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EXPERIMENTAL STUDIES ON SEMI-ACTIVE VIBRATION CONTROL OF JACKET PLATFORMS WITH MAGNETORHEOLOGICAL DAMPER

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ABSTRACT

Jacket platforms are inevitably undergoing the environmental loads such as wind, waves, current, ice and earthquake etc., which will induce continuous vibration of the platforms. The vibration, on one hand, will cause fatigue damage, decreasing the platform's reliability; on the other hand, the excessive vibration can't satisfy the basic psychological requirements of the personnel. In order to reduce the excessive vibration of jacket platforms effectively, many control strategy and control equipments are proposed and studied. In the present study, a model experiment is designed to investigate the effectiveness of semi-active vibration control system with Magnetorheological (MR) Damper.A typical jacket offshore platform in Mexico Gulf is selected as experimental prototype. The model of the jacket platform is designed based on dynamical similarity criterion by the scale of 1:50. Furthermore, the optimal semi-active system of MR damper is designed by fuzzy control theory. In order to investigate the control effect of MR damper on the jacket platform under regular and random wave state, several model experiment load cases are performed. The experimental results show that the MR system designed by fuzzy theory can reduce the vibration of the platform effectively and in the same time the control effect is stable.

Keywords: magnetorheological dampers; fuzzy controller; semi-active control; model experiment

1 INTRODUCTION

With the increasing worldwide demand for oil and gas, offshore structures are taking on a dominant role in drilling and production technology. Among various types of offshore structures, jacket platforms are one type of the most widely application of offshore structures. Jacket platforms are generally used on-site, inevitably undergoing the environmental loads such as wind, waves, current, ice and earthquake etc., which will induce continuous vibration of the offshore platforms. The vibration, on one hand, will cause fatigue damage, decreasing the platform's reliability; on the other hand, the excessive vibration can't satisfy the basic psychological requirements of the personnel.

During the offshore engineering developments, there are several serious accidents about offshore platforms, which induced enormous economic loss and worse social influence. Such as Bohai No.2 platform in China collapsed as a result of sea ice, inducing 2000,00 RMB economic loss, Alexander L Kielland platform in Gulf of Mexico overturned in 1980， killing 122 persons, Eco-Nightmare P-36 Offshore in Brazil collapsed in 2000, BP EI-322 in Gulf of Mexico was destroyed by Hurricane Lily in 2002.

Hence using smart control technology to enhance the structures' safety and reliability, prolong the service life and ensure the comfort of the personnel has become a very important research subject in ocean engineering and academic fields.

Among many control strategies, semi-active control method becomes a very valuable research direction for its excellence of needing less energy and obtaining the expected control effect [1]. With the development of new types of materials, the magnetorheological dampers (MR) as the semi-active control equipment have been paid much attention to. Guan and Huang investigated the effectiveness of the semi-active magnetorheological damping control for offshore platform. And the control algorithm was the classical LQG [2]. Li investigated the effectiveness of the lateral vibration control of wave-excited response of offshore platforms with MR damper. A semi-active control method based on optimal control theory was proposed considering that the yield stress of the MR damper can be varied continuously within a certain range [3]. Liu adopted genetic algorithm(GA) to optimize the look—up table of the fuzzy controller to reduce the vibration of a two—degree-of-freedom forced vibration system [4]. Sun and Liang adopted MR damper to control the seismic response of a new type single pile platforms [5]. Ji and Yin studied the effectiveness of MR damper designed by the fuzzy control strategy for controlling the vibration of offshore platforms. And the influence of uncertainties of external loads parameters and structural damping on control effect was analyzed in detail [6]. However above studies mainly focus on numerical investigations，experimental studies are few，especially for those experiments in wave tank, which did some research on the control effect on vibrations induced by wave force . Some investigations on the control effect of jacket platforms under ice load or seismic load were conducted [7-9]. In addition, Zhang and Deng presented a new kind of vibration reduction and impact resistance isolator system based on MR technique. The vibration and impact experiments were designed using MTS hydraulic loading system [10].

