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Advanced Vibration Control of the Resalat Offshore Jacket Platform Under Seismic Excitations: A Comparative Study of Active and Semi-Active Dampers

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Abstract

In this research is to study the vibration control of the Resalat offshore jacket platform in the Persian Gulf due to benchmark earthquakes, such as El Centro, Hachinohe, Kobe, and Northridge. In this respect, an offshore platform is controlled using active and semi-active damping systems. For the active control system, a linear actuator with the New Algorithm (NA) control algorithm was employed, while for the semi-active control, a magnetorheological (MR) damper was used in both passive-off and passive-on modes. The design of the MR damper was based on the maximum force determined by the NA algorithm, ensuring its capacity met the required damping force. Simulation of the structural model using MATLAB with Simulink was conducted, was analyzed the performance of the offshore platform under the various earthquake scenarios. The results show that the active control system significantly reduces the maximum displacement and has performed better than the semi-active MR damper in passive-off and passive-on modes. Maximum displacements under the benchmark earthquakes for uncontrolled and active systems were reduced from 0.49 (m) (uncontrolled) to 0.014 (m) (active) on average. However, in terms of maximum acceleration, the semi-active system was outperformed by the active system in certain cases, indicating a trade-off between displacement reduction and acceleration control. These findings demonstrate the effectiveness of both active and semi-active control systems in mitigating vibrations under seismic conditions, with potential implications for the design and optimization of offshore platforms in earthquake-prone regions.

Keywords: Offshore jacket platform; NA algorithm; Active damper; MR damper.

1. Introduction

The study of offshore jacket platform vibration control, particularly under seismic events, has gained significant attention due to the crucial role these structures play in oil and gas extraction and the high risks associated with their failure. Offshore platforms, such as the Resalat platform in the Persian Gulf, are often subjected to dynamic loading from waves, wind, and earthquakes. The critical nature of these platforms necessitates advanced methods for structural control, including active, semi-active, and passive damping systems.

Shear models are widely used to represent the lateral response of offshore structures to dynamic forces. Simplified shear models allow for an efficient approximation of the response of tall structures to earthquake forces by focusing on the lateral displacements and inter-story drifts. Recent studies have continued to validate the accuracy of these models for offshore platforms, emphasizing their use in preliminary design and control system assessment [1, 2]. These models are particularly effective for analyzing the lateral displacement of platforms under seismic conditions, providing a basis for the implementation of various control strategies. The dynamic analysis of offshore platforms often involves simplified shear models to represent the behavior of the structure under seismic loads. These models are beneficial in reducing computational complexity while providing accurate results for preliminary design and control assessment [3].

Offshore structures are highly susceptible to vibrations induced by both environmental forces and seismic activity. Over the years, researchers have explored several vibration control strategies. Initial studies focused on passive control systems such as tuned mass dampers (TMDs) and tuned liquid dampers (TLDs), which proved effective in reducing vibrations due to environmental forces but were limited in their response to seismic events [4]. Later advancements included active control systems and semi-active control systems [5], which allow more dynamic responses to seismic forces. Active systems use actuators to counteract the applied forces, while semi-active systems, such as MR dampers, adjust their properties in response to the external loading [6]. Fahimi Farzam, et al. [7] controlled the Resalat offshore platform using a self-powered semi-active tuned mass damper under wave load with a 100-year feedback period and concluded that this control system, in addition to generating energy, can also reduce the vibrations of the offshore jacket platform deck.

MR dampers operate by changing their damping properties in response to external signals. Real-time control of the damping forces is thus achievable [8]. Studies have shown that MR dampers can effectively reduce seismic-induced vibrations, with performance depending on the control strategy employed. When used in passive-on or passive-off modes, they act as traditional dampers but offer better flexibility when combined with an appropriate control algorithm [9, 10].

Active control systems, on the other hand, use actuators to apply external forces to counteract seismic loads. Active systems, when combined with advanced control algorithms such as neural networks or fuzzy logic, can significantly reduce the displacement of offshore platforms deck [11]. However, one of the major disadvantages of active systems is their dependence on external power; this may not be practical at all times in offshore environments. However, recent developments in actuators that are energy-efficient and predictive algorithms for control have made active systems more feasible [12]. One of the key challenges in designing vibration control systems for offshore platforms is the trade-off between displacement reduction and acceleration control. Active control systems typically excel at reducing displacement, but they may lead to higher accelerations [13]. On the other hand, semi-active systems offer a better balance, reducing both displacement and acceleration, but may not achieve the same level of displacement reduction as active systems[14]. Recent studies have explored this trade-off in depth, suggesting that a hybrid approach may offer the best overall performance [15]. Mousaviyan Safakhaneh, et al. [16] controlled a benchmark 10-story structure with an active control system and presented a new control algorithm and compared it with fuzzy and LQR algorithms, their results showed that the new algorithm performed better than other methods.

