スタガ配置された E 型ハイブリッド電磁石による除振台の六自由度制御

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6 Degree of Freedom Control of Vibration Isolation Stage by Employing A Novel Staggered E Type Hybrid Electromagnet

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Abstract:

The objective of this paper is firstly to introduce a novel isolation structure for vibration and disturbance isolation stages comprised of triple novel E Type **S**taggered **H**ybrid **E**lectromagnets (E Type SHE), which has capability of two degrees of freedom control, and secondly to develop 6 degrees of freedom control algorithms to isolate disturbances and vibrations for this novel configuration. The 6 degrees of freedom control algorithms under consideration are two approaches, the first one is decentralized control approach which disregards inclination dynamics and employs state space I (integral) regulator to control each one of three E Type SHEs, the second approach is centralized control that invokes appropriate transformation matrices and takes account inclination dynamics by using state space I (integral) regulator algorithm. Furthermore, due to usage of state space control technique, state measurements and/or knowledge is necessary, hence, to overcome this difficulty a zero disturbance observer is proposed not only to estimate the unknown states but also to improve isolation performance of the system by feed forwarding estimated disturbance values.

Keyword: E Type Staggered Hybrid Electromagnet (E Type SHE), vibration and disturbance isolation stage, 6 degree of freedom control.

1. Introduction & Motivation:

Many high precision manufacturing assemblies require vibration and disturbance isolation stages to isolate undesired disturbance and vibrations. In the past, to accomplish this task, mainly passive type isolation elements were employed. However, the vibration and disturbance sources have different natures, therefore, for isolation process, classic passive type isolators satisfy only restricted performance criteria. The combination of the passive type isolators with active type elements can widen the effective operation range of the isolation system.

In the literature [3], there have been presented many different active isolation structures which have been employing different active elements based on active force production such as hydraulic, pneumatic based and so on. However, among them, electromagnetic based actuators have some superior features as compared with others.[6] They can provide cleaner working environment, their realization is easier than the others and probably the most significant superiority is that they only need electrical energy and their efficiency is higher than the others. Recently there is a great trend on application of hybrid type electromagnets because of low cost of PMs to reduce energy consumption and decrease the size of magnets.[1]

U Type Staggered electromagnets, which has capability providing lateral and guidance force simultaneously, 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 novel vibration isolation configuration.

This novel isolation configuration has the capability of 6 degrees of freedom control. Therefore, to verify this property of the novel isolation configuration, we investigated two control algorithms, decentralized and centralized, by using state space I regulator procedure. Former approach disregards inclination dynamics and controls each E Type SHE individually, latter invokes appropriate transformation matrices and takes account inclination dynamics by employing state space I regulator procedure.

2. E Type Staggered Hybrid Electromagnet

Principle configuration of the novel E Type SHE is given in Fig.1. To analyze and develop a mathematical model, 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. This is an easy and straightforward approach, as we verify from the finite element (FEM) analysis field map of E Type SHE in Fig.2.

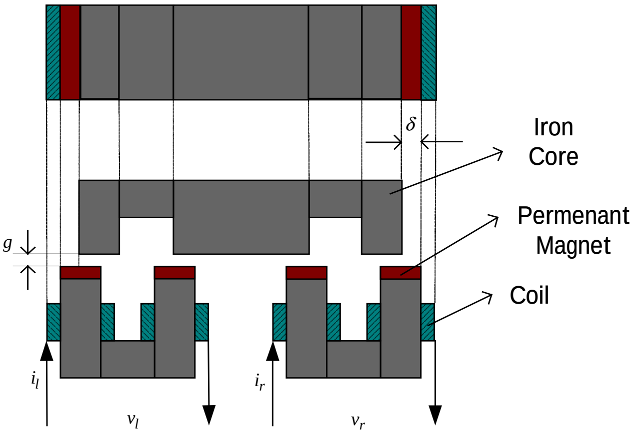

Figure.1. Principle configuration of the E Type SHE

FEM analysis has been carried out by using FemLab package to investigate the consistency of the analytical model of the E Type SHE with numerical analysis results. In the analytical analysis, saturation effect and reluctance of the iron parts are neglected and it is assumed that permeability of PM is equal to free space's permeability. The two dimensional FEM analysis field map of the E Type SHE is given in Fig.2.

