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Vibration Suppression in the Passively-Supported Direction by Varying Bias Currents in Magnetic Suspension System*

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Abstract— **Vibration in the passively-supported direction is reduced by varying the stiffness in the suspension. The magnetic suspension system using the attractive force of an electromagnet is inherently unstable in the normal direction; active control is necessary to achieve stable suspension. In contrast, it is usually stable in the lateral direction because of the edge effects in the magnetic circuits. However, damping in this direction is quite small so that vibration is easily induced. In this work, varying stiffness controls are applied to suppress the vibration. An experimental apparatus was built to examine the efficacy of the varying stiffness control. It has two electromagnets operated differentially. To adjust the stiffness in the passively-supported direction, the bias current of each electromagnet is varied simultaneously. First, the bias current is varied stepwise. The effect of the amplitude of step on vibration suppression is examined. Then, the bias current is varied continuously to avoid erroneous operations caused by noise included in the sensor signal. The efficacy of approximating the sign function by a continuous function is demonstrated experimentally**

I. INTRODUCTION

Magnetic suspension has advantages of no contact and no lubricant over conventional mechanical suspensions [1]. It has been utilized in Maglev systems [2], vacuum instruments [1] and artificial blood pumps [3].

There are various methods of magnetic suspension [1, 2]. Most widely used is active magnetic suspension using electromagnet. In this method, stable levitation is achieved by feedback control. The current flowing in the coil is increased when the the suspended object (floator) moves to increase the gap between the electromagnet and the floator. In contrast, it is usually stable in the lateral direction 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 used in combination with active suspension. Such systems are referred to as *partially active magnetic suspension systems*. One of the problems of partially active systems is small damping in the passively-supported direction [4]. Vibration is easily induced and hardly attenuated in this direction.

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In active suspension, 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 ferromagnetic floator. This work focuses on such differentially operated magnetic suspension systems [1].

We have proposed to apply switching stiffness control to differentially operated magnetic suspension systems to suppress vibration in the passively-supported directions [4]. In this method, the bias current of each electromagnet was switched between low and high values or varied stepwise according to the detected signal of the lateral motion. Such switching and varying stiffness controls have been studied in the in the fields of vibration control [5-7]. Our work was the first trial of applying the switching stiffness control to partially active magnetic suspension to suppress the vibration in the passively-supported direction [4]. The efficacy of the proposed vibration control was demonstrated experimentally [8]. However, the effects of the critical parameters such as the average value and amplitude of step in the bias current have not been studied sufficiently.

In this work, the performance of the switching stiffness control is studied extensively through experiments. In addition, it is pointed out that erroneous operation can be induced in the presence of noise in the sensor signal that is used to determine the switching points. To avoid such undesirable operations, continuously varying stiffness control is introduced. The effectiveness of the modified control method is confirmed experimentally.

II. PRINCIPLE OF LATERAL VIBRATION CONTROL

A. Basic model of magnetic suspension systems

Figure 1 shows a basic model of magnetic suspension system operating differentially [8]. A floator made of ferromagnetic material is sandwiched by two counteracting electromagnets EM1 and EM2. Because an electromagnet produces only attractive force on a ferromagnetic body, the floator is pulled from both sides and the net force acting on the floator is given by the difference between them. The vertical translational motion of the floator can be controlled by the differential force. 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. For example, when the floator moves downward, the current of EM1, denoted by I_1, is increased and the current of EM2, denoted by I_2, is decreased.

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.

(3) The effect of gravity is negligible.

Under these conditions, the equilibrium position of the floator in the vertical direction is just the center between the electromagnets in the vertical direction; the displacement from this position is denoted by z. In the lateral (horizontal) direction, the poles of the stator and the floator is just aligned in the the equilibrium and the displacement from this position is denoted by x.

