外乱オブザーバを用いたゼロパワ制御に基づく振動抑制の定量的な解析

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A Numerical Study on 3-Degrees of Freedom Active Vibration Control Based on Zero Power Maglev-Control by Employing Decoupled Disturbance Observers

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Abstract:

In this report, a novel active vibration and disturbance control system, comprised of triple configuration of U-type hybrid electromagnets, is introduced. The proposed system has 3-degrees of freedom active vibration control capability whereas only one U-type hybrid electromagnet can control 1-degree of freedom. To realize 3-degrees freedom active vibration control, current order type zero power controllers are designed in the state space by following two consistent approaches named as “centralized control” and “decentralized control”. Furthermore, to estimate the unobservable states two decoupled disturbance observers are proposed rather than employing expensive velocity sensors. The proposed active vibration control system is analyzed through numerical simulation studies.

Keyword: U-type Hybrid Electromagnet, active vibration control, 3-degrees freedom control, centralized control, decentralized control, zero power control.

1. Introduction & Motivation:

Many high precision manufacturing assemblies require vibration and disturbance isolation stages in order to isolate undesired disturbance and vibrations. Among passive, semi-active and active type approaches, the active vibration control approach gives better performance than the others by breaking through the inherited conflict of the vibration control systems for direct and base disturbances.

In this paper, we are proposing a novel active vibration control system in which three U-type hybrid electromagnets are employed as force actuators. Due to usage of permanent magnets in the construction of the U-type hybrid electromagnet, the electric power consumption can be so reduced that the zero power operation conditions are almost achieved. To attain the zero power operation conditions, a special controller called as “zero power controller” should be designed. To design a zero power controller, many approaches have been proposed for many different applications.[4] In this study, we preferred to employ state space based current order type zero power control algorithm for the sake of simplicity.

The 3-degrees of freedom control can be achieved straightforwardly by designing 3 current order type zero power controllers for each one of the U-type electromagnet by neglecting the inclination effects, decentralized control. On the other hand, using proper transformations can develop a more sophisticated approach that results in inclusion of the inclination dynamics, centralized control. In this report, the fundamentals of the two approaches will be explained through proposed active vibration control system.

Owing to the employment of the state space techniques, the states of the system should be known for controller design. However, in many practical applications to reduce the sensor cost of the system, observers are designed to estimate unknown and/or immeasurable states by using well-known observer design techniques. In our system, we have two different external disturbance sources, direct disturbance force and base displacement or mainly base acceleration. Since, the well-known linear systems based observer design methodologies cannot readily handle this situation, we are proposing decoupled disturbance observers to overcome this issue, for mechanical parts and electromagnet parts of the system distinctively.

In this report, at first, the fundamentals of the U-type hybrid electromagnet are simply explained and its conjunction with active vibration control and isolation system is illustrated for 1-degree of freedom active vibration control. Then, the proposed active vibration control system, comprised of triple configuration of U-type, is described, 3-degrees of freedom control algorithms are developed by following decentralized and centralized design approaches, respectively. Moreover, the decoupled disturbance observers' design procedures are expressed in logical manner. Finally, for predefined numerical simulation parameters, some numerical simulations are carried out by using Matlab & Simulink packages and the parameters' interactions on system performance are discussed.

2. U-type Hybrid Electromagnet

The principle configuration of the U-type hybrid electromagnet can be illustrated as in Fig. 1.

