



Gantry Crane Structure Seismic Control by the use of Fuzzy PID Controller

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ABSTRACT

This paper represents the design of fuzzy PID type controller (FPIDC) to improve seismic control performance of a gantry crane structure against earthquakes. Vibration control using intelligent controllers, such as fuzzy logic has attracted the attention of structural control engineers during the last few years, because fuzzy logic can handle, uncertainties and heuristic knowledge and even non-linearities effectively and easily. The simulated system has a six degrees-of-freedom and modeled system was simulated against the ground motion of the El Centro earthquake. Finally, the time history of the crane bridge and portal legs displacements, accelerations, control forces and frequency responses of the both uncontrolled and controlled cases are presented. Simulation results exhibit that superior vibration suppression is achieved by the use of designed fuzzy PID type controller.

Keywords: *Fuzzy PID type controller, Earthquake-induced vibration, Vibration control, Gantry crane structure*

1. INTRODUCTION

In the recent years, earthquakes have caused much more loss of life and financial damage compared with previous centuries. Cranes are also affected by seismic movements. A collapsed crane in an earthquake is shown in Figure 1. Cranes damaged in earthquakes also cause loss of life together with economical losses.

Moreover, cranes damaged on strategical points such as harbors and railways cause failure in logistic activities. Therefore, it is necessary to investigate the behavior of cranes during an earthquake to take suitable design precautions to prevent possible damages in the earthquake and to enable stability toward an earthquake with active-passive controllers.

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Figure 1. A collapsed crane in earthquake [1].

Abdel-Rahman *et al.* [2] examined the crane control strategies in their study; and consequently presented the related studies to be conducted in the future. Kobayashi *et al.* [3] observed the dynamic behaviors of container cranes under seismic effects. In the study, especially the contact problem between wheels and rails during the earthquake is the focus, a model of 1/8 ratio upon the wheel tray connection of crane is composed; dynamic effects on the system are then observed by applying actual earthquake data on an earthquake tray. Otani *et al.* [4] observed vertical vibrations that are formed with the effect of an earthquake on overhead cranes by composing a model of 1/8 ratio of an overhead crane to observe dynamic effects on the system by applying actual earthquake data on an earthquake tray. Soderberg and Jordan [5] observed the dynamic behavior of jumbo container cranes and put forward suggestions for the design to reduce damages of an earthquake and to prevent collapse.

Sagirli *et al.* [6] a self-tuning fuzzy logic controller is designed to reduce the seismic vibrations of the crane structure. In the study, the cable is considered as massless and rigid and two actuators are used to suppress earthquake induced vibrations. The first actuator is installed between the bridge and the portal legs and the second one is placed between portal legs and the ground. The simulated system has a five degrees-of-freedom and modeled system was simulated against the ground motion of the Marmara Kocaeli earthquake. Additionally, the performance of the designed STFLC is also compared with a PD controller.

In this study, fuzzy PID controller (FPIDC) have been implemented to a crane structural system to the seismic responses of a gantry crane in the El Centro earthquake. This paper is organized as follows: Section 2 describes mathematical model of the crane. FPIDC is designed in Section 3. Simulation results are demonstrated and discussed in Section 4. Finally, Section 5 concludes the paper.

2. MATHEMATICAL MODEL OF THE CRANE

In this study, a fuzzy PID type controller (FPIDC) is implemented to a six degrees-of-freedom gantry crane which is modeled using spring-mass-damper subsystems. Since the destructive effect of earthquakes is a result of horizontal vibrations, the degrees-of-freedom have been assumed to be occurring only in this direction. Control structure is defined as a mechanical system which is installed in a structure to reduce structural vibrations during loadings imposed by earthquakes. The control system can be divided into two parts: active control device and the control algorithm [7]. An important element of an active control strategy is the actuators. These are active control devices that attenuate disturbances at the corresponding subsystems or reduce the vibration on crane bridges when they are installed [8]. In this study, actuators are used to suppress earthquake induced vibrations. The actuators are placed between the portal legs and the ground. FPIDC is used as a control algorithm for both control devices. It supplies control voltage directly to suppress magnitude of undesirable earthquake vibrations. The crane system is shown in Figure 2.

