2 Degrees of Freedom Active Vibration Control by Employing E Type Staggered Hybrid Electromagnet

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Abstract-In this paper, a novel active vibration control structure, which uses E Type Staggered Hybrid Electromagnet (E Type SHE) as a single active force generator to get simultaneous lateral and vertical forces, is proposed. Since, E Type SHE is a joint configuration of conventional electromagnets and permanent magnets, its control can be handled so as to provide virtual zero power conditions. Control design of the proposed system is investigated by following voltage order type zero power control and passive elements' displacement following gap length type control via employment of state space techniques. Application of the state space techniques surely depends on the availability of the state variables. However, for some practical reasons, instead of measuring all state variables the reconstruction of the immeasurable state variables from the measurable ones have been preferred. To obtain the immeasurable state knowledge, a design procedure of decoupled observers is outlined. To verify the active vibration isolation and control property of the introduced system, some simulation studies are carried out.

I. INTRODUCTION & MOTIVATION

Many high precision manufacturing assemblies require vibration and disturbance isolation units 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 an E Type SHE is employed as a single unit force actuator to obtain simultaneous both lateral and vertical force values. Due to usage of permanent magnets in the construction of the E Type SHE, 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.[2][3] In this study, we have preferred to the employment of state space based voltage order type zero power control algorithm. However zero-power control based active vibration control system shows weakness especially over the low frequency excitation of the direct disturbance force. Here, we have introduced passive elements displacement following state space control technique to eliminate aforementioned weakness.

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 for each one of the axes. Since, the well-known linear 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 E Type SHE are simply explained and its conjunction with active vibration control and isolation system is illustrated. Then, for the proposed active vibration control system, zero power and gap length type control algorithms are developed. Moreover, the decoupled observers' design procedures are expressed in logical manner. Finally, some numerical simulations are carried out by using Matlab & Simulink packages and the results are discussed.

II. E TYPE SHE

Electromagnets based on staggered separation have been used extensively for many transportation applications since they can provide simultaneous lifting and guiding force. By keeping in mind this property of the staggered electromagnets, we would like to introduce E Type SHE not only to invoke the inherited feature of the staggered arrangement but also the advantage of integration of permanent magnets into magnet structure, which can help us to reduce power consumption and magnet size as well. Principle configuration of the proposed E Type SHE is given in Figure 1.

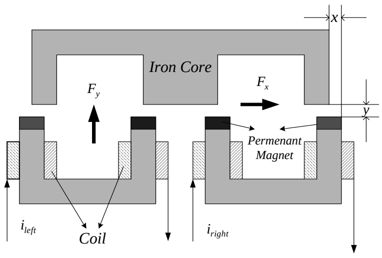

Figure 1. Principle configuration of E Type SHE.

To precisely define the lateral and vertical force values, a 2 dimensional FEM (Finite Element Method) analysis is carried out. The magnetic flux density map of the FEM analysis for nominal operation point is given in Fig. 2.

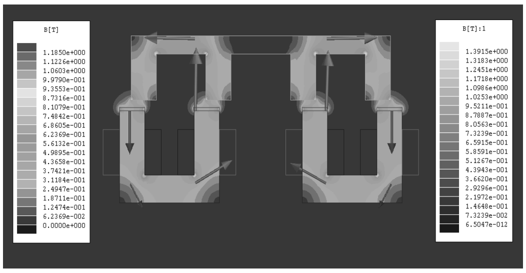

Figure 2. E Type SHE's magnetic flux density map from FEM analysis.

The FEM analysis result suggests that the analytical force expressions can be developed by assuming E Type SHE is comprised of two individual U Type staggered electromagnets. To derive analytical expressionss for the forces, mainly two ways, Schwards-Chrisstofell transformation approach and reluctance tube method, can be followed.[1] The forces are the nonlinear functions of lateral & vertical displacements and as well as the magnet coil currents. Change of lateral and vertical forces for displacements are illustrated in Fig. 3 and Fig. 4., respectively.