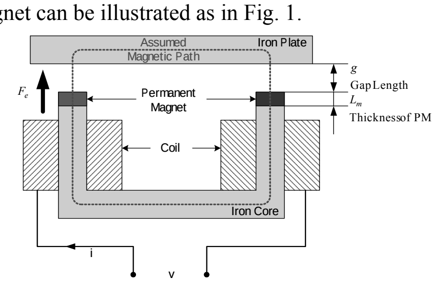

Figure 1. Principle configuration of the U-type hybrid electromagnet

The force of attraction at any instant of the time is

$$F_e = \frac{B^2}{\mu_0} S = \frac{\mu_0 S N^2}{4} \left(\frac{i + 2H_c L_m / N^2}{g + L_m / \mu_m} \right)^2 = k \left(\frac{i + I_m}{g + L_m / \mu_m} \right)^2 \quad (1)$$

This electromagnetic force equation can be linearized around nominal gap length for small excursions as following;

$$mg = \left(\frac{I_m}{g_0 + L_m / \mu_m} \right)^2, \quad K_a = \frac{\partial F_e}{\partial i}\Big|_{(0,g_0)}, \quad K_b = -\frac{\partial F_e}{\partial g}\Big|_{(0,g_0)} \quad (2)$$

$$F_e \cong -K_b \Delta g + K_a \Delta i \quad (3)$$

Specifications of the U-type electromagnet used for numerical studies are as;

Table 1. Magnet Specifications

m	4.716[kg]	g_o	0.0057[m]	k	$1.571\times10^{-5}[\text{Nm}^2/\text{A}^2]$
L_m	0.003[]m	I_m	15[A]	S	$6.25\times10^{-4}[\text{m}^2]$
N	200[turn]	K_a	6.1635[N/A]	K_b	10573.8[N/m]

3. Principle Active Vibration Control System

The considered principle active vibration control system consists of an active force actuator (U-type hybrid electromagnet) and passive vibration isolation elements (spring and damper). Configuration of the principle active vibration control system is given in Fig. 2.

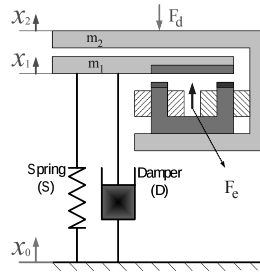

Figure 2. Configuration of the principle active vibration control system

Dynamical equations of the principle active vibration control system can be obtained in absolute coordinate system as following manner;

$$m_2 \ddot{x}_2 = F_e + F_d \quad (4)$$

$$m_1 \ddot{x}_1 = -F_e - F_{Spring} - F_{Damper} \quad (5)$$

The zero power based active vibration control idea is originated by availability of the relative displacements.[3] Thus, the cost of expensive vibration sensors will be eliminated. In this regard, changing the state variables from absolute coordinates to relative ones will give a more convenient mathematical structure, consistent with the zero power based active vibration idea. By using the following state variable definitions linearized state space equations are developed as,

$$q_1 = x_1 - x_2 \rightarrow \dot{q}_1 = q_2 = \dot{x}_1 - \dot{x}_2 \rightarrow \dot{q}_2 = \ddot{x}_1 - \ddot{x}_2 \quad (6)$$

$$q_3 = x_1 - x_0 \rightarrow \dot{q}_3 = q_4 = \dot{x}_1 - \dot{x}_0 \rightarrow \dot{q}_4 = \ddot{x}_1 - \ddot{x}_0 \quad (7)$$

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{B_d}\mathbf{u_d} \quad (8)$$

$$\mathbf{x} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix}, \quad \mathbf{u} = [i], \quad \mathbf{u_d} = \begin{bmatrix} F_d \\ \ddot{x}_0 \end{bmatrix} \quad (9)$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ K_b \frac{m_1 + m_2}{m_1 m_2} & 0 & -\frac{S}{m_1} & -\frac{D}{m_1} \\ 0 & 0 & 0 & 1 \\ K_b \frac{1}{m_1} & 0 & -\frac{S}{m_1} & -\frac{D}{m_1} \end{bmatrix} \quad (10)$$

$$\mathbf{B} = \begin{bmatrix} 0 \\ -K_a \frac{m_1 + m_2}{m_1 m_2} \\ 0 \\ -K_a \frac{1}{m_1} \end{bmatrix}, \quad \mathbf{B_d} = \begin{bmatrix} 0 & 0 \\ \frac{1}{m_2} & 0 \\ 0 & 0 \\ 0 & -1 \end{bmatrix} \quad (11)$$

4. Triple Symmetric Configuration of U-type Hybrid Electromagnets

Normally, by using only one U-type hybrid electromagnet, one vibration axis can be controlled. To control the other axes it is indispensable to employ multiple configurations of the U-type electromagnets. Here, we are proposing a triple symmetric configuration of the U-type electromagnets in order to control 3 disturbance axes simultaneously. The principle structure of the proposed system is given in Fig. 3.

