Fuzzy Model Based Nonlinear Control of an Active Oscillation Suppression System Comprised of Mechanically Flexible Elements and Triple Configuration of U-Shaped Electromagnets

K. Erkan* and T. Koseki**

* The University of Tokyo/Graduate School of Engineering/Department of Electrical Eng., Tokyo, Japan

** The University of Tokyo/School of Engineering/ Department of Information & Communication Eng., Tokyo, Japan

erkan@koseki.t.u-tokyo.ac.jp

koseki@koseki.t.u.-tokyo.ac.jp

***Abstract*—The objective of this paper is to introduce a TSK (Takagi-Sugeno-Kang) fuzzy model-based servo control design approach for an active oscillation suppression stage using triple configuration of hybrid electromagnets as active force generators. Furthermore, the authors apply zero order disturbance observers to estimate not only velocities but also equivalent external disturbance acting on gap clearance of hybrid electromagnet. Validity of the proposed method is verified through experimental studies.**

I. Introduction

Active oscillation suppression systems, especially equipped with electromagnetic suspension mechanisms, have some inherited merits such as contact and dust-free operation and only electrical power source necessity. Thereby, they have a great potential to satisfy recent demands of industrial applications ranging from high precision control & measurement to clean room prerequisites.

The principle structure of the active oscillation suppression system dealt with in this paper is depicted in Fig. 1. The system integrates permanent magnets into structure of electromagnet not only to overcome gravity bias but also to reduce the electromagnet size [1-5-8]. To obtain a more stable and realizable oscillation suppression system, employment of more than one electromagnet is indispensable [8]. Hence, not only full redundancy but also multiple degrees of freedom oscillation suppression capability can be achieved. To attain this goal, symmetrically arranged triple configuration of the U-shaped hybrid electromagnets has been proposed as seen in Fig. 2 [5-6-7]. Passive oscillation suppression systems comprised of springs and dampers can inherently attenuate disturbance effects only tuned operating area [4]. However, their combination with active elements, force generators, provides much more flexibility and effectively breaks through conflicts arising from fixed structure.

Two external disturbance sources, namely direct disturbance force, F_d, and base excitations, x_0, induce undesired oscillations on upper mass, m_2, of the system.

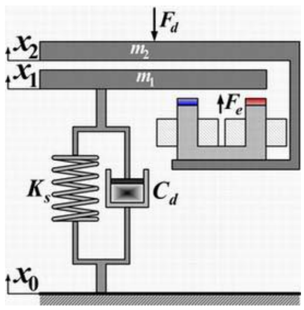

Figure 1. Fundamental structure of active oscillation suppression system equipped with a U-shaped hybrid electromagnet

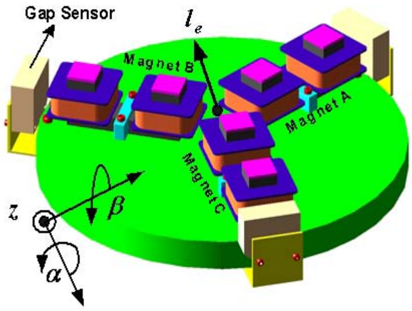

Figure 2. Symmetrically arranged triple configuration U-shaped hybrid electromagnets.

An active control strategy should reduce such effects while satisfying safe and comfortable levitation of the system.

II. Fundamentals of The System

By assuming that there is no leakage fringing flux over the poles of hybrid electromagnet and reluctance of the iron core is ignorable, developed electromagnetic attraction force between U-shaped hybrid electromagnet and iron bar located under middle mass, m_1, is derived from Maxwell's equations of electromagnetic theory by [1];

$$F_e = k\left(\frac{I_f + I_m}{x + L_m/\mu_m}\right)^2 \quad (1)$$

where, k represents attractive force coefficient which has close connection with physical configuration of hybrid electromagnet, I_m indicates equivalent current source interpretation value of permanent magnet, I_f and x stand for coil current and equivalent gap clearance, respectively and L_m & μ_m correspond to permanent magnet length and relative permeability, respectively. Motion dynamics of fundamental structure depicted in Fig. 1 is obtained as;