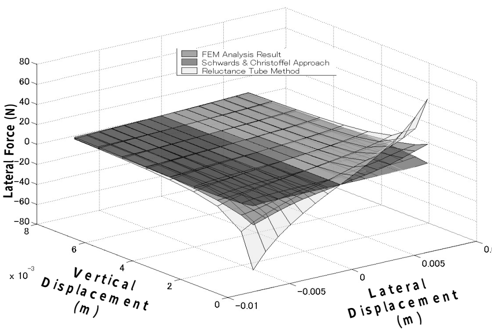

Figure 3. Change of lateral force for lateral and vertical displacement variations

III. COMBINATION OF E TYPE SHE WITH PASSIVE VIBRATION ISOLATION ELEMENTS

Passive vibration isolation elements such as springs and dampers have been extensively used in many applications up to now. However, passive element based systems are fixed structure systems and they cannot adapt themselves to various operation conditions.

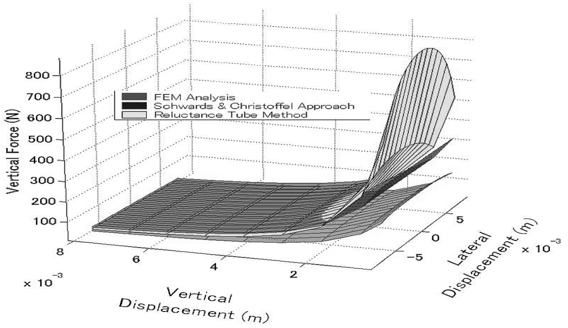

Figure 4. Change of vertical force for lateral and vertical displacement variations

Also, they cannot easily break through the inherited conflict of the vibration isolation and control systems. However, if passive elements are jointly used with active elements, force actuators, the system performance is increased and adaptation to numerous operation conditions is handled with ease. From this point of view, we have been taking into account a joint configuration of E Type SHE with passive elements as seen in Fig. 5.

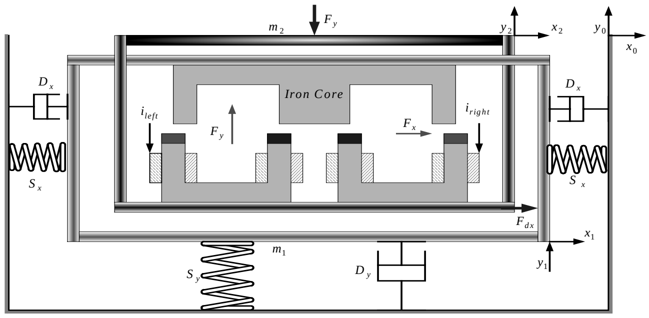

Figure 5. Fundamental joint configuration of E Type She with passive elements.

Dynamics of the system can be developed by following manner;

$$m_1 \ddot{x}_1 = F_x - F_{Sx} - F_{Dx} \tag{1}$$

$$m_2 \ddot{x}_2 = -F_x + F_{dx} \tag{2}$$

$$m_1 \ddot{y}_1 = -F_y - F_{Sy} - F_{Dy} \tag{3}$$

$$m_2 \ddot{y}_2 = F_y - F_{dy} \tag{4}$$

To design a controller by using linear state space techniques, it is indispensable to linearize force equations in the region of equilibrium for mall excursions. The linearized force equations are developed as;

$$F_x = K_x (x_2 - x_1) + K_{ix} i^- \tag{5}$$

$$F_y = K_y (y_2 - y_1) + K_{iy} i^+ \tag{6}$$

$$i^- = i_{right} - i_{left} \quad \Rightarrow \quad v^- = v_{right} - v_{left} \tag{7}$$

$$i^+ = i_{right} + i_{left} \quad \Rightarrow \quad v^+ = v_{right} + v_{left} \tag{8}$$

From the above expressions, we can conclude that the difference of the currents can control lateral force while the summation of the currents will give rise to control of vertical force. By taking relative displacements and velocities as state variables, Y-axis dynamics is expressed as follows in the state space form;