In the present study, a model experiment is designed to investigate the effectiveness of MR damper for the reducing the vibration of the jacket platform under wave loads. A typical jacket offshore platform in Mexico Gulf is selected as the experimental prototype. The model of the jacket platform is designed based on dynamical similarity criterion by the scale of 1:50. Furthermore, MR damper is taken as the semi-active control equipment governed by the fuzzy control theory to realize the semi-active control algorithm. Locations of acceleration sensors, displacement measurement system and MR are also given. In addition, in order to investigate the vibration control effect of MR damper of the jacket platform under different wave states, the experiments under two regular wave loads and five random wave loads are performed. The experimental results show that the semi-active system of MR damper designed by fuzzy theory can reduce the vibration of the platform effectively and in the same time the control effect is stable.

2 PROTOTYPES AND MODEL

A typical jacket offshore platform in Mexico Gulf is selected as experimental prototype. Its mass is 11680000kg, and its natural frequency is 0.427Hz. The model of the jacket platform is designed based on the geometry and dynamical similarity criterions (mainly satisfying the structural frequency similarity) by the scale of 1:50. In order to obtain the more obvious vibration and the easiness of machining, the experimental model is properly simplified. The natural frequency of the simplified model is more near the frequency of the external wave. The main material parameters of the prototype and model are given in table 1. Table 2 shows the main similarity ratios. The mass of the model is 40.2kg, and its natural frequency is 3.52Hz. The photo of the jacket platform model is given in figure 1.

Table 1 Main parameters of similarity ratios

Material and prosperities	Material name	Elasticity modulus	Poisson ratio	density
Prototype	model	2E+11Pa	0.3	7800kg/cm3
Model	Organic glass	3E+9Pa	0.35	1170kg/cm3

Table 2 Main similarity ratios

Similarity ratio	The similarity ratio of geometry	The similarity ratio of elasticity modulus	The similarity ratio of density	The similarity ratio of frequency	The similarity ratio of mass	The similarity ratio of stiffness
Actual similarity ratio	50：1	66.67:1	6.67:1	0.12:1	2.4E+5:1	3.46E+3:1
The required ratio by similarity criterion	--	--	--	0.14:1	8.3E+5:1	1.67E+4:1

3 FUZZY CONTROLLER

This paper adopted MR damper as the semi-active control equipment governed by the fuzzy control theory to realize the semi-active control algorithm in order to reduce the vibration of the offshore platform under wave sea state. The graph of control system is shown in figure 2.

3.1 Input and output variables

The safety of the platform is the most important, so the input variables of the fuzzy controller are the displacement error $e(i) = r - y(i)$ and the difference of error in the continuous time $ec(i) = e(i-1) - e(i)$ in this paper. Where y represents the displacement of the platform, γ is the referred input. In this paper $r = 0$ and the output variable is the optimal control force determined by fuzzy controller.

3.2 Parameters of fuzzy controller

The fuzzy inference range is [-6, 6] in the paper. The fuzzy model includes two input variables: error, E , the difference of error, EC , and one output variable: control force U . Each has seven membership functions, i.e. NB、NM、NS、ZE、PS、PM、PB. These membership functions are endued with fuzzy numbers of normal distribution, which are expressed as

$$\{\mathrm{NB, NM, NS, ZE, PS, PM, PB}\} = \{-3, -2, -1, 0, 1, 2, 3\} \quad (1)$$

Thus the three linguistic variables e , ec , u are inferred into the inference range [-6,6] by parameters K_e , K_{ec} , K_u .

