Variable stiffness approach to reduce vibration induced in passively-supported directions of an active magnetic suspension system

Asief Javed[a], Takeshi Mizuno [a], Masaya Takasaki [a], Yuji Ishino [a], Daisuke Yamaguchi [a]

[a] Saitama University, 255 Shimo Okubo, Sakura-ku, Saitama, Japan, asiefjaved@control.mech.saitama-u.ac.jp

***Abstract*—This study focuses on the vibration reduction in lateral directions by varying the stiffness of the system in a vertically active magnetic suspension system. Vibration can easily be induced in the lateral directions while the normal directions are actively controlled with a pair of electromagnets working in a differential driving mode. Switching stiffness control is applied to such a system to reduce the lateral vibration of a floator that is a 25 mm ferromagnetic ball. The normal position of the floator is unchanged even if the stiffness control is applied to the system. The efficacy of the control is evaluated by several experiments which show the reduction of lateral vibrations.**

I. Introduction

In an active magnetic suspension system, the forces are generated and controlled by electromagnets with a controller, sensors, and power amplifiers. It has advantages over passive system such as adjustable features like varying stiffness and damping by control, working capabilities with varieties of load [1]. In a vertically active magnetic suspension system where electromagnets in the normal direction operate in a differential driving mode, the lateral motions are lightly damped. The floator is stable in the lateral direction because of the edge effect between the electromagnets (EMs) and the floator. The edge effect is obtained due to the tendency of magnetic flux which tries to pass through less reluctant path [2]. However, when vibration is induced in the passively-supported directions, it takes long time to return to its settling state. Variable stiffness control is applied to attenuate the vibration.

Variable stiffness approach is applied to many devices to reduce vibration [3], [4], [5]. However, in these devices, the suspended object are mechanically supported. Ledezma-Ramirez et al. [4] used nylon wires to suspend the isolated mass. Leaf springs are used in Mizuno et al. [3] and Javed et al. [5]. In this work, the reduction of vibration is achieved while the floator is suspended without any contact.

There are several control methods such as proportional-integral-derivative (PID) control [6], robust control [7] which can be applied to reduce vibration. H-infinity robust control [7] and μ synthesis [8] show better performance, however, the control systems are complex. Moreover, these controllers are for actively controlled degrees-of-freedom (DOF) motions. The studies mentioned in [3], [6], [7], [8] focus on the vibration reduction in the direction of the actuators.

In this study, lateral vibration is attenuated in a three translational motions vertically active magnetic suspension system. Two electromagnets are arranged in the vertical direction to reduce vibration in the lateral direction as well as in the normal direction.

II. Principle

The equation of motion of a mass-spring system shown in Fig. 1 can be written as:

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

where m is the mass of the suspended object, k is the effective stiffness of the system, and x is the displacement with respect to time. In switching stiffness control, the stiffness is changed based on the conditions written in equation (2) [3].

$$k = \begin{cases} k_0 + \Delta k & \dots . x\dot{x} > 0 \\ k_0 & \dots . x\dot{x} < 0 \end{cases} \tag{2}$$

The three translational motions of the floator (ferromagnetic ball) are considered in this study as shown in Fig. 2 (a). The electromagnets are in differential driving arrangement. The varying stiffness control will be applied to attenuate vibration in the lateral directions which are X- and Y-directions. So, radial motion of the floator is considered to apply switching stiffness control. A new variable r is introduced that is defined as

$$r^2 = x^2 + y^2 \tag{3}$$

where x and y are the displacements in X- and Y-directions with respect to time, respectively. Figure 2(b) shows the radial position of the floator. To implement equation (2) in the target magnetic suspension system, the control current is varied according to the conditions as written in equation (4). When the floator will move to the outward directions the current will be increased to attain high stiffness. In the case of inward motion of the floator, the current will be decreased in the EMs.