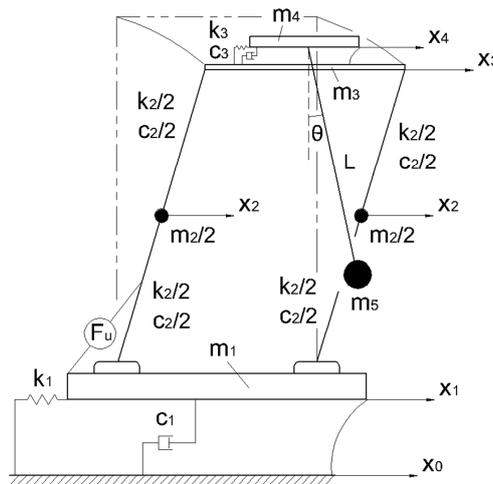


Figure 2. Physical model of gantry crane for earthquake motion.

The mathematical model includes the following assumptions: 1) The motion of the crane is modeled as a planar motion. The direction of the ground motion is on this plane and the motion of all masses is also in this plane. 2) The degrees-of-freedom have been assumed to be occurring only in the horizontal direction. 3) All springs and dampers are considered as acting only in a horizontal direction. 4) In this model, ground, portal legs, crane bridge, trolley and payload are considered as point masses m_1, m_2, m_3, m_4, m_5 , respectively. 5) The cable is considered as massless and visco-elastic. 6) In the model, portal legs are fixed on the ground. 7) The actuators are installed between the portal legs and the ground.

The equation of motion of the system is

$$[M] \ddot{x} + [C] \dot{x} + [K] x = F_d + F_u \quad (1)$$

where $x = [x_1 \ x_2 \ x_3 \ x_4 \ \theta \ L]^T$,

$$F_d = [-(c_1 \dot{x}_0 + k_1 x_0) \ 0 \ 0 \ 0 \ 0 \ 0]^T \text{ and}$$

$F_u = [-F_u \ F_u \ 0 \ 0 \ 0 \ 0]^T$. F_d is the force induced by an earthquake. F_u is the control force produced by linear motors. The equations of motion can be derived using the Lagrangian equation:

$$\frac{d}{dt} \left(\frac{\partial E_k}{\partial \dot{q}_i} \right) - \frac{\partial E_k}{\partial q_i} + \frac{\partial E_p}{\partial q_i} + \frac{\partial E_D}{\partial \dot{q}_i} = Q_i \quad (i=1, \dots, 6) \quad (2)$$

where E_k is system kinetic energy, E_p is system potential energy, E_D is system damping energy, q_i is generalized coordinate and Q_i is external force. Finally the following equations of motion are obtained:

$$m_1 \ddot{x}_1 + (k_1 + k_2)x_1 - k_2 x_2 + (c_1 + c_2)\dot{x}_1 - c_2 \dot{x}_2 = -(c_1 \dot{x}_0 + k_1 x_0) - F_u \quad (3)$$

$$m_2 \ddot{x}_2 + 2k_2 x_2 - k_2 x_1 - k_2 x_3 + 2c_2 \dot{x}_2 - c_2 \dot{x}_1 - c_2 \dot{x}_3 = F_u \quad (4)$$

$$m_3 \ddot{x}_3 + (k_2 + k_3)x_3 - k_2 x_2 - k_3 x_4 + (c_2 + c_3)\dot{x}_3 - c_2 \dot{x}_2 - c_3 \dot{x}_4 = 0 \quad (5)$$

