ARAŞTIRMA MAKALESİ

PD CONTROL OF VIBRATIONS OF MULTI-DEGREE OF FREEDOM STRUCTURAL SYSTEMS

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ÇOK SERBESTLİK DERECELİ YAPISAL SİSTEMLERİN TİTREŞİMLERİNİN PD KONTROLÜ

ÖZET

Bu çalışmada, çok serbestlik dereceli bir yapının depreme karşı aktif sismik izolasyonunu gerçekleştirmek amacı ile bir PD kontrol sistemi tasarlanmıştır. Simülasyonu gerçekleştirilen sistem, dört serbestlik derecesine sahiptir. Deprem etkisini temsilen temele bir giriş uygulanmıştır. Bu çalışmada, bir lineer motor aktif izolatör olarak kullanılmaktadır. Çalışmanın sonunda, katların yerdeğişimleri, denetim voltajının zaman cevapları ile kontrolcüsüz ve PD kontrolcülü yapının frekans cevapları elde edilmiş ve sonuçlar irdelenmiştir.

SUMMARY

In this study, a PD control system is designed for an active seismic isolation device considering a multi degrees of freedom structure against earthquake. The simulated system has four degrees of freedom. The disturbance input representing the effect of an earthquake is applied to the base. In this study a linear motor is used as the active isolator. At the end of the study the time history of the storey displacements, control voltage and frequency response of the both uncontrolled and PD controlled structures are presented and results are discussed.

1. INTRODUCTION

Recently many studies on structural vibration control have been made and practical applications have been realized. The vibration isolation using rubber bearings is one of the most popular method of passive vibration control. It is known that a seismic isolation rubber bearing consists of rubber sheets and steel plates is effective for an architectural structure whose base is subjected to an earthquake input [1]. Also semi-active vibration methods are proposed in literature. Yoshida and Fujio applied such a method to base in which viscous damping coefficient is changed for vibration control [2]. In recent years, there are studies where active actuators are used for isolation systems in order to isolate the earthquake induced vibrations. Fukushima *et al*. developed an active-passive composite tuned mass damper where it is aimed to reduce wind and earthquake induced vibrations of tall buildings [3]. Since there are uncertainties in structural systems and system parameters are not constant, different control methods are offered for the active control of the structures [4].

2. DYNAMIC MODEL OF FOUR DEGREES OF FREEDOM STRUCTURAL SYSTEM

The structure has four degrees of freedom all in horizontal direction. The physical system has been shown in Figure 1. Since the destructive effect of earthquake happens on first storey, the active control is applied on there. The mass of each storey are m_1, m_2 and m_3 respectively where m_0 is the mass of the base. All springs and dampers are acting in horizontal direction. The system parameters are presented at the Appendix.

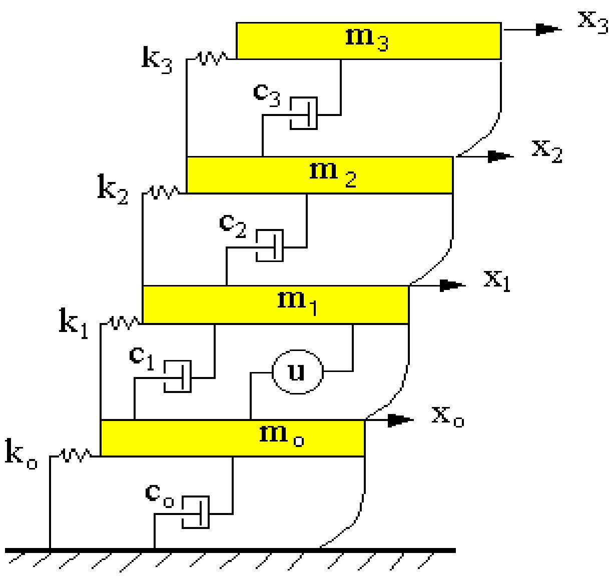

Figure 1. Physical model of structural system

The equation of motion of the system is given below:

$$[M]\underline{\ddot{x}} + [C]\underline{\dot{x}} + [K]\underline{x} = \underline{F_d} + \underline{F_u} \tag{1}$$

where, $\underline{x} = [\ x_0\ x_1\ x_2\ x_3\ ]^T$, $\underline{F_d} = [\ -F_d\ 0\ 0\ 0\ ]^T$ and $\underline{F_u} = [\ -F_u\ F_u\ 0\ 0\ ]^T$. F_d is a test input representing the disturbance force coming from earth and acting on base; F_u is the control force produced by a linear motor; [M], [C] and [K] are mass, damping and stiffness matrices and given at the Appendix.
The equation of the linear motor is:

$$R\,i + K_e(\dot{x}_1 - \dot{x}_0) = u \tag{2}$$

u and i are the voltage and current of the armature coil respectively where u is the control voltage input at the same time. R and K_e are the resistance value and induced voltage constant of the armature coil. The current of the armature coil and control force has the following relation:

$$F_u = K_f\, i \tag{3}$$

K_f is the thrust constant. The inductance of the armature coil is neglected. By combining the equations (1) through (3) and arranging them, it is also possible to get the governing equations in state space form. If the system is defined in state space form as:

$$\dot{\underline{x}} = \underline{f}(x) + [B] * \underline{F_u} + [W] * \underline{F_d} \tag{4}$$