First, we discuss on the motion in the normal direction. The suspension system is inherently unstable in this direction. For stabilization, the currents I_1 and I_2 must be varied differentially according to the motion of the floator. For example, when the floator displaces downward (approaches to EM2), I_1 must be increased whereas I_2 must be decreased. Thus,

$$\left.\begin{aligned} I_1(t) &= I_b + i(t) \\ I_2(t) &= I_b - i(t) \end{aligned}\right\} \qquad (1)$$

where I_b is the bias current (*common component*) and $i(t)$ is the control current (*differential component*). The most fundamental control law is PD control that is represented by

$$i(t) = -(p_d z(t) + p_v \dot{z}(t)) \qquad (2)$$

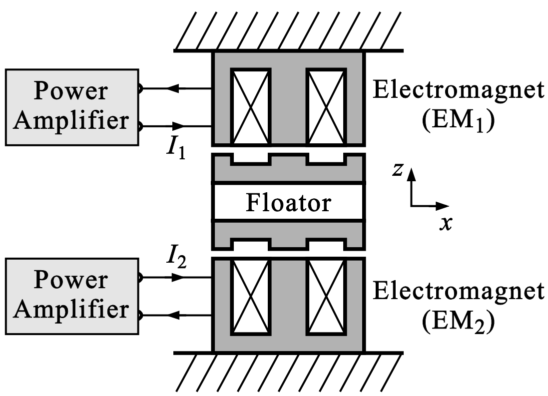


Figure 1. Basic model of magnetic suspension system operating differentially

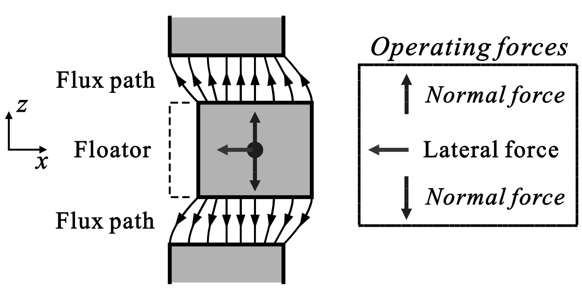


Figure 2. Edge effects produce lateral force.

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

Next, we discuss on the lateral motion and the edge effects of a magnetic circuit. Figure 2 illustrates the edge effects. 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 any feedback control. This effect is utilized to achieve complete noncontact suspension with less cost and space. 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 and/or the reduction of the cost and volume of instrument is highly required. However, in the passive suspension, damping is virtually zero so that induced vibrations are hardly attenuated.

B. Switching stiffness control

In the fields of vibration control, several switchable and variable stiffness strategies have been investigated [5-7]. The most fundamental principle of switching stiffness control is explained based on the model shown by Fig.3. A mass m is suspended by a spring k without damping. The equation of motion is given by

$$m\ddot{z}(t) + kz(t) = 0 \qquad (3)$$

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.4(a) and for a lower stiffness $k_0 - \Delta k$ in Fig.4(b). A typical switching stiffness control strategy is

$$k = k_0 + \Delta k \,\mathrm{sgn}(z\dot{z}) = \begin{cases} k_0 + \Delta k & z\dot{z} > 0 \\ k_0 & z\dot{z} = 0 \\ k_0 - \Delta k & z\dot{z} < 0 \end{cases}$$

Then, the phase plane plot changes as shown by Fig.4(c). It demonstrates that the vibration decreases despite no damping. This is the principle of vibration control by switching stiffness.

C. Lateral vibration control by switching bias current

The switching stiffness control is applied to magnetic

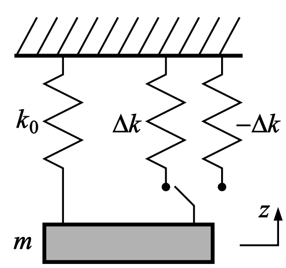


Figure 3. Switching stiffness

suspension systems operated in the differential mode to reduce vibration in the lateral direction(s). The principle is explained based on Fig.5. 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 ΔI to the bias current. Thus, the proposed control strategy is

$$I_b = I_0 + \Delta I \operatorname{sgn}(x\dot{x}) = \begin{cases} I_0 + \Delta I & x\dot{x} > 0 \\ I_0 & x\dot{x} = 0 \\ I_0 - \Delta I & x\dot{x} < 0 \end{cases} \tag{5}$$

This strategy is simple; the bias current is increased when the floator moves outward while it is decreased when the motor moves inward (toward the center). The important point is that the vertical (normal) net force is theoretically zero because the varied force cancel each other as indicated by Eq.(1). Therefore, the vertical motion of the floator is not affected by such control in principle.