$$m_1\ddot{x}_1 = -F_e - K_s(x_1 - x_0) - C_d(\dot{x}_1 - \dot{x}_0) - m_1 g \quad (2)$$

$$m_2\ddot{x}_2 = F_e - F_d - m_2 g \quad (3)$$

The system dynamics shows nonlinear feature due to nonlinearity involved in electromagnetic force of hybrid electromagnet. To design a controller from perspective of linear control theory, linearization process is carried out as indicated by;

$$K_a = -\frac{\partial F_e}{\partial(x_1 - x_2)} = 2k\frac{(I_f + I_m)^2}{((x_1 - x_2) + L)^3}\Bigg|_{\substack{x_1 = x_{10} \\ x_2 = x_{20} \\ I_f = I_{f0}}} \quad (4)$$

$$K_b = \frac{\partial F_e}{\partial I_f} = 2k\frac{(I_f + I_m)}{((x_1 - x_2) + L)^2}\Bigg|_{\substack{x_1 = x_{10} \\ x_2 = x_{20} \\ I_f = I_{f0}}} \quad (5)$$

$$F_e(x_1, x_2, I_f) \cong F_{e0}(x_{01}, x_{20}, I_{f0}) - K_a(\Delta x_1 - \Delta x_0) + K_b \Delta I_f \quad (6)$$

Subsequently, linearized system dynamics is obtained for the fundamental structure given in Fig. 1 as following;

$$m_1\Delta\ddot{x}_1 = K_a(\Delta x_1 - \Delta x_2) - K_b\Delta I_f - K_s(\Delta x_1 - \Delta x_0) - C_d(\Delta\dot{x}_1 - \Delta\dot{x}_0) \quad (7)$$

$$m_2\Delta\ddot{x}_2 = -K_a(\Delta x_1 - \Delta x_2) + K_b\Delta I_f - F_d \quad (8)$$

$$\frac{d\Delta I_f}{dt} = \frac{K_a}{K_b}(\Delta\dot{x}_1 - \Delta\dot{x}_2) - \frac{R}{L}\Delta I_f + \frac{1}{L}\Delta v \quad (9)$$

Dynamics of the multiple degrees of freedom system is developed by defining proper transformation matrices. Local displacements, x_1 & x_2, of hybrid electromagnets, *A, B* and *C* are converted to global ones by employing displacement transformation matrix.

$$\begin{bmatrix} z \\ \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{2}{3l_e} & -\frac{1}{3l_e} & -\frac{1}{3l_e} \\ 0 & \frac{1}{\sqrt{3}l_e} & -\frac{1}{\sqrt{3}l_e} \end{bmatrix} \begin{bmatrix} x_A \\ x_B \\ x_C \end{bmatrix} = \mathbf{T}\begin{bmatrix} x_A \\ x_B \\ x_C \end{bmatrix} \quad (10)$$

Accordingly, local coil currents of the hybrid electromagnets and developed local attraction forces are converted to global ones utilization of following transformation matrices, respectively;

$$\begin{bmatrix} i_z \\ i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ 1 & -\frac{1}{3} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \mathbf{H}\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} F_{ez} \\ F_{e\alpha} \\ F_{e\beta} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ l_e & -\frac{l_e}{2} & -\frac{l_e}{2} \\ 0 & \frac{\sqrt{3}}{2}l_e & -\frac{\sqrt{3}}{2}l_e \end{bmatrix} \begin{bmatrix} F_{eA} \\ F_{eB} \\ F_{eC} \end{bmatrix} = \mathbf{F}\begin{bmatrix} F_{eA} \\ F_{eB} \\ F_{eC} \end{bmatrix} \quad (12)$$