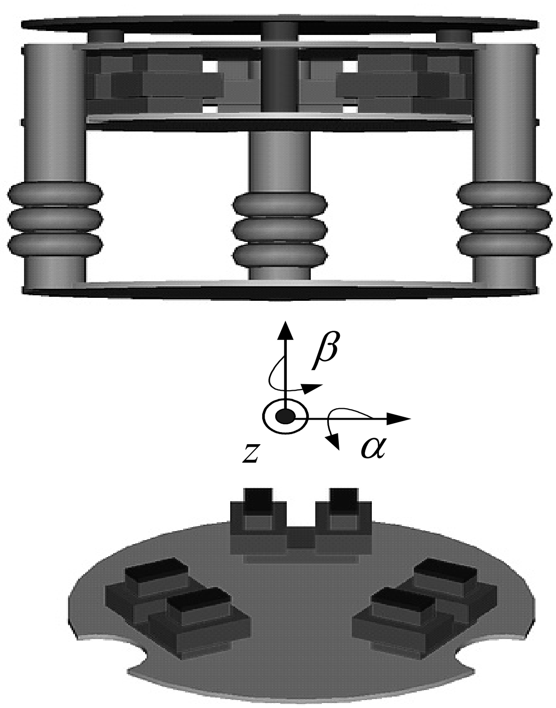

Figure 3. Configuration of the proposed active vibration control system.

5. 3-Degrees of Freedom Zero Power Based Decentralized Control

Probably the simplest control approach is the control of each U-type electromagnet solely by designing a controller for each one of them. We have named this approach as the decentralized control because the controller design is distributed to each one of the U-type electromagnet.

There are many ways of realizing zero power conditions by designing controllers such as voltage order type, gap order type and so on. In this study, we will follow the current order type zero power controller design approach for the sake of simplicity. In zero-power mode, the levitated body is suspended only by the permanent magnets' forces and the steady currents of the electromagnets converge to zero by changing the levitation gap length according to the load mass. [2] To let the steady currents converge to zero, the integral of the current deviation is added to the state space equation as a state variable. Decentralized zero power based controllers are developed by following manner for linearized system equations of the proposed active vibration control system.

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} + \mathbf{B_d u_d} \qquad (12)$$

$$\mathbf{x} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ \int i_{A,B,C} \end{bmatrix}, \quad \mathbf{u} = \lfloor i_{A,B,C} \rfloor, \quad \mathbf{u_d} = \begin{bmatrix} F_{d|A,B,C} \\ \ddot{x}_{0|A,B,C} \end{bmatrix} \qquad (13)$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 3K_b \dfrac{M_1+M_2}{M_1M_2} & 0 & -3\dfrac{S_{A,B,C}}{M_1} & -3\dfrac{C_{A,B,C}}{M_1} & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 3K_b \dfrac{1}{M_1} & 0 & -3\dfrac{S_{A,B,C}}{M_1} & -3\dfrac{C_{A,B,C}}{M_1} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (14)$$

$$\mathbf{B} = \begin{bmatrix} 0 \\ -3K_a \dfrac{M_1+M_2}{M_1M_2} \\ 0 \\ -3K_a \dfrac{1}{M_1} \\ 1 \end{bmatrix}, \quad \mathbf{B_d} = \begin{bmatrix} 0 & 0 \\ \dfrac{1}{M_2} & 0 \\ 0 & 0 \\ 0 & -1 \\ 0 & 0 \end{bmatrix} \qquad (15)$$

