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Effect of Feedforward Control on the Dynamics of a Zero-power Controlled Zero-compliance System

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Abstract

A horizontal single-axis zero-compliance system using zero-power control is studied both analytically and experimentally. The zero-compliance system is obtained by series combination of positive and negative stiffness isolators of equal absolute stiffness, in which negative stiffness isolator is obtained by a zero-power controlled voice coil motor (VCM) as a system with zero-power control behaves as if it has negative stiffness. The positive stiffness isolator in the experimental system is obtained by a PD controlled VCM. Nevertheless, it is noticed that the transient responses of the experimental system are unpleasant and do not match the objective function of a zero-compliance system. In order to suppress these unpleasant transient responses, a feedforward (FF) control is added to the zero-power controller in this study. Several experiments have been conducted to measure the performance of the zero-compliance system with the feedforward control. It is observed that the experimental zero-compliance system suppresses the transient peak significantly without deteriorating the zero-power characteristic of the system; an improved dynamic of the experimental system are confirmed with feedforward control.

Keywords: *Zero-power control, Negative Stiffness, Infinite stiffness, Zero compliance.*

1. Introduction

A zero-compliance system possesses the characteristic of zero displacement to disturbance and is one of the effective approaches to suppress disturbances [1-2]. The integral control is the most usual approach to obtain zero-compliance to direct disturbance; however an integral control provides zero-compliance to disturbance at the cost of increasing of control current. Moreover, conventional integral controlled systems are not suitable for vibration control as they transmit directly the ground vibration to the isolation table. In addition, position accuracy in Hi-tech micro manufacturing and high precision measuring processes has turned into submicron even nanometer range from micrometer range during the last two decays. Thus researches on zero-compliance system have been the focuses of different research groups with increasing emphasis [2-4]. In these regards, the authors have proposed an effective approach that is a series combination of positive and negative stiffness isolators of equal absolute magnitude to obtain a zero-compliance system with the capability of suppressing ground vibrations as well [4].

In the previous study, the authors have implemented this concept (zero-compliance mechanism) to develop the vibration isolation systems, where proper negative stiffness controlled pneumatic actuator are used as negative stiffness isolators and connected in series with mechanical springs [5]. It is observed that the developed vibration isolation system suppresses both direct and ground vibration sufficiently; however, the system consumes power even in the steady states. In contrast, a zero-power controller which has power saving characteristic converges current into zero at steady states. In this study, a zero-power controlled system is employed instead as it behaves if it has negative stiffness. The zero-power control was originally invented to use in the active magnetic bearings [6-7]. Because a zero-power controlled system converges current to zero in the steady states, a zero-power control system needs a passive isolator and this study uses permanent magnet as passive isolator. Therefore, in principle of the proposed method, the zero-power controlled VCM is connected in series with a PD controlled VCM, to obtain a zero-compliance system, in which the ferromagnetic isolation platform of the developed system is placed in between two permanent magnets fixed to the base.

The series combination of negative and positive stiffnesses of equal magnitude is in theory a convenient and easy to understand method to realize a zero-compliance system [4]. However, the transient displacement of this zero-compliance system are often unpleasant and does not satisfy the objective function required to have for using in high-precision micro-manufacturing processes. The higher gain of the closed-loop system in designing the controller is one of the approaches to overcome this problem but practically it is problematic [8]. Therefore, in this paper, feedforward (FF) control is added with zero-power controller to shorten the transient displacement as well as to improve the dynamics of the system. In a previous research, a feedforward control is added with negative stiffness control system used for vibration isolation [9]. In this research, feedforward control is added to the zero-power control system actuated with linear actuator (voice coil motor, VCM), and a new control network is considered so that the proposed controller does not hamper the power saving characteristic of a zero-power controller. This zero-power control system with feedforward control is connected in series with a positive stiffness system to obtain a zero-compliance system. Theoretically and experimentally, it is shown that the feedforward control with proposed control approach can suppress the transient displacement sufficiently.

