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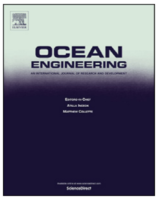

# Seismic vibration control of offshore jacket platforms using decentralized sliding mode algorithm

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ABSTRACT

A semi active control algorithm, using MR dampers, is developed for reduction of responses of offshore jacket platforms induced by earthquake ground motions and the responses are obtained for both nonlinear and linearized drag forces. The MR dampers are placed at different levels of the jacket structure and the coupled structure-damper system is modelled in Simulink. Decentralized sliding mode controllers are designed to drive the response trajectories into the sliding surfaces and the command voltage to the MR dampers are generated with the help of clipped-optimal control algorithm. The results of the numerical simulations show that the designed semi active sliding mode controller is effective in reducing the structural vibrations caused by earthquake ground motions. As a result of linearization of the drag force, the effectiveness of the controllers is reduced and responses obtained are conservative in nature, i.e., the increase in controlled responses are more when linearized drag force is considered. The control system is found to be stable and robust; however, the positions and the number of MR dampers have quite significant impact on the performance of the controller.

## 1. Introduction

The offshore jacket structures (Dawson, 1983), especially the oil and gas production platforms, play a very important role in the present day world economy. Being slender and flexible structures, these offshore steel jacket platforms are usually vulnerable to various dynamic excitations, such as earthquakes, wind, waves, ice loads, ship impact, etc. To prevent any structural damage, the vibration of the offshore platforms, under dynamic external loads, should be controlled to a desired level. Studies on vibration control of offshore jacket platforms using passive methods (Soong and Dargush, 1997; Li et al., 2002; Soong and Spencer, 2002; Karkoub et al., 2011; Chandrasekaran et al., 2013; Sethuraman and Venugopal, 2013; Moharrami and Tootkaboni, 2014; Ha and Cheong, 2016), active control techniques (Soong, 1990; Chen et al., 2008; Preumont and Seto, 2008; Stewart and Lackner, 2011; Olunloyo and Osheku, 2012; Zhang and Li, 2015) and semi-active control systems (Gurpinar et al., 1980; Wang, 2002; Fisco and Adeli, 2011; Sarrafan et al., 2012; Wang & Li, 2012; Caterino, 2015; Coudurier et al., 2015) have been reported in literature. Located in hostile ocean environments, the offshore jacket platforms are exposed to external disturbances (Ahmad and Ahmad, 1992) such as winds and earthquakes, along with self-excited nonlinear wave forces. Eventually these external disturbances lead to large oscillations of the system, thus affecting the operation and comfort of crew on the offshore platforms. And at the same time, the external disturbances inevitably affect required control cost adversely. Among these, a strong earthquake ground motion can have a disastrous effect and can cause severe damage to these types of structures. Approximately 100 offshore platforms have been installed in seismically active regions of the world's oceans. Therefore, it is absolutely necessary to design and develop controllers specifically for the reduction of responses of the jacket platforms caused by earthquake ground excitations (Gurpinar et al., 1980). In context of the above observation, however, it may be noted that most of the control schemes reported in literature have done more work on wave excitation (Wang, 2002; Ma et al., 2009; Sarrafan et al., 2011, 2012; Zhang et al., 2013; Zhang et al., 2014; Ahmadi and Nourisola, 2016) and the number of studies where seismic excitations were considered, is confined. Among these researches also, most have used passive control devices (Kawano et al., 1992; Jinping, 2006; Jin et al., 2007; Elshafey et al., 2009; Golafshani and Gholizad, 2009; Monir and Nomani, 2011; Komachi et al., 2011; Tabeshpour and Komachi, 2012; Mousavi et al., 2012; Jafarabad et al., 2014; Lotfollahi-Yaghin et al., 2016; Wu et al., 2016). Passive control devices have an inherent limitation in the sense that their control effectiveness for offshore platforms, subjected to an earthquake

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excitation, is less because of the complexity of the excitation. Their use is also confined due to large installation and maintenance cost. Studies have also been carried out on the application of active control techniques for seismic vibration mitigation (Li et al., 2005; Kim, 2009; Khaja and Kumar, 2015**)**. The limitation of the active control systems are the non-availability of precious deck space for housing the control system and high requirement of power and maintenance.

A semi active control system, however, overcomes these shortcomings. A semi-active control system has higher reliability, better control effect and smaller external energy requirement. They are also less vulnerable to power failure, which becomes a major drawback in active controllers. Limited work, however, has been done on vibration control of offshore jacket platforms, subjected to earthquake excitation, using semi active controllers. Yu et al. (2010) developed new semi-active control strategy to adjust the voltage/current of MR dampers to track the optimal/desired damping force by the LQR method. Wang and Li. (2012) proposed an intelligent control technique based on LQG method for seismic protection of offshore structures. Studies were done by Taghikhany et al. (2013) on the effect of $H_2$/LQG algorithm in Sirri jacket seismic vibration control under Kobe earthquake. Babaei et al. (2016) worked on semi active TMD, using LQG algorithm for the suppressing seismic induced vibration of Nosrat jacket platform, existing in Persian Gulf. It is nonetheless difficult to develop the mathematical model of the structure-controller system accurately in case of real structures, due to the parameter uncertainties involved in the process. This problem is even more critical for semiactive control of offshore jacket platforms using MR dampers as it involves the non-linear dynamics of the MR dampers and also the interaction between water and structure. These problems, however, need to be tackled in order to design and develop controllers which will effectively perform in such complex systems. The design of the controller becomes even more challenging when the external loads considered are earthquake excitations as against the wave loads because the uncertainties and randomness associated with the former are much more when compared with those associated with the latter. It may be noted that a semi-active control algorithm, which can accommodate uncertainty and imprecision in a more effective way than all the other semi-active algorithms mentioned so far, due to its inherent robustness and ability to cope with the parameter uncertainties and imprecision, is the sliding mode control algorithm. From the above discussion, it can be inferred that the sliding mode control technique is the most suitable control methodology for the problem considered in the present study. However, to the best of the authors' knowledge, there is no result reported in the published literature on sliding mode control for vibration control of offshore platforms subjected to earthquake excitations.