Benchmarking the performance of control systems under seismic events is essential for evaluating their effectiveness. Benchmark earthquake records, such as El Centro, Kobe, Northridge, and more recent records from 2003 onwards, have been widely used to test various control systems [17]. The results of these studies consistently show that active control systems, such as those using Neural network, perform best in terms of displacement reduction, while semi-active systems offer a good compromise between displacement and acceleration control [18].

As offshore platforms continue to be built in seismically active regions, the need for more advanced control systems will grow. Future research is likely to focus on the integration of deep learning algorithms for real-time adaptive control, as well as the development of more energy-efficient actuators for active systems [19]. Besides, new material designs for MR dampers-such as nanomaterial-enhanced fluids-may provide even more significant gains in damping performance [20]. Lastly, the use of digital twins for real-time monitoring and control of offshore platforms is a newer area of research that could revolutionize how these structures are managed during seismic events [21].

In this research, the active and semi-active control systems for controlling the vibrations of the Resalat offshore jacket platform under the effect of the dynamic load of the earthquake have been discussed. The actuator of the active system applies the force determined by the NA algorithm to the deck of the jacket platform. In semi-active control mode, MR damper is used in passive-on and passive-off strategies. Finally, the control performance of these systems have been compared based on the seismic response of the structure.

2. Mathematical model for offshore jacket platform with active and semi-active control system

The differential equation of a linear multi-degree-of-freedom shear structure under the effect of earthquake load in matrix forms is Eq. (1):

$$\mathbf{M}\ddot{\mathbf{U}}(t) + \mathbf{C}\dot{\mathbf{U}}(t) + \mathbf{K}\mathbf{U}(t) = \mathbf{P}(t) + \mathbf{F_D}(t)\,. \tag{1}$$

where **M**, **C** and **K** are N×N dimensions mass, damping and stiffness matrices for an N degree of freedom structure, respectively. $\ddot{\mathbf{U}}(t)$, $\dot{\mathbf{U}}(t)$ and $\mathbf{U}(t)$ are acceleration, velocity and displacement vectors, and $\mathbf{P}(t)$ is the earthquake force on the structure. **M** and **K** are the mass and stiffness matrixes, respectively, as follows.

$$\mathbf{M} = \mathrm{diag}[\mathrm{m}_1\ \mathrm{m}_2\ \ldots\ \mathrm{m}_\mathrm{N}\ \mathrm{m}_\mathrm{d}]\,. \tag{2}$$

$$\mathbf{K} = \begin{bmatrix} k_1+k_2 & -k_2 & & & & & \\ -k_2 & k_2+k_3 & -k_3 & & & & \\ & -k_3 & k_3+k_4 & \bullet & & & \\ & & \bullet & \bullet & \bullet & & \\ & & & \bullet & \bullet & \bullet & \\ & & & & -k_N & k_N+k_d & -k_d \\ & & & & & -k_d & k_d \end{bmatrix}. \tag{3}$$

Damping matrix of the structure is considered as Rayleigh damping and 2% damping ratio is assumed for its first and second modes. $\mathbf{F_D}(t)$ is as seen Eq. (4) is the 1×N matrix that indicates the position of applying the control force, and F_c represents the control force produced by the actuator and MR damper.

$$\mathbf{F_D}(t)=[0\ 0\ .\ .\ .\ F_c\ \text{-}F_c\ ]^{\mathbf{T}} \tag{4}$$

2.1 Active controlled force

Active control force is determined by NA algorithm. This algorithm was first presented by Mousaviyan Safakhaneh, et al. [16]. The control force calculated by this algorithm is based on Eq. (5). The input of this algorithm is the maximum displacement of the structure (usually the last floor), u_N , and its inverse is calculated according to Hooke's law in the stiffness of the level, k_d , where the actuator is installed to achieve ideal control. In addition, the determined control force is intensified by a factor of *n* which is determined by default to ensure optimal movement of the actuator.