$$(m_4 + m_5) \ddot{x}_4 + k_3 x_4 - k_3 x_3 + c_3 \dot{x}_4 - c_3 \dot{x}_3 + m_5 L \ddot{\theta} \cos \theta - m_5 L \dot{\theta}^2 \sin \theta + m_5 \ddot{L} \sin \theta + 2m_5 \dot{L} \dot{\theta} \cos \theta = 0 \quad (6)$$

$$m_5 L^2 \ddot{\theta} + m_5 L \ddot{x}_4 \cos \theta + m_5 g L \sin \theta + 2m_5 L \dot{L} \dot{\theta} = 0 \quad (7)$$

$$m_5 \ddot{L} + m_5 \ddot{x}_4 \sin \theta - m_5 L \dot{\theta}^2 - m_5 g \cos \theta + k(L - L_0) + c\dot{L} = 0 \quad (8)$$

where m_1, m_2, m_3, m_4, m_5 denote the mass of the ground, portal legs, bridge, trolley, and payload, respectively; $k_1, 2k_2, k_3$ denote the stiffness of the ground, portal legs, and wheels of trolley, respectively; $c_1, 2c_2, c_3$ denote the damping of the ground, portal legs, and wheels of trolley, respectively; L_0 is the rope length, k is the rope stiffness, c is the rope damping and g is the gravitational

acceleration. x_0 is the earthquake-induced ground motion disturbance imposing on the crane structure. All springs and dampers are acting in horizontal direction. The system parameters of a real gantry crane are presented in the Appendix.

3. DESIGNED OF FUZZY PID TYPE CONTROLLER

The theory of the sets have been extensively used in variety of fields including control applications since its first inventions by Zadeh [9-14]. Guclu and Yazici designed fuzzy logic based controllers for a structural system against earthquake [15-17]. The fuzzy based controller are able to handle the nonlinearities and uncertainties effectively so this type of controllers are used widely in structural systems. Therefore, fuzzy PID controller is a suitable choice for control algorithm. The superior qualities of this method include its simplicity, satisfactory performance and its robust character. The

aim of this study is to apply the fuzzy PID controller to crane structural systems.

In this study, Matlab Simulink with Fuzzy Toolbox is used. Fuzzy PID controller for the crane system uses the error ($e = x_{r,2} - x_2$) in the portal legs and their derivative ($de/dt = \dot{x}_{r,2} - \dot{x}_2$) as the inputs variable while the control voltage (u) are their output. Reference value ($x_{r,2}$) is considered to be zero. A block diagram of the fuzzy PID controller for crane system is shown in Figure 3.

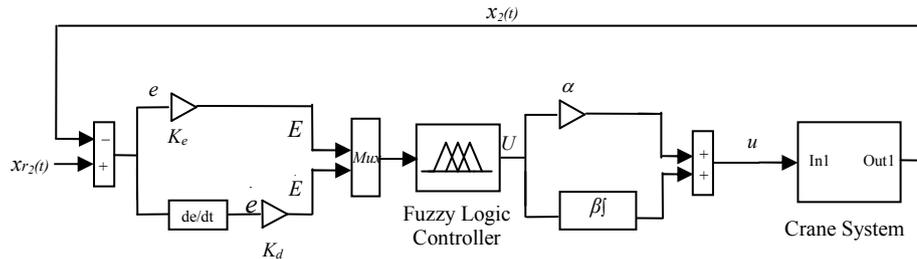


Figure 3. Block diagram of the FPIDC.

3.1. Formulation of the FPIDC for Structural System

The aim of this study is to apply the fuzzy PID controller to improved seismic control performance of crane structures. In literature, various structures for fuzzy PID (including PI and PD) controllers and non-PID controllers have been proposed. The conventional fuzzy PID controller needs three inputs and the rule base has three dimensions, it is more difficult to design the rule-base since three dimension information is usually beyond the sensing capability of a human expert. However, the fuzzy PID type controller has just two inputs and the rule-base is two dimensions. Its performance is also better than the fuzzy PI and fuzzy PD controller. The fuzzy PI control is known to be more practical than fuzzy PD because it is difficult for the fuzzy PD to remove steady state error. The fuzzy PI control, however, is known to give poor performance in transient response for higher order processes due to the internal integration operation. Thus, in practice the

