

6 Degrees of Freedom Zero Power Control of a Vibration Isolation Stage

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Abstract

The objective of this paper is firstly to introduce a novel isolation configuration for vibration and disturbance isolation stages comprised of a triple of novel E Type Staggered Hybrid Electromagnet (E Type SHE), which has the capability of two degrees of freedom control, and secondly to develop 6 degrees of freedom modified zero power control algorithm to isolate direct disturbances and vibrations for this novel configuration. The control algorithm is designed by invoking state space techniques, thereby; all state variables of the isolation stage should be measured and/or estimated correctly. To overcome this difficulty, we introduced a zero order disturbance observer not only to estimate the states and by feed forwarding the estimated disturbances to improve system performance but also to provide offset-set property to pure zero power control scheme.

1. Introduction & Motivation:

Vibrations and disturbance participating to system can be mainly classified into two categories, direct type and ground type. However, these two categories necessitate different configurations for isolation system. Former one requires higher stiffness than later one. In the case of designing passive isolation system, it is indispensable to make some trade of between them. Therefore, system performance will be limited. Applying active isolation techniques is going to break through this trade-off.

Electromagnetic based actuators can provide cleaner working environment, their realization is easier than the counterparts and probably the most significant superiority is that they only need electrical energy and their efficiency is higher than the others.[3]

U Type Staggered electromagnets, which has capability of providing lateral and guidance force simultaneously, are firstly introduced for transportation systems.[2] In this paper, by taking regard of aforementioned merits of (hybrid + staggered) electromagnets, we are proposing a novel E

Type Staggered Hybrid Electromagnet (E Type SHE) and a novel vibration isolation configuration.

Inherently the zero power control procedure shows negative stiffness property. If this property can be combined appropriately with a positive stiffness element, such as a spring, it is theoretically possible to get infinite stiffness. However, pure zero power control will fail when it is combined with unequal positive stiffness element, which is common difficulty in practical application. To cope with this drawback, we are proposing a modified zero power control algorithm with offset-set property for each degrees of freedom of the isolation stage.

2. An E Type Staggered Hybrid Electromagnet & Combination with Vibration Isolation Stage

Principle combined configuration of E Type SHE with vibration stage can be illustrated in Fig. 1. To analyze and develop a mathematical model for E Type SHE, magnetic circuit approach is preferred.[1] E Type SHE is divided two identically independent magnetic circuits and analysis is carried out individually neglecting coupling effect.

By taking account this principle configuration, the dynamic equation of the system can be developed as following manner.

For y axis;

$$m_1 \ddot{y}_1 = -F_{sy} - F_{dy} - F_v \quad m_2 \ddot{y}_2 = F_v - F_{dy} \quad (1)$$

For x axis;

$$m_1 \ddot{x}_1 = -F_{sx} - F_{dx} + F_h \quad m_2 \ddot{x}_2 = -F_h + F_{dx} \quad (2)$$

When we analyze closely the force equations of the E Type SHE, we realize that these force equations have nonlinear features. To develop an isolation control algorithm from the point view of linear control theory, these force equations are linearized an equilibrium point for small deviations as following.

$$K_{yy} = -\frac{\partial F_v}{\partial g} \quad K_{yi} = \frac{\partial F_v}{\partial i_r} = \frac{\partial F_v}{\partial i_l} \quad (3)$$

$$F_v \cong -K_{yy}\Delta g + K_{yi}(\Delta i_l + \Delta i_r) \quad \Delta i^+ = (\Delta i_r + \Delta i_l) \quad (4)$$

$$K_{xx} = \frac{\partial F_h}{\partial \delta} \quad K_{xi} = \frac{\partial F_v}{\partial i_r} = -\frac{\partial F_v}{\partial i_l} \quad (5)$$

$$F_h \cong K_{xx}\Delta \delta + K_{xi}(\Delta i_r - \Delta i_l) \quad \Delta i^- = (\Delta i_r - \Delta i_l) \quad (6)$$

