U 型電磁石を用いた振動抑制能動制御のためのファジー論理に基づく外乱同定

エルカンカディル*, 古関隆章,
(東京大学)

Disturbance Identification Based on Fuzzy Logic for Active Vibration Control Using U Type Electromagnet

Kadir ERKAN*, Takafumi KOSEKI,
(The University of Tokyo)

Abstract:
Maglev based active vibration control and isolation systems yield many merits for numerous industrial applications. Prosperous reduction of undesired effects of vibrations highly depend on precise identification of vibration source characteristics. This paper discusses a disturbance determination technique, which uses a fuzzy logic based hybrid electromagnet's parameter identification scheme and also explains a passive elements' displacement following gap length type control approach of a U type hybrid electromagnet actuated active vibration control system in conjunction with gap clearance velocity observer. The effectiveness of the proposed method is reported based on some simulation study results for simultaneous excitation of a maglev actuated active vibration and isolation system.

Keyword: active vibration control, maglev, parameter identification, fuzzy logic, disturbance identification.

1. Introduction & Motivation:

Many high precision manufacturing assemblies require vibration and disturbance isolation stages to isolate undesired effects of outer disturbance sources. In the past, to accomplish this task, mainly passive type isolation elements, springs and dampers, were employed. Since the vibration and disturbance sources have different natures and also require different arrangements for isolation purposes, 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.

Maglev based actuators have some inherited features which make them superior for some special applications, such as mechanical contact free actuation, fast response, only need for electric power source etc. Furthermore, combination of classical magnetic actuators with permanent magnets not only increases the energy efficiency but also reduces the magnet size and yields a more compact structure. In this paper, we have taken into consideration a system which comprises of passive elements and as well as a U type hybrid electromagnet.

In maglev-actuated systems, vibrations are imposed to the levitating magnetic part by generally two distinct sources, direct disturbance force source and base or support displacements. Successful attenuation of undesired effects of these disturbance sources very much depends on the exact knowledge of disturbance source characteristics. This paper discusses a disturbance determination technique, which uses a fuzzy logic based hybrid electromagnet's parameter identification scheme and also describes a passive elements displacements following gap length type control approach of a U type hybrid electromagnet actuated active vibration control system in conjunction with gap clearance velocity observer. The effectiveness of the proposed method is reported based on a series of simulation study results for simultaneous excitation of a maglev actuated active vibration and isolation system.

2. Fundamentals of U Type Hybrid Electromagnet

An analytical model of a U type hybrid electromagnet can be developed by simply employing Ampere's Law, then the resultant electromagnetic force equation is obtained as;

$$F_e = \frac{B^2}{\mu_0} S = \frac{\mu_0 S N^2}{4} \left(\frac{i + 2H_c L_m / N}{x + L_m / \mu_r} \right)^2 \qquad (1)$$

As we see from above force expression that the electromagnetic force is a nonlinear function of *i* (current) and *x* (gap clearance). Generally, this equation is linearized around an equilibrium point for small deviations to design a control system by using linear control design techniques as;[1][3]

$$F_e \cong -K_x \Delta x + K_i \Delta i \tag{2}$$

$$K_x = -\frac{\partial F_e}{\partial x} = \frac{\mu_0 \mu_r^{\,3} S}{2} \frac{\left(Ni + 2H_c L_m\right)^2}{\left(x\mu_r + L_m\right)^3}\Bigg|_{\substack{x=x_0 \\ i=0}} \tag{3}$$

$$K_i = \frac{\partial F_e}{\partial i} = \frac{\mu_0 \mu_r^{\,2} S}{2} \frac{\left(Ni + 2H_c L_m\right)}{\left(x\mu_r + L_m\right)^2}\Bigg|_{\substack{x=x_0 \\ i=0}} \tag{4}$$