FPIDC are more useful [17]. To obtain proportional, integral and derivative control action all together, it is intuitive and convenient to combine PI and PD actions together to form a FPIDC [12, 19]. FPIDC structure that simply connects the PD type and the PI type fuzzy controllers together in parallel is shown in Figure 3. The output of the FPIDC u is given by

$$u = \alpha U + \beta \int U dt \tag{9}$$

where U is the outputs of the fuzzy logic controller. The relation between the input and the output variables of the fuzzy logic controller is given by

$$U = A + PE + D \dot{E} \tag{10}$$

where $E = K_e \cdot e$ and $\dot{E} = K_d \cdot \dot{e}$. Therefore, from Eqs.(9, 10) the controller outputs are obtained as follows;

$$u = \alpha A + \beta A t + \alpha K_e P e + \beta K_d D e + \beta K_e P \int e dt + \alpha K_d D \dot{e} \tag{11}$$

Thus, the equivalent control components of the FPIDC is obtained as follows:

Proportional gain : $\alpha K_e P + \beta K_d D$

Integral gain : $\beta K_e P$

Derivative gain : $\alpha K_d D$

3.2. Membership Functions

In this study, one-input one-output type FPIDC is used. Symmetric triangles (except the two membership functions at the extreme ends) with equal base and 50% overlap with the neighboring membership functions are used to achieve a good controller performance as shown in Figure 4. All membership functions for controller inputs, error (e) and derivative of error (de) are defined on the common interval $[-1, 1]$ [20]. The values of actual

inputs (e and de) are mapped onto $[-1, 1]$ by the input scaling factors (K_e, K_{de}) and the values of actual outputs are mapped onto $[-1, 1]$ by the input and output scaling factors (α, β). The values of scaling factors are presented in the Appendix. Where P, N, ZE, B, M, S and V represent Positive, Negative, Zero, Big, Medium, Small and Very, respectively.

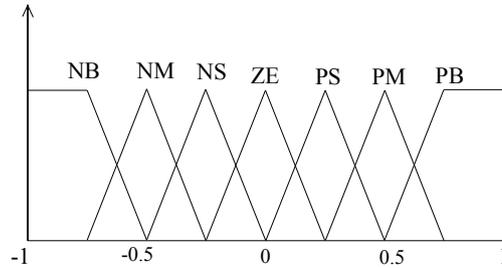


Figure 4. Membership functions of e, de, u .

3.3. The Rule Base

The rule base for computing u is shown in Table 1. This is very often used rule base designed with a two dimensional phase plane in mind where the FLC drives the system into the so-called sliding mode [20]. The controller output u is calculated using fuzzy rules of the form as below:

If e is NB and de is NB then u is NB . (12)

All the rules are written similarly using the Mamdani method to apply to fuzzification. In this study, the centroid method is used in defuzzification.

Table 1. Fuzzy rules for computation of u

de/e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

4. EARTHQUAKE EXCITATION AND THE RESPONSE OF THE CRANE

Modeled crane subjected to the ground motion of the El Centro earthquake has been simulated. Earthquake ground motion is used as input to a crane system. This earthquake motion is obtained using the seismic data of El Centro earthquake ground motion which is shown in Figure 5 [21].

