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Intermediate Control Concerning Integral and Zero-power Control for Low-power Consumption System

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Abstract- *Control systems with low power consumption have been the focuses of numerous industrial researches recently. This study investigates a zero-compliance system with minimum power consumption. A zero-compliance system provides zero displacement in the steady state in response of disturbance. Integral control is a common approach to achieve a zero-compliance system by cancelling the disturbances applied on it; however a zero-compliance system using an integral control accompanies power consumption even in the steady state. The zero-power control however is an effective approach to reduce power consumption; although the zero-power control system solely cannot realize zero-compliance system as a zero-power control system is subjected to negative displacement, and nonlinearity is inevitable with zero-power control Hence, this study proposes a new control mechanism named intermediate control to obtain zero-compliance system with minimum power consumption. The proposed control mechanism comprises a zero-power control and an integral control and they are connected in parallel.*

Keywords: Zero power control, Displacement cancellation control, Integral Control, Intermediate control

1. INTRODUCTION

Presently, the control with less power consumption has been a focus of industrial researches. A zero-power control is one of the means of reducing power consumption, which was originally invented to use in active magnetic bearings [1]-[2]. A zero-power control behaves like a negative stiffness control.

An integral control is a common approach for realizing zero-compliance. However, an integral control usually accompanies power consumption even in steady-states. In some applications, such power consumption should be avoided. Therefore, in this study, a suspension mechanism is proposed to make zero-compliance and zero-power characteristics compatible. Such idea has been already implemented in the field of vibration isolation [3-4]. This paper discusses the idea outlined above in a more general manner for applying this idea in various fields.

On the other hand, local integral feedback controls in the zero-power control causes the control current to be zero in the steady state, eventually a negative displacement occurs. Moreover, a passive isolator is needed to support the steady state bias forces as control current becomes zero in the steady state. Previously, the authors used permanent magnets as the passive isolator to obtain a vibration isolation system with zero-power control [5].This study proposes a zero-compliance mechanism with minimum power consumption, where a system controlled partially with an integral control and a zero-control simultaneously is connected with a positive stiffness system in series. The integral and zero-power controls are respectively based on displacement integral feed and local current integral feedback [6]. The simultaneous integral control and zero-power control partially is defined integral control in this study.

The integral control and positive stiffness control suspensions are achieved by the voice coil motor (VCM) guided by integral control and spring-mass system, respectively. Inherently, the proposed mechanism consumes minimum power at steady-state, and simultaneously can realize zero compliance when the absolute negative stiffness and positive stiffness of the suspensions are equal in magnitude. On the other hand, if an integral control solely is applied to obtain the proposed mechanism, in principle, it would cause zero compliance independently of equal stiffness, but there is power consumption. Likewise, if a zero-power control solely is applied to obtain the proposed mechanism, in principle, it would cause zero power consumption independently of equal stiffness, but there is a negative displacement.

In practical practice; however, it is difficult to maintain the exactly same absolute stiffness of the series connected suspensions used in a controlled system [7]. In such a case, either zero compliance or zero power characteristic of the system is inevitably lost. This study emphasizes on the either zero-compliance or zero-power on the basis of necessity, for that why an intermediate control is used to realize the proposed mechanism. The relation between difference in stiffness and respective steady-state deflection is studied experimentally. In addition, the cost function minimizing of the system, utilizing the proposed mechanism, is carried out to find the optimal operating point.

2. ZERO COMPLIANCE AND ZERO POWER SYSTEM

A suspension system with infinite stiffness provides zero compliance to direct disturbance. In this study, a series combination of negative and positive stiffness suspensions is considered to acquire an infinite stiffness system. The concept of infinite stiffness by a series combination of positive and negative stiffness is presented in below.

The combined stiffness of two springs connected in series (Fig. 1) can be expressed as

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

where k_1 and k_2 denote the stiffnesses of the springs. If one of the springs has negative stiffness and both of them are equal in absolute magnitude of stiffness, i.e., "($|k_1| = |-k_2|$)", then the combined stiffness k_c becomes infinite,

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

The relative displacement of the upper mass (table) (Fig. 1) against a direct disturbance can be obtained as follows:

$$|k_1| = |-k_2| \Rightarrow \left|\frac{Force}{x_1 - x_0}\right| = \left|-\frac{Force}{x_2 - x_1}\right| \Rightarrow x_2 - x_0 = 0\,. \tag{3}$$

Therefore, even if a direct disturbance acts on the upper table, it has no steady-state displacement independently of whatever low absolute equal magnitude of stiffness of the springs. This concept is applied to realize the proposed mechanism, where the negative stiffness and positive stiffness are realized using a zero-power control and a normal spring, respectively. Because a zero-power system consumes zero power and behaves as it has negative stiffness, the proposed mechanism can hold the zero-power and zero-compliance properties simultaneously.