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} + \mathbf{B}_1 \mathbf{u} \tag{9}$$

$$\mathbf{x} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \end{bmatrix},\ u = v^+,\ \mathbf{u}_d = \begin{bmatrix} F_{dy} \\ \ddot{y}_0 \end{bmatrix},\ \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1/L \end{bmatrix},\ \mathbf{B_1} = \begin{bmatrix} 0 & 0 \\ 0 & -1 \\ 0 & 0 \\ 1/m_2 & 0 \\ 0 & 0 \end{bmatrix} \tag{10}$$

$$\mathbf{A}=\begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -\dfrac{S_y}{m_1} & -\dfrac{D_y}{m_1} & \dfrac{K_y}{m_1} & 0 & \dfrac{-K_{iy}}{m_1} \\ 0 & 0 & 0 & 1 & 0 \\ -\dfrac{S_y}{m_1} & -\dfrac{D_y}{m_1} & \dfrac{K_y(m_1+m_2)}{(m_1\cdot m_2)} & 0 & \dfrac{-K_{iy}(m_1+m_2)}{(m_1\cdot m_2)} \\ 0 & 0 & 0 & \dfrac{K_y}{K_{iy}} & -\dfrac{R}{L} \end{bmatrix} \qquad (11)$$

In the same manner, X-axis dynamics can be written in state space form.

IV. CONTROLLER DESIGN

Since E Type SHE has been constructed by using permanent magnets, it is possible to apply zero power based control algorithms. One of the techniques of building up zero power controllers is to extend state space equations by integral of the coil voltage, so called voltage order type zero power control. The voltage extended state space equations of Y-axis is as follows;

$$\frac{d}{dt}\begin{bmatrix} \mathbf{x} \\ \int(0-v^{+})dt \end{bmatrix}=\begin{bmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & 0 \end{bmatrix}\begin{bmatrix} \mathbf{x} \\ \int(0-v^{+})dt \end{bmatrix}+\begin{bmatrix} \mathbf{B} \\ -1 \end{bmatrix}v^{+}+\begin{bmatrix} \mathbf{B}_1 \\ \mathbf{0} \end{bmatrix}\begin{bmatrix} F_{dy} \\ \ddot{y}_0 \end{bmatrix} \qquad (12)$$

By using one of the well-known pole placement techniques, stabilizing zero power controller designed. Zero power control by itself can give negative stiffness and serial combination of this negative stiffness with appropriate positive stiffness element such as spring can perfectly isolate vibrations.[3] However, the success of this technique is highly relevant on the equalization of negative and positive stiffness elements, especially for low frequency excitations of the direct forces. In practical applications, it is almost impossible to get equalization constraint in appropriate manner. Yet, the idea behind zero power based active vibration can be still used by some modifications. If the gap length of the electromagnet can follow passive elements' displacements then equalization constraint is to be realized automatically. This approach can be implemented with a state space integral control algorithm easily. As in the case zero power controller design, state space equations are extended by integral term of the gap length as;

$$\mathbf{C}=\begin{bmatrix} 0 & 0 & 1 & 0 & 0 \end{bmatrix} \qquad (13)$$

$$\frac{d}{dt}\begin{bmatrix} \mathbf{x} \\ \int(r-q_3)dt \end{bmatrix}=\begin{bmatrix} \mathbf{A} & \mathbf{0} \\ -\mathbf{C} & 0 \end{bmatrix}\begin{bmatrix} \mathbf{x} \\ \int(r-q_3)dt \end{bmatrix}+\begin{bmatrix} \mathbf{B} \\ 0 \end{bmatrix}v^{+}+\begin{bmatrix} \mathbf{B}_1 \\ \mathbf{0} \end{bmatrix}\begin{bmatrix} F_{dy} \\ \ddot{y}_0 \end{bmatrix} \qquad (14)$$

The passive elements' displacement is inserted to control path for integral control as a reference trajectory,.