Finally, by equalizing the system transfer function to any desired dynamics of a known transfer function, the state feedback gains are obtained.

$$\left| s\mathbf{I} - \mathbf{A} + \mathbf{BK} \right| = 0 \qquad (16)$$

Generalized axes values are handled from local axes values by using geometrical relationship illustrated in Fig. 4. Evaluation of the geometrical relationships results in a transformation matrix. (16)

$$\begin{bmatrix} z \\ \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} 1/3 & 1/3 & 1/3 \\ 2/3r_e & -1/3r_e & -1/3r_e \\ 0 & 1/\sqrt{3}r_e & -1/\sqrt{3}r_e \end{bmatrix} \begin{bmatrix} q_{1,2,3,4|A} \\ q_{1,2,3,4|B} \\ q_{1,2,3,4|C} \end{bmatrix} = \mathbf{T} \begin{bmatrix} q_{1,2,3,4|A} \\ q_{1,2,3,4|B} \\ q_{1,2,3,4|C} \end{bmatrix} \qquad (17)$$

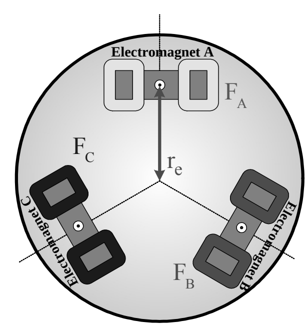

Figure 4. Geometrical locations of the electromagnets.

General control block diagram of the proposed decentralized control system is given in Fig. 5.

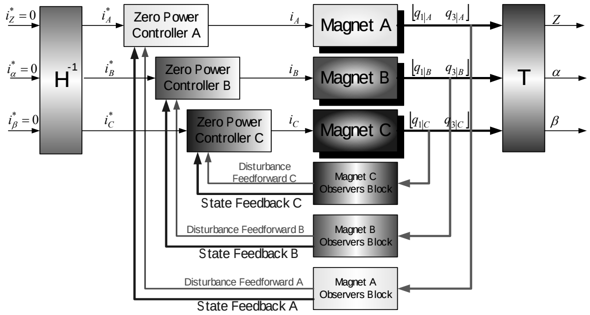

Figure 5. Decentralized Control Block diagram.

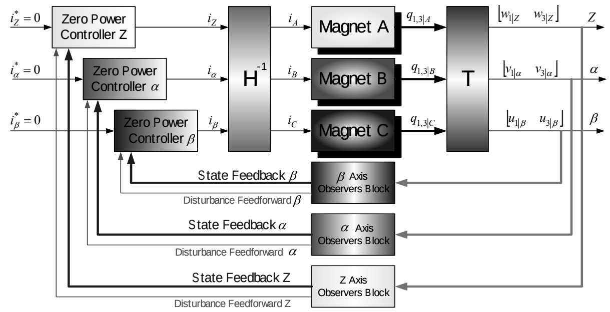

Figure 6. Centralized Control Block Diagram

6. 3-Degrees of Freedom Zero Power Based Centralized Control

A more general and sophisticated way of realizing 3-degrees of freedom zero power control in absolute vibration coordinates is the employment of full transformation of the local coordinates of the electromagnets including the electrical parts. We call this approach as the centralized control. The electrical parts can be transformed by using a current transformation matrix. This matrix is also a transformation measurement of the local electromagnetic forces to general ones. The current transformation matrix is determined as;

$$\begin{bmatrix} i_Z \\ i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ r_e & -r_e/2 & r_e/2 \\ 0 & \sqrt{3}r_e/2 & -\sqrt{3}r_e/2 \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \mathbf{H} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \tag{18}$$