$$F_{\mathrm{c}}=\text{-}u_N\,nk_d \tag{5}$$

2.2 Semi-active controlled forced

MR damper is used in semi-active control mode. The equations for calculating the force produced by this damper using the modified Book-Wen model shown in Fig. 1. are as follows:

$$F_{MR}=C_1\dot{y}+k_1(x_d+x_0) \tag{6}$$

$$\dot{z}=-\gamma\left|\dot{x}_d+\dot{y}\right|z\left|z\right|^{n-1}-\beta(\dot{x}_d-\dot{y})\left|z\right|^{n}+A(\dot{x}_d-\dot{y}) \tag{7}$$

$$\dot{y}=\frac{1}{c_0+c_1}\left\{\alpha z+c_0\dot{x}_d+k_0(x_d-y)\right\} \tag{8}$$

$$\alpha=\alpha_a+\alpha_b u \tag{9}$$

$$c_1=c_{1a}+c_{1b}u \tag{10}$$

$$c_0=c_{0a}+c_{0b}u \tag{11}$$

$$\dot{u}=-\eta(u-\upsilon) \tag{12}$$

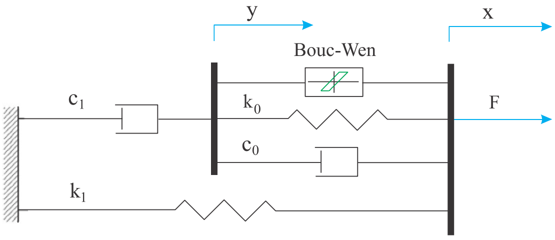

Figure 1. Simple Mechanical MR Damper Model Dyke, et al. [5].

F_{MR} is the force generated by the damper and $\dot{z}$ represents its time history behavior. υ was the input voltage to the damper, which is in the passive-on strategy is a 10 (V) and in the passive-off strategy is a 0 (V). x_d is a displacement of the structure at the attachment point of the MR. other sources in these equations (c_{0a} , c_{0b} , k_0 , c_{1a},c_{1b} , k_1, x_0 , α_a , γ , *u*, *A*, *n*, η) is specified and explained in the article by Dyke, et al. [5] for a magnetic fluid damper and to simulate the control force obtained from the NA control strategy.

The initial MR damper model presented by Dyke, et al. [5] cannot be used in real structures. One way to incorporate this model into the oil platform is to modify the parameters of the MR damper, multiplying the damping, stiffness and hysteretic constants of the model by a modification factor, MF, to magnify the damper force. But this factor should be determined in such a way that the semi-active system behaves optimally. The maximum active control force can be used to find the optimal *MF*. To find suitable answers, equivalent linearization techniques [22, 23] should be used to represent the damper model. In this article, MF is determined using a simple method of Eq. (13) and based on the deterministic analysis of the active system instead of the random vibration analysis of the semi-active system.

$$MF = \frac{F_c^{\max}}{F_{MR}^{\max}} \tag{13}$$

3. Numerical study

The structure studied in this research is the Resalat offshore platform located at a depth of 68.2 meters in the Persian Gulf under the effect of dynamic earthquake loads. Resalat offshore platform is modeled as a 7-degree-of-freedom equivalent shear structure. The period of its first and second mode is 2.355 and 0.502 seconds, respectively. The parameters of the mass and stiffness of the Resalat offshore platform levels are presented in Table 1. The damping matrix of the structure is formed using the Rayleigh damping relation for the damping ratio of 2% and its first and second modes.

The lateral loads on this structure are benchmark earthquakes far field ground motions (El Centro and Hachinohe) and near field ground motions (Kobe and Northridge), as shown in Table 2.

Table 1. Modified Resalat offshore jacket platform parameters [24].

level	1	2	3	4	5	6	7
Mass (ton)	106	129	116	105	92	63	1790
Stiffness (MN/m)	179	146	146	121	106	90	38

Table 2. Input ground motions [25].

Name	Earthquake	Station	Date	PGA	Mw
El-Centro	Imperial Valley	El Centro Station	1940	0.3417	6.9
Hachinohe	Tokachi-Oki	Hachinohe	1968	0.2250	8.2
Kobe	Hyogo-ken	KJMA	1995	0.8178	6.9
Northridge	Northridge	SCH	1994	0.8267	6.7

For active control, an actuator is used between levels 6 and 7 of the structure and the NA control algorithm. The parameters k_d and u_N are the hardness of level 7 and displacement of the offshore platform deck, respectively. Intensification factor *n* is considered to be 50 by default.