Frequency responses of the disturbances to upper mass displacement is given in Fig. 6~7. For the isolation of direct disturbances, the proposed approach shows better performance then zero power-controlled system, especially for low frequency region. In high frequency region, their responses are almost identical to each other. As we see from Fig. 6., isolation performance of zero power controller and gap length type controller are nearly equivalent to each other for base perturbations except for some anti-resonance peak occurred 7~9 Hz..

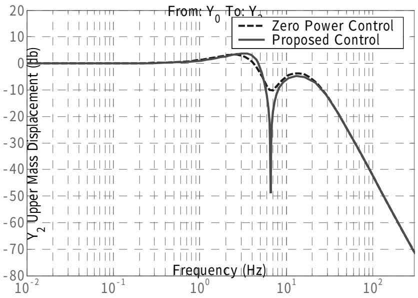

Figure 6. Frequency response; from base disturbance to upper mass displacement.

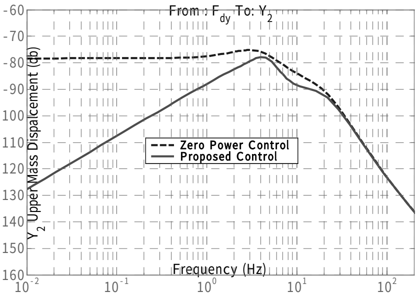

Figure 7. Frequency response; from direct disturbance to upper mass displacement

V. DECOUPLED OBSERVER DESIGN

Since we have integrated state space control approach into our system, it is indispensable to get full state knowledge. For some practical reasons it is almost impossible to measure all state variables by employing sensors. Thereby, we will outline a decoupled observers design technique here after. In maglev control systems, gap clearance sensor and current sensor are inevitable measurement sensors. We will adapt these measurements into our system. For motion sensing, accelerometers will be used both for upper masses and lower masses of each axis. However, by inserting these measurements inside well-known linear observer design procedure, the observability conditions cannot be fully meet. Hence, these measurements are only to be used to reconstruct immeasurable state knowledge. The gap velocity of the E Type SHE for Y-axis can be observed by using following state dynamics;

$$\frac{d}{dt}\begin{bmatrix} q_3 \\ q_4 \\ i^{+} \end{bmatrix}=\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & \dfrac{K_y}{K_{iy}} & \dfrac{-R}{L} \end{bmatrix}\begin{bmatrix} q_3 \\ q_4 \\ i^{+} \end{bmatrix}+\begin{bmatrix} 0 & 0 & 0 \\ 1 & -1 & 0 \\ 0 & 0 & \dfrac{1}{L} \end{bmatrix}\begin{bmatrix} \ddot{y}_1 \\ \ddot{y}_2 \\ v^{+} \end{bmatrix} \qquad (15)$$

$$y=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} q_3 \\ q_4 \\ i^{+} \end{bmatrix} \qquad (16)$$

The displacement of passive elements can be numerically calculated by assuming that passive elements' properties are not changing too much around predefined operation region.

$$\overline{q_1}=\left(K_{iy}i^{+}-m_1s^2y_1-K_yq_3\right)\big/\left(sD_y+S_y\right) \qquad (17)$$

Then to get passive elements velocity, following observer dynamics defined;

$$\frac{d}{dt}\begin{bmatrix}\overline{q_1}\\ q_2\\ \ddot{y}_0\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & -1\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\overline{q_1}\\ q_2\\ \ddot{y}_0\end{bmatrix}+\begin{bmatrix}0\\ 1\\ 0\end{bmatrix}\ddot{y}_1 \tag{18}$$

$$y=\begin{bmatrix}1 & 0 & 0\end{bmatrix}\begin{bmatrix}\overline{q_1}\\ q_2\\ \ddot{y}_0\end{bmatrix} \tag{19}$$

By placing the observer poles much faster than the system poles, state observation issue is solved. To investigate feasibility of the proposed system some simulation studies are carried out.