In the previous work [4, 8], the following control strategy was used:

$$I_b = \begin{cases} I_0 + \Delta I & x\dot{x} > 0 \\ I_0 & x\dot{x} \le 0 \end{cases} \tag{6}$$

In this case, the average of the bias current I_b is $I_0 + \Delta I / 2$ when the switching are conducted symmetrically. Meanwhile, the bias current without switching control is I_0 that is different from the above value. It may not seem consistent so that the control law given by Eq.(5) is used in this work.

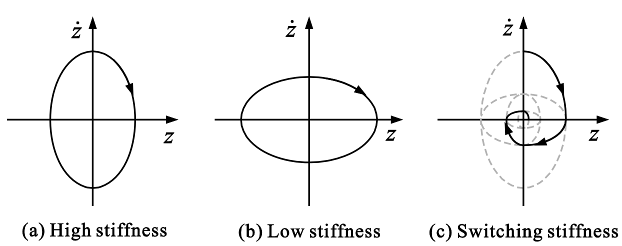


Figure 4. Principle of vibration control by switching stiffness

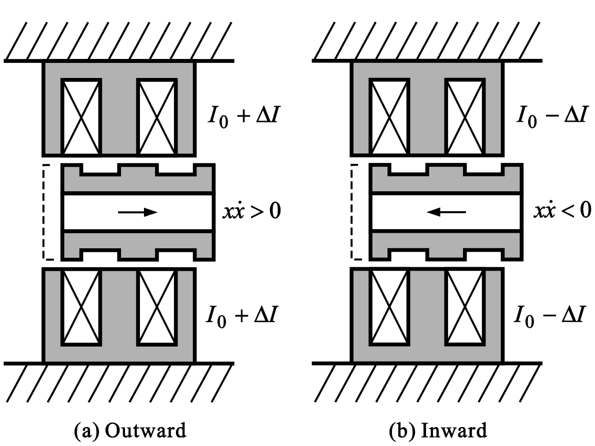


Figure 5. Switching bias current control

III. EXPERIMENT

A. Experimental apparatus

Figures 6 and 7 shows a picture and a schematic drawing of the fabricated experimental apparatus, respectively [8, 10]. The floator is suspended by a pair of leaf springs to restrict the motion in the lateral direction solely to examine the effects of varying stiffness control purely. As shown in the basic model (Fig.1), two electromagnets is placed above and below the floator. A voice coil motor (VCM) is installed in the lateral direction to add disturbance to the floator. The displacement of the floator in this direction is denoted by x, which is detected by an optical sensor installed in the lateral direction. The detected signal is inputted to a digital controller DS1103 manufactured by dSPACE™ thorough an A/D converter. The designed control algorithms are implemented with this controller. The command signals are sent to power amplifiers through D/A converters. Each electromagnet is excited by the power amplifier with current output.