Here, $\underline{x} = [x_0\ x_1\ x_2\ ....\ x_7]^T$ where $x_4 = \dot{x}_0$, $x_5 = \dot{x}_1$, $x_6 = \dot{x}_2$, $x_7 = \dot{x}_3$. $\underline{f}(x)$ is vector functions composed of first order differential equations, [B] is the controller force matrix and [W] is the disturbance force matrix. $\underline{f}(x)$, [B] and [W] are given in Appendix with nomenclature of vehicle parameters.

3. THE PD CONTROLLER DESIGN

In general the closed loop diagram of the feedback system is shown in Figure 2.

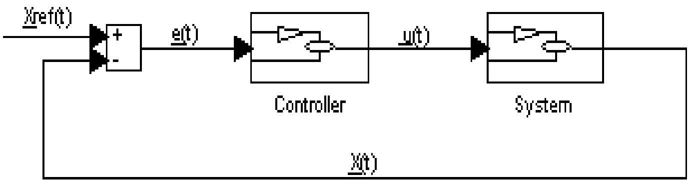

Figure 2. Closed loop block diagram with controller

Here, $\underline{x}_{ref}(t)$ is the desired value for the output of the system. $\underline{x}(t)$ is the output, $\underline{e}(t)$ is error and $\underline{u}(t)$ is the control signal. PD Control has been used in industry widely and successfully. The control input $\underline{u}(t)$ is obtained as follows:

$$\underline{u}(t) = K\,[\underline{e}(t) + \frac{1}{\tau_i}\int_0^t \underline{e}(t)dt + \tau_d \frac{d\underline{e}(t)}{dt}] \tag{5}$$

K , τ_i and τ_d are proportionality constant, integral time and derivative time respectively. These values are obtained using Ziegler-Nicholes method [5].

4. SIMULATION

Structural system has been simulated against 10000 N. of step input to the base starting at fifth second. Figures 3.a and 3.b show the controlled and uncontrolled time responses of the first and third storeys. It is observed that there is an important improvement when the horizontal displacements of the structure are considered.

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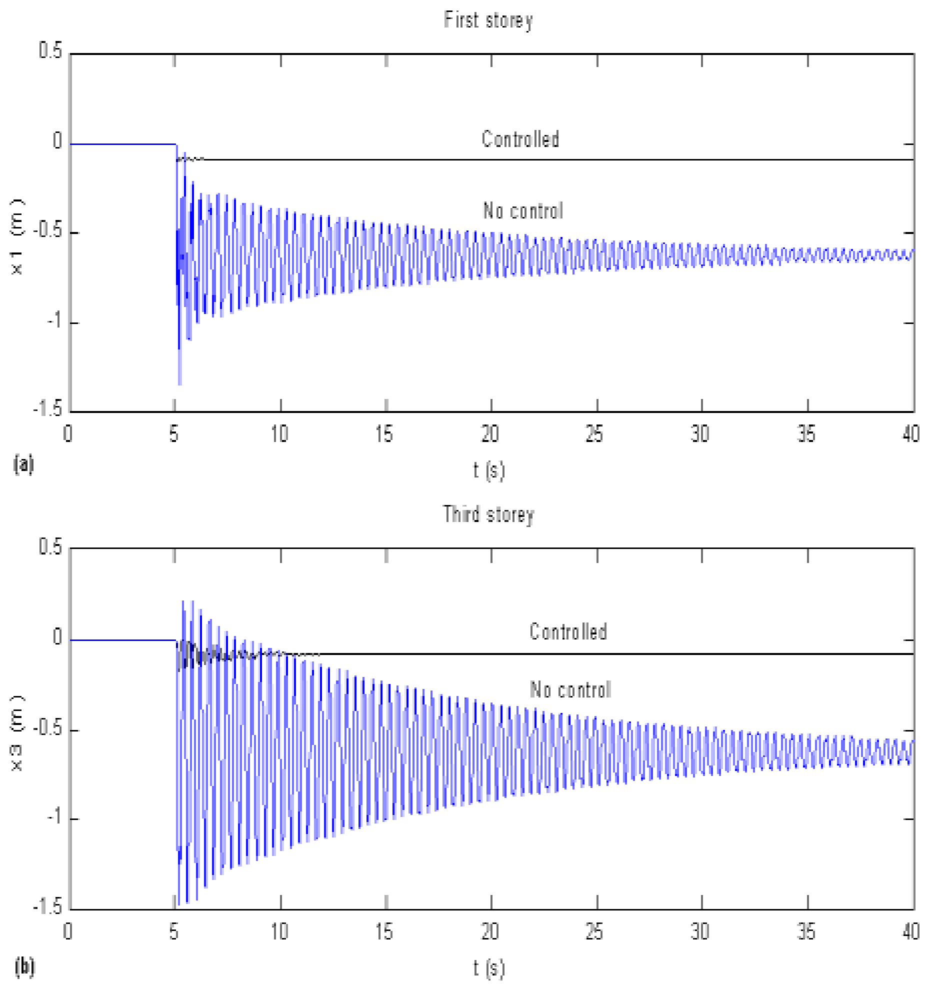