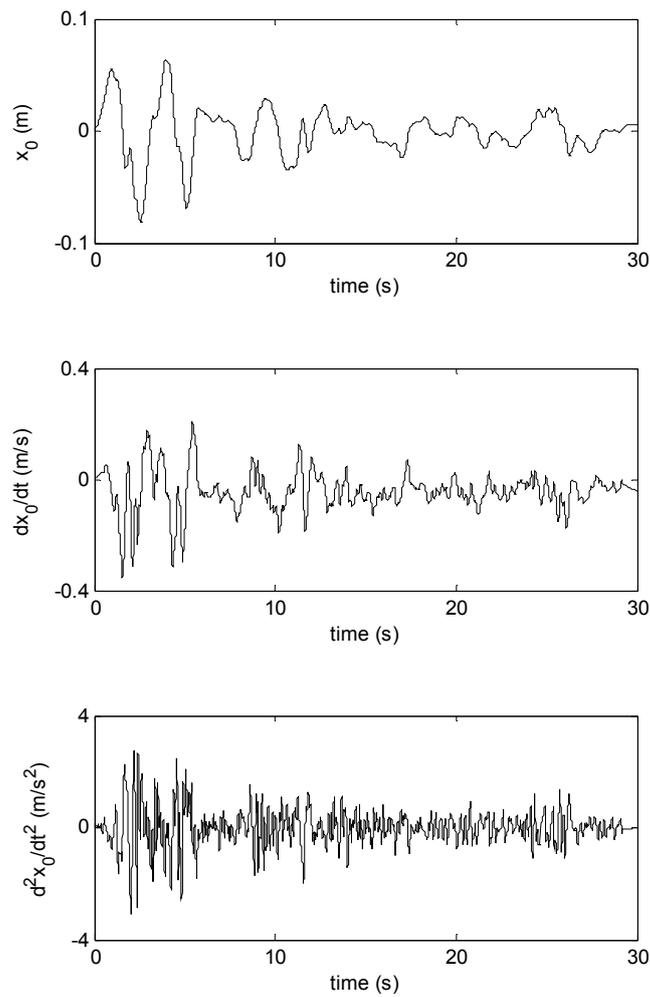


Figure 5. El Centro earthquake ground motion.

Figure 6 shows the time responses of the portal legs, bridge and trolley displacements and accelerations, load sway angle and angular acceleration, respectively for both controlled and uncontrolled cases. The bold line indicates the controlled case by designed FPIDC and the dashed line indicates the uncontrolled case. It is well

known that the maximum displacements are expected at the top of the crane during an earthquake. Displacements of the crane bridge and trolley are minimized successfully using the FPIDC. Figure 7 shows the time history of control force.