On the other hand, electrical dynamics is expressed as following;

$$v = Ri + \frac{d\lambda}{dt} = Ri + \frac{\partial \lambda}{\partial i}\frac{di}{dt} + \frac{\partial \lambda}{\partial x}\frac{dx}{dt} \tag{5}$$

$$\frac{di}{dt} \cong \frac{K_x}{K_i}\frac{dx}{dt} - \frac{R}{L} i + \frac{1}{L} v \tag{6}$$

where *L* is inductance and described by;

$$L = \frac{1}{2}\frac{\mu_0 \mu_r S N^2}{x\mu_r + L_r}\Bigg|_{\substack{x=x_0 \\ i=0}} \tag{7}$$

Although K_x K_i & L parameters have been processed as coefficients for equilibrium point values, actually, they are varying according to operating point. These variations are illustrated in Fig 1-2.

Table 4. Simulation Specifications & Notation Definitions

S	2.2500e-004 [m^2]	Pole Area
Hc	900000 [A/m]	Coercivity of PM
μ_0	4.7 π e-7 [H/m]	Permeability of Free Space
R	1.5 [Ω]	Resistance of Coil
g_0	0.004 [m]	Equilibrium Gap Clearance
N	200 [Turn]	Number of Coil Turns
Lm	0.003 [m]	PM Length
μ_r	1.01	Permeability of PM
L	9.5895e-004 [H]	Inductance of Coil
i_0	0 [A]	Equilibrium Current
S_1	6125 [N/m]	Spring Coefficient
D_1	280 [N/(m/sec^2)]	Damper Coefficient
m_1	5 [kg]	Lower Mass
m_2	5 [kg]	Upper Mass

3. Combination of U Type Hybrid Electromagnet with Passive Elements

Fundamental configuration of the investigated U type hybrid electromagnet actuated active vibration system is depicted in Fig. 3. Employing well-known Newton's second law, as following manner, can develop dynamics of the system;

$$m_1 \ddot{x}_1 = -F_e - F_S - F_D \tag{8}$$

$$m_2 \ddot{x}_2 = F_e - F_d \tag{9}$$

Simply from the above equations, the external disturbance values can be calculated as;

$$F_d = F_e - m_2 \ddot{x}_2 \tag{10}$$

$$x_1 - x_0 = -\frac{m_1 \ddot{x}_1 + F_e}{D_1 s + S_1} \tag{11}$$

Notice that, in (11), hybrid representation of the time and frequency variables are used.

Sensor selection is one of the most issues in active vibration control systems, to solve this we have addressed following sensors combination;

- Current and displacement sensors for electromagnet,
- Upper and lower mass accelerometers for motion sensing.

4. Fuzzy Logic Based Identification of Electromagnet Force Values

Fuzzy logic based inference algorithms can approximate nonlinear functions in arbitrary accuracy.[2] Since the reasoning mechanism behaves like a white box, even under the uncertain model conditions successful applications can be handled.[2] Fuzzy logic based approaches have some advantages over curve fitting based counterparts especially if there is strong couplings among system variables and as well as system includes more than one degree of freedoms. Of course, combination of fuzzy systems with neural networks improves approximation accuracy, even for some unreachable region of input/output data pair sets; it permits the inclusion of heuristic hand crafted coding.

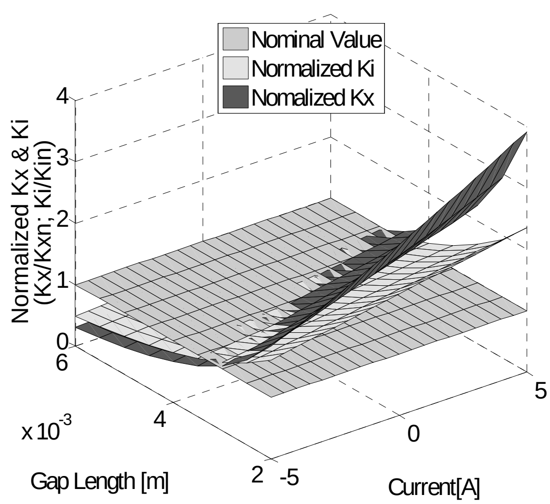

Figure 1. Variations of normalized K_x & K_i according to nonlinearity of eq. (3 & 4).