2. Zero-compliance System

The aim of this section is to show how zero-compliance to direct disturbance can be realized by two series-connected isolators, where one of them has positive stiffness and the other has negative stiffness of equal absolute magnitude. Two series-connected isolators with stiffness coefficients, k_1 and k_2, provide a combined stiffness, k_c, (see Fig. 1) that can be expressed as follows:

$$k_c = \frac{k_1 k_2}{k_1 + k_2}. \tag{1}$$

This combined stiffness would be infinite if one of the isolators has negative stiffness and both of them are equal in absolute magnitude, which is shown in below:

$$|k_c| = \left| \frac{(-k_2)k_2}{-k_2 + k_2} \right| = \infty. \tag{2}$$

In a consequent, the relative displacement of the upper table (Fig. 1) against a direct disturbance becomes zero, which is shown as follows:

$$k_1 = -k_2 \Rightarrow \frac{F_0}{x_m - x_b} = -\frac{F_0}{x_u - x_m} \Rightarrow x_u - x_b = 0, \tag{3}$$

where F_0 is the disturbance applied on the upper table, and x_m, x_u and x_b denote the displacements of the middle mass, the upper table and the base, respectively. This study uses the concept mentioned above to develop a horizontal zero-compliance system to direct disturbance, in which zero-power control and PD (proportional derivative) control are applied to realize negative and positive stiffness isolators, respectively.

3. Negative stiffness isolator

Basic equation

To realize a negative stiffness isolator, a ferromagnetic stage of mass m between two permanent magnets is actuated by a VCM with zero-power control which is shown in Fig. 2. The permanent magnets provide bias force in the steady states, whereas the VCM (voice coil motor) provides control force to operate the stage along the horizontal direction (translation motion) in the transient states. It is assumed that there is no magnetic force on the stage at zero position; hence, the motion equation of the stage can be presented as follows:

$$m\ddot{x}(t) = k_s x(t) + k_i i(t) + f_d(t), \tag{4}$$

where x: displacement of the stage, k_s: gap-force coefficient of the permanent magnets, k_i: coefficient of the VCM, i: control current, f_d: disturbance acting on the stage. The Laplace transform of Eq. (4) is given in below:

$$X(s) = \frac{1}{s^2 - a}\left(bI(s) + dF_d(s)\right), \tag{5}$$

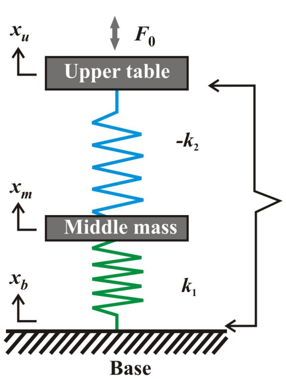

Fig. 1 Series connected isolators

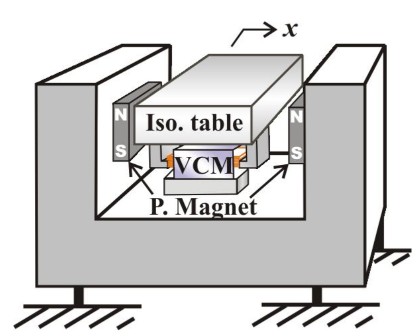

Fig. 2 Horizontal suspension system

where $a = \dfrac{k_s}{m}$, $b = \dfrac{k_i}{m}$, $d = \dfrac{1}{m}$, and each Laplace transform variable is denoted by its capital.

Zero-power controlled suspension

The basic characteristics of a zero-power control magnetic suspension system are shown in Fig. 3. The suspended object moves upward to a new equilibrium position after adding load, and in the steady states the control current converges to zero; the permanent magnets solely provide balancing force in the steady states. In this study, the same concept is applied to obtain a horizontal suspension system actuated by VCM, and a typical block diagram of a Zero-power controlled system (table) is shown in Fig. 4. The controller parameters are determined so that the system shown in Fig. 2 is stable under the zero-power controller which possesses the control current expressed by the following Laplace transform:

$$I(s) = -\frac{\left(P_d s + P_v s^2\right)}{s - P_i} X(s)\ , \tag{6}$$

where P_d, P_v and P_i denote the proportional derivative and local current integral feedback gains of the controller, respectively. Substituting Eq. (6) into Eq. (5) yields the transfer function representation of the system's dynamics under zero-power control as a function of the displacement to direct disturbance; the results is as follows:

$$\frac{X(s)}{F_d(s)} = \frac{d(s - P_i)}{s^3 + s^2(bP_v - P_i) + s(bP_d - a) + aP_i}\ . \tag{7}$$

To estimate the steady-state displacements of the stage in response to a direct disturbance, it is assumed that the disturbance, F_d, is stepwise, and there is no ground vibration (X_0=0). The steady-state displacement of the stage is as follows:

$$\frac{x(\infty)}{F_0} = \lim_{s\to 0} \frac{X(s)}{F_d(s)} = \frac{-dP_i}{aP_i} = -\frac{1}{k_s}\ . \tag{8}$$

Equation (8) indicates that the stage has steady-state negative displacement in response to a direct disturbance, and this displacement depends on the gap-force coefficient of the permanent magnet attached in the system (see Fig. 2). Inherently, the stage with zero-power controller behaves as a negative stiffness system; and, in the principle of proposed approach, this negative stiffness system is connected in series with a positive stiffness isolator to obtain a zero-compliance system.