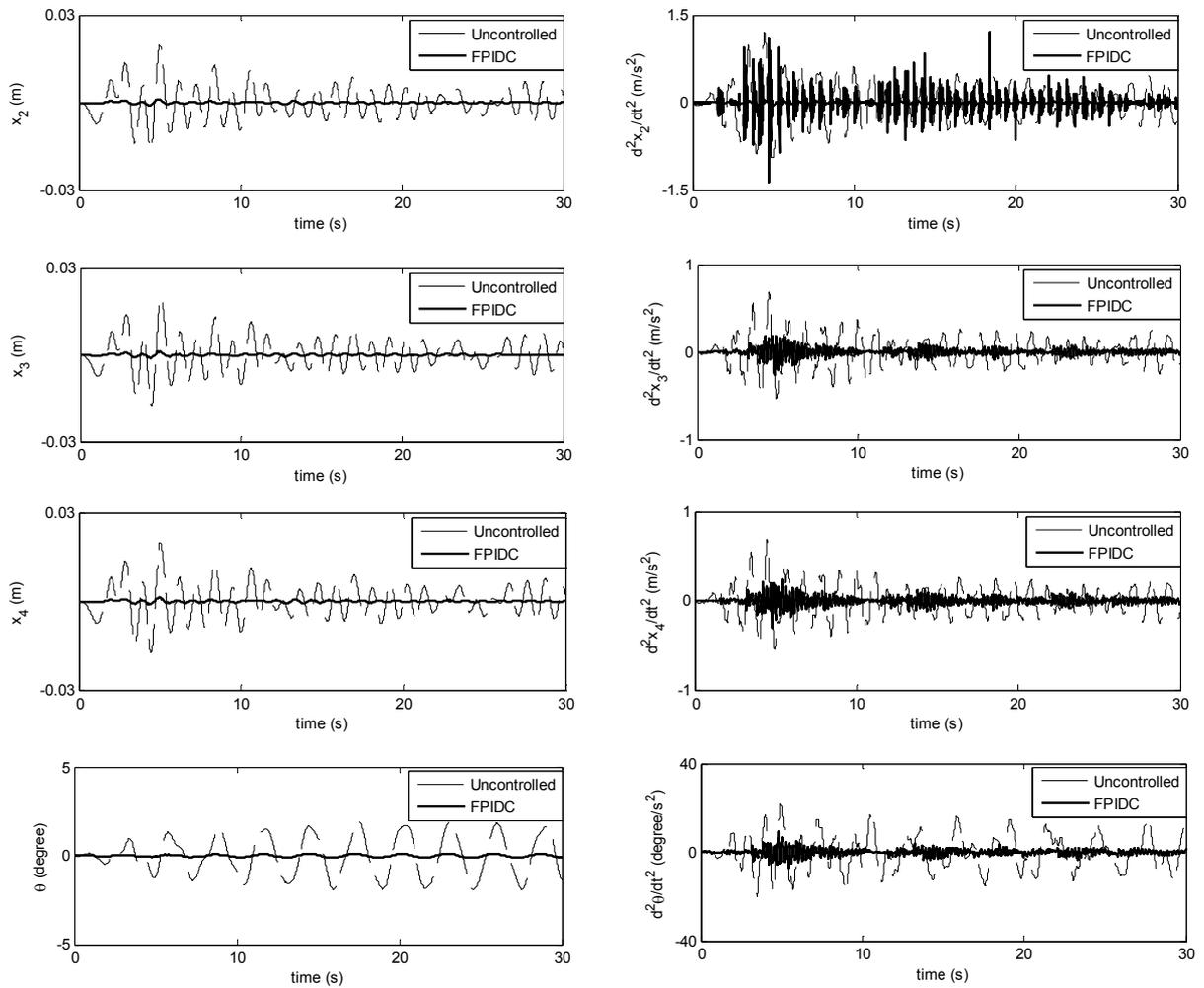


Figure 6. Displacement and acceleration time responses of portal legs, bridge, trolley and load sway angle.

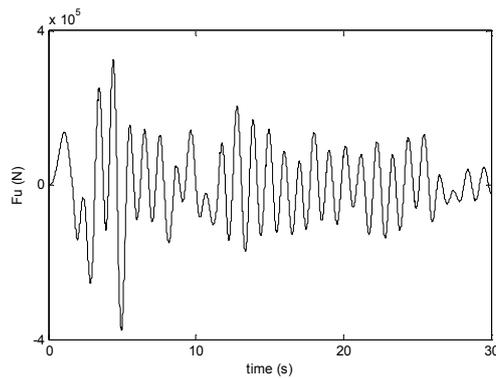


Figure 7. Time history of control force.

Figure 8 shows the frequency responses of the bridge displacements and accelerations, respectively, for both uncontrolled and controlled cases. Since the system has six degrees-of-freedom, there are six resonance values at 0.34, 0.92, 3.13, 5.03, 10.23, and 22.59 Hz. As expected the lower curves belong to the controlled systems. When the response plots of the structural

systems with uncontrolled and controlled cases are compared, a superior improvement in terms of magnitudes with FPIDC has been witnessed. The first mode is expected to be the most dangerous for crane structures during an earthquake and it is suppressed successfully using FPIDC [15].