Figure 3. Controlled and uncontrolled time responses of the first and third storeys

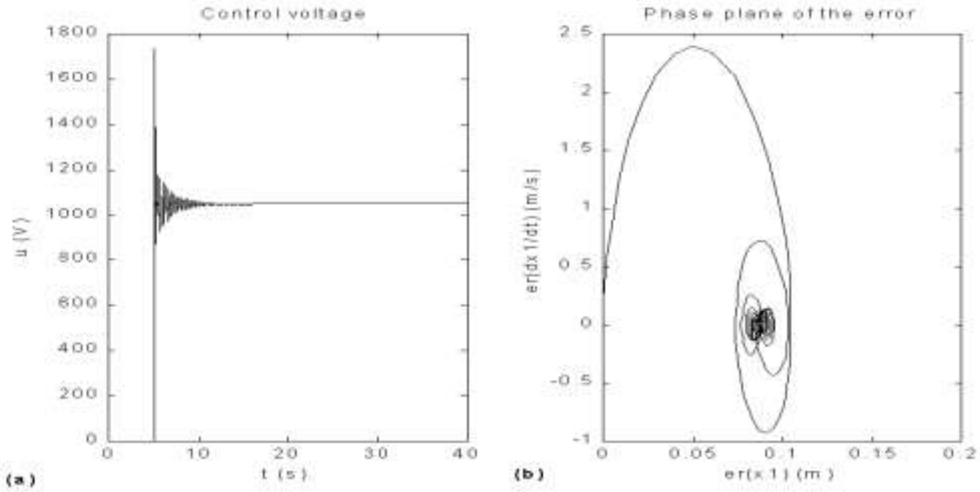

Figure 4. Time history of control voltage and phase plane of error of x_1

Figure 4.a demonstrates the change in voltage input. The aimed improvement of the stability is shown in Figure 4.b. Since the system has four degrees of freedom, there are four resonance values. First resonance value belongs to the third storey and around 2.5 Hz. Second resonance value belongs to the first storey and at 7 Hz. Third and fourth resonance values are closed and coinciding on each other. Figures 5.a and 5.b show the frequency responses of the first storey displacements and accelerations respectively for both controlled and uncontrolled cases.