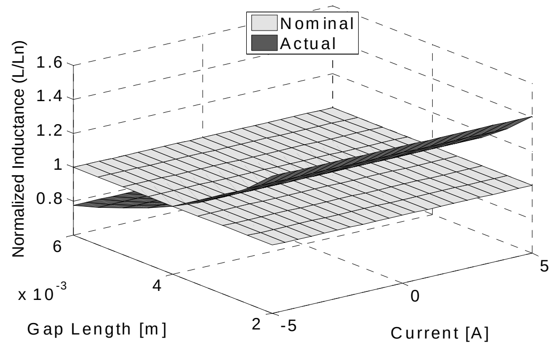

Figure 2. Variations of normalized *L* (inductance) according to nonlinearity of eq. (7).

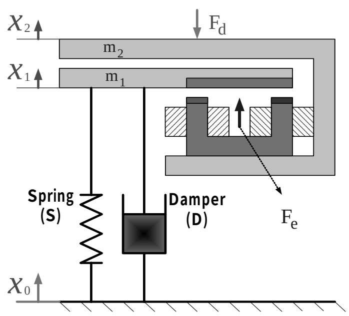

Figure 3. Principle configuration of the investigated active vibration control system.

The electromagnetic force can be approximated by following mainly two ways; direct identification and indirect calculation based identification. In direct approach, inputs might be current and gap clearance and the output of the fuzzy logic inferencing system will be electromagnetic force values. On the other hand, indirect approach, electromagnet displacement and current stiffness coefficients, K_x, K_i are identified for numerous operating points then by utilizing (2), the electromagnet force is calculated easily. Although, the second approach looks a bit complex and as well as somehow senseless, as compared with direct one, it has some very significant merits. The electromagnet has inherited nonlinear nature and generally control algorithms are designed by using linear control techniques, which yield a narrow operating range. Hence, it is indispensable to introduce some sophisticated control algorithms, which can improve system performance. One technique is the employment of adaptive based algorithms, which need identification of system parameters. Since the indirect method relies on electromagnet parameters identification scheme, it perfectly fits adaptive control algorithms. We will take into account indirect identification technique from now and then.

In this study, for the sake of simplicity and practical applicability, Takagi-Sugeno-Kang based fuzzy reasoning algorithm is selected as a candidate approach with constant consequent parts rather than polynomic expressions. Design of fuzzy reasoning system begins with the definition of possible input numbers and their ranges. Since fuzzy inference engine process fuzzy variables, inputs converted to fuzzy variables via input membership functions. Fig. 5 illustrates input membership functions used in simulation studies. Selection of the candidate input variables as current and gap clearance would be logical manner, as we confirm from Fig. 2-3. The outputs will be normalized magnet parameters, K_{xn}, K_{in}, & L_n. The second step is the definition of rule base in which input fuzzy knowledge is treated to output in order to infer associated output value. In Takagi-Sugeno-Kang based fuzzy reasoning algorithm, the consequent part of the rules comprised of polynomic expression of antecedent parts.

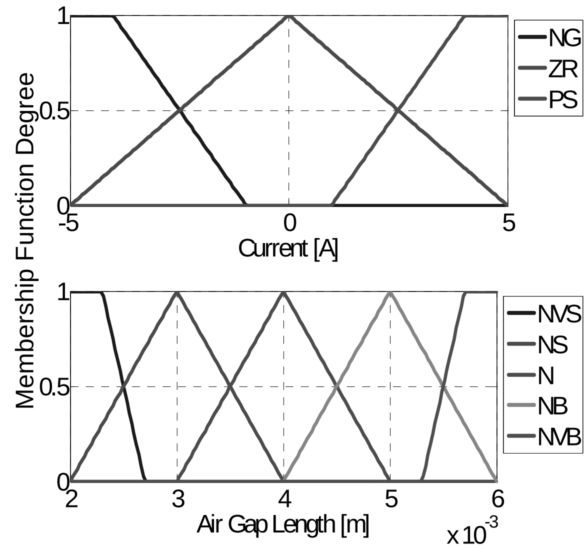

Figure 4. Input membership functions.