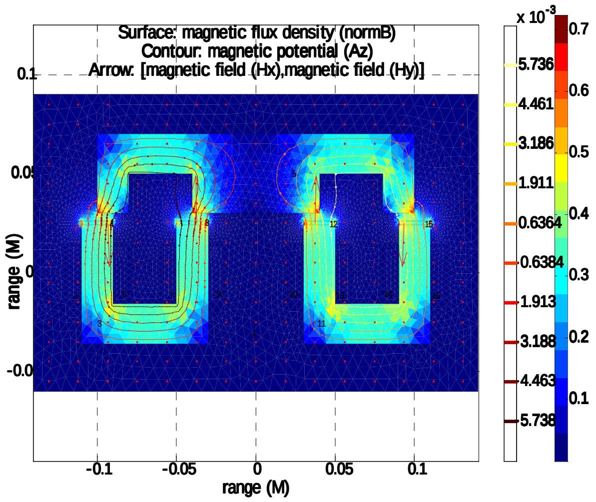

Figure.2. Field map of the E Type SHE.

Electromagnetic force equations of the E Type SHE are developed as following by using virtual displacement approach;

$$F_{vl}=\left(\tfrac{1}{4}\right)\frac{\left(\mu_0 d w^2\left(2l_{pm}H_c+Ni_l\right)^2\pi^2\left(4wg+w\pi(\delta_0-\delta)-\pi\right)(\delta_0-\delta)^2\right)}{\left(\left(g\pi w+l_{pm}\pi\delta-l_{pm}(\delta_0-\delta)-8l_{pm}g\ln(2)+4l_{pm}g\ln\left(\frac{4g+\pi(\delta_0-\delta)}{g}\right)\right)^2\left(4g+\pi(\delta_0-\delta)\right)\right)} \tag{1}$$

$$F_{hl}=\left(\tfrac{1}{4}\right)\frac{\left(\mu_0 d w^2\left(2l_{pm}H_c+Ni_l\right)^2 g\pi^3(\delta_0-\delta)\right)}{\left(\left(g\pi w+l_{pm}\pi\delta-l_{pm}(\delta_0-\delta)-8l_{pm}g\ln(2)+4l_{pm}g\ln\left(\frac{4g+\pi(\delta_0-\delta)}{g}\right)\right)^2\left(4g+\pi(\delta_0-\delta)\right)\right)} \tag{2}$$

$$F_{vr}=\left(\tfrac{1}{4}\right)\frac{\left(\mu_0 d w^2\left(2l_{pm}H_c+Ni_r\right)^2\pi^2\left(4wg+w\pi(\delta_0+\delta)-\pi\right)(\delta_0+\delta)^2\right)}{\left(\left(g\pi w+l_{pm}\pi\delta-l_{pm}(\delta_0+\delta)-8l_{pm}g\ln(2)+4l_{pm}g\ln\left(\frac{4g+\pi(\delta_0+\delta)}{g}\right)\right)^2\left(4g+\pi(\delta_0+\delta)\right)\right)} \tag{3}$$

$$F_{hr}=\left(\tfrac{1}{4}\right)\frac{\left(\mu_0 d w^2\left(2l_{pm}H_c+Ni_r\right)^2 g\pi^3(\delta_0+\delta)\right)}{\left(\left(g\pi w+l_{pm}\pi\delta-l_{pm}(\delta_0+\delta)-8l_{pm}g\ln(2)+4l_{pm}g\ln\left(\frac{4g+\pi(\delta_0+\delta)}{g}\right)\right)^2\left(4g+\pi(\delta_0+\delta)\right)\right)} \tag{4}$$