B. Experimental results

First, to study on the relation between the bias current and

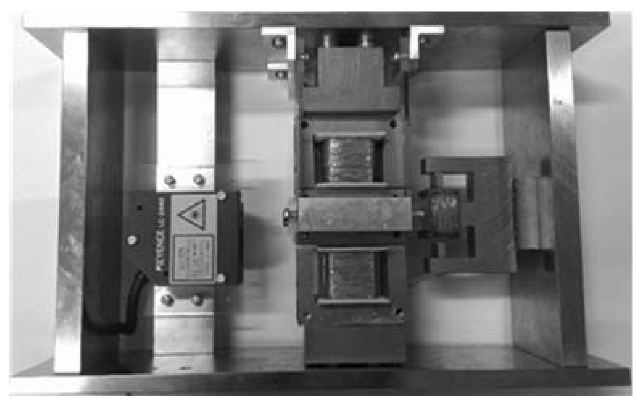


Figure 6. Picture of apparatus

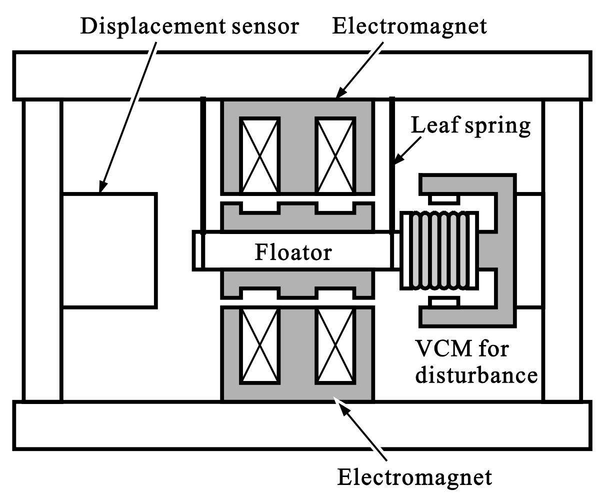


Figure 7. Schematic drawing of apparatus

the lateral stiffness, free vibrations are observed when

(a) $I_b = 0.4\,[\mathrm{A}]$, (Low stiffness),

(b) $I_b = 0.6\,[\mathrm{A}]$, (High stiffness).

An impulse disturbance is added to the floator by the VCM to start vibrations. Figure 8 shows the observed damped vibrations, from which the natural angular frequency ω_d and the settling time t_s are estimated; the settling time is defined as the time when the peak of response decreases to 5% of the initial peak.

(a) $\omega_d = 2\pi \times 4.004\,[\mathrm{rad/s}]$, $t_s = 57.4[\mathrm{s}]$,

(b) $\omega_d = 2\pi \times 4.086\,[\mathrm{rad/s}]$, $t_s = 52.6[\mathrm{s}]$.

Comparing the response (a) with response (b), we find that the frequency of vibration in the response (b) is 0.08 Hz higher than that in the response. From this result, the increased lateral stiffness is approximately 4%.

Second, the switching stiffness control with $I_0 = 0.5\,[\mathrm{A}]$ and $\Delta I = 0.1[\mathrm{A}]$ is applied; the bias current is switched between 0.4 [A] and 0.6 [A]. Figure 9 shows the observed response. The settling time is $t_s = 11.0[\mathrm{s}]$ that is approximately one fifth of those of the free vibrations. Figure 10 shows the phase portrait of the lateral motion. These results demonstrate the efficacy of the switching stiffness control well.

Third, to study on the relation between the increment (decrement) current ΔI and the reduction of settling time, the switching stiffness control is applied with $I_0 = 0.5\,[\mathrm{A}]$ and

(a) $\Delta I = 0.05[\mathrm{A}]$,

(b) $\Delta I = 0.20[\mathrm{A}]$,

The results are shown in Fig.11. The settling times are obtained as

(a) $t_s = 16.0\,[\mathrm{s}]$,

(b) $t_s = 6.1[\mathrm{s}]$,

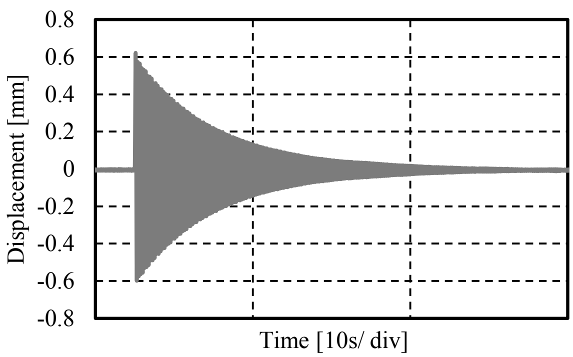
These results indicate that the settling time decreases as the increment (decrement) current increases.