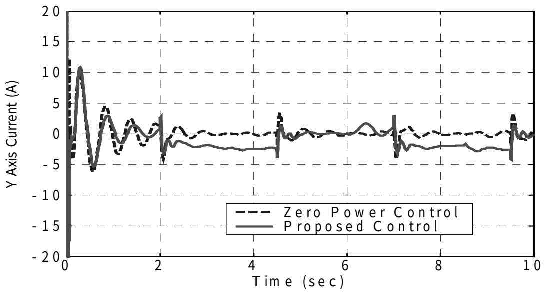

Figure 8. Change of Y Axis Current.

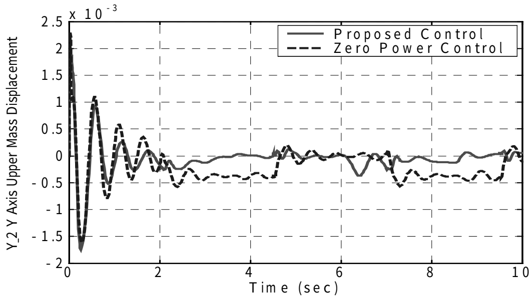

Figure 9. Time response for Y axis upper mass displacement.

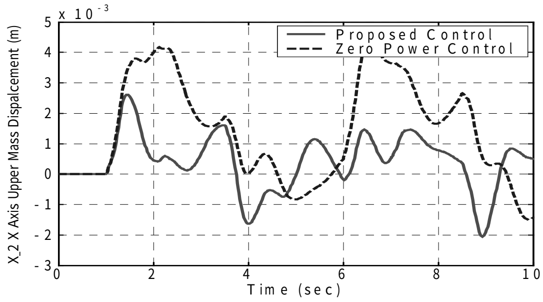

Figure 10. Time response for X axis upper mass displacement.

In simulations, two simultaneous periodic direct disturbance force applied to both X and Y-axis at 1sec. 0.75 N amplitude and at 2 sec 3 N amplitude, respectively. From Fig. 8. we see that in zero power control mode, the current converges to zero readily, on the other hand, the time response of the upper mass displacements gets worsen as we compared with gap length type controller. Effectiveness of the proposed control approach also can be recognized from Fig. 10. that this approach not only increase the system performance over the zero power based counterpart but also it does eliminates the force interactions in some level. Proposed observer design procedure can overcome the sensor issue in the case of there is no big change in passive elements' characteristics. The estimated and actual value of the passive elements displacement is given in Fig. 11.

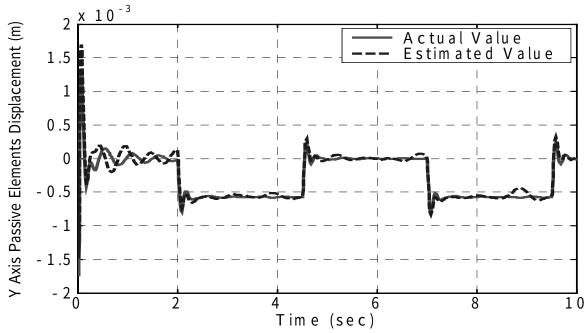

Figure 11. Time history of estimated and actual value of passive elements displacement.

VI. CONCLUSIONS

In this paper, we have proposed a novel E Type SHE joint with passive elements for active vibration control purposes. Since, permanent magnets are embedded into E Type SHE, zero power based control algorithm have been employed. However, we have seen from numerical studies, zero power based approach has showed weakness especially in the low frequency excitations of the direct disturbance forces. To cope with this difficulty, we have proposed passive elements displacement following gap length type controller. Proposed controller is not only eliminates the weakness of the zero power controller but also it does increase the highly coupled system performance for each axis. The investigated control algorithms use the state space techniques; therefore sensor selection is one of the significant issues. To overcome this problem, the decoupled observer design procedures are introduced and their effectiveness are verified by numerical studies.

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