Where

$$E = e \cdot K_e ,\ EC = ec \cdot K_{ec} ,\ U = u \cdot K_u \quad (2)$$

3.3 Fuzzy control model

The fuzzy model based on fuzzy control methods need define membership functions, which has exceeds the experience of operating persons. In addition, the compiling heuristic inference rule depends on the designer's experience and intuition, therefore the precision of control effect are not assured. In the same time the heuristic inference rule are not adjusted flexibly for the complication of deduction, while it is a key point to design an expected fuzzy controller. This paper builds a fuzzy number model based on the analytical expression. The structure of fuzzy number model adopts the following expression, which has four revised parameters.

$$U=\begin{cases}\langle \alpha_1 E+(1-\alpha_1)EC\rangle & \text{when}\quad E=0\\ \langle \alpha_2 E+(1-\alpha_2)EC\rangle & \text{when}\quad E=\pm1,\pm2\\ \langle \alpha_3 E+(1-\alpha_3)EC\rangle & \text{when}\quad E=\pm3,\pm4\\ \langle \alpha_4 E+(1-\alpha_4)EC\rangle & \text{when}\quad E=\pm5,\pm6\end{cases} \tag{3}$$

Where $\alpha_i, i=1,2,3,4$ is adjusting parameter, which are obtained by minimizing the ITAE integral objective function by optimal method; E, EC represent the error and the difference of error; $\langle \alpha_1 E+(1-\alpha_1)EC\rangle$ represents the integer, whose value is the nearest the value of $\alpha_1 E+(1-\alpha_1)EC$.

The fuzzy variables in equation 1 carries out positive, so the fuzzy control algorithm will operate only when E and EC exactly equal to NB、NM、NS、ZE、PS、PM、PB respectively. In order to assure the stability of fuzzy controller and simplifying the controller design, the paper adopts the linear insert fuzzy control system. After linear insert operation i.e. the values of divided numbers of E and EC region near to infinite, the heuristic inference rule defined in equation 7 are satisfied. And the abutting division region is supplied with many new and minute control rule trough the linear insertion method. The equality of control system is improved remarkably.

Figure 1 Photo of the jacket platform model

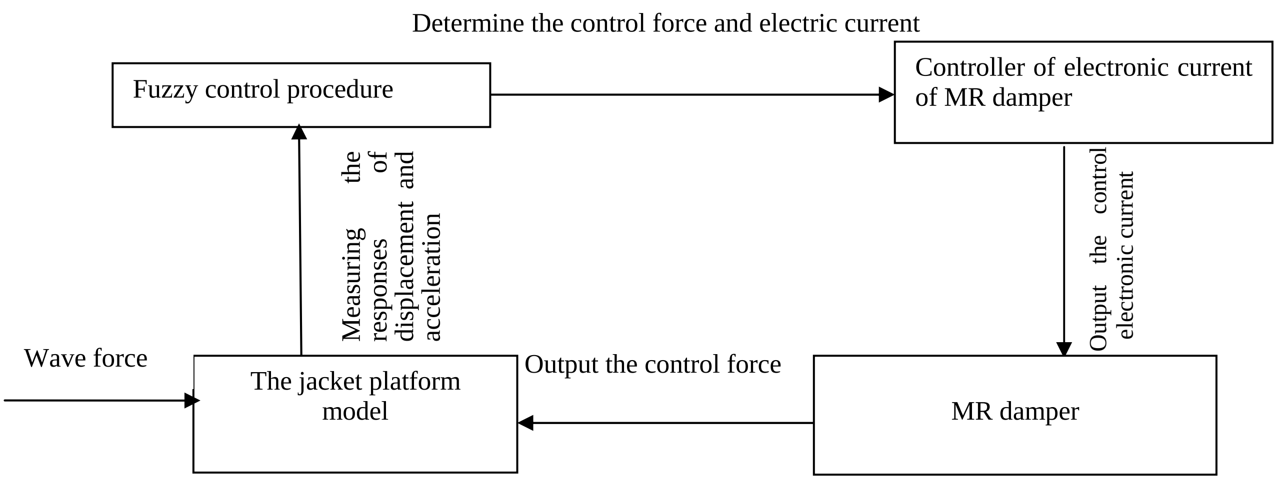


Figure 2 Graph of the semi-active control system

4 SEMI-ACTIVE SYSTEM OF MR-DAMPER

4.1 Structural parameters of MR and its mechanics model

The structure of MR damper is shown in figure 3. The design of MR damper is mainly based on the magnitude of the needed control force and the possible sizes produced by the factory. The main parameters of MR used in this paper are shown in table 3.

