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Sliding Mode Control of Fixed Jacket Offshore Platform Structures

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Abstract—*This research examines performance of active control of structures using Active Bracing System (ABS).Earthquake loading has to be considered when the offshore platform is constructed in active fault zone. To ensure safety, the displacements of the platforms need to be limited, whereas for the comfort of people who work at the structures, accelerations also need to be restricted. This paper is devoted to developing a proper procedure of applying sliding mode control algorithm for controlling the seismically induced lateral vibration of steel jacket offshore platforms by using an active bracing system .The controllers have no adverse effect should the actuator be saturated due to unexpected extreme earthquakes. Results of the vibration responses for the system subjected to sliding mode control are presented and compared to the responses of uncontrolled structures. Based on the obtained results, it was observed that this control method significantly decreases structure response, such that ABS was about 88.9% effective in reducing topside displacement of the jacket structure. It is observed that the effect of the vibration mitigation and the dynamic performance of the offshore structural system are greatly improved when the structural algorithm are applied to this offshore structural system.*

Keywords: *Sliding mode Control, Jacket Offshore Platform, Earthquake response, Vibration control, Numerical simulation*

1. INTRODUCTION

Steel jacket platforms are usually slender and flexible structures that are vulnerable to dynamic excitations, such as earthquakes, waves, ship impact, etc. Therefore, vibrations of these systems should be regulated to a desired level. Passive control methods (Soong and Dargush, 1997; Soong and Spencer, 2002) and active control methods (Soong, 1990; Preumont and Seto, 2008) seem to be appropriate for use in reducing the excessive vibrations of these flexible structures. Vibration control of offshore platforms has been examined by Wang (2002) using magnetorheological dampers. Mahadik and Jangid (2003) investigated the effect of an active tuned mass damper on the response of jacket platforms. Patil and Jangid (2005) have studied the effects of friction, viscous and viscoelastic dampers on the jacket platforms and found that viscoelastic dampers can dissipate responses more effectively. Friction dampers have been studied by Golafshani and Gholizad (2009) in order to suppress vibrations of offshore platforms. In all of these studies, waves were considered as the dynamic excitation; therefore, it is necessary to consider an earthquake as the dynamic loading. However, there are some limited studies where seismic excitation was considered. Jin *et al.* (2007) carried out some experimental and numerical studies for control of seismic induced vibrations of jacket platforms using a tuned liquid damper, TLD. T. Taghikhany, Sh. Ariana,R. Mohammadzadeh, S. Babaei used Magnetorheological (MR) fluid dampers as a powerful tool to control seismic vibration of platform. Habib Saeed Monir, Hiva Nomani developed lead-rubber isolation system developed for vibration control of steel jacket offshore platform structures. However, the oscillation amplitudes of the system are still relatively large; and the control force required to stabilize the system is also large. How to further reduce both the control force and the oscillation amplitudes of the offshore platform is the motivation of the current study.In this paper, we will explore the possibility of using an integral sliding mode control scheme to reduce vibration of the offshore jacket platform at a satisfactory level more specifically; an uncertain system model of the offshore platform will be first developed. The simulation results of uncontrolled structure subjected to seismic vibrations is then obtained. Then a sliding mode controller (SMC) will be designed to reduce the seismic vibrations. The simulation results will be given to demonstrate the effectiveness of the proposed sliding mode control scheme. Then a comparative study will be done between the simulation results of controlled and uncontrolled jacket structure

2. FORMULATION

2.1 Dynamic model of offshore steel Jacket platform

The jacket platform was modeled in SimuLink, considering water-structure interaction. First, it is essential to pay attention to the equation of motion for an offshore jacket platform. The equation of motion for an offshore jacket platform subjected to seismic excitations can be written as (Chakrabarti, 1987),

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=HU(t)+\eta\ddot{x}_g+f \quad (1)$$

where, $f=-K_d\left(\{\dot{x}\}+[1]\dot{x}_g\right)\cdot\left|\{\dot{x}\}+[1]\dot{x}_g\right|$ (2)

$M=M_s+M_a$, $M_a=\rho(C_I-1)B$, $K_d=\rho\, C_D A$ (3)

Where ***M***a, ***M***s, ***C***, ***K*** are added mass, the jacket platform mass, damping, and stiffness matrices, respectively; ρ, C_I, C_D, ***A*** and ***B*** are the sea water density, inertia coefficient, drag coefficient, area and volume matrices. The dot operator denotes element wise multiplication between two vectors.