$$\Re 1: \overbrace{\text{IF}\, Q_1 \text{ is } \delta \text{ and } Q_2 \text{ is } \beta \,.....\, Q_n \text{ is } \alpha}^{Antecedent\ \ Part}$$

$$\underbrace{\text{THEN}\, W^1{}_1 = f^1{}_1(Q_1, Q_2, ...Q_n) \text{ and } ......W^1{}_k = f^1{}_k(Q_1, Q_2, ...Q_n)}_{Consequent\ \ Part}$$

$$\vdots$$

$$\Re m: \text{IF}\, Q_1 \text{ is } \varpi \text{ and } Q_2 \text{ is } \theta \,.....\, Q_n \text{ is } \sigma$$

$$\text{THEN}\, W^m{}_1 = f_1^m(\delta, \beta, ..\alpha) \text{ and } ......W^m{}_k = f_k^m(\delta, \beta, ..\alpha)$$

Inferred output is defuzzified by center of average as;

$$O_k = \frac{\sum_{l=1}^{m} \prod_{j=1}^{k} \mu_{Q_j^l}(.) W_1^l}{\sum_{l=1}^{m} \prod_{j=1}^{k} \mu_{Q_j^l}(.)} \tag{12}$$

Rule base for each output is expressed in table forms as following;

Table 1. Rule Base for Normalized Value of K_{xn}

Gap / Current	NG	ZR	PS
NVS	1.80	2.73	3.86
NS	1.02	1.54	2.18
N	0.65	0.98	1.39
NB	0.44	0.65	0.93
NVB	0.30	0.46	0.65

Table 2. Rule Base for Normalized Value of K_{in}

Gap / Current	NG	ZR	PS
NVS	1.59	1.96	2.33
NS	1.10	1.35	1.60
N	0.80	1.00	1.18
NB	0.62	0.76	0.90
NVB	0.49	0.60	0.71

Table 3. Rule Base for Normalized Value of L_n

Gap / Current	NG	ZR	PS
NVS	1.40	1.40	1.40
NS	1.18	1.18	1.18
N	0.99	0.99	0.99
NB	0.87	0.87	0.87
NVB	0.77	0.77	0.77

These tables' row and columns are interpreted as following; for example, first column and row;

IF *Gap* is ***N**egative**V**ery**S**mall* and *Current* is ***N**e**G**ative*

THEN *NormK*$_x$ is 1.80 and *NormK*$_i$ is 1.59 and *NormL* is 1.40.

The approximation accuracy of the designed Takagi-Sugeno-Kang based fuzzy reasoning algorithm is verified by simulation studies and as a result, the identification surfaces are depicted in Fig 6-8. When the identification surfaces are closely analyzed, we can conclude that they can quite precisely capture the nonlinear features of the normalized magnet parameters, K_{xn}, K_{in}, & L_n.

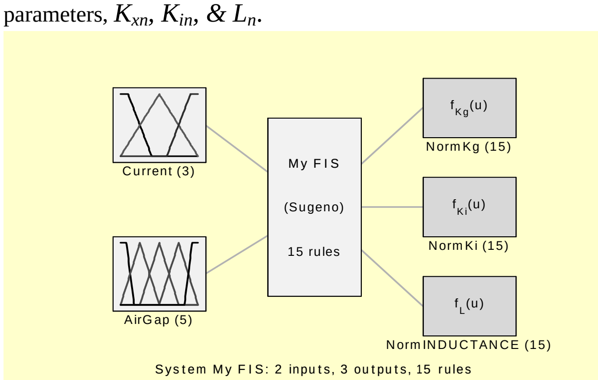

Figure 5. Structure of Takagi-Sugeno-Kang Based Fuzzy Inference System.

5. Controller & Observer Design

Since hybrid electromagnet includes permanent magnets, zero power based control algorithm may be applied.[7] However, equalization constraint of negative and positive stiffness values are violated by practical reasons. To overcome this problem, employment of passive elements' displacement following gap length type control approach would be more rationale technique.[8] On the other hand, another issue is the availability of the state variables to design a controller by using state space techniques, since predefined measurement sensor's combination can not satisfy the full observability conditions. The control problem of all vibration isolation system can be reduced to

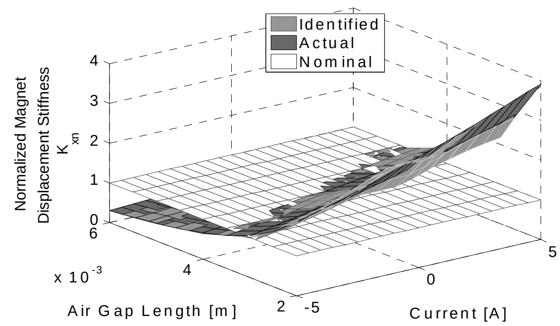

Figure 6. Identification surface of normalized magnet displacement stiffness (K_{xn}).

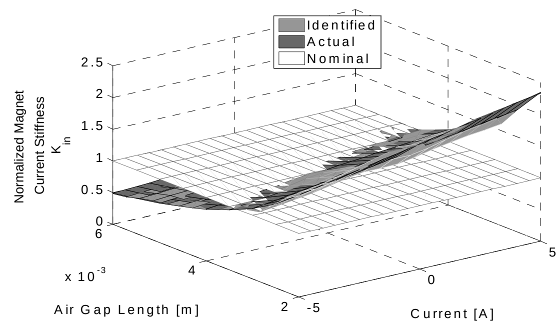

Figure 7. Identification surface of normalized magnet current stiffness (K_{in})

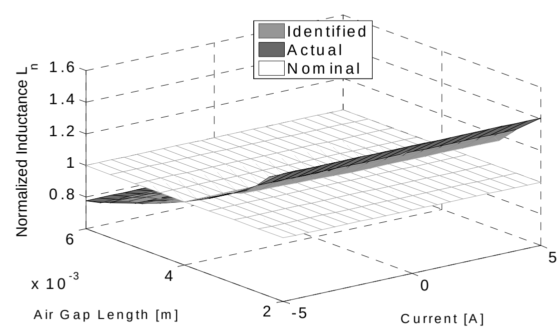

Figure 8. Identification surface of normalized magnet inductance (L_n).

the control of hybrid electromagnet. Because, the function of electromagnet is to provide virtual damping and/or spring property which may take negative or positive values. The virtual damping and/or spring property is achieved by controlling the electromagnet's gap clearance. The electromagnet dynamics with extension of integral term is given by;

$$\frac{d}{dt}\begin{bmatrix} x_1-x_2 \\ \dot{x}_1-\dot{x}_2 \\ i \\ I \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & -1 \\ \frac{K_x}{m_2} & 0 & -\frac{K_i}{m_2} & 0 \\ 0 & \frac{K_x}{K_i} & -\frac{R}{L} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1-x_2 \\ \dot{x}_1-\dot{x}_2 \\ i \\ I \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \\ 0 \end{bmatrix} v \tag{13}$$

$$I = \int ((x_1 - x_0) - (x_1 - x_2))dt \tag{14}$$

The gap clearance velocity can be estimated by using following observer dynamics;

$$\frac{d}{dt}\begin{bmatrix} \hat{q}_3 \\ \hat{q}_4 \\ \hat{i} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{K_x}{K_y} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} \hat{x}_1-\hat{x}_2 \\ \dot{\hat{x}}_1-\dot{\hat{x}}_2 \\ \hat{i} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 1 & -1 & 0 \\ 0 & 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ v \end{bmatrix} + \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \\ L_{31} & L_{32} \end{bmatrix} \begin{bmatrix} q_3-\hat{q}_3 \\ i-\hat{i} \end{bmatrix}$$

$$\hat{q}_3 = \hat{x}_1 - \hat{x}_2, \quad \hat{q}_4 = \dot{x}_1 - \dot{x}_2 \tag{15}$$

State feedback and observer gains are determined to obtain desired pole locations. Block diagram presentation is depicted in following Fig. 9.