Table 3 Main parameters of the MR damper

D/mm	d/mm	h/mm	L/mm	$\eta/pa\cdot s$	$\tau_{y\max}/kpa$
100	40	1.5	200	1	40

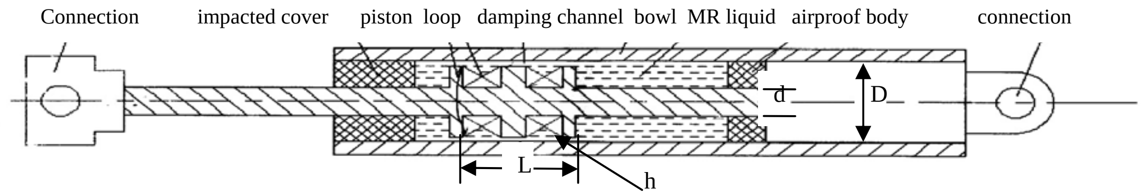


Figure 3 Graph of the structures of MR damper

The mechanical properties of MR are obtained by a mechanical experiment, which are conducted on a MTS810-material experimental equipment. The impulsive amplitude is 20mm, and its frequency is 1Hz. The impulsive electronic currents are 0A，0.3A, 0.6A, 0.9A, 1.2A, 1.5A, 1.8A and 2.1A respectively. The experimental results are shown in figure 4, which indicates that the damping force increases with the impulsive velocity linearly in the different zone. The constructive relation of the magnetorheological liquid satisfies Bingham model basically, which is defined as

$$\tau = \tau_y \operatorname{sgn}(\dot{\gamma}) + \eta\dot{\gamma} \qquad (4)$$

Where τ is the shear stress of magnetorheological liquid; $\dot{\gamma}$ is the shear strain velocity; τ_y is the maximum yield shear stress of the MR fluid; η is the dynamic viscosity coefficient of MR liquid. Based on the stress grads equation of liquid in narrow gab in Bing－ham model, the mechanics model can be expressed as：

$$F = \frac{3\eta L\left[\pi\left(D^2-d^2\right)\right]^2}{4\pi D h^3}\dot{x}(t) + \frac{3L\pi\left(D^2-d^2\right)}{4h}\tau_y \operatorname{sgn}(\dot{x}(t))$$
$$= c_d\dot{x}(t) + f_{dy}\operatorname{sgn}(\dot{x}(t)) \qquad (5)$$

Where F is the output damping force by MR damper; L is the length of magnetorheological region; h is the gab between piston and cylinder；D is the inner diameter of cylinder，d is the diameter of piston rod; $\dot{x}(t)$ is the relative velocity between piston and cylinder；Sgn is sign function; c_d and f_{dy} are viscosity damping ratio and the alterable damping force.

4.2 Semi-active control strategy

From above equations, the alterable magnetorheological strength can adjust the output damping force, but the damping force can't equal the optimal control force decided by fuzzy control algorithm at any time considering the limits for output force. Based on semi-active control strategy, the actual output control force can be determined by the following equation, which is near the optimal control force by adjusting magnetorheological strength.

$$u_d = \begin{cases} c_d\dot{x} + f_{dy\max}\operatorname{sgn}(\dot{x}) & \left(u\dot{x} < 0 \text{ 且 } |u| > u_{d\max}\right) \\ |u|\operatorname{sgn}(\dot{x}) & \left(u\dot{x} < 0 \text{ 且 } |u| < u_{d\max}\right) \\ c_d\dot{x} + f_{dy\min}\operatorname{sgn}(\dot{x}) & \left(u\dot{x} \geq 0\right) \end{cases} \qquad (6)$$

Where $u_{d\max}$ is the maximum output control force by MR damper, $u(t)$ is the optimal control force decided by the fuzzy control algorithm.