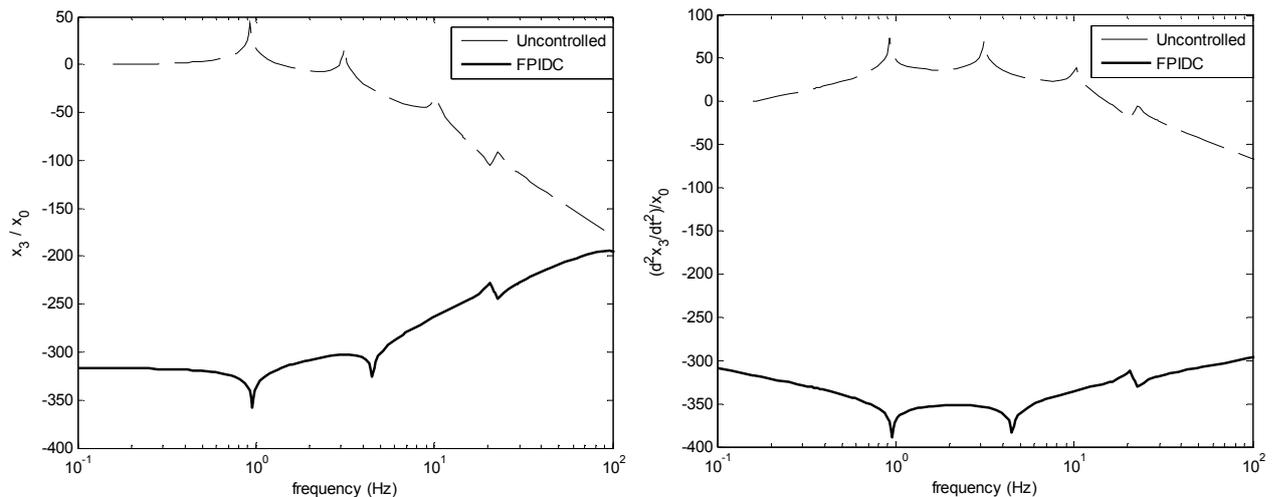


Figure 8. Controlled and uncontrolled frequency responses of the crane bridge.

5. CONCLUSION

In this study, FPIDC has been implemented to suppress structural vibrations of earthquake excited crane. The performance of the designed FPIDC is demonstrated by simulations of a six degrees-of-freedom gantry crane subjected to El Centro earthquake ground motion. System can be effectively handled by the controller. Therefore, FPIDC is applied to crane model as control algorithm. In this method, to obtain proportional, integral and derivative control action all together, fuzzy PI and fuzzy PD actions are combined to form as a FPIDC. The crane system is then subjected to El Centro earthquake vibrational effects, treated as disturbance. From simulation results it is observed that the proposed controller has a satisfactory performance in reducing vibration amplitudes against El Centro earthquake ground motion when the horizontal displacement and acceleration responses of crane structure are considered. This results reveal that proposed FPIDC has great potential in crane structure seismic control. Study also shows the destructive effects of high accelerations which occur during the earthquake. These effects can not be ignored during the structural design of cranes. It is seen that this controller descends the effects of such accelerations substantially. It can be concluded that the controller used may affect the structural design of cranes drastically.

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APPENDIX

Parameters of the Gantry Crane and FPIDC

Mass parameters	Stiffness parameters	Damping parameters	Length parameters	FPIDC scaling factors
$m_1 = 500000 \text{ kg}$	$k_1 = 18050000 \text{ N/m}$	$c_1 = 26170 \text{ Ns/m}$	$L_0 = 2 \text{ m}$	$K_e = 4$
$m_2 = 10800 \text{ kg}$	$k_2 = 27850000 \text{ N/m}$	$c_2 = 12000 \text{ Ns/m}$	$L_{portal} = 8,3 \text{ m}$	$K_{de} = 0.1$
$m_3 = 20800 \text{ kg}$	$k_3 = 67000000 \text{ N/m}$	$c_3 = 30000 \text{ Ns/m}$	$H = 10,9 \text{ m}$	$\alpha = 60000000$
$m_4 = 4000 \text{ kg}$	$k = 20000000 \text{ N/m}$	$c = 15000 \text{ Ns/m}$		$\beta = 15000000$
$m_5 = 20000 \text{ kg}$				