$$F_h=F_{hr}-F_{hl} \tag{5}$$

$$F_v=F_{vr}+F_{vl} \tag{6}$$

Symbol	Description	Value
μ_0	Permeability of free space	$4\pi 10^{-7}$
g	Gap length	0.004(m)
d	Pole width	0.02(m)
w	Pole pitch	0.02(m)
l_{pm}	Length of PM	0.002(m)
H_c	Coercivity of PM	900000 (A/m)
N	Turn number of coil	300 （turns）
δ_o	Staggered separation value for equilibrium	0.01(m)
δ	Staggered separation value	
i_r	Right part coil current	
i_l	Left part coil current	
F_{hr}	Right part horizontal force	
F_{vr}	Right part vertical force	
F_{hl}	Left part horizontal force	
F_{hl}	Left part vertical force	
F_h	Total horizontal force	
F_v	Total vertical force	

These force equations are identical with FEM analysis results of the E Type SHE as we see from the following figures.(Fig.3&4) According to these two analyses results, we can conclude that the equations derived previously can be used not only to develop a mathematical model but also to design a controller analytically. In the development of the paper, we will follow this approach to develop dynamical equations of vibration stage and to design a controller, as well.

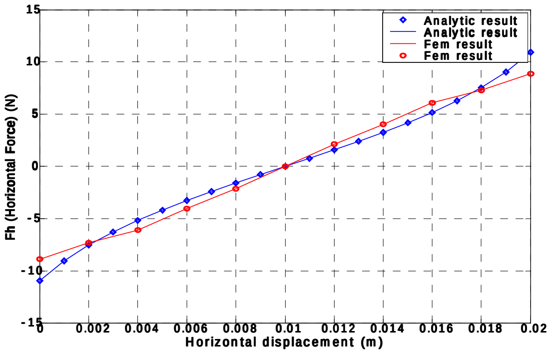

Figure.3. Change of Horizontal Force for Horizontal Displacement

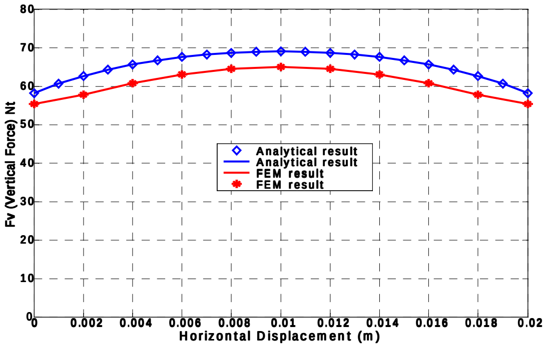

Figure.4. Change of Vertical Force for Horizontal Displacement

3. Combination of E Type Staggered Hybrid Electromagnet with Vibration Stage

The principle combined configuration of E Type SHE with vibration stage can be illustrated in Fig.5.

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

For y axis;

$$m_1 \ddot{y}_1 = -F_{Sy} - F_{Dy} - F_v \qquad m_2 \ddot{y}_2 = F_v - F_{dy} \tag{7}$$

For x axis;

$$m_1 \ddot{x}_1 = -F_{Sx} - F_{Dx} + F_h \qquad m_2 \ddot{x}_2 = -F_h + F_{dx} \tag{8}$$

When we investigate closely the force equations of the E Type SHE, we realize that these force equations have nonlinear features. Therefore, to develop an isolation control algorithm from the point view of linear control theory, these force equations should be linearized an equilibrium point for small deviations. The linearization process can be handled by using Taylor's series expansion. The linearized force equations derived by using Taylor's procedure as following;

$$K_{yy} = -\frac{\partial F_v}{\partial g} \qquad K_{yi} = \frac{\partial F_v}{\partial i_r} = \frac{\partial F_v}{\partial i_l} \tag{9}$$

$$F_v \cong -K_{yy}\Delta g + K_{yi}(\Delta i_l + \Delta i_r) \qquad \Delta i^+ = (\Delta i_r + \Delta i_l) \tag{10}$$

$$K_{xx} = \frac{\partial F_h}{\partial \delta} \qquad K_{xi} = \frac{\partial F_v}{\partial i_r} = -\frac{\partial F_v}{\partial i_l} \tag{11}$$

$$F_h \cong K_{xx}\Delta\delta + K_{xi}(\Delta i_r - \Delta i_l) \qquad \Delta i^- = (\Delta i_r - \Delta i_l) \tag{12}$$