Figure 12 summarizes the relation between the settling time t_s and the increment (decrement) current ΔI, which is increased from 0 [A] to the intermediate value of current I_0. by a step of 0.05 [A]. The intermediate current is also varied from 0.4 [A] to 0.6 [A] by a step of 0.1 [A]. It shows that the settling time decreases the increment (decrement) current increases and also the intermediate current increases. The latter effect is, however, smaller than the former.

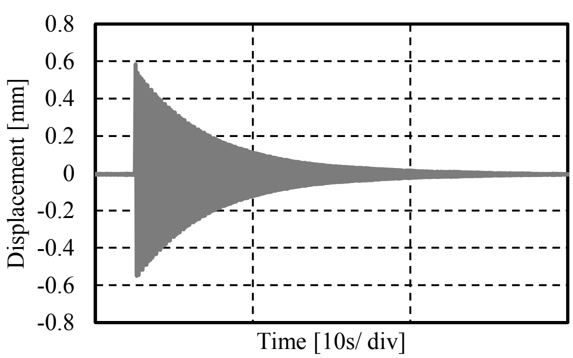
IV. CONTINUOUSLY VARYING STIFFNESS CONTROL

A. Introduction of continuous function

In our previous work [4], the settling time became longer



(a) $I_b = 0.4\,[\mathrm{A}]$



(a) $I_b = 0.6\,[\mathrm{A}]$

Figure 8. Free vibration

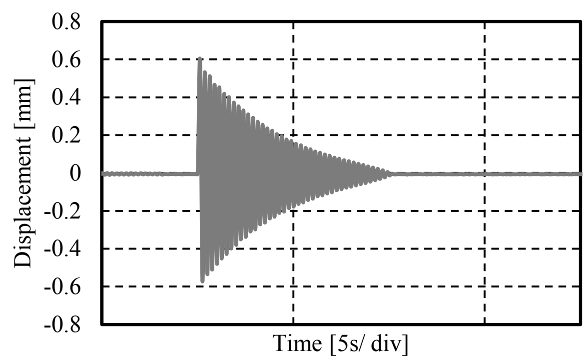


Figure 9. Switching bias current control; $I_0 = 0.5\,[\mathrm{A}]$ and $\Delta I = 0.1\,[\mathrm{A}]$.

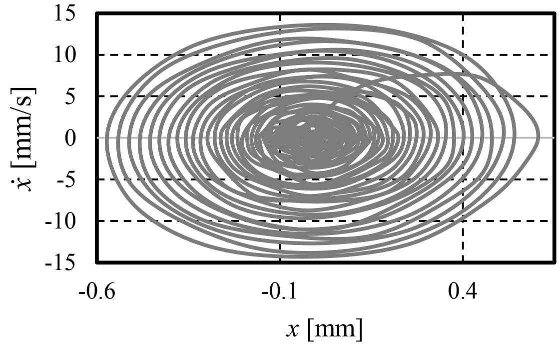
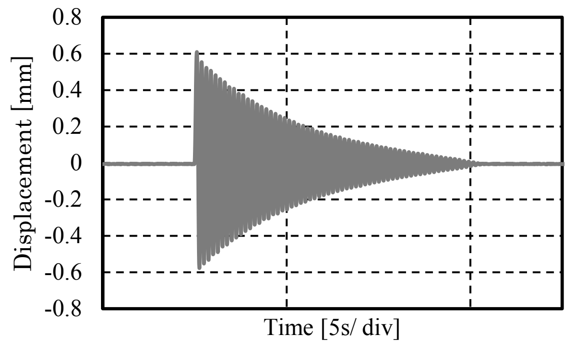
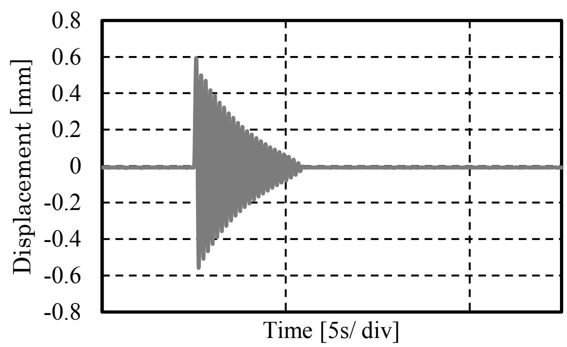