Similarly, to estimate the steady-state current consumption to the stage, the disturbance is assumed stepwise. Substituting Eq. (7) into Eq. (6) yields the current consumption behaviors in response to a direct disturbance; and at steady state, the result is as follows:

$$\frac{i(\infty)}{F_0} = \lim_{s\to 0} \frac{I(s)}{F_d(s)} = \frac{0}{aP_i} = 0\ . \tag{9}$$

Equation (8) indicates that the steady-state current consumption to the stage is zero against a direct disturbance applied to it. Inherently, it is confirmed theoretically that the zero-power controlled horizontal system can hold a negative displacement without consuming power in the steady states.

Zero-power controlled suspension with Feedforward control

In this study, to improve the transient displacement as well as the dynamics of the zero-power controlled suspension system (see Fig. 2), a feedforward control is proposed with its original controller (zero-power). A block diagram of the proposed Zero-power controller which contains a Feedforward control is shown in Fig. 5. The displacement is assumed to be a feedback parameter, and the parameters of the proposed controller are determined so that the system is stable. The control current for the proposed controller is expressed by the

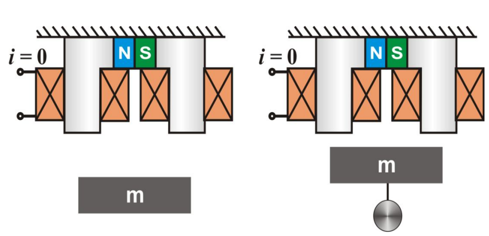

Fig. 3 Concept of zero-power control suspension

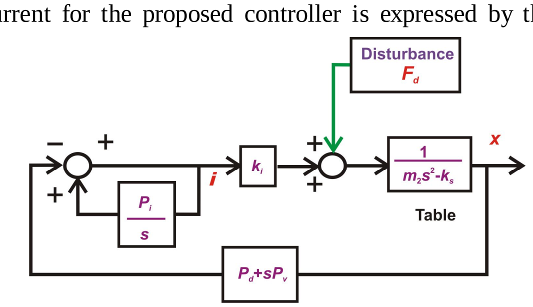

Fig. 4 Block diagram of zero-power control suspension

following Laplace transform:

$$\hat{I}(s) = \frac{-\left(P_d s + P_v s^2\right)X(s) + F_d H(s)s}{s - P_i}, \tag{10}$$

where $H(s)$ is transfer function for the feedforward controller and the other symbols have the same meaning as they did in the earlier sections. Substituting Eq. (10) into Eq. (5) yields the transfer function representation of the system's dynamics under the proposed zero-power control as a function of the displacement to direct disturbance; the results is as follows:

$$\frac{X(s)}{F_d(s)} = \frac{d\{s(1+k_i H) - P_i\}}{s^3 + s^2(bP_v - P_i) + s(bP_d - a) + aP_i}. \tag{11}$$

The dynamics shown by Eqs. (7) and (11) indicate that the characteristic equations of the zero-power controlled system with and without feedforward control are identical; however, the numerator parts that define the transient peak differ from each other. Moreover, by selecting appropriate feedforward gain, $H(s)$, in Eq. (11), the numerator parts with feedforward control can be made smaller compared to that of without feedforward control. It is theoretically confirmed that the transient peak as well as the dynamic behaviors of the zero-power controlled system improves sufficiently while a feedforward control involves in the controller with the gain given in below:

$$H(s) = -\frac{1}{k_i}. \tag{12}$$

In the same way mentioned in the earlier section, the steady-state displacement of the stage in response to a stepwise direct disturbance with respect to the proposed control approach is determined as follows:

$$\frac{x(\infty)}{F_0} = \lim_{s\to 0}\frac{X(s)}{F_d(s)} = \frac{-dP_i}{aP_i} = -\frac{1}{k_s}. \tag{13}$$

Eq. (13) states that, the adding of feedforward controller does not change the stiffness of the stage. It means, the stage has the same negative steady state displacements for both with and without feedforward control to the zero-power controller. In addition, substituting Eq. (11) into Eq. (10) yields the current consumption characteristics in response to a direct disturbance under the proposed control approach (zero-power with feedforward); and at steady state, the result is as follows:

$$\frac{\hat{i}(\infty)}{F_0} = \lim_{s\to 0}\frac{\hat{I}(s)}{F_d(s)} = \frac{0}{-aP_i^2} = 0. \tag{14}$$

Equation (14) indicates that the steady-state current consumption to the stage is zero; inherently, it is theoretically confirmed that a system with the proposed zero-power control approach does not hamper the characteristics that are associated to a conventional zero-power control system. However, the system utilizing the proposed control approach possesses an improved dynamic.