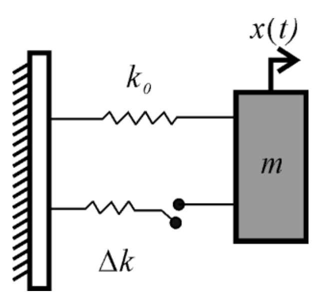


Figure 1. Switching stiffness system

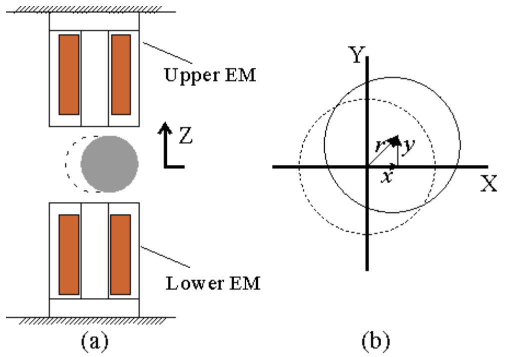


Figure 2. (a) Target magnetic suspension system, (b) radial position of the floator (top view).

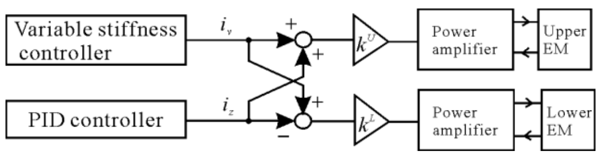


Figure 3. Modal control.

$$I = \begin{cases} I_b + \Delta I_s \; \ldots . r\dot{r} > 0 \\ I_b \quad \ldots\ldots.. \; r\dot{r} = 0 \\ I_b - \Delta I_s \; \ldots . r\dot{r} < 0 \end{cases} \qquad (4)$$

where I_b is bias current, and ΔI_s is switching current.

In a magnetic suspension system, the sensor measures the position of the floator with respect to the desired position. This signal is passed to the controller, and the controller delivers a control signal to a power amplifier. The power amplifier converts it to control current, and the current passes through the coils of electromagnets [1]. In the developed experimental set up, proportional-derivative (PD) and proportional-integral-derivative (PID) controllers both are used in Z-direction. PD control is applied to find out the current-force coefficient of the electromagnets. This parameter is necessary to balance the forces of EMs in Z-direction when variable stiffness control is applied. PID control is applied to suspend the floator to the set position during the stiffness control.

A modal control is used to distribute the control signal from the variable stiffness controller and PID controller to pass currents through the coils of EMs as shown in Figure 3. The coefficients k^U and k^L are the gains of upper EM and lower EM, respectively, to balance the forces of the EMs. The differentiation of r is performed by using a filtered derivative with a cut off frequency of 100 Hz which is much greater compared to the natural frequency of the lateral motions.

III. Experimental Apparatus

To study the variable stiffness control in magnetic suspension system, an experimental device is developed. Figure 4 shows the schematic, and Figure 5 shows the photograph of the developed system. The device has two electromagnets operating in the differential mode. The upper and lower electromagnets have 364 number of turn. However, the permanent magnets have different sizes. The permanent magnets (PMs) are used to provide bias flux. An optical sensor is developed to measure the displacement of the floator in X-, Y-, and Z-directions. It consists of two units placed in both sides of the floator. A ferromagnetic ball is used as floator

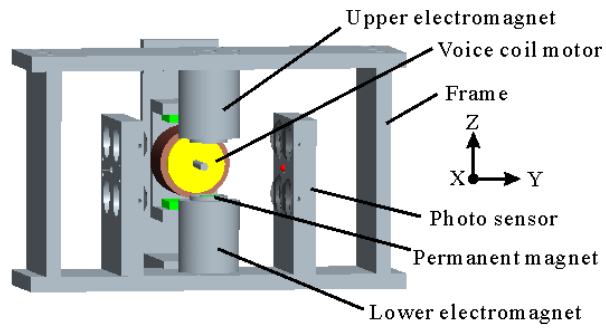


Figure 4. Schematic of developed experimental device

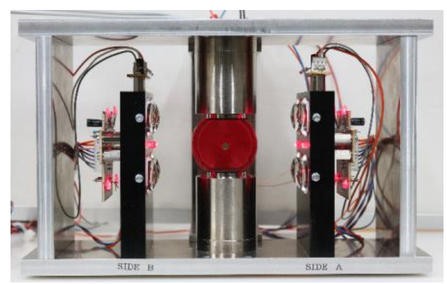


Figure 5. Photograph of experimental device.