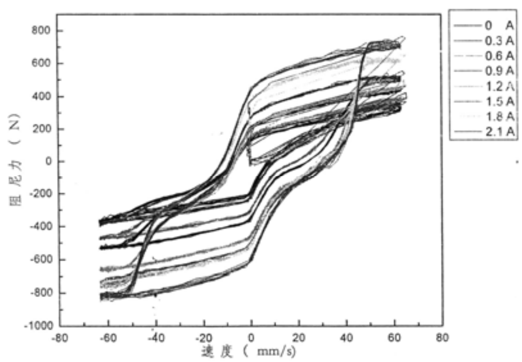


Figure 4 Curves of relations between damping force and impusive velocity and displacement

5 MODEL EXPERIMENTAL INVESTIGATION

The model experiment was carried out in the wave tank in Chinese Ship Scientific Research Center. The wave tank is 69-m long, 46-m wide and 4-m deep, and it can simulate regular and random waves.

5.1 Experimental set-up

Four measurement points which output acceleration response are set on two legs of the offshore platform model on the water level of 0.4m and 0.7m, which are shown in figure 5 and figure 6. The locations of these measurement points are determined by the left height of the platform model over the water level and the amptitude of motion. Two acceleration sensors are located on every measurement point to measure the different direction acceleration response, i.e. X and Y, which are shown in figure 6. The displacement measurement system is located on the center of top desk to measure the displacement response of the jacket platform model. Considering the constraints on the sizes of the jacket platform model, one MR damper is used to control the vibration of the jacket offshore platform model, whose location is given in figure 5.

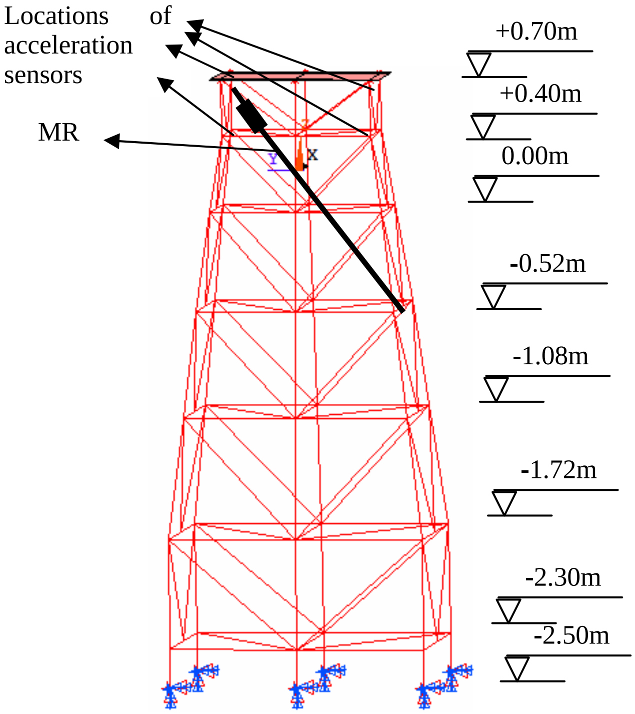
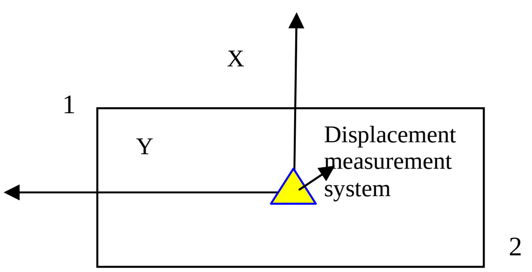
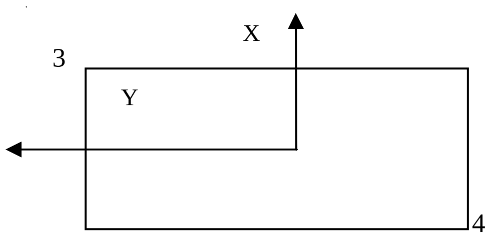