In the displacement cancellation technique, one of the two series connected isolators has a soft positive stiffness (e.g., a soft coil spring) and the other is controlled to cancel displacement due to the soft positive stiffness isolator against a force, which is shown in Fig. 3. Because the stiffness k_1 is positive, the displacement of the upper table " $\bar{y}$ " takes place along the direction of disturbance. This displacement is cancelled by the upper isolator (Fig. 2), which is controlled with integral-proportional derivative (I-PD) control. Inherently, the upper isolator behaves as if it has a negative stiffness. The displacement $\bar{y}$ can be defined as follows:

$$\bar{y} = (y_1 + y_2) - (y_1 - \Delta y_1 + y_2 - \Delta y_2)\,, \tag{4}$$

where Δy_1 and Δy_2 are the displacement of the lower and upper isolators, respectively. The displacement $\bar{y}$ would be zero if the following condition is satisfied:

$$0 = (y_1 + y_2) - (y_1 - \Delta y_1 + y_2 - \Delta y_2) \Rightarrow \Delta y_1 = -\Delta y_2\,. \tag{5}$$

Equation (5) indicates that the static zero-compliance to a direct disturbance using the displacement cancellation technique occurs when the compression in one isolator is equal to the extension in the other isolator (i.e., $|\Delta y_1| = |-\Delta y_2|$), as shown in Fig. 2. For a ground vibration, the combination of a middle mass and a soft isolator works as a mechanical filter that attenuates the transmitting of ground vibrations to the upper table. In addition, a low-pass filter in the feedback loop between the displacement of the middle mass and the actuator of the upper table can further improve the performance of ground vibration transmissibility (Mizuno et al., 2010). In this study, an electronic low-pass filter is inserted between the two tables of the developed experimental system using the displacement cancellation technique. The displacement-cancellation isolator and positive-stiffness isolator are created using VCMs guided by I-PD and PD control, respectively. A simple application of PID control hardly can achieve the criteria associated to a vibration isolation system (infinite stiffness and low stiffness). Therefore, an integral control with regard to a command signal and a PD control are applied in the same time to attain the desired infinite stiffness in the experimental system; this is known as I-PD control.

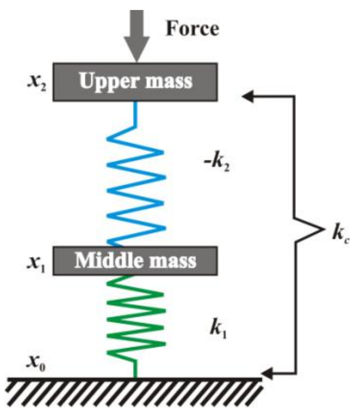

Fig. 1 Springs are in series connected

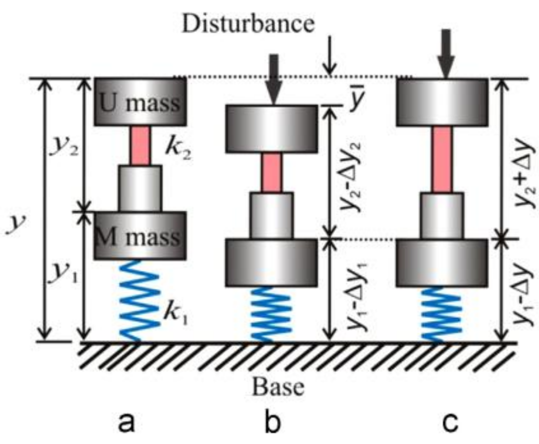

Fig. 2 Concept of displacement cancellation

3. BASIC SUSPENSION SYSTEM

This research focuses on a horizontal suspension system to fabricate a zero-compliance system. A ferromagnetic positioning stage (upper mass) with mass m is assumed to move only in the horizontal direction (translation) and a VCM guides the motion of the table. The motion equation of the table can be represented as follows:

$$m\ddot{x}(t) = k_g x(t) + ki(t) + f_d(t) \qquad (6)$$

where x: displacement of the table, k_g: gap force coefficient of the permanent magnet, k_i: coefficient of the VCM, i: the control current, f_d: the disturbance acting on the table.

The each Laplace transform variable is denoted by its capital, and the initial values are assumed to be zero for simplicity, the transfer function representation of the dynamics described by Eq. (6) becomes

$$X(s) = \frac{1}{s^2 - a_0}\left(b_0 I(s) + d_0 F_d(s)\right) \qquad (7)$$

where $a_0 = k_g/m$, $b_0 = k_i/m$ and $d_0 = 1/m$.

3.1 Series connection of intermediate control with positive stiffness control

This study focuses the zero-compliance and zero power using the series connection of the intermediate control with positive stiffness control of the system. Intermediate control is achieved using the combination I-PD and displacement cancellation control is applied on the positioning table and positive stiffness control is achieved using PD control (Positive stiffness: PS control) is applied on the middle table. The block diagram of the intermediate control with positive stiffness control is shown in Fig 3.

4. INTERMEDIATE CONTROL

The basic block diagram of the proposed intermediate control is shown in Fig. 4. The control current of the proposed intermediate control which is combination of zero power control and displacement cancellation control can be represented as follows:

$$i(t) = i_1(t) + i_2(t) \qquad (8)$$

where $i_1(t)$ and $i_2(t)$ denotes the control current for zero power and displacement cancellation respectively.

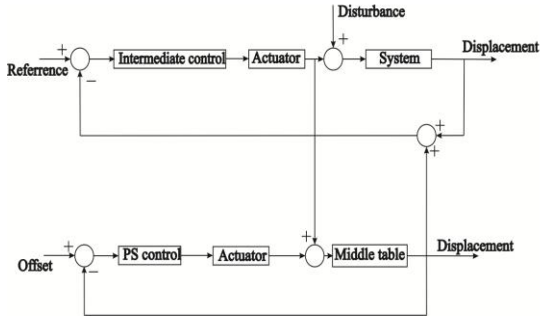

Fig 3 Block diagram of the series connection between intermediate and positive stiffness control

The control current of the zero power control is given by

$$i_1(t) = -\left(p_d x(t) + p_v \dot{x}(t)\right) + p_i \int i_1 dt \qquad (9)$$

The current in displacement cancellation control can be written as

$$i_2(t) = p_z \int x(t) \qquad (10)$$

The Laplace transorm of the Eq. (9) and (10) is as follows

$$I_1(s) = \frac{-\left(p_d s + p_v s^2\right)}{\left(s - p_i\right)} X(s) \qquad (11)$$

$$I_2(s) = \frac{p_z}{s} X(s) \qquad (12)$$

Substituting Eq. (11) and Eq. (12) into the Laplace transform of Eq. (8) leads to

$$I(s) = -\left[\frac{P_v s^3 + P_d s^2 + P_z s - P_i P_z}{s(s - P_i)}\right] X(s) \qquad (13)$$

where P_d, P_v, P_i and P_z are proportional, derivative, integral and integral gain of zero power and displacement control respectively.

The transfer function of the closed-loop control system regarding displacement to direct disturbance is obtained by substituting Eq. (13) into Eq. (7) given as follows

$$\frac{X(s)}{F_d(s)} = \frac{d_0 s(s - P_i)}{t_c(s)} \qquad (14)$$

Here, $t_c(s)$ defines the 4th order characteristics equation of the intermediate control system which is characterized in bellow:

$$\begin{aligned} t_c(s) &= s^4 + (b_0 P_v - P_i)s^3 + (b_0 P_d - a_0)s^2 \\ &+ (a_0 P_i + P_z b_0)s - P_i P_z b_0 \end{aligned} \qquad (15)$$

The characteristics equation of the 3rd order ideal system is assumed to be defined as:

$$\begin{aligned} t_d(s) &= \left(s^2 + 2\xi_1\omega_1 s + \omega_1^2\right)\left(s^2 + 2\xi_2\omega_2 s + \omega_2^2\right) \\ &= s^4 + \alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0 \end{aligned} \qquad (16)$$

According to the pole assignment method, the controller gains are determined uniquely by comparing the characteristics equations (15) and (16). Finally, intermediate controller gains are obtained as follows:

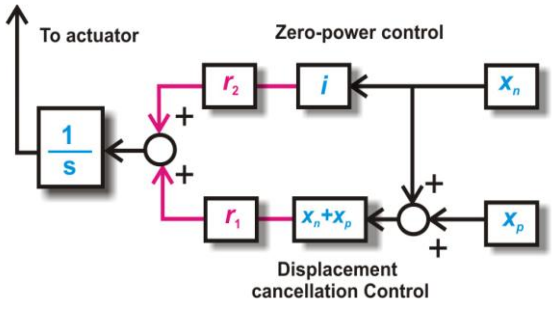

Fig. 4 Intermediate control

$$(b_0 P_v - P_i) = \alpha_3$$
$$(b_0 P_d - a_0) = \alpha_2$$
$$(a_0 P + P_z b_0) = \alpha_1$$
$$-(P_i P_z b_0) = \alpha_0$$

where

$\alpha_3 = 2\xi_1\omega_1 + 2\xi_2\omega_2$, $\alpha_2 = \omega_1{}^2 + \omega_2{}^2 + 4\xi_1\xi_2\omega_1\omega_2$, $\alpha_1 = 2\xi_1\omega_1\omega_2{}^2 + 2\xi_2\omega_2\omega_1{}^2$, $\alpha_0 = \omega_1{}^2\omega_2{}^2$

The disturbances is considered to be stepwise and it can be modeled as

$$F_d(s) = \frac{F_0}{s} \quad F_0\text{:(const).} \tag{17}$$

where F_0 is magnitude of the applied step (cons.). The controller gains are selected stable closed-loop system in long run. Thus the steady-state displacement x (∞) could be defined as follows:

$$\frac{x(\infty)}{F} = \lim_{s \to 0} \frac{s(s - P_i)d_0}{s^4 + (b_0 P_v - P_i)s^3 + (b_0 P_d - a_0)s^2 + (a_0 P_i + P_z b_0)s - P_i P_z b_0} = 0$$

Thus the steady state displacement is zero using intermediate control method.

5. STABILITY

From Eq. 15, the characteristics equation of the developed system using proposed control method can be written as

$$t_c(s) = s^4 + (b_0 P_v - P_i)s^3 + (b_0 P_d - a_0)s^2 + (a_0 P_i + P_z b_0)s - P_i P_z b_0$$

According to Routh Hurwitz criteria, the system will be stable only if it satisfies the following conditions,

$$b_0 P_d - a_0 \rangle 0 \text{ and}$$
$$P_i P_Z b_0 \langle 0 .$$

6. EXPERIMENTAL SETUP

An experimental setup is fabricated for examining the concept of proposed mechanism. Figure 5 shows a photograph of the experimental setup. In the experimental setup, the positioning stage (upper moving mass) is connected in series with a middle mass (positive stiffness system). In this apparatus, both masses are driven by VCMs. Particularly; one of the VCMs is used instead of a mechanical spring for realizing variable positive stiffness in the experiment. The controller gains are selected so that the actuators belong to upper and middle mass can maintain the same magnitude of negative and positive displacement, respectively. Eddy-current gap sensors are used to measure the relative displacements. The current-output power amplifiers manufactured by *Takasago Co. Ltd.* are used to supply current according to the command signal. The designed control algorithm is implemented with a digital signal processor *DS* 1105 manufactured by dSPACE^{TM}.

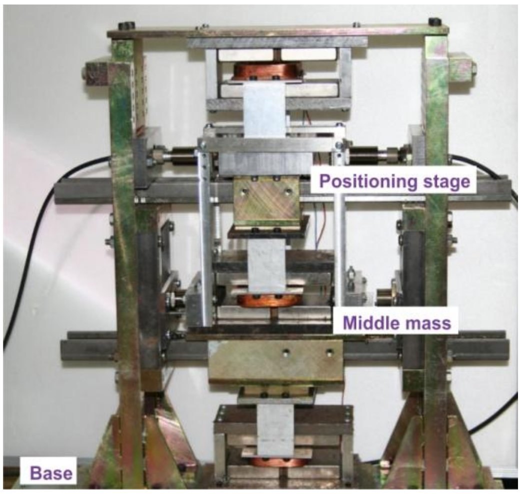

Fig. 5 Photograph of the experimental setup

7. EXPERIMENTAL RESULTS

Figure 6 shows the step responses of the positioning stage and middle mass of the experimental setup utilizing the proposed mechanism. The relative displacements of these moving stages are measured against a step-wise disturbance. It is observed that the positioning stage can cancel the step-wise disturbance applied on it and returns almost to its original position and maintain this zero-compliance at steady-state.

Concurrently, it is also confirmed that the control current converse to zero at steady-states. Hence, the zero

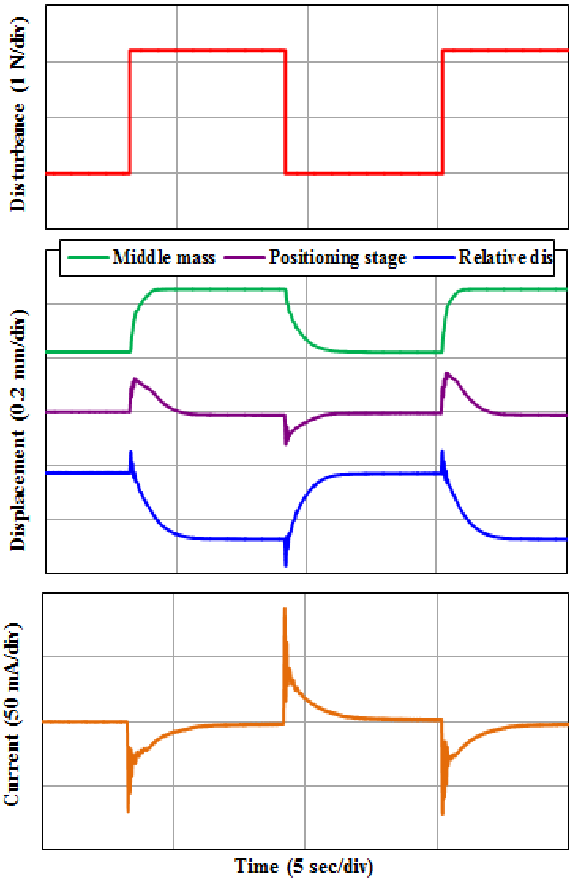

Fig. 6 Step responses of the positioning stage and middle mass

compliance and zero-power characteristics are simultaneously achieved.

Furthermore, with respect to the priority of achieving zero-compliance, the displacement cancellation control (integral control) is implemented instead of the zero-power control. The step responses of the positioning stage and middle mass, using proposed mechanism with displacement cancellation control, are measured against the same step-wise disturbance on the positioning stage, and the corresponding results are shown in Fig. 7. It is observed that, at steady-state, the positioning stage can maintain zero compliance independently of the magnitude of difference between stiffnesses, but there is power consumption. Moreover, this power consumption increases with the increase of difference between the magnitudes of stiffnesses.

8. CONCLUSIONS

The mechanism corresponded to simultaneous zero-power and zero-compliance is studied in both analytically and experimentally. A Zero-power control and a displacement cancellation control both are implemented individually to achieve the proposed zero-power and zero-compliance mechanism. The results presented in the results and discussion section indicate that (i) the mechanism based on the zero-power control gives priority on zero power consumption, and (ii) the mechanism based on the displacement cancellation control gives priority on zero displacement. In practical situation, either zero compliance or zero power is lost for $|k_s| \neq |k_p|$, that is the reason of incompatible control respect to zero-power control and displacement cancellation control. Thus intermediate control with positive stiffness control is proposed to achieve zero power and zero-compliance simultaneously.

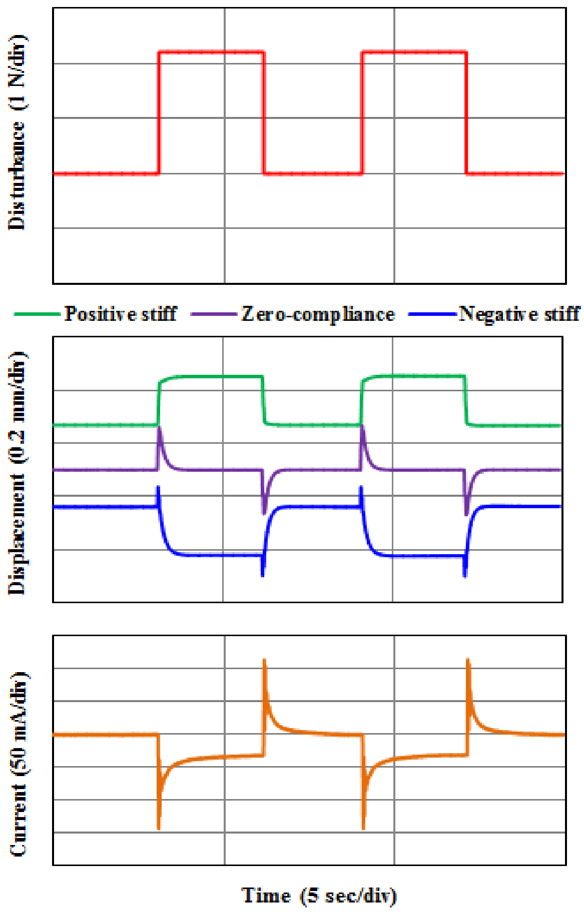

Fig. 7 Step response of the zero-compliance system with displacement cancellation control.

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