The extended Z-axis equations become as following to design a current order zero power controller;

$$w_1 = z_1 - z_2 \rightarrow \dot{w}_1 = w_2 = \dot{z}_1 - \dot{z}_2 \rightarrow \dot{w}_2 = \ddot{z}_1 - \ddot{z}_2 \tag{19}$$

$$w_3 = z_1 - z_0 \rightarrow \dot{w}_3 = w_4 = \dot{z}_1 - \dot{z}_0 \rightarrow \dot{w}_4 = \ddot{z}_1 - \ddot{z}_0 \tag{20}$$

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{B_d}\mathbf{u_d} \tag{21}$$

$$\mathbf{x} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ \int i_Z \end{bmatrix}, \quad \mathbf{u} = [i_Z], \quad \mathbf{u_d} = \begin{bmatrix} F_{d|Z} \\ \ddot{x}_{0|Z} \end{bmatrix}, \quad \mathbf{B_d} = \begin{bmatrix} 0 & 0 \\ \frac{1}{M_2} & 0 \\ 0 & 0 \\ 0 & -1 \\ 0 & 0 \end{bmatrix} \tag{22}$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ K_Z\frac{M_1+M_2}{M_1M_2} & 0 & -\frac{S_Z}{M_1} & -\frac{C_Z}{M_1} & 0 \\ 0 & 0 & 0 & 1 & 0 \\ K_Z\frac{1}{M_1} & 0 & -\frac{S_Z}{M_1} & -\frac{C_Z}{M_1} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 \\ -K_a\frac{M_1+M_2}{M_1M_2} \\ 0 \\ -K_a\frac{1}{M_1} \\ 1 \end{bmatrix} \tag{23}$$

where relative coordinate values are selected as state variables rather than absolute values.

$$K_Z = 3K_b, \quad S_Z = 3S_{A,B,C}, \quad D_Z = 3D_{A,B,C} \tag{24}$$

$$F_{d|Z} = F_{d|A} + F_{d|B} + F_{d|C}, \quad \ddot{x}_{0|Z} = \tfrac{1}{3}\left(\ddot{x}_{0|A} + \ddot{x}_{0|B} + \ddot{x}_{0|C}\right) \tag{25}$$

By using similar way, inclination dynamics' equations are developed. The fundamental control block diagram of the centralized approach is given in Fig. 6.

7. Decoupled Disturbance Observers Design

In many situations, the relative displacements, gap length of the U-type hybrid electromagnet and deflection of the passive elements, can be measured easily by cost effective displacement sensors, in the meanwhile, the measurements of the velocities requires highly expensive velocity sensors. To overcome this difficulty, firstly, one can use approximate numerical derivative of the measured displacements, however as stated in many studies, this approach will deteriorate the system performance.[2-4] To improve system performance and at the same time to compensate the undesired effects of the disturbances, a disturbance observer can be designed. Yet, it is not too easy the application of this technique to our system in order to estimate the velocities due to two distinct external disturbance sources. If one tries to estimate the immeasurable states by employing only one disturbance observer, the unobservability condition will limit the trial. Hence, at this point, we are proposing a decoupled disturbance observers' design procedure. In our design, the main idea is to decouple the system to observable modes. Our system can be subdivided to observable forms as mechanical parts and electromagnet parts. In the design procedure only for Z-axis is outlined, for other axes, the proposed approach can be employed in the same manner. The first step includes the design a zero order disturbance observer for the mechanical part. Disturbance extended state space equations are;

$$\frac{d}{dt}\begin{bmatrix} q_3 \\ q_4 \\ \ddot{x}_{0|z} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -\frac{S_Z}{M_1} & -\frac{C_Z}{M_1} & -1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} q_3 \\ q_4 \\ \ddot{x}_{0|z} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -\frac{K_a}{M_1} & \frac{K_Z}{M_1} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_z \\ q_1 \end{bmatrix} \tag{26}$$

$$= \mathbf{A_m}\mathbf{x_m} + \mathbf{B_m}\mathbf{u_m}$$

$$y_m = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}\mathbf{x_m} = \mathbf{C_m}\mathbf{x_m} \tag{27}$$

$$\dot{\hat{\mathbf{x}}}_{\mathbf{m}} = \mathbf{A}_{\mathbf{m}}\mathbf{x}_{\mathbf{m}} + \mathbf{B}_{\mathbf{m}}\mathbf{u}_{\mathbf{m}} + \mathbf{L}_{m}\left(y_{m} - \mathbf{C}_{\mathbf{m}}\hat{\mathbf{x}}_{m} \right) \tag{28}$$