After some tedious manipulations, eventually, dynamics of overall multiple degrees of freedom system is obtained as;

$$M_2\Delta\ddot{z}_2 = K_{az}(\Delta z_2 - \Delta z_1) + K_{bz}\Delta i_z - F_{dz} \quad (13)$$

$$J_{\alpha 2}\Delta\ddot{\alpha}_2 = K_{a\alpha}(\Delta\alpha_2 - \Delta\alpha_1) + K_{b\alpha}\Delta i_\alpha - F_{d\alpha} \quad (14)$$

$$J_{\beta 2}\Delta\ddot{\beta}_2 = K_{a\beta}(\Delta\beta_2 - \Delta\beta_1) + K_{b\beta}\Delta i_\beta - F_{d\beta} \quad (15)$$

$$M_1\Delta\ddot{z}_1 = -K_{az}(\Delta z_2 - \Delta z_1) - K_{bz}\Delta i_z - K_{sz}(\Delta z_2 - \Delta z_1) - C_{dz}(\Delta\dot{z}_2 - \Delta\dot{z}_1) \quad (16)$$

$$J_{\alpha 1}\Delta\ddot{\alpha}_1 = -K_{a\alpha}(\Delta\alpha_2 - \Delta\alpha_1) - K_{b\alpha}\Delta i_\alpha - K_{s\alpha}(\Delta\alpha_2 - \Delta\alpha_1) - C_{d\alpha}(\Delta\dot{\alpha}_2 - \Delta\dot{\alpha}_1) \quad (17)$$

$$J_{\beta 1}\Delta\ddot{\beta}_1 = -K_{a\beta}(\Delta\beta_2 - \Delta\beta_1) - K_{b\beta}\Delta i_\beta - K_{s\beta}(\Delta\beta_2 - \Delta\beta_1) - C_{d\beta}(\Delta\dot{\beta}_2 - \Delta\dot{\beta}_1) \quad (18)$$

$$\frac{d\Delta I_{fz}}{dt} = \frac{K_{az}}{K_{bz}}(\Delta\dot{z}_1 - \Delta\dot{z}_2) - \frac{R_z}{L_z}\Delta I_{fz} + \frac{1}{L_z}\Delta v_z \quad (19)$$

$$\frac{d\Delta I_{f\alpha}}{dt} = \frac{K_{a\alpha}}{K_{b\alpha}}(\Delta\dot{\alpha}_1 - \Delta\dot{\alpha}_2) - \frac{R_\alpha}{L_\alpha}\Delta I_{f\alpha} + \frac{1}{L_\alpha}\Delta v_\alpha \quad (20)$$

$$\frac{d\Delta I_{f\beta}}{dt} = \frac{K_{a\beta}}{K_{b\beta}}(\Delta\dot{\beta}_1 - \Delta\dot{\beta}_2) - \frac{R_\beta}{L_\beta}\Delta I_{f\beta} + \frac{1}{L_\beta}\Delta v_\beta \quad (21)$$

III. LINEAR CONTROLLER & DISTURBANCE OBSERVER DESIGN

Close investigation of (13)-(21) reveals that the system shows instable characteristic in open loop. Therefore, one of the most central issues is to satisfy stability conditions.

Since, the system employs hybrid electromagnets as active force generators, designing a zero power controller could be a solution. Hence, in steady state, input power converges to zero in theoretical sense. Furthermore, this approach can be consistent with active oscillation suppression aim [4].

The function of the hybrid electromagnets in the active oscillation suppression system is mainly to attribute adjustable damping and stiffness property between upper and middle mass, m_1 & m_2, so that, suppression of the oscillations can be achieved easily. Zero power controlled hybrid electromagnet behaves like a negative stiffness element when it is disturbed by a payload mass, namely, gap clearance of the hybrid electromagnet gets smaller. Serial connection of a negative and positive stiffness element results in infinite stiffness. Thus, oscillations imposed by base transmission and direct form are eliminated effectively. This is the basic idea proposed in [4].