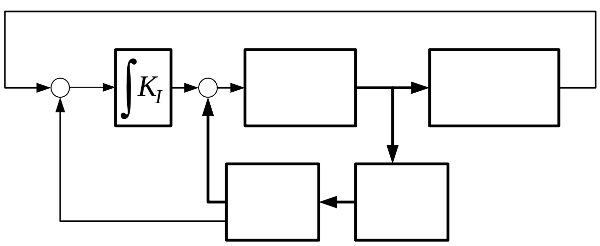

Figure 9. Control block diagram.

To evaluate the effectiveness of the proposed control and identification scheme some simulation studies are carried out.

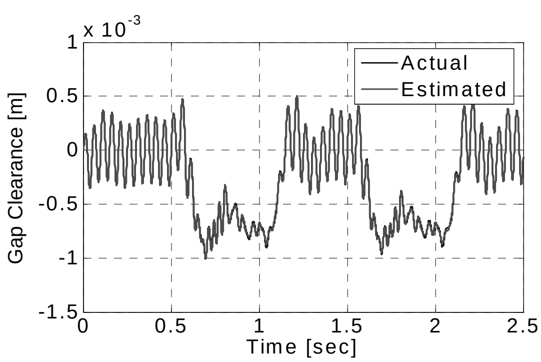

Figure 10. Actual & estimated time response of gap clearance (x_1-x_2).

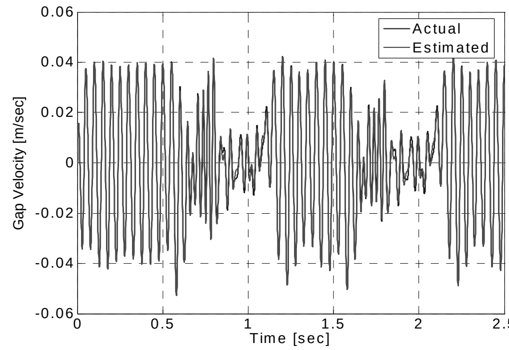

Figure 11. Actual & estimated time response of gap velocity.

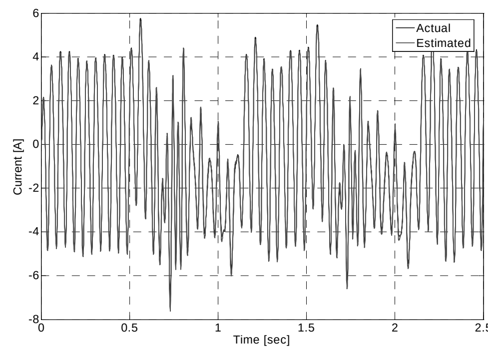

Figure 12. Actual & estimated time response of current (i)

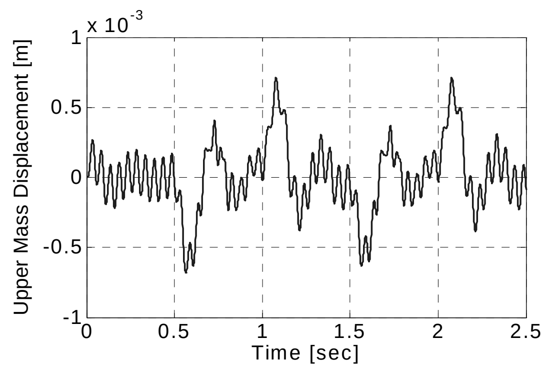

Figure 13. Time response of upper mass displacement (x_2).