For semi-active control, the MR damper is installed between levels 6 and 7, and to determine its optimal capacity, the maximum force of the active damper in the El-Centro earthquake and the MR damper of 3 (kN) were used, the specifications of which are shown in Table 3.

Table 3. Modified MR damper parameters [5].

Parameter	Value	Parameter	Value
c_{0a} (N.s/cm)	21	α_a (N/cm)	140
c_{0b} (N.s/cm.V)	3.5	α_b (N/cm.V)	695
k_0 (N/cm)	46.9	$\gamma(cm^{-2})$	363
c_{1a} (N.s/cm)	283	$\beta(cm^{-2})$	363
c_{1b} (N.s/cm.V)	2.95	A	301

k_1 (N.s/cm)	5	n	2
x_0 (cm)	14.3	$\eta(s^{-2})$	190

The vibration control of offshore platforms is a crucial aspect of ensuring the structural integrity and operational safety of such facilities, particularly in seismic-prone areas. This study focused on the Resalat offshore platform located in the Persian Gulf, which was subjected to benchmark earthquakes, namely El Centro, Hachinohe, Kobe, and Northridge. The results show that implementing both active and semi-active control strategies significantly improved the platform's response to seismic events.

In terms of displacement control, the active control system, which utilized an actuator and the NA algorithm, was the most effective, reducing the maximum displacements by a considerable margin across all tested earthquakes. For example, as shown in Table 4, under the Northridge earthquake, the maximum displacement was reduced from 0.94 (m) in the uncontrolled case to 0.011 (m) in the active control case. On average, active control achieved a displacement reduction of approximately 97%, showing its superiority in reducing structural movements.

The semi-active control using an MR damper in passive-on and passive-off modes also provided significant benefits. Although not as effective as the active control, the passive-on mode was particularly successful in reducing displacements, with an average reduction of 86%. The MR damper's performance was calibrated based on the maximum force from the NA algorithm, ensuring that its capacity was optimized for the seismic loads.

While active control demonstrated the best displacement reduction, it did not always achieve the lowest accelerations. For example, as shown in Table 5, under the El Centro earthquake, the active control system reduced the acceleration by a very small amount (4.1%) compared to the uncontrolled scenario. This highlights the trade-off between reducing displacement and managing accelerations, suggesting that in certain cases, semi-active control could be preferable if acceleration reduction is prioritized.

In general, the combination of both control strategies, depending on the specific requirements of the structure, provides a flexible and efficient approach to seismic vibration control. Active control offers precision and superior displacement reduction, while semi-active control with MR dampers provides a practical solution with lower energy demands and still achieves substantial improvement.

Table 4. Maximum displacement of the Resalat offshore jacket platform deck under benchmark earthquakes.

Earthquake	Uncontrolled (m)	$MR_{Passive-off}$ (m)	$MR_{Passive-on}$ (m)	Active (m)
El - Centro	0.31	0.060	0.031	0.009
Hachinohe	0.32	0.046	0.027	0.004
Kobe	0.37	0.130	0.094	0.031
Northridge	0.94	0.200	0.110	0.011
Average	0.49	0.110	0.066	0.014

Table 5. Maximum acceleration of the Resalat offshore jacket platform deck under benchmark earthquakes.

Earthquake	Uncontrolled (m/s^2)	$MR_{Passive-off}$ (m/s^2)	$MR_{Passive-on}$ (m/s^2)	Active (m/s^2)
El - Centro	4.10	3.26	2.94	3.93
Hachinohe	2.74	1.57	1.37	1.02
Kobe	10.6	8.33	5.64	5.03
Northridge	9.45	7.33	5.19	6.05
Average	6.72	5.12	3.79	4.01

4. Conclusion

This study demonstrates that both active and semi-active control strategies significantly enhance the seismic performance of the Resalat offshore platform. The active control system, utilizing an actuator and the NA algorithm, was the most effective in reducing structural displacements, achieving an average reduction of 97% under benchmark earthquakes. Semi-active control using MR dampers in passive-on mode was also highly effective, particularly in displacement reduction, with an average improvement of 86%. However, the acceleration results indicate that active control does not always guarantee the lowest accelerations, and in some cases, the semi-active system may be more suitable.

Ultimately, the choice between active and semi-active control methods should depend on the specific goals of the vibration control strategy—whether minimizing displacement or managing accelerations. By carefully selecting and optimizing control systems, it is possible to significantly improve the safety and stability of offshore platforms in seismic regions.

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