On the one hand, a damper would be inserted parallel to positive stiffness element, spring, due to time delay of control signal in order to damp oscillation energy. On the other hand, it is necessary inclusion of a middle mass representing ferromagnetic material to successfully achieve levitation. Eventually, structure of the system will be different from ideal shape due to addition of middle mass and a damper. Another issue is the availability of a perfect positive stiffness element which can equalize its positive stiffness to negative stiffness of hybrid electromagnet in all operating area. (1) suggests that the positive stiffness element should show a nonlinear positive stiffness behavior.

In this paper, to relax and partially eliminate the outlined pitfalls of the zero power based active vibration control; servo gap clearance control approach has been proposed. In this approach, basic idea has the same roots as proposed in [4], that is, equalization of positive and negative stiffness of respective system components. To achieve equalization, gap clearance of the hybrid electromagnet should track displacement of passive elements, parallel connected spring and damper. Hence, designing a servo gap controller which eliminates steady state error via integral action is rationale. Besides, control design needs proper selection of measurement sensors. It is one of the most significant restrictions that absolute displacement sensors are unavailable, while relative ones have been under exploitation. Although, by double integration stage, absolute displacements can be reconstructed from accelerometer outputs, they induce additional problems such as drift and noise sensitivity. From this point of view, here, usage of relative displacement sensors will be under discussion. Due to having relatively higher degree in system equations, it has been preferred to follow modern control methods rather than conventional ones. This dictates availability of overall state variables. Yet, owing to cost and impracticality, velocity meters are disregarded. Under such circumstances, the basic observability analysis results in unobservability of the system due to two explicit external disturbance sources for a disturbance observer design. To overcome such a difficulty, dynamics of the mechanical part is ignored, namely it is assumed that control of gap clearance is essential issue, due to role of the hybrid electromagnet in suppression of induced vibrations. This suggests solely hybrid electromagnet control which leads to observable form. In this case, further assumption is necessary that designed disturbance observer can estimate disturbances acting upon gap of hybrid electromagnets. Gap length type servo controller is formulized as follows via extension of reduced system equations via integral of tracking error for fundamental structure given in Fig. 1.

$$\dot{\mathbf{x}}_{ce} = \frac{d}{dt}\begin{bmatrix} \Delta x_1 - \Delta x_2 \\ \Delta \dot{x}_1 - \Delta \dot{x}_2 \\ \Delta I_f \\ \int \left((\Delta x_1 - \Delta x_0) - (\Delta x_1 - \Delta x_2) \right) dt \end{bmatrix} \tag{22}$$

$$\mathbf{A}_{ce} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{K_a}{m_2} & 0 & -\frac{K_b}{m_2} & 0 \\ 0 & \frac{K_a}{K_b} & -\frac{R}{L} & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \tag{23}$$

$$\mathbf{B}_{ce} = \begin{bmatrix} 0 & 0 & \frac{1}{L} & 0 \end{bmatrix}^T \tag{24}$$

$$\mathbf{C}_{ce} = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \tag{25}$$

$$\dot{\mathbf{x}}_{ce} = \mathbf{A}_{ce}\mathbf{x}_{ce} + \mathbf{B}_{ce}\Delta v \tag{26}$$

$$y_{ce} = \mathbf{C}_{ce}\mathbf{x}_{ce} \tag{27}$$

For (26), feedback gains are determined by utilizing one of the standard pole placement techniques. To reconstruct the immeasurable states, velocity and current, a zero order disturbance observer is designed by extending reduced system equations.

$$\dot{\hat{\mathbf{x}}}_{oe} = \frac{d}{dt}\begin{bmatrix} \Delta \hat{x}_1 - \Delta \hat{x}_2 \\ \Delta \dot{\hat{x}}_1 - \Delta \dot{\hat{x}}_2 \\ \Delta \hat{I}_f \\ \hat{F}_{de} \end{bmatrix} \tag{28}$$

$$\mathbf{A}_{oe} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{K_a}{m_2} & 0 & -\frac{K_b}{m_2} & 0 \\ 0 & \frac{K_a}{K_b} & -\frac{R}{L} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{29}$$

$$\mathbf{B}_{oe} = \begin{bmatrix} 0 & 0 & \frac{1}{L} & 0 \end{bmatrix}^T \tag{30}$$

$$\mathbf{C}_{oe} = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \tag{31}$$

$$\dot{\hat{\mathbf{x}}}_{oe} = \mathbf{A}_{oe}\hat{\mathbf{x}}_{oe} + \mathbf{B}_{oe}\Delta v \tag{32}$$