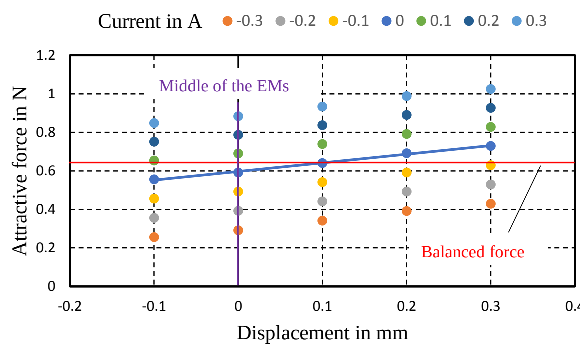


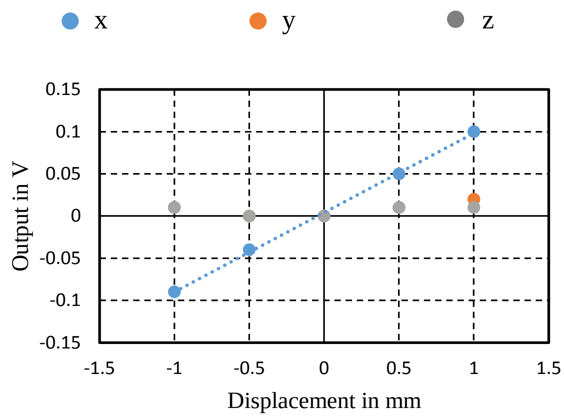
Figure 6. Relation between attractive force and displacement of the floator for different currents (analytical result).

which is 25 mm in diameter and 63.9 g in mass. A voice coil motor (VCM) with internal bearing placed in X-direction is utilized to produce impulse disturbances to the ball. The current-force relation of the VCM is measured by attaching the shaft of VCM with a load cell. The position of the ball is 0.1 mm above from the middle of the distance between the two EMs. This position is found out by considering cancellation of gravitational force of the ball by the permanent magnets in finite element method analysis.

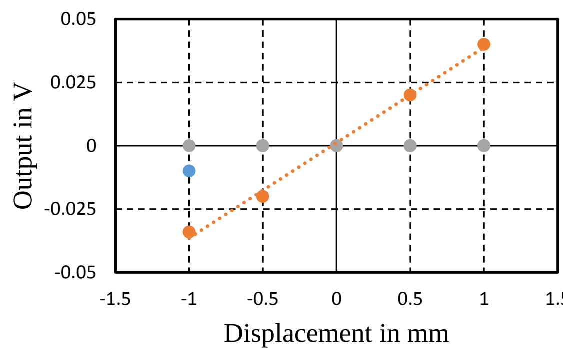
IV. Identification of Parameters

Figure 6 shows the relation between the attractive force and the displacement of the floator in Z-direction for various control current i_z. Finite element method (FEM) is applied to find out the relationship. The displacement zero is the position of the floator in the middle of the two EMs. The equilibrium position of the floator when no current is applied is at 0.1 mm.

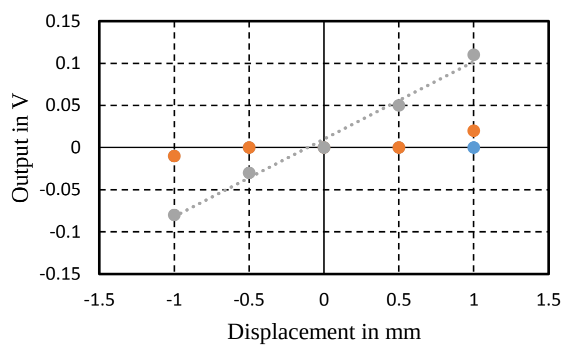
The sensor gains of three translational directions are measured by fixing a ball with a three axes translation stage.