By providing the error dynamics of the observer faster than the system dynamics, the observer gain matrix is determined. The electromagnet part's observer equations are developed as;

$$\frac{d}{dt}\begin{bmatrix} q_1 \\ q_2 \\ F_{d|z} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ K_Z \dfrac{M_1+M_2}{M_1M_2} & 0 & \dfrac{1}{M_2} \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \\ F_{d|z} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ -K_a \dfrac{M_1+M_2}{M_1M_2} & -\dfrac{S_Z}{M_1} & -\dfrac{C_Z}{M_1} \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i \\ q_3 \\ \hat{q}_4 \end{bmatrix} \tag{29}$$

$$= \mathbf{A}_e\mathbf{x}_e + \mathbf{B}_e\mathbf{u}_e$$

$$y_e = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}\mathbf{x}_e = \mathbf{C}_e\mathbf{x}_e \tag{30}$$

$$\dot{\hat{\mathbf{x}}}_{e} = \mathbf{A}_{e}\mathbf{x}_{e} + \mathbf{B}_{e}\mathbf{u}_{e} + \mathbf{L}_{e}\left(y_{e} - \mathbf{C}_{e}\hat{\mathbf{x}}_{e} \right) \tag{31}$$

Then. Finally, the observer poles are fixed to give a faster response than the system response. In the second observer, even though, the inclusion of the estimated velocity value by first observer is the key point, in practical application it would become a drawback when initial value is not correctly selected.

8. Numerical Study Results

In order to verify the effectiveness of the outlined procedures and evaluate the performance characteristics, various numerical simulation studies are carried out in Matlab and Simulink environment. The specifications used in numerical studies are as follows;

Table 2. Numerical study specifications

$J_{1\alpha}$	0.0574[kgm^2]	$J_{1\beta}$	0.0557[kgm^2]	M_1	14.15[kg]
$J_{2\alpha}$	0.0638[kgm^2]	$J_{2\beta}$	0.0696[kgm^2]	M_2	14.15[kg]
K_α	158.61[N/rad]	K_β	158.61[N/rad]	K_Z	31721.40[N/m]
S_α	75[N/rad]	S_β	75[N/rad]	S_Z	15000[N/m]
D_α	1.05[N/(rad/sec)]	D_β	1.05[N/(rad/sec)]	D_Z	210[N/(m/s)]
$S_{A,B,C}$	5000[N/m]	$D_{A,B,C}$	70[N/(m/s)]	r_e	0.085[m]

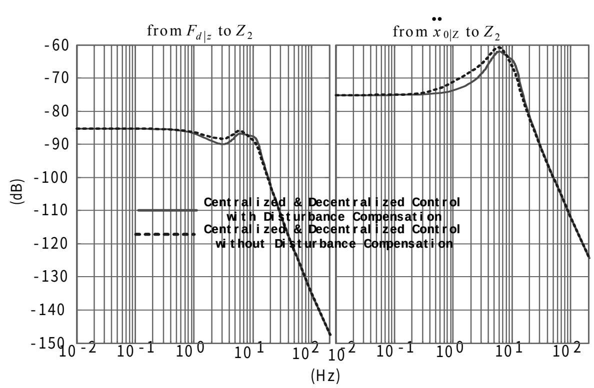

Figure 7. Frequency response of Z axis upper mass absolute displacement against to Z axis direct disturbance force & base acceleration.