Figure 5 Plot of the locations of MR damper and acceleration sensors



(a) Number of acceleration sensors on the seventh floor of the model （z=0.7m）



(b) Number of acceleration sensors on the sixth floor of the model（z=0.4m）

Figure 6 Plot of acceleration sensors and displacement measurement system

5.2 Experimental load cases

In order to investigate the vibration control effect of MR damper under different load cases including different types of wave, different wave heights and different wave periods, the experimental load cases include two types of wave, i.e. regular wave and random wave, totally seven load cases which are shown in table 4. The experimental water depth is 2.5m.

Table 4 Load cases of the model experiment

Number	Wave type	Significant wave height (m)	Wave direction （degree）	Wave period（s）
R01	Regular wave	0.32	Along X axis(see the coordinate	1.5
R02	Regular wave	0.20	Along X axis	1.0
I01	Random wave	0.32	Along X axis	1.5(peak wave period)
I02	Random wave	0.32	Along Y axis	1.5(peak wave period)
I03	Random wave	0.32	45 degree along X axis	1.5(peak wave period)
I04	Random wave	0.20	Along X axis	1.0(peak wave period)
I05	Random wave	0.10	Along X axis	1.0(peak wave period)

EXPERIMENTAL RESULTS

The photos of the jacket platform model without MR damper and with MR damper are shown in figure 7 and figure 8 respectively. The dynamical responses including displacement, velocity and acceleration recorded by measurement system are shown in table 5, where velocity responses are obtained by differing the displacement responses. In the same time only the acceleration responses of number 1 point are given in table 5 for little difference among different measurement points.

Figure 7 Photo of the jacket platform model without MR damper

Figure 8 Photo of the jacket platform model with MR damper

The experimental results in table 5 illustrate that the semi-active control system of MR damper can reduce the vibration responses of the jacket platform model under wave loads effectively, where the average reduction ratios of displacement, velocity and acceleration responses are 29%, 26% and 30% respectively. The vibration control effect of acceleration response is the best, and those for displacement and velocity are little worse. Comparing the vibration control effects between X and Y directions indicates that the control effect for X direction is better than that for Y because of the location of MR damper and the frequency property of the model. In addition, the vibration control effect for oblique wave is worse than that for longitudinal or transverse waves. Analyzing the vibration control effect among different parameters of sea state, such as, wave height and wave period illustrates that the MR damper designed by fuzzy control algorithm behaves fuzziness in some degree and the vibration control effects are stale. However, it also shows that the vibration control effect for regular wave is better than that for random wave and the vibration control effect decreases with the increase of wave height. Figures from 9 to 14 give the vibration control effect of displacement, velocity and acceleration responses of I01 load case (wave height is 0.32m, peak wave period is 1.5s, wave direction is along X axis). The results in these figures illustrate that the semi-active control system with MR damper can reduce the dynamical response in time domain effectively, especially for larger vibration response in some time.