Figure 10. Phase portrait of the lateral motion

when the switching amount exceeded some value. In the proposed system in which the lateral vibration control was operated based on force detection, similar behavior was observed [11]. Such problem may be caused by noise included in the sensor signal and discretization error in the digital controller. The sliding mode control also uses switching in the operation [12]. It is known that such control systems sometimes suffer from undesirable behavior such as chattering.



(a) $\Delta I = 0.05$[A]



(b) $\Delta I = 0.20$[A]

Figure 11. Effect of the amplitude of step in the bias current

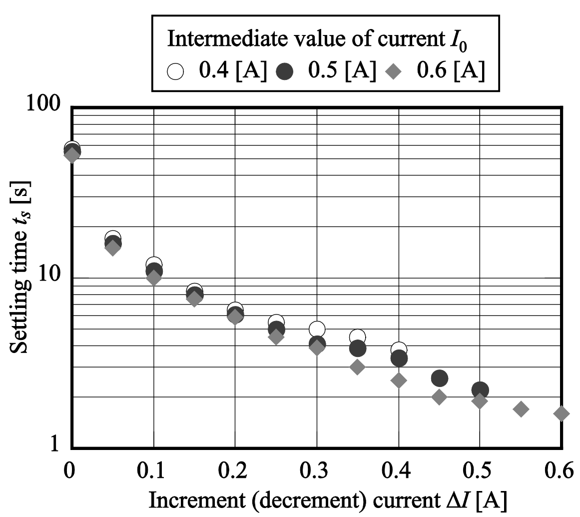


Figure 12. Relation between the settling time t_s and the increment (decrement) current ΔI for various values of I_0

To avoid such undesirable behavior, the control law given by Eq.(5) is modified to operate continuously as

$$I_b = I_0 + \Delta I \frac{2}{\pi} \tan^{-1}(q x \dot{x}) . \tag{7}$$

In Eq.(7), the sign function is approximated by an arctangent function and the degree of approximation is adjusted by the parameter q; the approximation function approaches the sign function as this parameter increases.

B. Experiment

In the apparatus shown by Fig.6, a high-performance optical sensor was used to detect the lateral displacement of the floator. Because the noise level is quite low in this sensor, no erroneous operation occurred in the previous experiments. However most industrial magnetic bearings use inductive sensors that are often more noisy. To simulate such a situation, white noise is superimposed over the output of the optical sensor.

Figure 13 shows an original signal of the sensor and a pseudo signal including more noise in observing a free vibration with $I_b = 0.5$[A]. Apparently, the latter is more noisy.

Figure 14 shows the result of the switching stiffness control with $I_0 = 0.5$[A] and $\Delta I = 0.1$[A] based on the noisy signal. The settling time increases almost twice. In addition, the vibration grows after once settled.