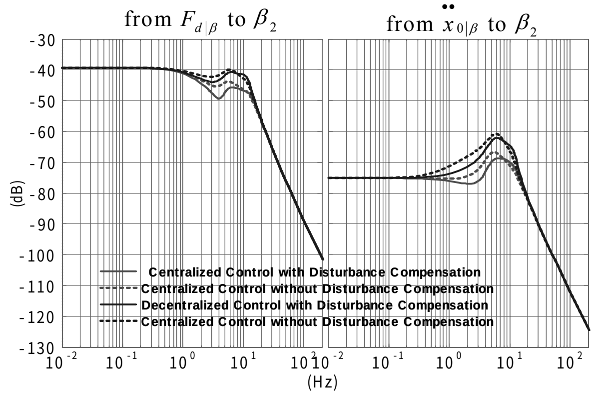

Figure 8. Frequency response of β axis upper mass absolute displacement against to β axis direct disturbance force & base acceleration.

In simulations studies, Kessler's canonical form is used to determine desired system poles for controllers' and disturbance observers' design by setting up the time constant to 0.07 sec and the stability index to 2. In the design of mechanical part disturbance observer, the observer poles are fixed 3 times faster than controller the controller poles, beside this, for magnet disturbance observer, the dynamics is adjusted to give 5 times faster dynamics than the system dynamics.

As we see from the Fig. 6-7, Z-axis is more robust to direct disturbances than those of inclinations. On the other hand, vibration suppression against base accelerations is almost same for each axis. For Z-axis, the decentralized and centralized control approaches give the same result as clarified with the Fig. 6, also we can deduce this outcome at the control design steps. However, for inclinations' dynamics, the centralized control shows better performance development. By feed forwarding the estimated disturbance, more robustness is achieved even though in some sense robustness is an inherited feature of zero power control strategies due to integral action on the control path. Particularly in low frequency region, the disturbance compensation process reduces the undesired effects of the disturbances. This result is valid for both centralized and decentralized design cases.

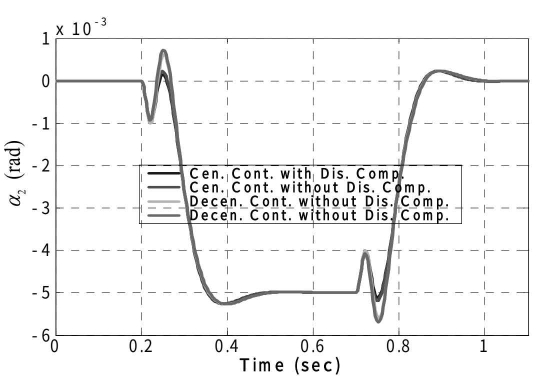

Figure 9. α Axis upper inertias' time response for 0.5 [Nm] direct disturbance torque.

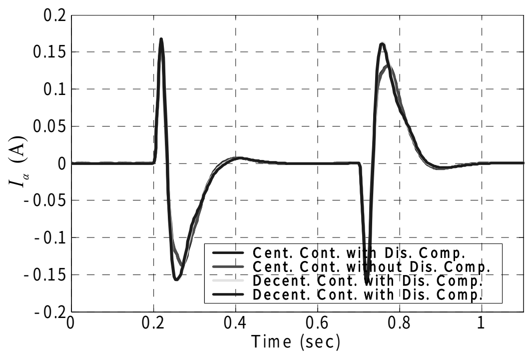

Figure 10. α Axis currents' time response for 0.7 [Nm] direct disturbance torque.

