s = 4.9$ [s]

(b) $\Delta I = 1.0$ [A], $t_s = 2.5$ [s]

(c) $\Delta I = 1.5$ [A], $t_s = 0.9$ [s]

(d) $\Delta I = 2.0$ [A], $t_s = 1.0$ [s]

Fig.9 Effects of the increase of current in switching stiffness control.
(a) 64.0 [s] (Low stiffness),
(b) 59.5 [s] (High stiffness),
(c) 2.5 [s] (Switching stiffness).

The settling time is reduced to 1/25 by applying the switching stiffness control.

Next, the effect of the increase of current $\Delta I$ is investigated experimentally. It is changed as

(a) $\Delta I = 0.5$ [A],
(b) $\Delta I = 1.0$ [A],
(c) $\Delta I = 1.5$ [A],
(d) $\Delta I = 2.0$ [A],

while $I_b$ is kept to be 0[A]. The results are shown in Fig.9. The settling time decreases as the $\Delta I$ increases from the responses (a) to (c). However, the settling time become longer in the response (d) than that in the response (c). It may be due to wrong switching because the effects of noises including in the sensor output increases relatively when the detected displacement becomes small. It can be improved by varying the currents continuously instead of rapid switching [11].

4. Conclusion

Switching stiffness control was applied to suppress vibration in the lateral directions in active magnetic suspension system with electromagnets operated in the differential mode. Damping in the lateral directions is generally small so that induced vibrations in these directions are hardly attenuated. Such vibration was suppressed by switching stiffness control without any additional electromagnet in the lateral direction. The stiffness in the lateral direction is adjusted by varying the bias currents of an opposed pair of electromagnets located in the normal direction simultaneously according to the motion of the floator. The effectiveness of the proposed control method was confirmed experimentally.

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