Zero order disturbance observer gains are determined by placing poles of observer equations deeper than those of controller in the left hand side of complex plane.

IV. Fuzzy Model-Based Control Design

Stability is one of the most significant issues which must be solved effectively. Linear control designs solve the issue by means of linearization process around a specified equilibrium point for tiny deviations. Thereby, their validity is limited given an equilibrium point.

When the gap clearances of the hybrid electromagnets get away from the specified linearization point, stiffness parameters of the hybrid electromagnets, K_a & K_b, rather than being fixed, they change correspondingly. The basic reason of such a change is the nonlinearity introduced by attraction force. Therefore, comfortable and stable levitation is threatened when wide range of gap clearance operation is desired. To maintain stability and safer operation for wide range of gap clearance change, fuzzy model-based control design approach has been proposed.

In fuzzy model-based control design approach, for admissible pair of operation points, a linearized local model is developed. Aggregation of the linearized local models by fuzzy inference algorithm constructs a fuzzy dynamical model which can represent the actual behavior of the system better than a single linear model. Then, parallel distributed control design methodology comes into action by designing a feedback controller for each one of the linearized local model and threading them fuzzy implications. The final control action is nonlinear in nature and a proper composition of several linear control actions. From this point of view, fuzzy controller performs gain scheduling process. Determination of controller gains is similar to linear controller designs except for construction of eventual control signal via aggregation [2-3].

Application of fuzzy model based control to solely levitation control of hybrid electromagnet can improve the system performance and at the same time allows to operation in wide range of gap clearances [6]. Design process of fuzzy model-based control is relatively easier than those of other nonlinear control techniques since application of linear controller design methodology has central role.

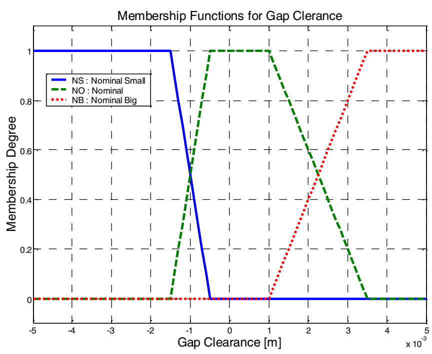

Figure 3. Membership functions for gap clearance.

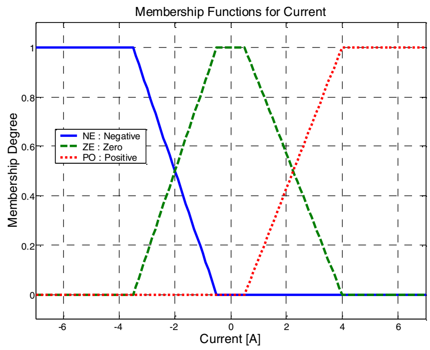

Figure 4. Membership functions for coil current.

In active vibration suppression system using U-shaped hybrid electromagnets as actuators, dominant disturbances acts on vertical axis, z, due to directly gap clearance change is required. To simplify the controller design process, fuzzy model-based control will be fulfilled over this axis. For the control of inclination axes, α & β, linear control design methods will be applied. Furthermore, even though design of an observer from the point view of fuzzy model-based control design theory is possible, to simplify again design process, linear disturbance observer design approach will be followed.

Inputs to the fuzzy controller are current of hybrid electromagnet coil and gap clearance in absolute vertical axis values, z. Membership functions fuzzyfying the crisp values of current and gap clearance are determined in trapezoidal shapes as depicted in Fig. 3-4.