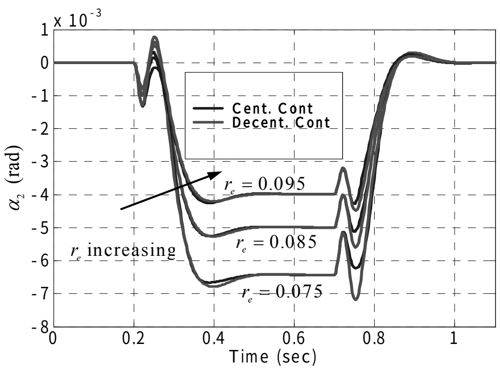

Figure 11. Change Effect of r_e on α axis inclination dynamics

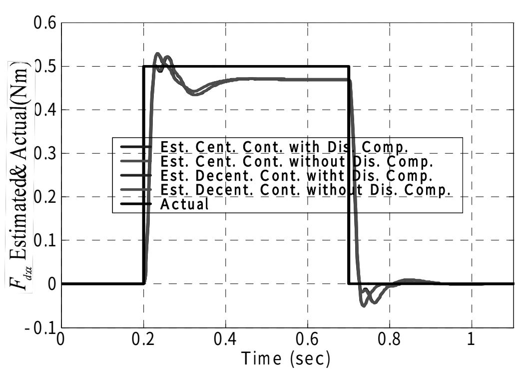

Figure 12. Estimated and actual value of direct disturbance torque.

To investigate the effects of disturbance compensation and proposed control approaches on inclination axes of the system, α axis is disturbed by 0.5 [Nm] stepwise direct disturbance torque as seen Fig. 12. The centralized control approach takes account the inclination dynamics whereas the decentralized approach just tries to adjust locally gap length of the each electromagnet. Inclusion of the inclination dynamics gives superiority to centralized control approach especially for small r_es than its counterpart when suppressing undesired effects of the disturbance as we clarify from the Fig. 9-11. Moreover, we can not view this property for Z axis since centralized and decentralized design approaches are equivalent features in controller design steps. The zero power operation condition is almost achieved, especially for stepwise direct disturbance excitation of α axis. This result, as we expect, is valid for other axes, Fig. 10. From Fig. 11, it is seen that direct disturbance is almost estimated, even though the estimated disturbance in some form has slight differences from the actual one. However, this slight discrepancy reveals the one of the most significant property of the disturbance observer that the disturbance observer does not only estimate the external disturbance but also it does observe inner disturbance, electromagnet nonlinearity. So that, the collection of the disturbance are estimated and by employing estimated total disturbance as a control compensation input through the control loop, that is feed forwarding the estimated disturbances, the plant nominalization and better performance are realized successfully.

9. Conclusions

In this paper, a novel active vibration control system, which has 3-degrees of freedom control capability is introduced. To achieve 3-degrees of freedom active vibration control based zero power maglev control, two consistent control algorithms, centralized and decentralized control approaches, are explained. Furthermore, to get rid of the expensive sensor cost, the decoupled disturbance observers are proposed and design procedures are stated. Finally, to verify the effectives of the proposed system, some numerical studies are carried out. As future works, the numerical results will be compared with experimental test bench results both applying voltage and current order zero power maglev control approaches.

10. References

[1] Furlani, E.P.: "Permanent Magnet and Electromechanical Devices: Materials, Analysis, and Applications", Academic Press, 2001, Newyork.

[2] Yakushi K., Koseki T. and Sone S.,"3 Degree-of-Freedom Zero Power Magnetic Levitation Control by a 4-Pole Type Electromagnet", International Power Electronics Conference IPEC-Tokyo 2000, Vol. 4, pp. 2136-2141, April, 2000, Tokyo, Japan.

[3] Mizuno T., Takasaki M., Suzuki H.: "Application of Zero Power Magnetic Suspension to Vibration Isolation System", 8th International Symposium on Magnetic Bearing, pp 151-156,August 26-28, 2002, Mito, Japan.

[4] Yusuke M., "Six Degrees of Freedom Control through Three Hybrid Electromagnets and Three Linear Induction Motors for Two Dimensional Conveyance System", Master's Thesis, 2004, The University of Tokyo, Electrical Engineering Department.