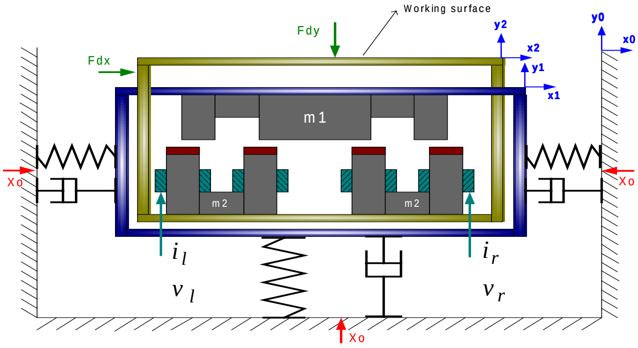

Figure.5.The principle configuration for a combination of E Type SHE with vibration stage

Generally, voltage controlled power supplies are used 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. Finally, linearized voltage equations are obtained as following;

$$\Delta v_r = R\Delta i_r + L_o \Delta\dot{i}_r - S_h\Delta\delta - S_v\Delta g \tag{13}$$

$$\Delta v_l = R\Delta i_l + L_o \Delta\dot{i}_l + S_h\Delta\delta - S_v\Delta g \tag{14}$$

$$\Delta v^+ = \Delta v_r + \Delta v_l = R\Delta i^+ + L_o \Delta\dot{i}^+ - 2S_v\Delta g \tag{15}$$

$$\Delta v^- = \Delta v_r - \Delta v_l = R\Delta i^- + L_o \Delta\dot{i}^- - 2S_h\Delta\delta \tag{16}$$

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

$$\Delta g = y_1 - y_2 \qquad \Delta\delta = x_2 - x_1 \tag{17}$$

$$\dot{x}_y = A_y x_y + B_y U_y + B_{yd} F_{ddy} \qquad y_y = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_y \end{bmatrix}^T \tag{18}$$

$$\dot{x}_x = A_x x_x + B_x U_x + B_{xd} F_{xdd} \qquad y_x = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_x \end{bmatrix}^T$$

$$\frac{d}{dt}\begin{bmatrix} y_1 \\ y_2 \\ \dot{y}_1 \\ \dot{y}_2 \\ \Delta i^+ \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \frac{K_{yy} - C_{sy}}{m_1} & -\frac{K_{yy}}{m_1} & -\frac{C_{dy}}{m_1} & 0 & -\frac{K_{yi}}{m_1} \\ -\frac{K_{yy}}{m_2} & \frac{K_{yy}}{m_2} & 0 & 0 & \frac{K_{yi}}{m_1} \\ 0 & 0 & \frac{2S_v}{L_o} & -\frac{2S_v}{L_o} & -\frac{R}{L_0} \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ \dot{y}_1 \\ \dot{y}_2 \\ \Delta i^+ \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{L_o} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{C_{sy}}{m_1} & \frac{C_{dy}}{m_1} & 0 \\ 0 & 0 & \frac{1}{m_2} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} y_o \\ \dot{y}_o \\ F_{dy} \end{bmatrix} \tag{19}$$