To develop a fuzzy dynamical model, 5 admissible linearization points are selected; therefore, total dynamics of the system will be represented by proper aggregation of those 5 linear local models. Table I summarizes the data pairs of specified linearization points.

After developing linear local models, each one of the linear local model a servo gap controller tracking passive elements displacement is designed as outlined in (22)-(27). To obtain overall state knowledge only for "model 3", which is the nominal model, a zero order disturbance observer design is carried out. The relationship among inputs, current and gap clearance, and outputs, linear local models are built up by a rule base. Table II represents the rule base used in this study. The rule table is interpreted as, for example;

If gap clearance is ***NS*** and current is ***NE*** **then** output model is ***Model 1***.

TABLE I. Linearization Points

($\Delta z_{10} - \Delta z_{20}$) Gap Clearance [m]	(I_{fz0}) Current [A]	Model Number
0.0025	-2.6	1
0.0035	-0.2	2
0.0045	0.0	3
0.0055	0.2	4
0.0065	2.6	5

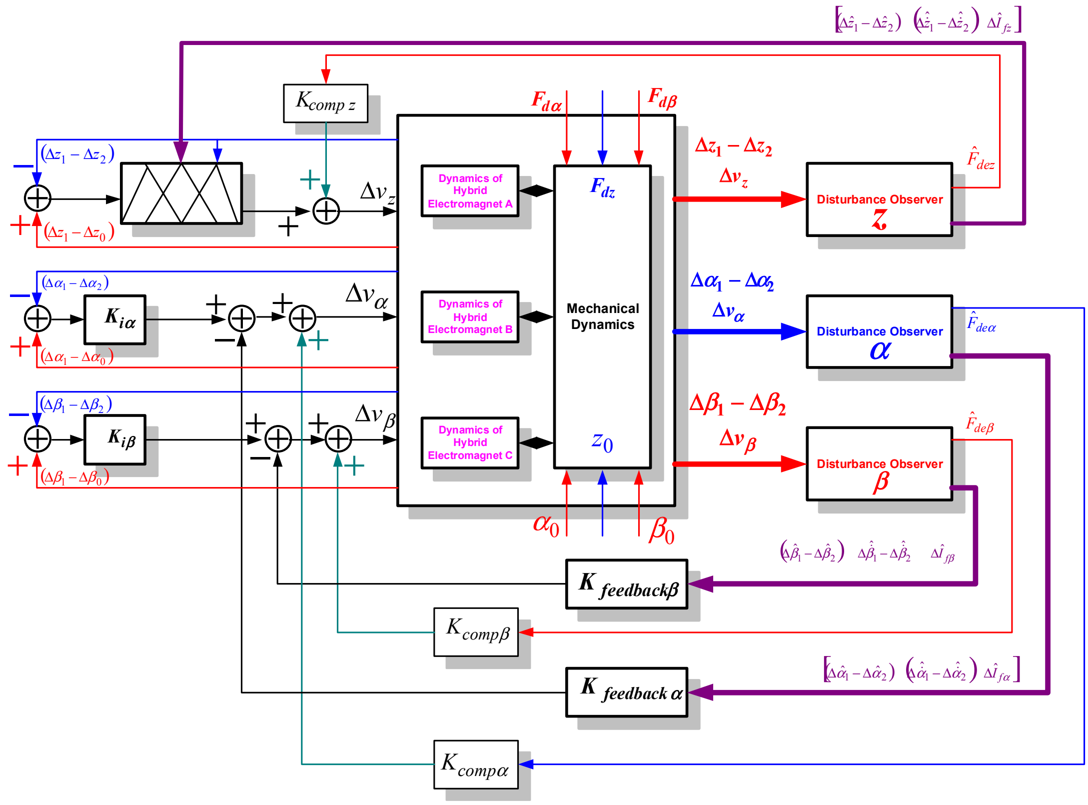

Figure 5. Control block diagram for multiple degrees of freedom system.