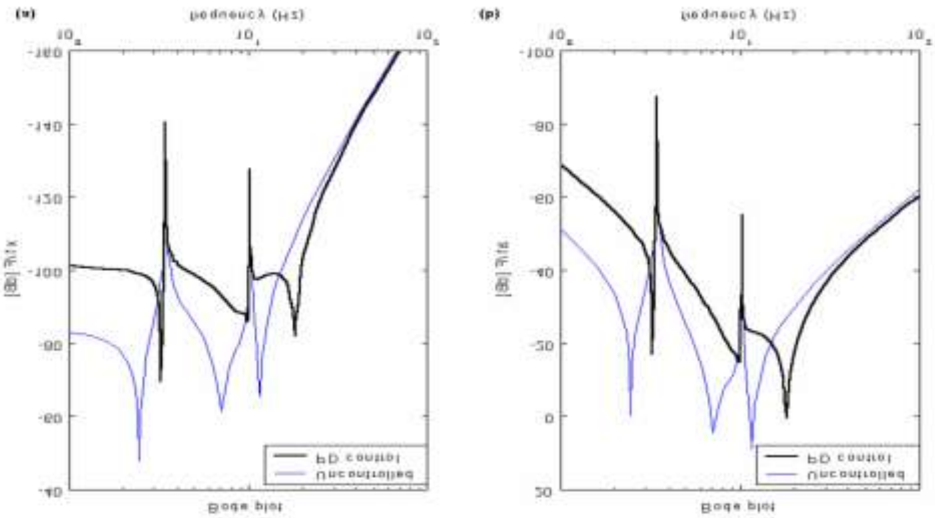

Figure 5. Controlled and uncontrolled frequency responses of the first storey

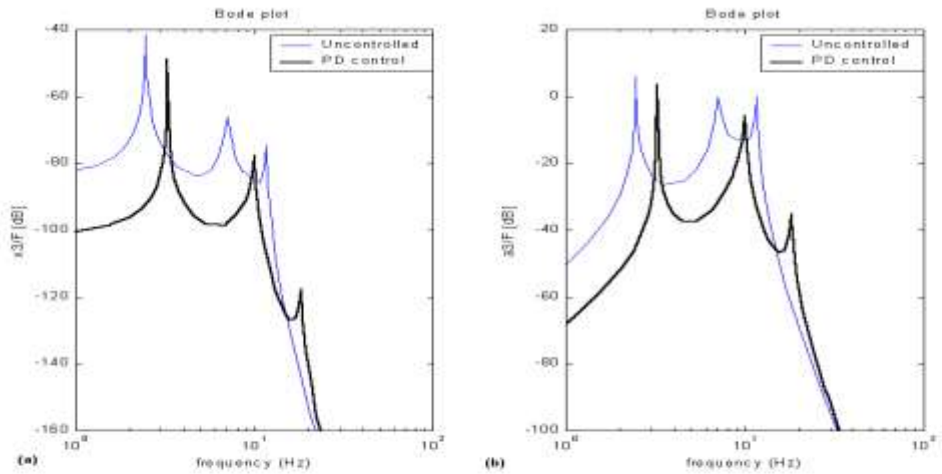

Figure 6. Controlled and uncontrolled frequency responses of the third storey

As expected the upper curves belong to the uncontrolled system. An excellent improvement in terms of magnitudes have been witnessed again. Particularly at the resonance value of the displacement response of the first storey, there is a significant improvement. In Figures 6.a and 6.b, for the displacement and acceleration of the third storey, again satisfactory results have been obtained.

5. CONCLUSION

A PD controller has been designed for a multi degrees of freedom structural system. Since the destroying effect of earthquakes are sourced as a result of horizontal vibrations, in this study, the degrees of freedom have been assumed only at this direction. System is modeled including the dynamics of linear motor which is used as the active isolator. Against the disturbances coming from the earth, it is shown that designed PD controller has brought satisfactory seismic isolation performance.

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APPENDIX

Mass, Stiffness and Damping Matrices

Mass matrix,

$$[M] = \begin{bmatrix} m_0 & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 \\ 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & m_3 \end{bmatrix}$$

Stiffness matrix,

$$[K] = \begin{bmatrix} k_0 + k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2 + k_3 & -k_3 \\ 0 & 0 & -k_3 & k_3 \end{bmatrix}$$

Damping matrix,

$$[C] = \begin{bmatrix} c_0 + c_1 & -c_1 & 0 & 0 \\ -c_1 & c_1 + c_2 & -c_2 & 0 \\ 0 & -c_2 & c_2 + c_3 & -c_3 \\ 0 & 0 & -c_3 & c_3 \end{bmatrix}$$

Parameters of The Four Degrees of Freedom Structural System

m_o	5	kg	c_o	100	N.s/m
m_1	1.7	kg	$c_1= c_2= c_3$	0.08	N.s/m
m_2	1.5	kg	R	1.5	Ω
m_3	2.3	kg	K_f	2	N/A
k_o	16000	N/m	K_e	2	Volt
$k_1= k_2= k_3$	2600	N/m			

The controller force and the disturbance force matrices:

$$[B] = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\dfrac{1}{m_o} \\ \dfrac{1}{m_1} \\ 0 \\ 0 \end{bmatrix} \quad , \quad [W] = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\dfrac{1}{m_o} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

State equations excluding control inputs:

$$f_1(x) = x_4 \ , \quad f_2(x) = x_5 \ , \quad f_3(x) = x_6 \ , \quad f_4(x) = x_7$$

$$f_5(x) = 1/m_0 \, [-(c_0 + c_1)x_4 + c_1x_5 - (k_0 + k_1)x_0 + k_1x_1]$$

$$f_6(x) = 1/m_1 \, [-(c_1 + c_2)x_5 + c_1x_4 + c_2x_6 - (k_1 + k_2)x_1 + k_1x_0 + k_2x_2]$$

$$f_7(x) = 1/m_2 \, [-(c_2 + c_3)x_6 + c_2x_5 + c_3x_7 - (k_2 + k_3)x_2 + k_2x_1 + k_3x_3]$$

$$f_8(x) = 1/m_3 \, [-c_3 \, x_7 + c_3x_6 - k_3x_3 + k_3x_2]$$