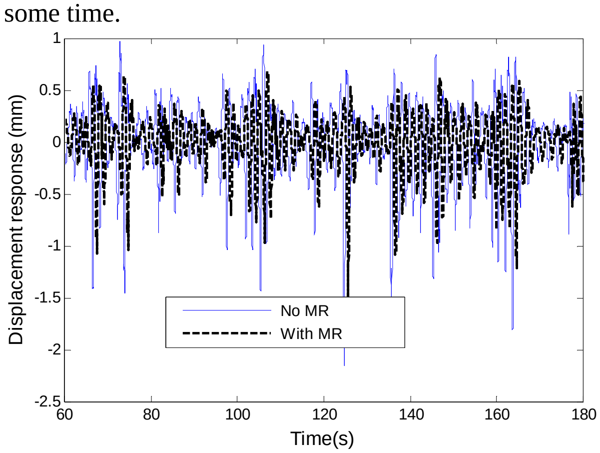


Figure 9 Vibration control effect of displacement in X direction with MR damper

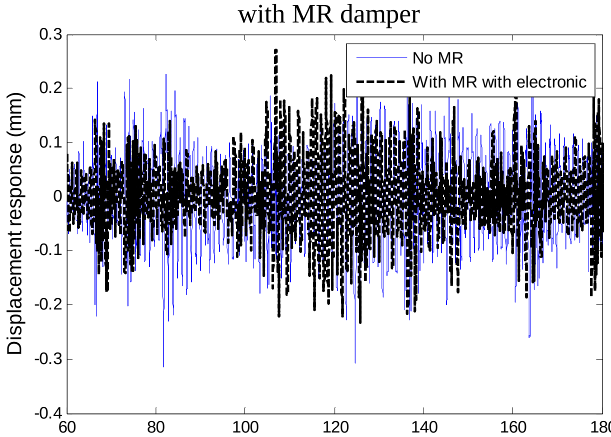


Figure 10 Vibration control effect of displacement in Y direction with MR damper

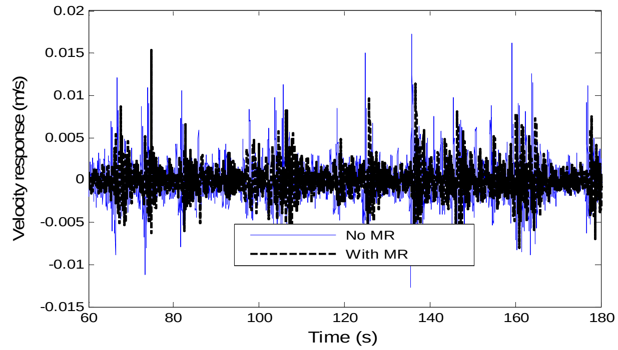


Figure 11 Vibration control effect of velocity in X direction with MR damper

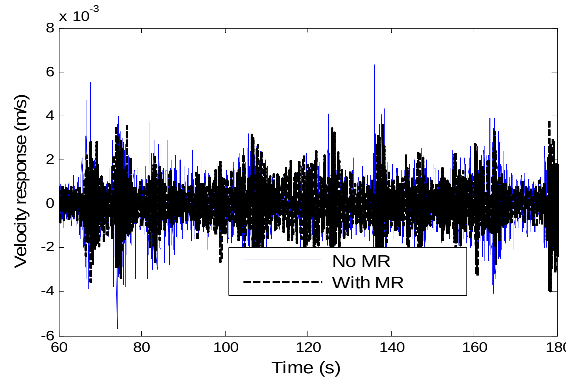


Figure 12 Vibration control effect of velocity in Y direction with MR damper

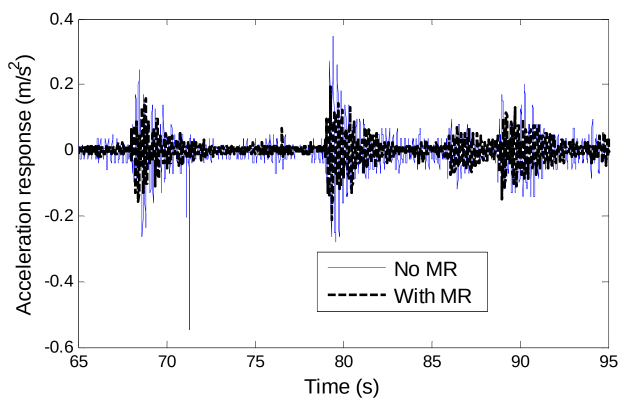


Figure 13 Vibration control effect of acceleration in X direction with MR damper

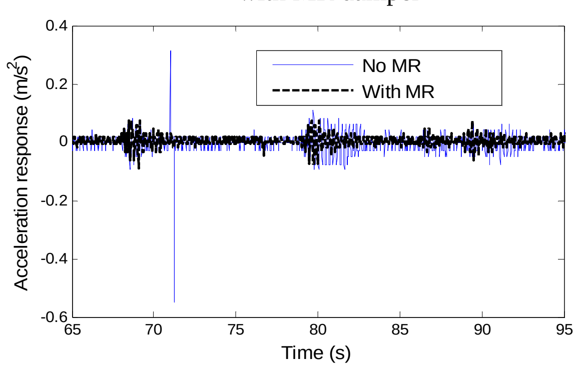


Figure 14 Vibration control effect of acceleration in Y direction with MR damper

Table 5 Vibration control effect of semi-active control system of MR damper

Number of load case	direction	RMS of disp. without MR （mm）	RMS of velo. Without MR （m/s）	RMS of ace. without MR （m/s2）	RMS of disp. with MR （mm）	RMS of velo. Without MR （m/s）	RMS of acce. without MR （m/s2）	Reduction ratio of disp. （%）	Reduction ratio of velo. （%）	Reduction ratio of acce. （%）
R01	x	0.3982	0.0029	0.0548	0.2560	0.00210	0.0342	35.7	27.6	37.7
	y	0.0772	9.67E-04	0.0283	0.0502	0.00069	0.0162	35.0	28.1	42.7
R02	x	0.1252	0.0035	0.0422	0.0779	0.00256	0.0279	37.8	26.7	33.8
	y	0.0658	0.0011	0.0162	0.0370	0.00078	0.013	43.8	28.7	19.8
I01	x	0.2639	0.0017	0.0491	0.1852	0.00132	0.0328	29.8	22.4	33.1
	y	0.0450	6.03E-04	0.0415	0.0326	4.70E-04	0.0289	27.6	22.1	30.3
I02	x	0.0413	6.95E-04	0.0206	0.0321	5.14E-04	0.0134	22.2	25.9	34.9
	y	0.1320	8.12E-04	0.0197	0.1068	5.82E-04	0.0132	19.1	28.4	33.0
I03	x	0.0877	5.56E-04	0.0162	0.0690	0.00041	0.0131	21.3	25.6	19.2
	y	0.0662	4.07E-04	0.0099	0.0550	2.94E-04	0.0082	16.9	27.7	17.2
I04	x	0.1074	0.0012	0.0396	0.0787	0.00085	0.0280	26.8	29.1	29.3
	y	0.0309	5.31E-04	0.0204	0.0222	4.11E-04	0.0135	28.1	22.6	33.8
I05	x	0.0698	8.23E-04	0.0217	0.0456	5.69E-04	0.0128	34.6	30.9	40.9
	y	0.0566	4.33E-04	0.0082	0.3978	3.13E-04	0.0061	29.7	27.7	25.6