TABLE II. RULE BASE

<table>
<tr><td rowspan="2" colspan="2">RULE BASE</td><td colspan="3">Gap Clearance</td></tr>
<tr><td>NS</td><td>NO</td><td>NB</td></tr>
<tr><td rowspan="3">Current</td><td>NE</td><td>Model 1</td><td>Model 4</td><td rowspan="2">Model 4</td></tr>
<tr><td>ZE</td><td rowspan="2">Model 2</td><td>Model 3</td></tr>
<tr><td>PO</td><td>Model 2</td><td>Model 5</td></tr>
</table>

TABLE III. PARAMETERS OF THE TEST BENCH

k [Nm^2/A^2]	1.89×10^{-5}	I_m [A]	13.39
m_1 [kg]	8.500	m_2 [kg]	9.320
$J_{\alpha 1}$ [kgm^2]	0.050	$J_{\alpha 2}$ [kgm^2]	0.045
$J_{\beta 1}$ [kgm^2]	0.056	$J_{\beta 1}$ [kgm^2]	0.049
K_{sz} [N/m]	2941	C_{dz} [N/(m/sec^2)]	17.50
K_{s_α} [Nm/rad]	75.6	C_{d_α} [Nm/(rad/sec^2)]	1.650
K_{s_β} [Nm/rad]	75.6	C_{d_β} [Nm/(rad/sec^2)]	1.650
(z_{10}-z_{20}) [m]	0.00456	I_{fz0} [A]	0

When more than one rule is fired, output models are aggregated by average of weighted sum to yield appropriate modeling behavior.

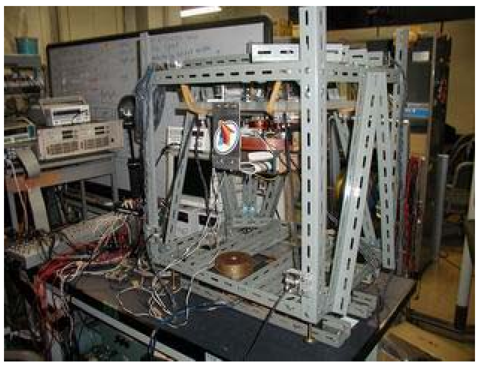

Figure 6. A photo of experimental test bench.

To provide simplicity and consistency in the composition of control actions resulted in firing more than one rule, at the same time average of weighted sum is applied. Overall sketch of outlined control design for a multiple degrees of freedom system is illustrated in Fig. 5.

V. EXPERIMENTAL RESULTS

A test rig as seen in Fig. 6 was constructed to experimentally verify developed fuzzy model-based control approach on the purpose of active oscillation suppression. Parameters of the test bench are tabulated in Table III.

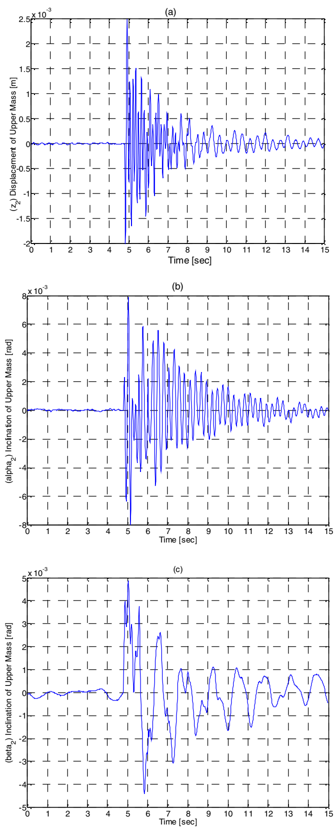

Figure 7. Experimental results of impulsive base excitation. (a) z_2, (b) α_2 and (c) β_2

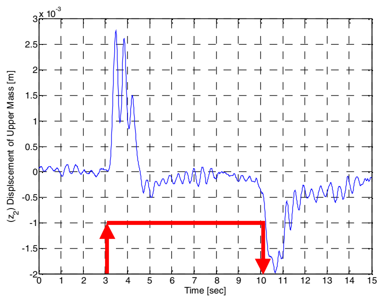

Figure 8. Experimental result of stepwise direct disturbance excitation for vertical axis z_2.