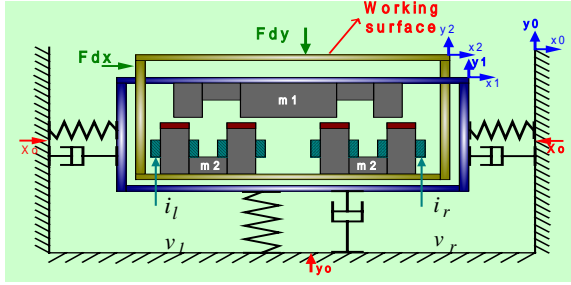


Figure 1. The principle configuration for a combination of E Type SHE with vibration stage

Generally, voltage controlled power supplies are employed to drive electromagnets because of realization convenience. Thereby, it is required to develop voltage equations for E Type SHE. Flux linkages also have nonlinear natures as similar to the forces hence; linearization process should be employed for voltage equations, too.[1]

Finally, state space form of the dynamic equations, will take following forms;

$$\dot{x}_y = A_y x_y + B_y U_y + B_{yd} F_{dy} \quad y_y = [0 \ 1 \ 0 \ 0 \ 0] [x_y]^T \quad (7)$$

$$\dot{x}_x = A_x x_x + B_x U_x + B_{xd} F_{xdd} \quad y_x = [0 \ 1 \ 0 \ 0 \ 0] [x_x]^T \quad (8)$$

$$\frac{d}{dt} \begin{bmatrix} y_1 \\ y_2 \\ y_1 \\ y_2 \\ \Delta i^+ \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \frac{K_{yy} C_{yy}}{m_1} & \frac{K_{yy}}{m_1} & -\frac{C_{dy}}{m_1} & 0 & -\frac{K_{xi}}{m_1} \\ -\frac{K_{yy}}{m_2} & \frac{K_{yy}}{m_2} & 0 & 0 & \frac{K_{xi}}{m_2} \\ 0 & 0 & \frac{2S_v}{L_o} & -\frac{2S_v}{L_o} & -\frac{R}{L_o} \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ y_1 \\ y_2 \\ \Delta i^+ \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{L_o} \end{bmatrix} U_y + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{C_{dy}}{m_1} & \frac{C_{dy}}{m_1} & 0 \\ 0 & 0 & \frac{1}{m_2} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} y_o \\ y_o \\ F_{dy} \end{bmatrix} \quad (9)$$

$$\frac{d}{dt} \begin{bmatrix} x_1 \\ x_2 \\ x_1 \\ x_2 \\ \Delta i^- \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \frac{K_{xx} C_{xx}}{m_1} & \frac{K_{xx}}{m_1} & -\frac{C_{dx}}{m_1} & 0 & \frac{K_{xi}}{m_1} \\ -\frac{K_{xx}}{m_2} & \frac{K_{xx}}{m_2} & 0 & 0 & \frac{K_{xi}}{m_2} \\ 0 & 0 & \frac{2S_h}{L_o} & -\frac{2S_h}{L_o} & -\frac{R}{L_o} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_1 \\ x_2 \\ \Delta i^- \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{L_o} \end{bmatrix} U_x + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{C_{dx}}{m_1} & \frac{C_{dx}}{m_1} & 0 \\ 0 & 0 & \frac{1}{m_2} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_o \\ x_o \\ F_{dx} \end{bmatrix} \quad (10)$$

3. Triple Symmetric Configuration of E Type Staggered Hybrid Electromagnets & Development of A Mathematical Model for Each Degree of Freedom

Inherently, it is not only possible to control independently each one of two axes of principle isolation

configuration around an equilibrium point but also by using proper geometrically symmetric arrangement, it is possible to develop a structure, which has 6 degrees of freedom vibration isolation capability. The principle idea for this novel structure can be illustrated as in Fig. 2.