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \\ \dot{x}_1 \\ \dot{x}_2 \\ \Delta i^- \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ -\frac{K_{xx} + C_{sx}}{m_1} & \frac{K_{xx}}{m_1} & -\frac{C_{dx}}{m_1} & 0 & \frac{K_{xi}}{m_1} \\ \frac{K_{xx}}{m_2} & -\frac{K_{xx}}{m_2} & 0 & 0 & -\frac{K_{xi}}{m_2} \\ 0 & 0 & -\frac{2S_h}{L_o} & \frac{2S_h}{L_o} & -\frac{R}{L_0} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \dot{x}_1 \\ \dot{x}_2 \\ \Delta i^- \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{L_o} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{C_{sx}}{m_1} & \frac{C_{dx}}{m_1} & 0 \\ 0 & 0 & \frac{1}{m_2} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_o \\ \dot{x}_o \\ F_{dx} \end{bmatrix} \tag{20}$$

4. Triple Symmetric Configuration of E Type Staggered Hybrid Electromagnets

Inherently, as we see from the previous analysis, 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.6.

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 (z, α, β) axes variables.[7][5]
- ✧ Generally, in many industrial processes, the dominant vibration and disturbance axis is *z*, by employing this novel configuration this axis disturbances and vibrations effectively isolated.
- ✧ This novel configuration also minimizes the number of passive elements.

5. Decentralized Control Approach

Probably, the simplest control algorithm is to control each E Type SHE individually by designing a controller without taking account inclination dynamics. (Decentralized control) In this control algorithm, the idea behind is to design 6 controllers for each magnet's vertical and horizontal axes and finally, according to vertical and horizontal displacement values to isolate the vibrations and disturbances by applying appropriate control inputs (voltages) to each E Type SHE. If we closely investigate dynamic equations of the vibration isolation stage in Fig.5, we can easily see that it will practical to design the controller by employing state space techniques even though some states are unavailable (immeasurable). The most well-known state space algorithm is the state space regulator algorithm which gives zero steady state error in the case of no disturbance and invariant plant parameters.

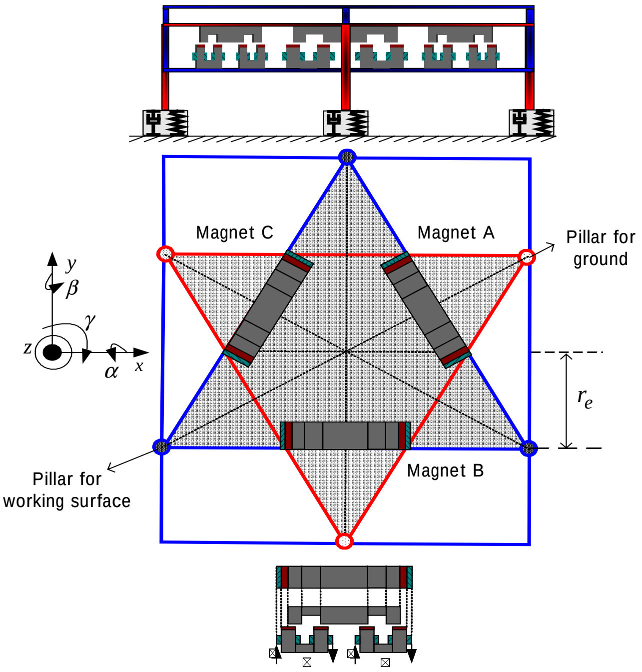

Figure.6. Principle configuration for triple symmetric replacement of E Type SHE.

However, in actual case there will be some disturbances and vibrations that must be isolated. Hence, a more robust and simple algorithm can be handled by extending this algorithm with an I element, the state space integral (I) control algorithm. For this reason, in this study, state space I control algorithm is employed for each E Type SHE's vertical and horizontal axes. Moreover, because of some immeasurable states, a zero order disturbance observer, an extension of Lunberger observer, is designed not only estimate unavailable states but also estimate the zero order disturbances. One merit of the disturbance observer over Luenberger observers is the fact that it gives more correct estimations even in the case of disturbances. Also, feed forwarding the estimated disturbance through control loop can cancel the effect of disturbances and plant uncertainties as well.