(a) X-direction



(b) Y-direction



(c) Z-direction

Figure 7. Calibration of the sensor.

Figure 7 shows the output voltages of the phototransistors with respect to displacement. Almost no interaction between the axes are found out especially within $\pm$0.5 mm.

The current-force coefficients of the upper and lower EMs are found out to be 0.405 N/A and 0.23 N/A, respectively, by using equation (5) and equation (6). At first, PD control is applied and the ball is suspended at set position of 0.1 mm. Then current I_0 is added to both EMs. The ball moves upward

$$\frac{k_{iU}}{k_{iL}} = \frac{I_0}{(I_0-\Delta I_U)} \tag{5}$$

$$k_{iU} + k_{iL} = k_i \tag{6}$$

which is returned to its set position by reducing current $\triangle I_U$ from upper EM. The total current-force coefficient, k_i of the system is estimated from the slope of the stiffness $m\omega^2$ with respect to proportional gain of PD controller. The detail is mentioned in [9]. To balance the forces generated by EMs, the gains k^U and k^L are assigned to be 0.23 N/A and 0.405 N/A, respectively. However, these values cause large current flow through the coils of EMs. As a result, the values are lowered to 0.13 N/A and 0.23 N/A for upper and lower EMs, respectively, without affecting the balance.

The correct gains of the EMs are necessary to find out, because vibration will induce in the normal direction (Z-direction) otherwise. The upper EM gain is changed while the lower EM gain is fixed when the switching stiffness control is applied with the switching current 0.2 A. The amplitude of vibration in Z-direction is at minimum when the correct gain is assigned in upper EM. This is shown in Fig. 8 and found out that at correct ratio the amplitude of displacement in normal direction is minimum. Figure 9 shows almost same amplitude of displacement for the selected gains with and without the application of switching stiffness control.

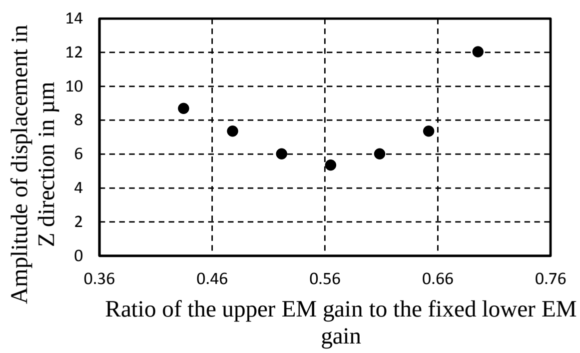


Figure 8. Correct gains reduce the vibration in Z-direction to its minimum while switching stiffness control is applied.

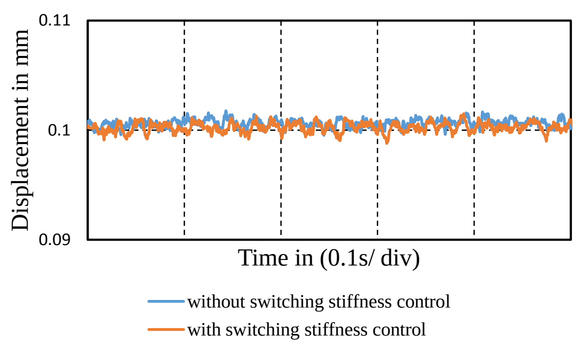
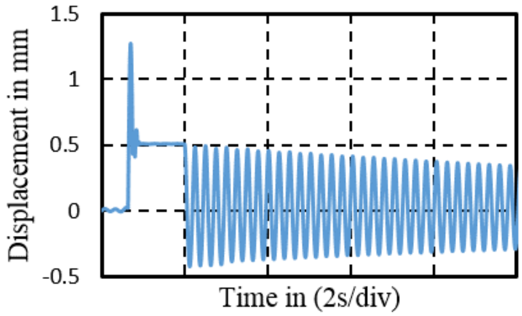