4. Experiment

Experimental zero-compliance system

With respect to the proposed zero-compliance system, a zero-power controlled system is connected in series with a positive stiffness system of equal stiffness. Therefore, the developed horizontal zero-compliance

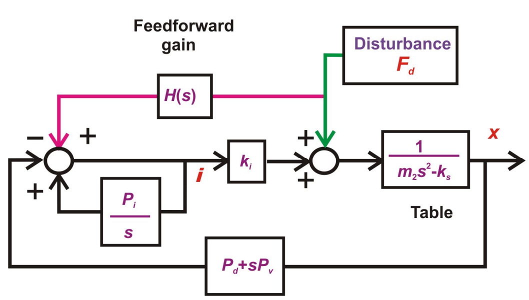

Fig. 5 Block diagram of zero-power with FF control suspension

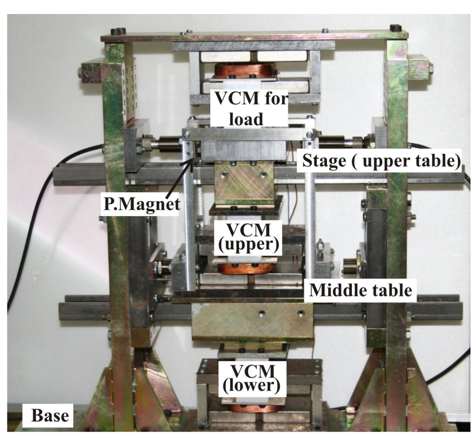

Fig. 6 Concept of zero-power control suspension

system consists of two suspension systems, in which the upper table (stage) suspended with zero-power controlled VCM behaves as a negative stiffness system and the middle table suspended with PD controlled VCM behaves as a positive stiffness system and they are connected in series. A photograph of the experimental zero-compliance system is shown in Fig. 6. The upper table is placed at the top of these two series connected isolators (VCMs) and the middle table is placed in between these two isolators which acts as a mechanical filter to suppress disturbances from base. Since the magnitude of positive stiffness in a PD controlled system varies with the varying of P_d gain, the positive stiffness of the middle table in the developed system is adjusted and made equal to magnitude of negative stiffness in the upper table by varying the P_d gain.

The two permanent magnets provide bias force to the upper table in the steady states, which are attached with respect to the middle and made of NdFeB with dimension 20 x 20 x 2 mm^3. The two VCMs which derive the upper table and middle table have nearly the same dimensions including permanent magnets. The average thrust coefficient of the VCMs is 16 N/A. Eddy-current gap sensors are used to detect the relative displacements of the tables. The power amplifiers manufactured by *Takasago Co. Ltd*. are used to supply current to the VCMs according to the command signals. The designed control algorithm is implemented with a digital controller DS 1105 manufactured by dSPACE^{TM}.

Experimental results:

Several experiments have been conducted to confirm the improvement of the dynamic behavior of the experimental zero-compliance system with feedforward control. The dynamic behaviors of the system with and without feedforward control are measured experimentally against direct static and dynamic disturbances. The direct disturbances were generated by an additional VCM that was mounted on the upper table and fixed with respect to the base. The VCM used to generate disturbances was operated independently from those used to control the motion of the tables. To find the comparative features between with and without feedforward control, the dynamic behaviors of the system are drawn in the same graph. The magnitude of disturbance and maximum stroke length in the upper table are respectively considered 5 N and ± 1.5 mm, respectively.

Figure 6 illustrates the comparative step responses of the upper table in the experimental zero-compliance system with and without feedforward control. In these experiments, the magnitude of disturbances applied to the

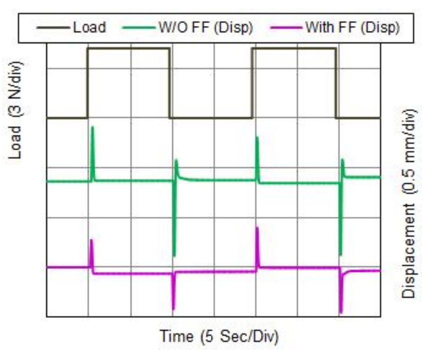

Fig. 7 Displacement of the upper table in the experimental system to stepwise direct disturbance