The state space I control algorithm and zero order disturbance observer is designed by extending the vertical and horizontal dynamic equations of the each E Type SHE's.[4] Desired system poles can be determined by using Kessler's canonical form. In simulation studies, this approach is employed by fixing the index to 2 and time rise constant to 0.05sec.

6. Centralized Control

A more straightforward approach to obtain 6 degrees freedom control of this novel isolation stage is to develop a centralized control algorithm by invoking appropriate transformation matrices.[5] In this approach, the merit is that the inclination

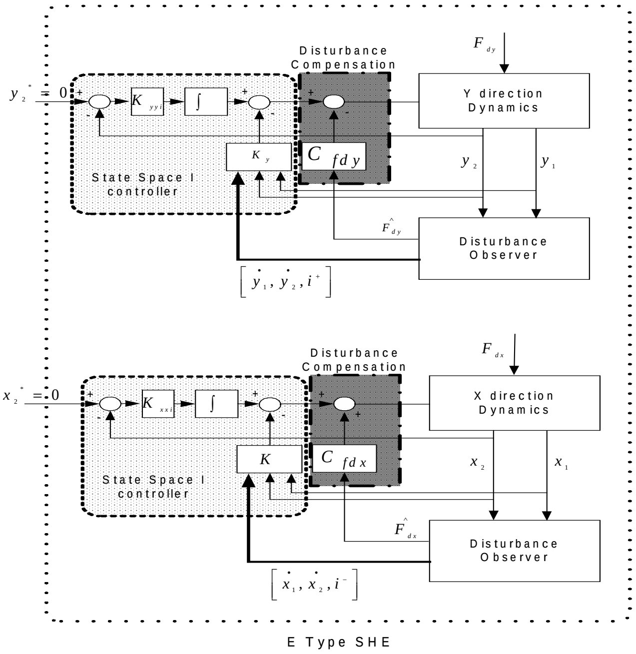

Figure.7. Control block diagram for an E Type SHE

dynamics are taken account. To develop a centralized control algorithm, it is required to develop centralized dynamic models for each degree of freedom by invoking an axis transformation matrix for mechanical part and a current transformation matrix for electrical part. An axis transformation matrix defined as following to relate relative axes of the E Type SHEs to the actual axes of the overall system.

$$\begin{bmatrix} \Delta z \\ \Delta \beta \\ \Delta \alpha \\ \Delta \gamma \\ \Delta y \\ \Delta x \end{bmatrix} = \begin{bmatrix} -\frac{1}{3} & -\frac{1}{3} & -\frac{1}{3} & 0 & 0 & 0 \\ \frac{1}{\sqrt{3}} & 0 & \frac{-1}{\sqrt{3}} & 0 & 0 & 0 \\ \frac{1}{3r_e} & \frac{2}{3r_e} & -\frac{1}{3r_e} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{3r_e} & \frac{1}{3r_e} & \frac{1}{3r_e} \\ 0 & 0 & 0 & \frac{-1}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \\ 0 & 0 & 0 & \frac{1}{3} & \frac{-2}{3} & \frac{1}{3} \end{bmatrix} \begin{bmatrix} \Delta g_A \\ \Delta g_B \\ \Delta g_C \\ \Delta \delta_A \\ \Delta \delta_B \\ \Delta \delta_C \end{bmatrix} \tag{21}$$

The current transformation matrix is derived a similar manner to the axes transformation matrix as following;

$$\begin{bmatrix} \Delta i_z \\ \Delta i_\beta \\ \Delta i_\alpha \\ \Delta i_\gamma \\ \Delta i_y \\ \Delta i_x \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ \frac{-r_e\sqrt{3}}{2} & 0 & \frac{r_e\sqrt{3}}{2} & 0 & 0 & 0 \\ \frac{r_e}{2} & -re & \frac{-r_e}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & -r_e & -r_e & -r_e \\ 0 & 0 & 0 & \frac{\sqrt{3}}{2} & 0 & \frac{-\sqrt{3}}{2} \\ 0 & 0 & 0 & \frac{-1}{2} & 1 & \frac{-1}{2} \end{bmatrix} \begin{bmatrix} \Delta i_A^+ \\ \Delta i_B^+ \\ \Delta i_C^+ \\ \Delta i_A^- \\ \Delta i_B^- \\ \Delta i_C^- \end{bmatrix} \tag{22}$$