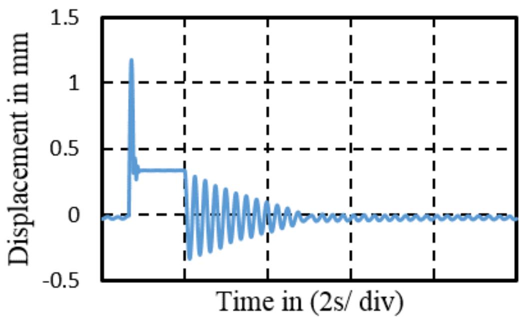
Figure 9. Displacement in Z-direction for the selected gains without stiffness control and with the application of stiffness control

V. EXPERIMENTAL RESULTS

Figure 10 shows the displacement in X-direction with respect to time in the case of (a) free vibration, and (b) when switching stiffness control is applied. For switching current, ΔI_s = 0.1 A, the settling time in X-direction is 3.1 s. The applied disturbance is same for the cases shown in Fig.10 (a) and (b), the initial displacement is different as the switching stiffness control is acted on the latter case. Figure 11 shows the displacement in

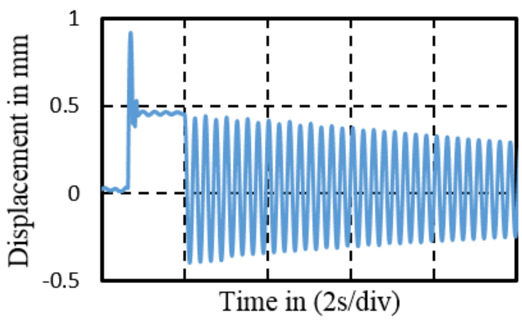


(a)

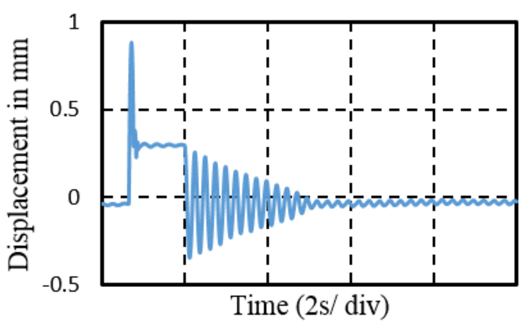


(b)

Figure 10. Vibration reduction by switching stiffness control in X-direction. (a) free vibration, and (b) application of switching stiffness control with switching current 0.1 A.



(a)



(b)

Figure 11. Vibration reduction by switching stiffness control in Y-direction. (a) free vibration, and (b) application of switching stiffness control with switching current 0.1 A.

Y-direction with respect to time for (a) free vibration and (b) with switching stiffness control for switching current 0.1 A.

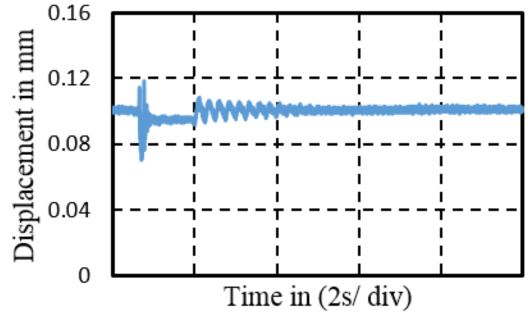


Figure 12. Displacement of floator with respect to time in PID controlled Z-direction (normal direction) while switching stiffness control is applied to reduce lateral vibration.

The settling time becomes 3.22 s when control is applied. Though vibration induces in Z-direction, it reduces with time as shown in Fig. 12 because PID control is applied to that direction. The gains of the PID controllers are obtained by trial and error method. The controller is implemented in the digital signal processor (DS1005) with sampling frequency 10 kHz.

VI. CONCLUSION

The switching stiffness control was applied to the developed system and it has been found out that the switching stiffness approach can reduce lateral vibration. The vertical direction remains unchanged even if the variable stiffness approach is implemented. The current-force coefficient should be found out exactly to avoid vibration in Z-direction. Measuring frequency response and removal of the sensor from lateral direction are intended to perform in future.

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