U (t) = an r-vector consisting of r control forces; and ɳ is an *n-vector* denoting the influence of the earthquake excitation is a ($n \times$ r) matrix, denoting he location of r controller.

In this case, according to Eq. (22), the effect of the water-structure interaction can be considered as a series of added masses and absolute velocity dependent nonlinear dashpots (Fig. 1(b))

3. SLIDING MODE CONTROL ALGORITHM

It is nonlinear control method that alters the dynamics of a nonlinear system by application of discontinuous control signal that forces the system to "slide" along a cross-section of the system's normal behaviour. The theory of variable structure system or sliding mode control is to design controllers to drive the response trajectory into the sliding surface (or switching surface), whereas the motion on the sliding surface is stable. In the design of the sliding surface, the external excitation *E (t)* is neglected; however, it is taken into account in the design of controllers. For simplicity, let S = [S_1, S2,... , Sr]' be an r-dimensional sliding surface with *r* sliding variables, $S_1, S_2, \ldots, S_n$ given by

$$S=PZ=0, \quad (4)$$

Where P = an *(r* x *2n)* matrix to be determined such that the motion on the sliding surface is stable. One systematic approach for the determination of the P matrix is to convert the state equation of motion, into the so-called regular form by the following transformation. The design of the sliding surface S = PZ = 0 is obtained by minimizing the integral of the quadratic function of the state vector (Yang et al. 1994).

$$J=\int_0^\infty Z'(t)QZ(t)dt. \quad (5)$$

The design of sliding surface consists of two phases:

Phase 1 (Sliding Surface Design)

Constructing Switching Surfaces so that the system restricted to the switching surface produces a desired behaviour.

Sx(t)=0 ....(6)

Phase 2 (Controller Design)

Constructing switched feedback gains which drive the state trajectory to the sliding surface and maintain it there. For the existence of a sliding mode on the switching surface, the state velocity vectors should be directed towards the surface, i.e., the system must be stable to the switching surface. Therefore there must exist a Lyapunov function V in the neighborhood of the switching surface.

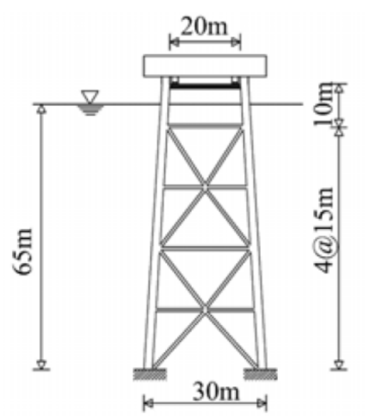
$$V=0.5S'S=0.5Z'P'PZ \quad (7)$$

The sufficient condition for the sliding mode S = 0 to occur as $t \rightarrow \infty$ is

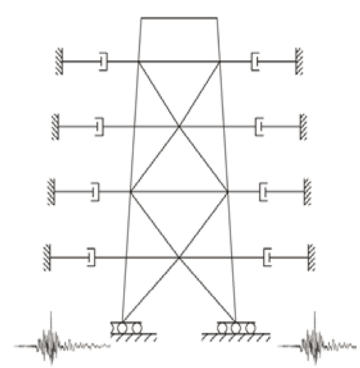
$$\dot{V}=S'\dot{S}\leq 0 \quad (8)$$

Numerical Simulation

To show the contribution of the Sliding mode control, a typical steel jacket platform is considered (Mousavi 2012). Note that this is a simplified example and all elements are assumed to remain elastic. The main aim of this study is to evaluate the effectiveness of sliding mode in control of this structure. The platform considered is a four leg platform with the same properties in both directions. The density of water is 1000 kg/m3, density of steel is 7800 kg/m3, the drag and inertia coefficients are 0.7 and 2, respectively, and the deck mass of the platform is 1000 ton. The platform is modelled as a 5DOF system.