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

$$\begin{aligned} F_z &= 3K_{yy}\Delta z + K_{yi}\Delta i_z & \Delta v_z &= L_o \Delta \dot{i}_z + R\Delta i_z + 6S_v \Delta \dot{z} \\ F_\beta &= \frac{3r_e^2 K_{yy}}{2}\Delta \beta + K_{yi}\Delta i_\beta & \Delta v_\beta &= L_o \Delta \dot{i}_\beta + R\Delta i_\beta + 3r_e^2 S_v \Delta \dot{\beta} \\ F_\alpha &= \frac{3r_e^2 K_{yy}}{2}\Delta \alpha + K_{yi}\Delta i_\alpha & \Delta v_\alpha &= L_o \Delta \dot{i}_\alpha + R\Delta i_\alpha + 3r_e^2 S_v \Delta \dot{\alpha} \\ F_\gamma &= -3r_e^2 K_{xx}\Delta \gamma + K_{xi}\Delta i_\gamma & \Delta v_\gamma &= L_o \Delta \dot{i}_\gamma + R\Delta i_\gamma + 6r_e^2 S_h \Delta \dot{\gamma} \\ F_y &= -\frac{3}{2}K_{xx}\Delta y + K_{xi}\Delta i_y & \Delta v_y &= L_o \Delta \dot{i}_y + R\Delta i_y + 3S_h \Delta \dot{y} \\ F_x &= -\frac{3}{2}K_{xx}\Delta x + K_{xi}\Delta i_x & \Delta v_z &= L_o \Delta \dot{i}_x + R\Delta i_x + 3S_h \Delta \dot{x} \end{aligned} \tag{23}$$

Then combining these force equations with vibration isolation stage will give the each degree of freedom's dynamic equations similar to (20). By using state space I control algorithm, each degree of freedom is controlled independently.

To evaluate effectiveness of the aforementioned control algorithms, a series of simulation studies are carried out for each degree of freedom. In many cases, dominant vibration and disturbance sources are direct disturbance sources. Therefore, in simulation studies, this point has been kept in mind and simulations are carried out for periodic direct disturbance excitations. For each degree of freedom, the period of the disturbances are same (0.5sec) meanwhile the magnitudes are different. In figures, equilibrium deviations are illustrated to give insight of overshoot and undershoot.