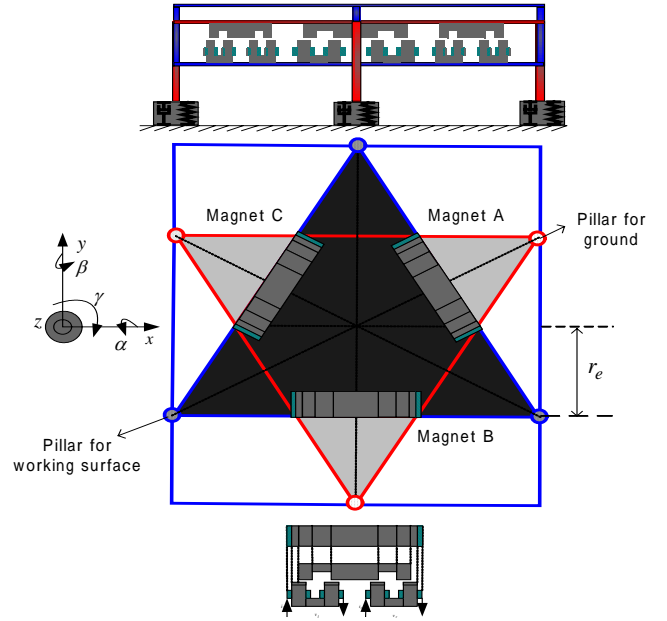


Figure 2. Principle configuration for triple symmetric replacement of E Type SHE.

The merits of this configuration can be summarized as following;

- ✧ Because of symmetric replacement, system will not consume energy if there is no vibration and disturbance.
- ✧ In many conventional cases more than 3 actuators have been employed as active control elements. However in this novel configuration only 3 E Type SHE's have been employed.
- ✧ This novel configuration consists of 6 control output variables ($x, y, z, \alpha, \beta, \gamma$) and 6 input variables ($v_{Ar}, v_{Al}, v_{Br}, v_{Bl}, v_{Cr}, v_{Cl}$). Thereby, axes transformations can be realized respectively among input output pairs without loss of knowledge.
- ✧ It is also possible to implement a zero power based isolation scheme for virtual axes variables.[6][5]
- ✧ Generally, in many industrial processes, the dominant vibration and disturbance axis is z , by employing this novel configuration this axis disturbances and vibrations can be isolated effectively.
- ✧ This novel configuration also minimizes the number of passive elements.

A mathematical model for this new configuration can be developed by taking account inclination dynamics with employment of appropriate current and axes transformation matrices as following;

$$\begin{bmatrix} \Delta z \\ \Delta \beta \\ \Delta \alpha \\ \Delta \gamma \\ \Delta y \\ \Delta x \end{bmatrix} = \begin{bmatrix} -\frac{1}{3} & -\frac{1}{3} & -\frac{1}{3} & 0 & 0 & 0 \\ \frac{1}{\sqrt{3}} & 0 & -\frac{1}{\sqrt{3}} & 0 & 0 & 0 \\ \frac{1}{3r_e} & \frac{2}{3r_e} & -\frac{1}{3r_e} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{3r_e} & \frac{1}{3r_e} & \frac{1}{3r_e} \\ 0 & 0 & 0 & -\frac{1}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \\ 0 & 0 & 0 & \frac{1}{3} & -\frac{2}{3} & \frac{1}{3} \end{bmatrix} \begin{bmatrix} \Delta g_A \\ \Delta g_B \\ \Delta g_C \\ \Delta \delta_A \\ \Delta \delta_B \\ \Delta \delta_C \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} \Delta i_z \\ \Delta i_\beta \\ \Delta i_\alpha \\ \Delta i_\gamma \\ \Delta i_y \\ \Delta i_x \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ -r_e\sqrt{3} & 0 & r_e\sqrt{3} & 0 & 0 & 0 \\ \frac{2}{r_e} & -re & -\frac{2}{r_e} & 0 & 0 & 0 \\ 0 & 0 & 0 & -r_e & -r_e & -r_e \\ 0 & 0 & 0 & \sqrt{3} & 0 & -\sqrt{3} \\ 0 & 0 & 0 & \frac{2}{2} & 0 & \frac{2}{2} \\ 0 & 0 & 0 & -\frac{1}{2} & 1 & -\frac{1}{2} \end{bmatrix} \begin{bmatrix} \Delta i_A^+ \\ \Delta i_B^+ \\ \Delta i_C^+ \\ \Delta i_A^- \\ \Delta i_B^- \\ \Delta i_C^- \end{bmatrix} \quad (12)$$