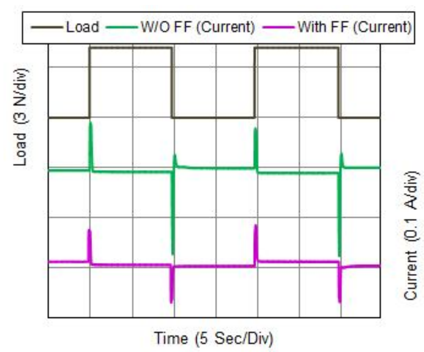

Fig. 8 Current to the upper actuator in the experimental system to stepwise disturbance

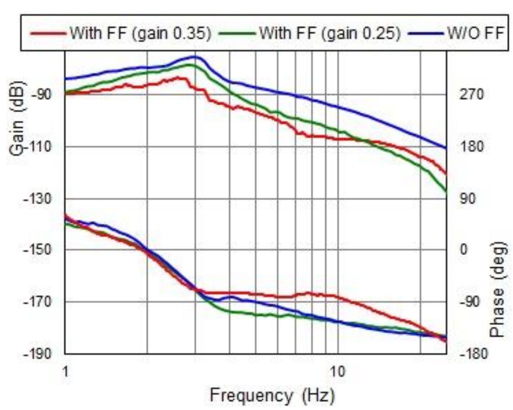

Fig. 9 Frequency response of the upper table's displacement to direct disturbance

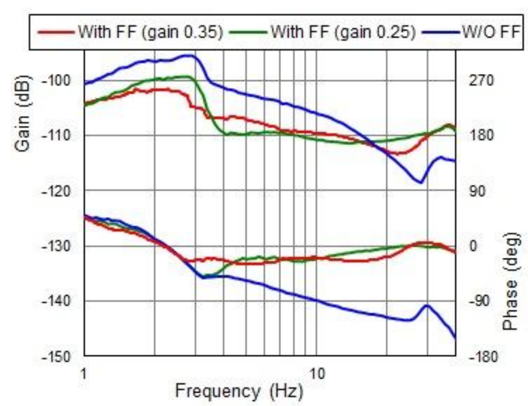

Fig. 10 Frequency response of current to upper actuator to direct disturbance

upper table is kept the same for both with and without feedforward control. It is observed that the upper table resumes its original position and maintains this position in the steady states; hence, zero-compliance characteristic in the experimental system is confirmed. Nevertheless, it is noticed that the step responses contain larger transient peaks (green line) at the beginning of step in and step out of step disturbance. This phenomenon occurs because active feedback control may not accomplish sufficiently fast responses as delays are contained in the control scheme. In this study, these unpleasant transient peaks are reduced by adding feedforward control with respect to disturbance in the original controller (pink line in Fig. 6), as the numerator part of the upper table's dynamics, Eq. (11), becomes smaller with feedforward control that is shown theoretically in section 3. Similarly, the behaviors of current consumption of the upper actuator in response to direct stepwise disturbance are measured with and without feedforward control and shown together in Fig. 7. Figure 7 reveals that the experimental zero-compliance system has the zero-power characteristic either with or without feedforward control. In addition, a shorter transient peak of control current is observed with feedforward control compared to without feedforward control for the same magnitude of disturbance.

The frequency responses to direct disturbance of the upper table in the experimental system with and without feedforward control are measured. The swept sinusoidal direct disturbance is applied on the upper table; the swept sinusoidal signal is generated by digital signal analyzer. The frequency responses of the upper table with and without feedforward control are shown together in Fig. 8 where the applied direct disturbances and the corresponding displacements of the upper table were the input and output signals, respectively; and log of output to input ratios are shown over the frequency of swept direct disturbance. The results showed that displacement gain is lowered sufficiently with feedforward control compared to that without feedforward control. Similarly, the control current to upper actuator in response to dynamic disturbances is measured experimentally and shown in Fig 9, in which the effect of feedforward control on the behavior of control current to upper actuator is illustrated. It is apparent in this figure that the behavior of current consumption with feedforward control improves sufficiently with shorter resonance peak.

5. Conclusions

An active zero-compliance system was developed by using a zero-power controlled VCM connected in series with a positive stiffness system. The behaviors of the developed system were investigated with and without feedforward control associated to disturbance. The experimental results showed that the experimental system with feedforward control, utilizing the control network proposed in this study, suppresses the transient peak of displacement and current consumption significantly compared to that without feedforward control. The reducing of transient peaks with feedforward control was also confirmed theoretically. In addition, the dynamic behaviors of the experimental zero-compliance system were enhanced by feedforward control.

6. References

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