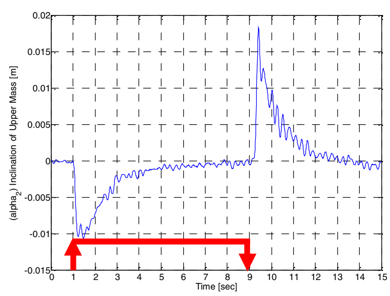

Figure 9. Experimental result of stepwise direct disturbance excitation for inclination axis α_2.

In the first experiment, impulse effects of base disturbance were tested. A 3.4 kg payload is dropped over 3 cm to the flexible base of test rig. Fig. 7. a-c shows the results of this experiment for upper mass, m_2, for vertical and inclination axes. Results reveal that system damps the effect of impulsive base excitations. However, due to relatively small mechanical damping, convergence to zero takes time. Second and third experiments conducted to observe the characteristics of the system under stepwise direct disturbance excitation for vertical axis, z_2, and inclination axis, α_2. Fig. 8-9 depicts the results. From the results, it can be concluded that though there is a difference between negative and positive stiffness of corresponding system components. The proposed servo control approach breaks through this inconsistency. Utilization of fuzzy model based control approach in control design improves the stability and allow to wide range of gap clearance operation.

CONCLUSIONS

In this paper, a fuzzy model-based servo gap control approach which is tracking passive elements' displacement has been proposed to suppress undesired effects of external disturbance sources. Since the system is MIMO, design of fuzzy model-based control approach was handled only for vertical axis to simplify the design, besides it can be extended to other axes. Effectiveness of the proposed control approach is supported by experimental results. Even under stiffness difference between hybrid electromagnet and passive elements, spring and damper, proposed active control method can overcome easily such a difficulty and final values of the displacement and inclinations converge to zero under external disturbance excitations.

REFERENCES

[1]. E. P. Furlani, *Permanent Magnet and Electromechanical Devices*, Academic Press, 2001.

[2]. K. Tanaka and H. O. Wang, *Fuzzy Control Systems Design and Analysis: A Linear Matrix Inequality Approach*, Wiley-Interscience, 2001.

[3]. S. K. Hong and R. Langari, "Robust Fuzzy Control of Magnetic Bearing System Subject to Harmonic Disturbances", *IEEE Transactions on Control Systems Technology*, Vol.08, No.02, pp.366-371, 2000.

[4]. T. Mizuno, M. Takasaki and H. Suzuki, "Application of Zero Power Magnetic suspension to Vibration Isolation, *8th International Symposium on Magnetic Bearing,* Mito, Japan, pp. 151-156, 2002

[5]. Y. Makino, *Six Degrees of Freedom Control Through Three Hybrid Electromagnets and Three Linear Induction Motor for Two Dimensional Conveyance System*, Master Thesis, The University of Tokyo, 2004.

[6]. K. Erkan and T. Koseki, "3 Degrees of Freedom Fuzzy Model Based Nonlinear Control of Triple Configuration of U-Type Hybrid Electromagnets", *The 5th International Symposium on Linear Drives for Industrial Applications,* Awaji, Kobe, Japan, pp. 338-342, Sep. 2005.

[7]. K. Erkan and T. Koseki, "Disturbance Identification Based on Fuzzy Logic for Active Vibration Control Using U Type Hybrid Electromagnet", *The IEE Japan Tech. Meeting on Linear Drives,* LD-04-84-96, Dec. 2004.

[8]. J. Liu and T. Koseki, "3 Degrees of Freedom Semi-Zero-Power Maglev Scheme for Two-Dimensional Linear Motor", *Proceeding of Linear Drives for Industry Applications*, pp.30-35, Oct. 2001.