Finally, transformed force and voltage equations can be handled as following;

$$\begin{aligned} F_z &= 3K_{yy}\Delta z + K_{yy}\Delta i_z & \Delta v_z &= L_o \Delta i_z + R\Delta i_z + 6S_v \Delta z \\ F_\beta &= \frac{3r_e^2 K_{yy}}{2} \Delta \beta + K_{yy}\Delta i_\beta & \Delta v_\beta &= L_o \Delta i_\beta + R\Delta i_\beta + 3r_e^2 S_v \Delta \beta \\ F_\alpha &= \frac{3r_e^2 K_{yy}}{2} \Delta \alpha + K_{yy}\Delta i_\alpha & \Delta v_\alpha &= L_o \Delta i_\alpha + R\Delta i_\alpha + 3r_e^2 S_v \Delta \alpha \\ F_\gamma &= -3r_e^2 K_{xx} \Delta \gamma + K_{xx}\Delta i_\gamma & \Delta v_\gamma &= L_o \Delta i_\gamma + R\Delta i_\gamma + 6r_e^2 S_h \Delta \gamma \\ F_y &= -\frac{3}{2} K_{xx} \Delta y + K_{xx}\Delta i_y & \Delta v_y &= L_o \Delta i_y + R\Delta i_y + 3S_h \Delta y \\ F_x &= -\frac{3}{2} K_{xx} \Delta x + K_{xx}\Delta i_x & \Delta v_x &= L_o \Delta i_x + R\Delta i_x + 3S_h \Delta x \end{aligned} \quad (13)$$

It is also possible to employ individual mathematical model of the each one of triple for control purposes, which results in decentralized control approach.[6] In this current generalized axis approach, the merit is that the inclination dynamics have been taken account. Thus, each one of the generalized axes can be controlled individually.

Eventually, the total dynamics of the vibration isolation stage can be developed for each one of the generalized axes in a similar manner given for a single E Type (1~10) by using equivalent values of the electrical force equations(13) and passive elements .

4. Proposal of Modified Zero Power Control

The proposed fundamental block diagram of the modified zero power control is given Fig. 3. In this figure if we take out the offset branch, we can get the pure zero power control algorithm. To accomplish the task of eliminating undesirable disturbances successfully, the offset-set branch has a significant meaning.

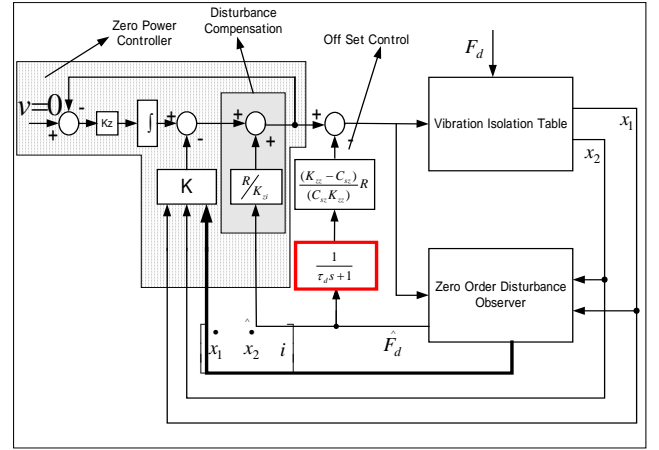


Figure 3. Fundamental block diagram of the modified zero power controller.

However, the estimated disturbance value includes high frequency components, when we use this pure estimated disturbance value for offset-set we can mainly achieve the goal, but the system will be excited by high frequency components of the pure estimated disturbance.

One practical solution for this drawback is to insert a Low Pass Filter (LPF) to offsetset path. To evaluate the aforementioned situations, a series of simulation is carried out for Z-axis of the system. (Fig. 4~5).

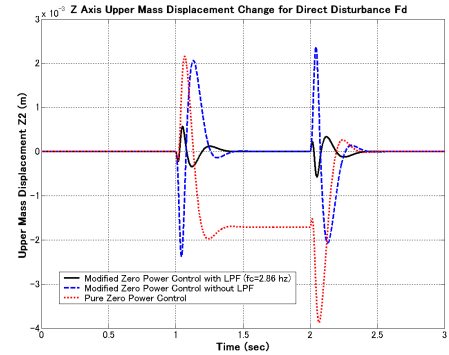


Fig 4. Z-axis upper mass displacement change for direct disturbance ($F_{dc} = 30Nt$, 1~2 sec.)