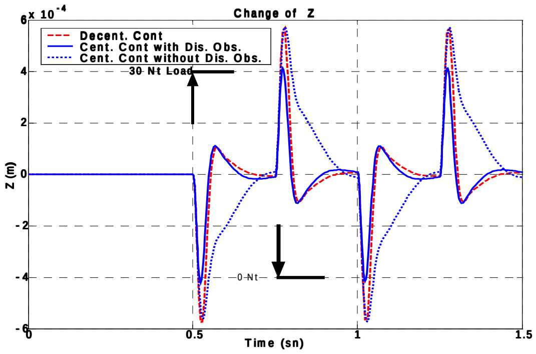

Figure.8. Change of z_2 under periodic direct disturbance

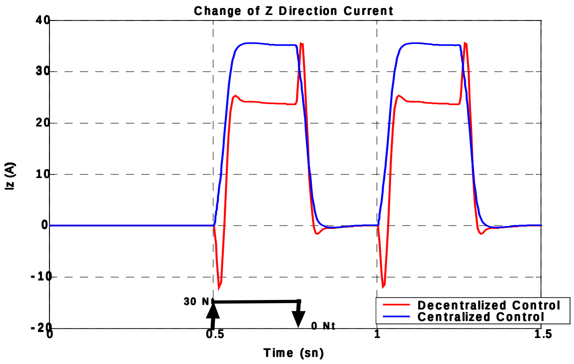

Figure.9. Change of Δi_z under periodic direct disturbance

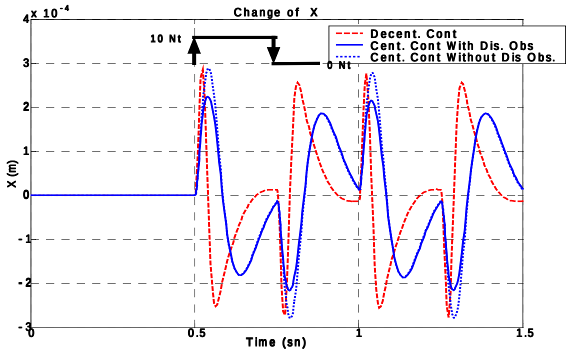

Figure.10. Change of x_2 under periodic direct disturbance

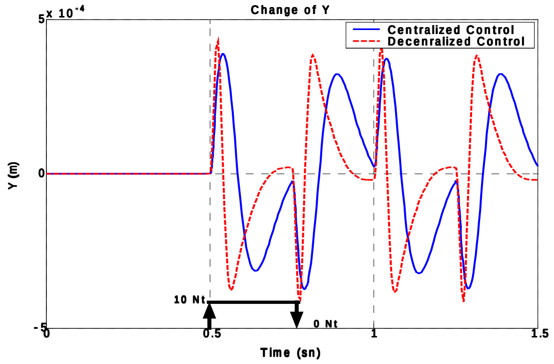

Figure.11. Change of y_2 under periodic direct disturbance

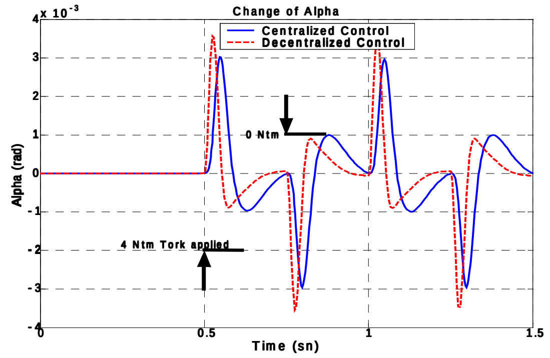

Figure.12. Change of α_2 under periodic direct disturbance

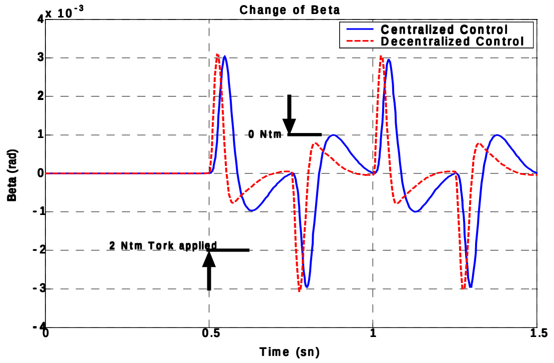

Figure.13. Change of β_2 under periodic direct disturbance

7. Conclusion and Future Studies

In this paper, we firstly introduced a novel E Type SHE, which has the two degrees of freedom control capability for vibration and disturbance isolation purposes. Secondly, described 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.

Two control approaches, centralized and decentralized, were investigated for 6 degrees of freedom control purposes through simulation studies by employing zero order disturbance observers. As we see from the simulation studies employment of centralized control approach, mainly, improves the system's isolation performance and reduces the peak values of overshoots. Furthermore, employment of disturbance observer gives superiority to the isolation property of the system.

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.

In this paper our analysis method is based on linearized model of the electrical and mechanical parts of the system. However, if we closely investigate system equations there is a great coupling effect between horizontal and vertical force equations and also inherently, mechanical components have nonlinear properties in actual case. Moreover, as a next issue, to extend operation range and improve the performance of the system, we are planning to study compensation of undesired nonlinear effects by employing soft computing techniques.

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