(a)



(b)

Fig. 1: Steel jacket platform of the numerical example (a) its dimensions (b) water structure interaction

According to these assumptions, the stiffness, mass, area, volume and damping matrices are obtained as follows.

$$K=10^9\times\begin{bmatrix} 1 & -0.444 & 0 & 0 & 0 \\ -0.444 & 0.819 & -0.375 & 0 & 0 \\ 0 & -0.375 & 0.661 & -0.286 & 0 \\ 0 & 0 & -0.286 & 0.353 & -0.067 \\ 0 & 0 & 0 & -0.067 & 0.067 \end{bmatrix}\text{(N/m)} \quad (9)$$

The diagonal elements of the mass, area and volume matrices from bottom to top, respectively, are {157, 154,151, 137, 1087} ×1000 kg, {294, 289, 282, 202, 0} m^2, {258, 253, 248, 177, 0} m^3. Stiffness and mass proportional damping matrix is considered, according to the Rayleigh damping. A value of 2% is considered as the damping ratio of all modes in air (Chopra, 1995).

The jacket is subjected to the San Fernando 1971 scaled to PGA=0.3g, and the response of the uncontrolled and controlled structure is compared. These records are selected because their resonance index is about 0.3 according to the fundamental period of the structure in water.

Design of Sliding Surface

An ABS is installed at the top side of the offshore jacket platform, and hence there is only one sliding surface. For full-state feedback, the LQR method is used for the design of the sliding surface with a diagonal weighting matrix Q, as follows:

$$Q= (10, 10^2, 10^3, 10^4, 10^5, 1, 1, 1, 1, 1) \quad (10)$$

The Performance Index J can be minimized by solving the Riccati equation. This results in a sliding surface as follows:

$$S_1=2.8x_1+2.6x_2+9.6x_3-48.1x_4+302.5x_5-74.2\dot{x}_1+318.3\dot{x}_2+1165\,\dot{x}_3-2118.1\,\dot{x}_4+1.00\,\dot{x}_5 \quad (11)$$

Design of control strategy using Lyapunov Direct method

The controllers are designed to drive the state trajectory into the sliding surface S= 0. To achieve this goal, a Lyapunov function V = 0.5S'S = 0.5Z'P'PZ is considered. The San Fernando 1971 scaled to PGA=0.3g is used as the input excitation. The sufficient condition for the sliding mode S=0 to occur as $t\rightarrow\infty$ is $V = S'\dot{S} \leq 0$. Taking the derivative and using the state equation of motion

$$\dot{V}=\lambda\left(U-G\right)=\sum_{i-1}^{r}\lambda_i(u_i-G_i) \quad (11)$$

where λ' and G = r-vectors with the i^{th} elements λ_i and G_i, respectively, and U_i = $U_i(t)$ is the i^{th} control force, where $\lambda=S^{'}PB$, $G=-(PB)^{-1}P(AZ+E)$ ....(12)

4. RESULTS AND DISCUSSIONS

The structural vibration control with Active Bracing System based on Sliding mode control is investigated. This Jacket platform model given by (1) was used directly in the SimuLink model, and was subjected to the ground motion of San Fernando 1971 scaled to PGA=0.3g .After the model was verified and the uncontrolled response of the jacket structure was calculated, the contribution of sliding mode control on the response of jacket platform was evaluated.Figure3 illustrates the effect of the Sliding mode control on suppressing the topside displacement of the platform.

The bottom side and top side displacement of the platform with the Sliding mode control is depicted in Figs. 2 and 3respectively. From these figures, it is evident that the Active Bracing System based on Sliding mode control method can effectively reduce the response of the platform.

It is clear that from the given results that, Sliding mode controller effectively suppresses the maximum responses in Jacket platform.