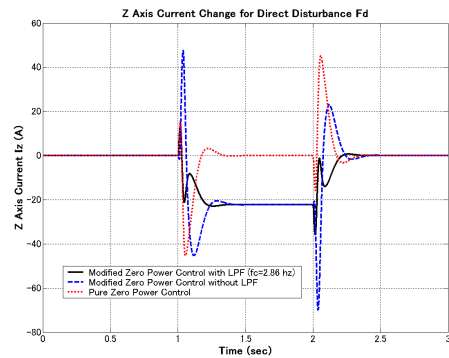


Fig 5. Z-axis current change for direct disturbance ($F_{dc} = 30Nt$ 1~2 sec.)

The frequency responses of the direct disturbance force to Z-axis upper mass displacement and current are plotted as following graph.

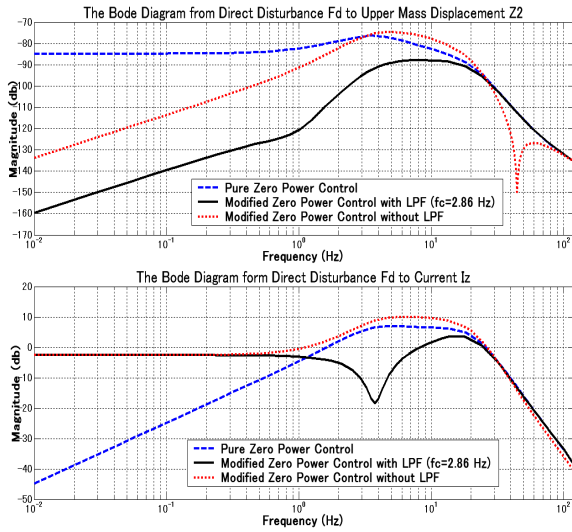


Fig 6. Frequency response of direct disturbance (F_{dz}) to Z-axis upper mass displacement and current.

If we look at the Fig 4~6 we see that LPF based modified zero power control algorithm gives superior results than others. This approach can be extended to other generalized axes so that 6 degrees of freedom modified zero power control can be achieved easily. Some simulations are conducted for α and β axes by employing LPF based modified zero power control for direct disturbance excitations.(Fig. 7~8)

5. Conclusion and Future Studies

In this paper, we introduced a novel vibration and disturbance isolation stage, which employs geometrically symmetric triple configuration of E Type SHEs and has the 6 degrees of freedom control capability.

Zero power control algorithm is selected because of negative stiffness property. To improve the system performance and offset the parameter inconsistency, the modified type zero power control algorithms are proposed. Effectiveness of the proposed control algorithms is investigated by various simulation studies.

For future development, firstly we are planning to construct a test bench based on previous descriptions and verify simulation study results on this test bench, then, investigate the base disturbances isolation property.

Moreover, as a next issue, to extend operation range and improve the performance of the system, we are going to study compensation of undesired nonlinear effects by employing soft computing techniques.

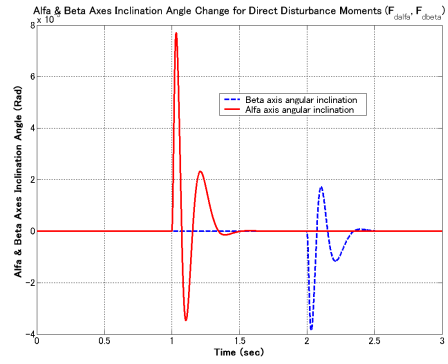


Fig 7. α and β axis upper mass displacement change for direct disturbance ($T_{d\alpha} = -8Ntm$, $T_{d\beta} = 5Ntm$)

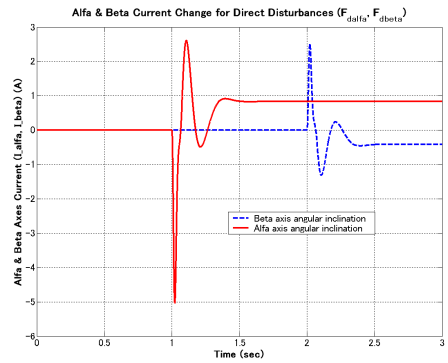


Fig 8. α and β axis current change for direct disturbance ($T_{d\alpha} = -8Ntm$, $T_{d\beta} = 5Ntm$)

6. References

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