Note: disp represents the short of displacement; velo represents the short of velocity; acce represents the short of acceleration; RMS represents the root mean of square

6 CONCLUSIONS

This paper deals mainly with an experimental study on a typical jacket platform with semi-active control system of MR damper in order to investigate the vibration control effect of MR damper for jacket platforms under wave loads. The model is designed based on dynamical similarity criterion by the scale of 1:50. Furthermore, the optimal semi-active system of MR damper is designed by fuzzy control theory. In order to investigate the vibration control effect of MR damper for the jacket platforms under regular and random wave state, seven experimental load cases are performed. The following conclusions can be drawn from the experimental results:

(1) The semi-active control system of MR damper designed by fuzzy control algorithm can reduce the vibration responses of the jacket platform under wave loads effectively, especially for larger vibration response in some time. Therefore it is effective and reliable to adopted semi-active system of MR damper to control the vibrations of jacket platforms.

(2) The vibration control effect of MR damper acceleration response is the best, and those for displacement and velocity are little worse. The control effect for X direction is better than that for Y because of the location of MR damper and the frequency property of the model. In addition, the vibration control effect for oblique wave is worse than that for longitudinal or transverse waves.

（3）The semi-active control system of MR damper designed by fuzzy control algorithm behaves fuzziness in some degree and the vibration control effect is stale. However, it also shows that the vibration control effect for regular wave is better than that for random wave and the vibration control effect decrease with the increase of wave height.

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