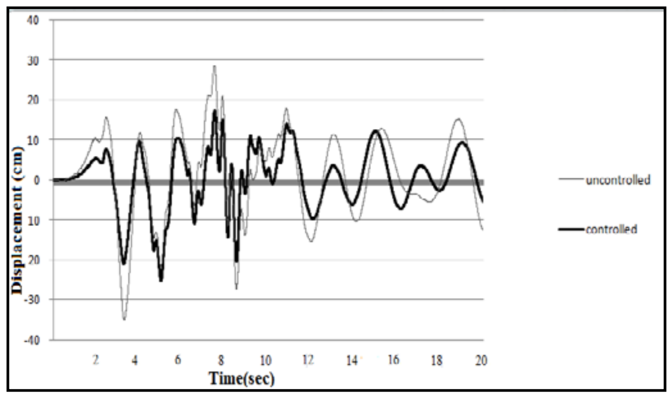


Fig. 2: Response of Jacket Platform at the base when subjected to ground motion of San Fernando 1971 scaled to PGA=0.3g

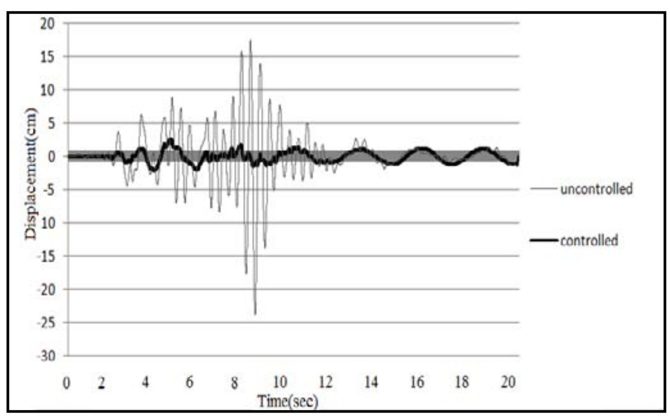


Fig. 3: Response of Jacket Platform at the topside when subjected to ground motion of San Fernando 1971 scaled to PGA=0.3g

Here the maximum control force (Fig.3) is 5, 00,000 KN, which is about 3.3 % of the entire mass of the structure.

From Fig. 3, we can evaluate that Sliding Mode controller reduces the topside displacement of the jacket structure by about 88.9 %.

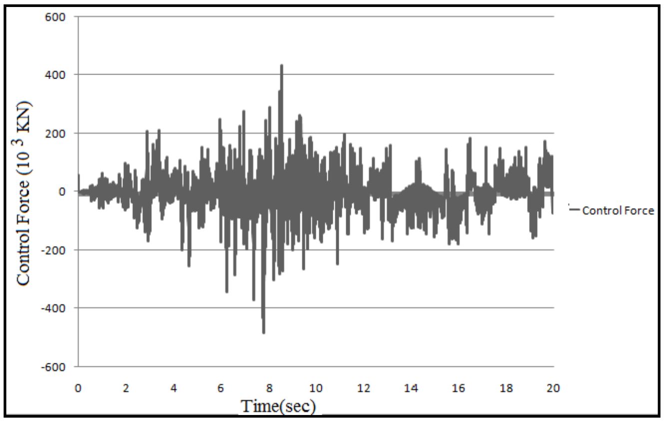


Fig. 4: Control Force applied to Jacket Platform using Sliding mode controller

Similarly from Fig. 2, we can see that, the bottom side displacement has been reduced by about 43% using Sliding mode controller.

5. CONCLUSION

In this study, CSMC methods for seismically excited linear structures have been presented. A nonlinear continuous sliding mode control strategy is presented to control responses of a offshore jacket platform subjected to ground motion of San Fernando 1971 scaled to PGA=0.3g. The control algorithm is presented for the state vector containing structural displacement and velocity.

A sliding mode control algorithm may lead to various levels of performance depending upon the choice of a set of control parameters. These parameters include the sliding margin and the diagonal weighing matrices. A number of systematic trial runs are necessary to arrive at the combination of parameters, which provide desirable levels of performance.

The results of the sliding mode control showed that for very low range of control force, the sliding mode control strategies provide higher reduction of displacement response. It was found that the sliding mode control can effectively reduce the maximum responses such as maximum displacement of the Jacket platform.

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