Figure 15 shows the result of the modified vibration control also based on the dirty signal; the approximation

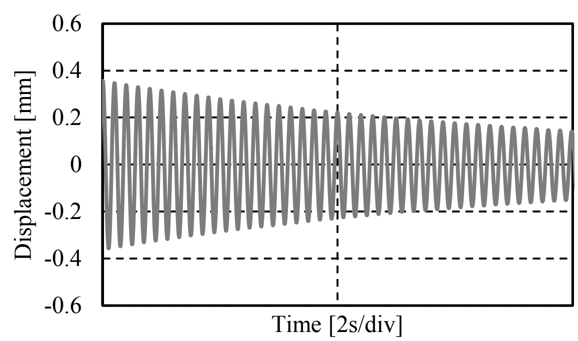


Figure 13. Original signal of the displacement sensor

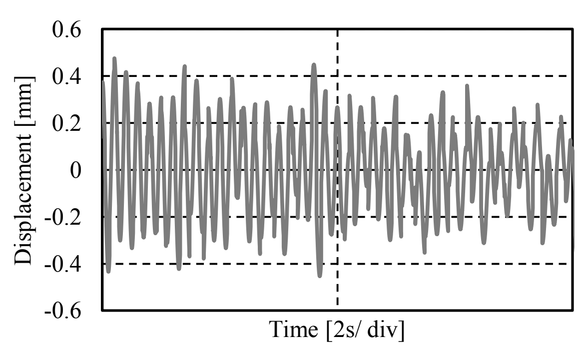


Figure 14. Signal disturbed by adding white noise

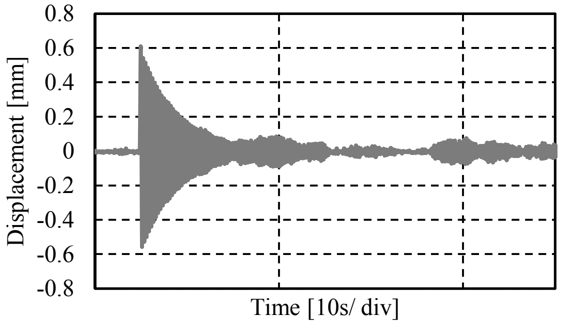
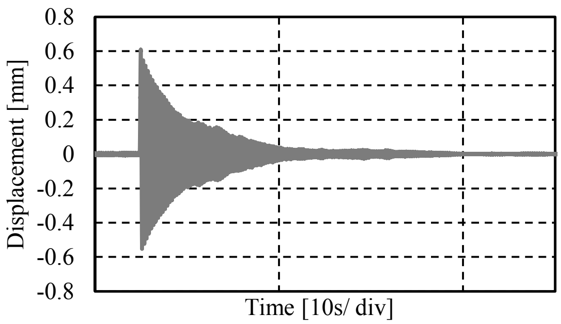
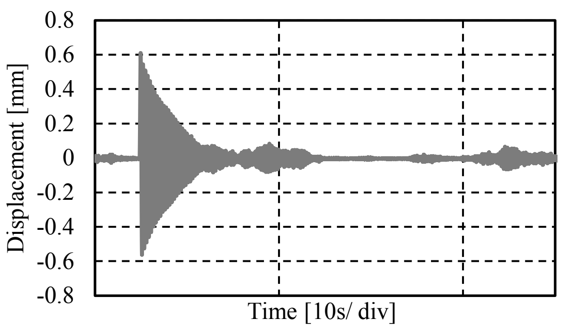


Figure 15. Results of switching bias current control



(a) q=10



(b) q=100

Figure 15. Varying bias current control

parameter is set as

(a) $q = 10$, (b) $q = 100$.

In the former case, the settling time increases almost three times. However, the growth of vibration does not occur after once settled. Contrast, in the latter case, the behavior is similar to that of the original system. These results indicate that erroneous behavior can be avoided by the modified controller, and that the performance degradation can be minimized by selecting the approximation parameter appropriately.

V. CONCLUSION

The effectiveness of lateral vibration suppression by varying the bias currents was studied experimentally. The experimental results demonstrate that the performance is improved as the increment (decrement) current is increased in switching-based operation. Meanwhile, it was pointed out that strong switching operation may induce undesirable behavior when the sensor signal is noisy. To avoid such problem of switching control, the modified control law where the bias current is varied continuously was introduced. The experimental results indicate that erroneous behavior can be avoided by the modified controller.

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