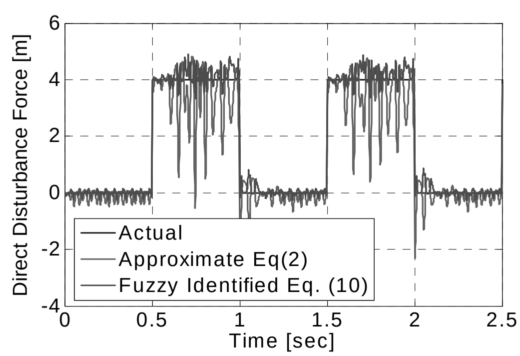

Figure 14. Actual, approximated and fuzzy identified direct disturbance values (F_d).

Passive Elements Displacement

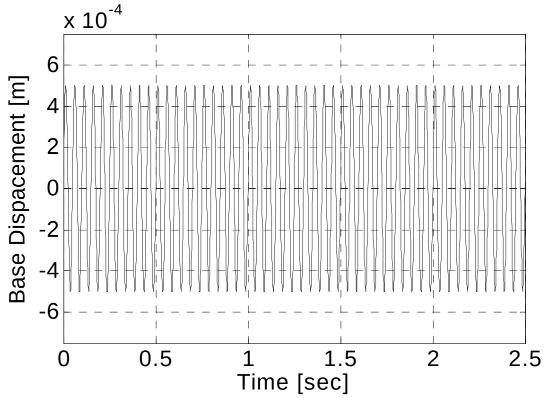

Figure 15. Applied base disturbance (x_0),

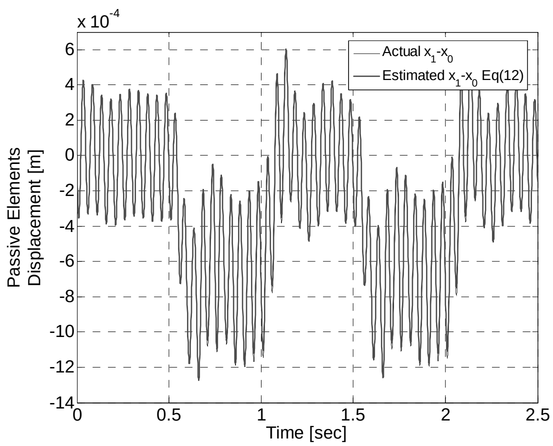

Figure 16. Actual & fuzzy identified passive elements displacement *(x_1-x_0)*.

Simulation results, Fig. 10-16, show that proposed technique works well under simultaneous disturbance excitation. Especially, the disturbance identification results are quite promising, Fig. 14 & 16. The approximation accuracy also can be evaluated by employing following squared error measure.

$$e = \frac{\int (\hat{w} - w)^2 \, dt}{\int w^2 dt} \qquad (16)$$

Where, w and $\hat{w}$ stand for actual and estimated signal values, respectively.

Table 4. Error Measure Table for Identified variables.

Variable	Error Measure
F_d equ. (2)	0.0911
F_d Fuzzy Ide. & equ. (10)	0.0070
X_0 Fuzzy Ide. & equ. (11)	3.6777e-007

The quality of identification and estimation can be improved by introducing training techniques, neuro-fuzzy systems, with system input/output data pairs.[2]

6. Conclusions & Future Prospects

In this paper, a U type hybrid electromagnet actuated active vibration isolation and control system is introduced. The system is excited, mainly, by two simultaneous external disturbance sources. To obtain perfect disturbance attenuation, the characteristics of external disturbances should be known. A fuzzy logic based identification algorithm is proposed and its effectiveness verified by simulation studies. The simulation results are fairly plausible.

Currently, we have been studying on the design and practical implementation of experimental test rig. The outlined identification procedure uses intuitive guidelines to design fuzzy identification algorithm. However, training the fuzzy logic identification architecture with system input/output data pairs can improve the approximation quality, therefore as future study we have been planning to introduce training techniques to identification scheme. Furthermore, since magnets parameters can be identified, adaptive controller and observer design are other future considerations.

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