In order to simplify the analysis procedure in case of offshore structures, it is a general practice to linearize the non-linear expression of the drag force and replace it with an equivalent linearized term. In order to have a proper understanding of the behaviour of the jacket platform, it is necessary to study the effect of this linearization on the structure. In addition to this, a semi-active controller is designed and the values of different design parameters are determined based on the response feedback of the structure. Hence, it is evident that the linearization of the drag force has an effect on the performance of a semiactive controller. When the actual external excitation (or the actual water-structure interaction phenomenon) is non-linear in nature, its linearization may result in an erroneous design of the controller which may eventually lead to its poor performance in terms of response reduction. No study to investigate the effect of this linearization on the responses of jacket platforms and also on the performance of controllers, however, is reported in literature. Unlike the onshore structures, in case of offshore structures like jacket platforms which are built in hostile sea environment, the optimum number and placement of dampers is a crucial aspect as there is a trade-off between controller effectiveness and issues related to cost and difficulties involved in the installation, operation and maintenance of the dampers. No work is reported in literature in this regard and hence, a detailed parametric study on the optimum number and placement of dampers is carried out in the present paper. Lei et. al (2012) states, "decentralized control strategy is more suitable for structural control of large-scale structural systems as it increases in the feasibility of control implementation and decreases the risk on the failure of the control system compared with the conventional centralized control approach." It is also reported in literature that the "complexities inherent to large-scale modern civil structures pose many challenges in the design of feedback structural control systems for dynamic response mitigation. Key issues in such large-scale structural control systems include reduced system reliability, increasing communication requirements, and longer latencies in the feedback loop. To effectively address these issues, decentralized control strategies provide promising solutions, that allow control systems to operate at high nodal counts" (Wang et. al., 2009). These problems become even more aggravated in case of a large structure like offshore jacket platform where operation, maintenance and repair becomes more difficult due to the hostile sea environment. The control systems reported in literature for attenuation of seismic responses of jacket platforms are based on the conventional centralized approach. In order to overcome the above mentioned inherent drawbacks of the centralized controllers, a decentralized control system is developed in the present study.

In view of the above discussion, it may be summarized that the objectives of the study are to develop a semi-active control system (for seismic vibration mitigation of offshore jacket platforms) which is robust against uncertainties and imprecision and is also based on the decentralized approach, to investigate the effect of drag force linearization on the structural behaviour and controller performance, and to carry out a parametric study on the optimum number and placement of dampers. The semi-active control algorithm considered is the sliding mode algorithm using MR dampers installed at different positions and the command voltages supplied to these dampers are regulated through the clipped-optimal algorithm. A jacket platform, available in literature is taken for numerical simulation and it is subjected to real earthquake ground motion.

## 2. Formulation

### 2.1. Dynamic model of offshore jacket platform

The jacket platform is modelled in Simulink, considering water-structure interaction. The equation of motion for an offshore jacket platform, subjected to seismic excitations, can be written as (Chakrabarti, 1987),

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

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

$$\mathrm{M} = \mathrm{M_s} + \mathrm{M_a},\ \mathrm{M_a} = \rho\ (\mathrm{C_I}\text{-}1)\ \mathrm{B},\ \mathrm{K_d} = \rho\ \mathrm{C_D A} \tag{3}$$

where $\boldsymbol{M}_a$, $\boldsymbol{M}_s$, $\boldsymbol{C}$, $\boldsymbol{K}$ are the added mass, the jacket platform mass, damping, and stiffness matrices, respectively; $\boldsymbol{\rho}$**,** $\boldsymbol{C}_\mathbf{I}$**,** $\boldsymbol{C}_\mathbf{D}$, $\boldsymbol{A}$ and $\boldsymbol{B}$ 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)**is an r-vector consisting of r control forces; and **η** is an *n-vector* denoting the influence of the earthquake excitation. **H** is a ($n \times$ r) matrix, denoting the location of r controllers. In this case, the effect of the water-structure interaction can be considered as a series of added masses and absolute velocity dependent nonlinear dashpots as shown in Fig. 3.

### 2.2. Modelling of MR damper

The design of MR damper is done using Bouc-Wen model (Dyke et al., 1998; Zahrai and Salehi, 2014). The MR damper model consists of a viscous damper, tied with original Bouc-Wen model in series, and a spring, which works in parallel with the whole system. Force produced by the MR damper in the Bouc-Wen model is described as follows: