

Optimized SMA Dampers in Vibration Control of Jacket-type Offshore Structures (Regular Waves)

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ARTICLE INFO

Article History:

Received: 6 Dec. 2018

Accepted: 10 Mar. 2019

Keywords:

Vibration Control

Steel Jacket Platforms

Shape Memory Alloys (SMA)

Idealized Constitutive Model.

ABSTRACT

Undesired oscillations of jacket platform may influence the structural functionality and sometimes fatigue occurs. The main objective of this research is to control wave-induced vibrations of fixed jacket platforms with the use of optimized shape memory alloys dampers. To model the hysteretic behavior of SMA elements and performing dynamic analysis an efficient isothermal idealized constitutive model is developed in this research and direct integration time history analysis is carried out. Dynamic responses of multi-degree of freedom system of jacket platform, with 90 m height and equipped with SMA dampers, is estimated and compared with the bare jacket. Furthermore, an optimization algorithm such as Ideal Gas Molecules Movements (IGMM) is implemented in this research to improve the efficiency of the dampers and minimize the deck displacements under the action of extreme wave. The results show that the optimized SMA dampers can improve the structural response by decreasing 47.5 percent of deck displacement, 56.5 percent of deck acceleration and finally 28 percent of base shear. In an SMA damper-equipped platform, reduced wave intensity will reduce the damper efficiency.

1. Introduction

Undesired vibrations of offshore jacket platforms increase the destructive effects of fatigue in joints, risers, and mechanical equipment on the deck, disrupt the operations of the platform drilling equipment, reduce the personnel comfort feeling and endanger their long-term health by the deck's back-and-forth movements [1]. Hence, jacket platform vibrations should be reduced by control devices.

In recent decades, many smart materials have been invented to be used as energy dissipative devices. Shape memory alloys (SMAs) are materials investigated by researchers for use in aeronautics, automobile, biomedical engineering, and civil engineering, especially vibration control of structures [2]. The main objective of this research is to present an efficient SMA damper to control the vibrations of a jacket platform under the wave and current actions.

Vibration control of offshore structures is much more difficult than that of land based structures because the former should withstand the wave-caused force besides wind and earthquake. Since inspection, repair,

and replacement of in-depth dampers are quite costly, it is necessary to use those that are highly durable and do not undergo permanent deformations under relatively large loads. A feature of SMA dampers is their lack of need for replacement or repair after lateral loads and large deformations in jacket platforms of which underwater repair and inspection are difficult.

Vandiver and Mitome [3] were among the early researchers who studied controlling the offshore jacket platforms vibrations and found that liquid-reservoirs on the platform deck can be used as the dynamic absorber. Bargi et al. too have been able to reduce the vibrations of the offshore wind turbine using tuned liquid column gas damper. Their research is all-inclusive because they controlled the vibrations under the simultaneous effects of wind, wave, and earthquake forces [4] [5].

Patil and Jungid [6], analyzed three jacket structures equipped with friction dampers, viscose dampers, and viscoelastic dampers under the action of wave forces. They have concluded that the friction damper is quite

efficient in reducing deck displacements and shear forces of jacket levels.

Investigation of dampers' performances and improving the platform dynamic behavior has been a topic of interest of Jafarabad, Kashani, Adlparvar and Golafshani, [7]. They have compared the performance of friction damper and tuned mass damper (TMD) as hybrid dampers aiming at improving the platform dynamic responses under seismic and wave loads.

In offshore structures, as well as land-based structures, isolating the platform and deck is considered as a suitable way to control the vibrations. In the recent study, Zhang has used hybrid SMA-PFD (pall friction damper) dampers to reduce the deck displacement due to seismic and ice-induced excitation [8].

Since passive dampers used on jacket platforms often work for a limited loading range, many researchers have used active and semi-active dampers to control the jacket platform vibrations [9]. Another merit of the SMA dampers is that their stiffness can be adjusted by a source of heat [10].

In this research, some SMA material features are presented in Section 2. The implementation of SMA elements, the structure of SMA damper and dampers installation in the jacket platform are explained in Section 3. In Section 4, first, the vibration equation of un-damped multi-degree of freedom system equipped with SMA dampers is developed. Then, a multi-linear formulation has been presented to develop the constitutive material modeling of the SMA elements. In this research, the linear time history responses of equipped-SMA dampers structure have been estimated using the implicit direct integration alpha-method by MATLAB based computer code [11]. Therefore, at the end of this section, two comparisons are made with reference research and finite element analysis to validate the constitutive modeling of SMA and dynamic responses of jacket platform.

In Section 5, a 90 m height jacket platform is selected as a case study and vibrated under the action of extreme regular wave with 11.8 m height and 7.8 s period. In this section, dynamic properties of MDOF system of jacket platform, dynamic characteristics of wave/current loads and SMA mechanical properties are presented first. Then, an optimization algorithm 'ideal gas molecules movements' (IGMM) is used to find optimal characteristics of SMA elements geometry based on two different objective functions [12]. Finally, numerical results of installing optimized SMA dampers to jacket platform are presented and discussed. At the end of Sec. 5, an offshore platform equipped with optimized dampers has been acted by two other regular waves and the dampers have been studied for their efficiency.

In Section 6, the results of optimized SMA dampers usage in vibration reduction of jacket platform and

some recommendations for future studies, are presented.

2. Shape Memory Alloys (SMAs)

Shape memory alloys (SMA) are a class of smart materials that possess unique properties, including shape memory effect (SME), super-elasticity effect (SE), extraordinary fatigue and corrosion resistance and high damping capacity. The shape memory effect of nickel-titanium alloy was recognized by William Buehler and Frederick Wang in 1962. The alloy was named as NiTiNol (NiTi stands for nickel-titanium and nol is naval ordnance laboratory).

Micromechanical phase transitions take place during deformation and/or temperature processes, when the SMA crystallographic structure switches from an austenitic phase to a martensitic phase (Figures 1 and 2). Martensite phase of SMA may appear in detwinned arrangement or twinned arrangement. At low temperatures ($T < M_f$), SMAs exhibit the shape memory effect (Figure 1). While, at high temperature ($T > A_f$), SMAs show super-elastic behavior, during loading and unloading steps (Figure 2). At the temperature above (M_d), SMAs suffer plastic deformations with much higher strength in their pure austenitic form.

The mechanical behavior dependence on stress, strain, and the temperature is because of the SMAs' thermo-elastic nature which increases the temperature to decrease the stress in the material. SMAs are primarily austenitic in the super-elastic phase. However, upon loading, stress-induced martensite is formed. Upon unloading, the martensite reverts to austenite at a lower stress level, resulting in the hysteretic behavior [13].

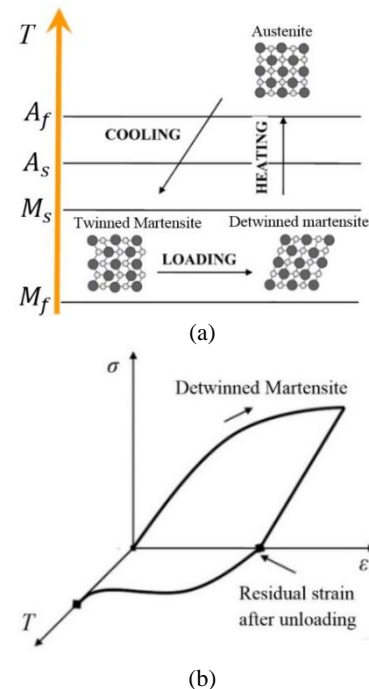


Figure 1. SMAs shape memory effect (SME) [13]; (a): crystal arrangement due to changes in loading and heating, (b): SMA's stress-strain-temperature curve

SMA's are excellent candidates for designing dampers and energy dissipation devices because of their intrinsic ability to undergo large deformations, up to 10% without remaining residual strain [14]. SMA materials have numerous combinations such as Ni-Ti, Cu-Al-Ni, Cu-Zn-Al, Au-Cd, Mn-Cu, Ni-Mn-Ga and Fe-based alloys, but most practical ones are Ni-Ti-based alloys [15].

With numerous SMA applications in different fields over the past decades, material modeling of such SMA's peculiar mechanical behavior has been a subject of interest to many researchers. The studies on SMA's behaviors were lead to the development of many constitutive models that describe the thermo-mechanical, thermo-electrical and thermo-chemical behavior; nonetheless, most of them are too complicated to be conveniently used in such practical applications as vibration control problems.

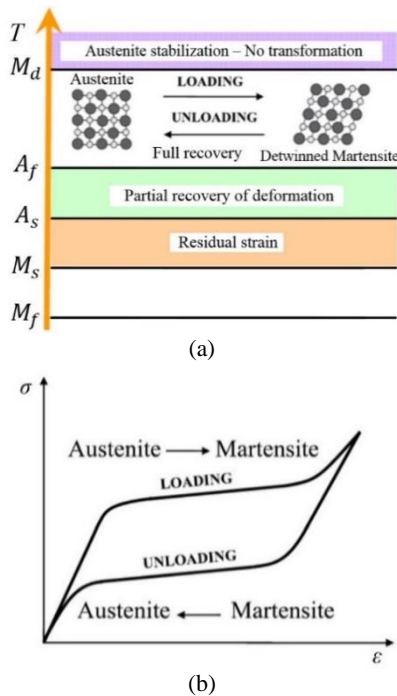


Figure 2. SMA's super elasticity effect (SE) [13]; (a): SMA's crystal arrangement due to loading and unloading, (b): SMA's stress-strain hysteresis loop

In structural vibration control field, widely used constitutive models for one dimensional isothermal superelastic SMA's can be mainly divided into polynomial constitutive model, idealized multi-linear constitutive model and equivalent linear elastic-viscous damping model. Polynomial constitutive material modeling of SMA's initially developed by Graesser and Cozzarelli (1991), is a development of a rate-independent model for hysteretic behavior proposed by Ozdemir. Differences between hysteresis loops obtained from the polynomial equations and lab results made researchers present more precise constitutive models to express the SMA force-displacement behavior. A highly applicable model is

the one presented by Wilde et al. (known also as the modified Graesser-Cozzarelli (2000) model) [16].

In many SMA-based dampers, use is made of idealized constitutive models proposed by Auricchio for faster and simpler analysis. He suggested that a super-elastic SMA-based damper's force-displacement relationship that defines a nonlinear hysteretic model can be expressed as an idealized multi-linear hysteresis loop [17] [18]. The third method of modeling the hysteretic behavior of the SMA-based damper is the transformation of the nonlinear SMA hysteresis loops to equivalent linear elastic stiffness and viscous damping model [19]. So, the damper nonlinear force-displacement behavior can be replaced by an equivalent linear model that has two parameters, namely the effective elastic stiffness and effective viscous damping. In this research, an efficient multi-linear constitutive model has been implemented that will be explained and verified in the following sections.

Research activities of SMA's applications in civil structures and implementation for field applications found effective [20]. Energy dissipation system and ground isolation system are the two widely used mechanisms by which SMA's could be utilized in an effective manner for the purpose of passive control technique.

3. SMA Damper

In this research, the proposed SMA damper shown in Figure 3 is housed by the extra rigid bracing system (Figure 4).

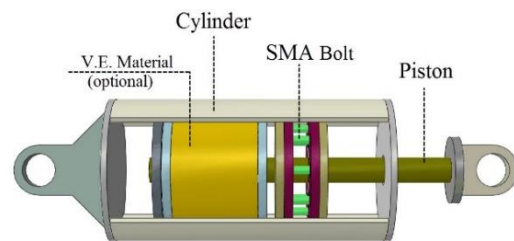


Figure 3. Schematic design of the proposed SMA damper

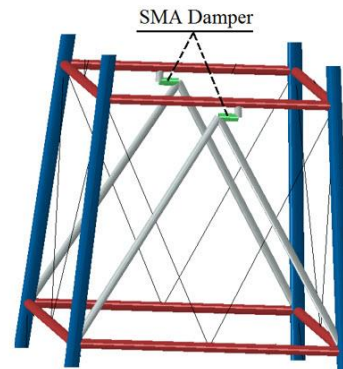


Figure 4. Connection of SMA damper with the jacket platform

As shown in Figure 3, the damper performance is such that SMA bars operate in tension and their buckling limitations are omitted under the piston strokes. In such dampers, the piston stiffness is large enough and its strain is negligible in comparison with SMA's strain. Therefore, the piston stroke is equal to SMA bars deformation, and the damper restoring force is the same as that of the SMA's.

Considering the inherent characteristics of SMA elements, it can be concluded that SMA dampers are quite appropriate options to control the vibrations of jacket platforms. These intrinsic features that distinguish them from other dampers and justify their use in controlling such vibrations are:

- SMA's are quite versatile and have different ductility and damping capabilities; therefore, the versatility of dampers designed with them can be very large too.
- Fabrication of many dampers and vibration control devices is often monopolized by certain companies and they are quite expensive. The advantage of the SMA damper is that if its elements are provided, its other parts can be made and assembled in smithies.
- SMA elements, especially the NiTiNol alloys, possess high thermal stability and corrosion resistance and have high ductility and very good fatigue performance; therefore, their use is highly recommended in offshore structures with a condition of large amplitude oscillations and corrosive environments.
- The SMA's elastic modulus is a function temperature; hence, a heat producing source can set its bar stiffness desirably; this feature can be used in the design of active and semi-active dampers.

4. Method and Verification

4.1. Dynamic Formulations

In this research, the responses of the dynamic equations and advanced analytical algorithms of the constitutive modeling of the superelastic SMA have been estimated by a computational MATLAB based computer code wherein use is generally made of the idealized constitutive model. In the developed code, the linear time history analysis is done on a jacket platform structure modeled as a multi-degree of freedom (MDOF) system and equipped with the SMA dampers (Figure 5). The vibration equation of MDOF system and SMA dampers is as follows:

$$[M]\{\ddot{\mathbf{v}}\} + [K]\{\mathbf{v}\} + \{F_{SMA}\} = \{F_{w,c}\} \quad (1)$$

In Eq. (1), matrices $[M]$ and $[K]$ are mass and stiffness matrices of the jacket structure, and $\{\ddot{\mathbf{v}}\}$, $\{\dot{\mathbf{v}}\}$ and $\{\mathbf{v}\}$ are the acceleration, velocity and displacement vectors, respectively. Vector $\{F_{SMA}\}$ is SMA dampers restoring forces and will be explained in Section 3 and vector $\{F_{w,c}\}$ is the wave and current forces. Due to

the object of this research, in vibration control of jacket platform through optimized SMA dampers, structural damping is ignored.

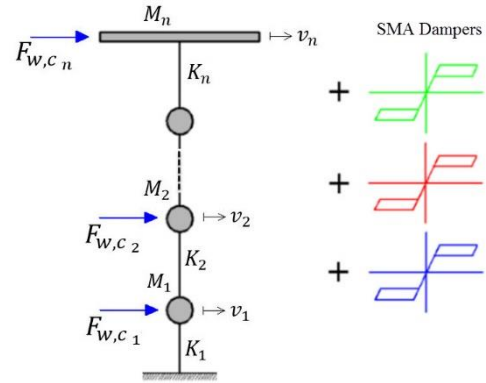


Figure 5. Multi degree of freedom system of Jacket platform equipped with SMA dampers

In this research, the Morison equation is used to estimate the wave and current loads acting on jacket members [21]. This equation is originally developed to compute hydrodynamic forces acting on a vertical cylinder and is given by the following expression.

$$F(z, t) = \rho \pi \frac{D^2}{4} C_m \ddot{u}(z, t) + \dots \quad (2)$$

$$\dots \frac{1}{2} \rho D C_d |\dot{u}(z, t)| \dot{u}(z, t)$$

In Eq. (2), function $F(z, t)$ is the in-line force per unit length acting on the submerged section at position z from the mean water level. Functions $\ddot{u}(z, t)$ and $\dot{u}(z, t)$ are the relative wave acceleration and velocity and can be calculated by the wave theory. Parameter ρ is the density of water usually considered as 1030 kg/m^3 . Parameters D , C_m and C_d are cylinder outer diameter, inertia coefficient, and drag coefficient, respectively [22].

4.2. SMA's Constitutive Model

For solving differential equations of the motion presented in Eq. (1), the direct HHT integration method has been implemented. Vector $\{F_{SMA}\}$ is the most important term of Eq. (1), which defines the SMA damper restoring force.

As stated in Sec. 3, in the dynamic analyses, the set of the damper's piston, cylinder, and supports are assumed to be rigid and the total section area of the SMA bolts of each damper is equivalent to that of a 2-DOF axial member the end displacements of which equal those of the platform's lower and upper levels.

Numerical methods of solving vibration differential equations (alpha-method) calculate the structural dynamic responses by integrating in time intervals. Therefore, it is possible, at any forward step, to calculate the changes in the damper force and add it to the one in the previous step.

The SMA's one-dimensional isothermal idealized linear force-displacement constitutive model is shown

in Figure 6. In the j^{th} step and due to x_j piston displacement, the damper restoring force $F_{sh j}$ can be estimated with the following expressions.

$$x_j \leq x_f^{MA}$$

$$F_{sh j} = F_{sh j-1} + k_1 (x_j - x_{j-1}) \quad (3)$$

$$x_f^{MA} < x_j < x_f^{AM}$$

$$F_{sh j} = F_{sh j-1} + k_1 (x_j - x_{j-1}) \quad (4)$$

IF: $F_{sh j} > \text{Upper Plateau}$

$$F_{sh j} = A \times \sigma_s^{AM} + k_2 (x_j - x_s^{AM}) \quad (4a)$$

IF: $F_{sh j} < \text{Lower Plateau}$

$$F_{sh j} = A \times \sigma_f^{MA} + k_3 (x_j - x_f^{MA}) \quad (4b)$$

$$x_f^{AM} \leq x_j$$

$$F_{sh j} = F_{sh j-1} + k_1 (x_j - x_{j-1}) \quad (5)$$

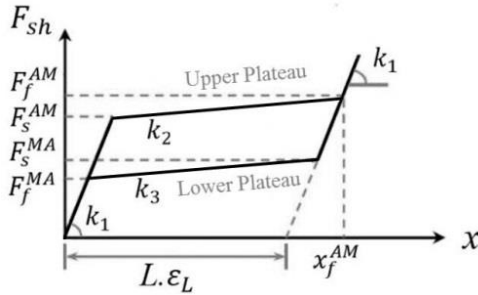


Figure 6. SMA's One-dimensional isothermal constitutive model

Where A , k_1 , k_2 and k_3 are SMA bars total section areas, axial stiffness in the elastic region, axial stiffness in the austenite to martensite phase transition stage and axial stiffness in the martensite to austenite phase transition stage, respectively. In x (or ε), F and σ superscript AM stands for the austenite to martensite phase transition and MA stands for the martensite to austenite case. Again, subscript s stands for the starting of the phase transition and f stands for its finishing. Axial stiffness of SMA bars can be estimated through Eqs. (6 to 8).

$$k_1 = \frac{A}{L} \times E_{SMA} \quad (6)$$

$$k_2 = \frac{A}{L} \times \frac{\sigma_f^{AM} - \sigma_s^{AM}}{\varepsilon_f^{AM} - \varepsilon_s^{AM}} \quad (7)$$

$$k_3 = \frac{A \times (\sigma_s^{MA} - \sigma_f^{MA})}{x_j - x_f^{MA}} \quad (8)$$

Parameters L , E_{SMA} and ε_L are the length of SMA bars, the initial modulus of elasticity and full phase transition strain, respectively. The advantage of the above mentioned idealized constitutive model of the SMA element is that it does not need to know the \dot{x} (velocity) information to determine the F_{sh} . As a

result, the speed of analysis is increased without causing any changes in the dynamic responses.

4.3. Verifications

The MATLAB code developed in this study has two main output groups: 1) structural time history responses and 2) the SMAs hysteresis loops. To ensure their correctness and accuracy, two different validations have been made.

In comprehensive research, Asgarian and Moradi placed an SMA bar member under the quasi-static deformation loading and found its stress-strain hysteresis loops [23]. Therefore, for the first validation, a comparison has been made between the outputs of the SMA hysteresis loops calculated by MATLAB and the results of Asgarian and Moradi analysis. The SMA hysteresis loops presented in Figure 7 show that the results exactly coincide.

For the second validation, a steel jacket platform modeled as a 5-DOF system has been analyzed by the MATLAB code and the finite element analysis (ABAQUS). In the three dimensional ABAQUS model of the jacket, all the members considered as beam element (B32). The jacket platform geometrical and mechanical characteristics, wave dynamic properties and other considerations are explained in the next section (Section 5). Comparison of the dynamic responses shown in Figure 8, confirm an acceptable precision of developed MATLAB code.

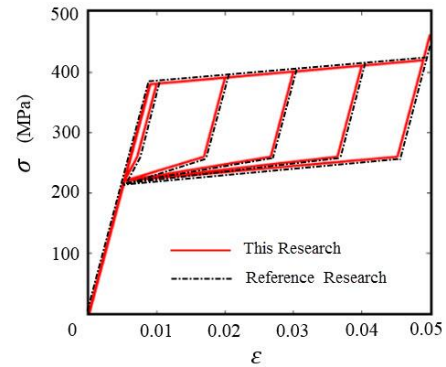


Figure 7. SMA stress-strain hysteresis loops by MATLAB based computer code (this research) and reference research [23]

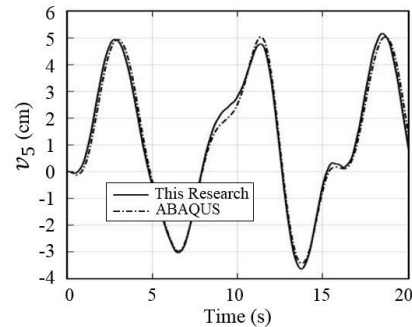


Figure 8. Time history deck displacement responses (v_5) of steel jacket platform with MATLAB based computer code (this research) and finite element analysis (ABAQUS)

5. Case Study

5.1. MDOF system characteristics

To perform the final analysis and obtain the efficiency of SMA dampers in vibration control, a steel jacket platform has been selected as a case study. These types of platforms are quite common and are even similar to real ones [24]. The total height of the structure is 90 m and is symmetrical in the plan. The Jacket has 4 legs and its dimensions on the sea floor and deck level are 32 m × 32 m and 20 m × 20 m, respectively. The deck's total dead and live load is 4800 tons. To take into account the effects of the soil-pile interaction, use has been made of the column-base clamping rule at a height equivalent to 8 times the pile's diameter [25]. The elevation view of the jacket is shown in Figure 9 and geometrical and mechanical specifications of the members are presented in Table 1.

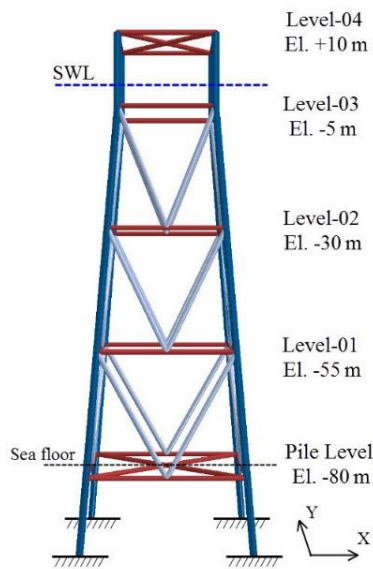


Figure 9. Elevation view of steel jacket platform [24]

Table 1. Mechanical and geometrical characteristics of jacket platform members

Mechanical	
Steel modulus of elasticity	200 GPa
Poisson's ratio	0.3
Yield stress	320 MPa
Ultimate stress	405 MPa
Mass of the deck	4800 ton
Steel density	7800 kg/m ³
Geometrical	
	Diameter (mm)
	Thickness (mm)
Horizontal bracings	1000
Vertical bracings	1100
Legs	1500

Dynamic characteristics of waves and current velocity have been so selected that the platform can have relatively large displacements under wave loads and, at the same time, may not enter its nonlinear region. Jacket platform members' entering the nonlinear region and experiencing large deformations will cause

damage to drilling equipment, risers, and the related structural connections. Therefore, to analyze the SMA dampers' effects on the jacket platform vibrations, an extreme wave 11.8m high and 7.8sec period has been considered. The water depth, wave height, its period, and in-depth current velocity have been shown in Table 2.

To calculate the wave and current forces acting on the jacket members, the inertia and drag coefficients of the Morison equation (Eq. (2)), are 2.0 and 0.8 (constant in depth), respectively [7]. To estimate the wave acceleration and velocity, the 5th order stokes theory was selected after checking the wave theory validation. In this research, a side plan has been developed where the platform members are divided into 20 elements. The wave velocity and acceleration are calculated at the elements' beginning and end joints where the wave horizontal velocity is added to that of the current (current velocity variation in depth is considered linear). The forces applied on the elements are assembled and finally transferred to the members' beginning and end joints. Therefore, the force applied to each degree of freedom is the sum of the current and wave forces acting on the horizontal beams and half of the member forces above and below the beams. Regarding Eq. (1), the dynamic characteristics of the 5-DOF system of jacket platform are shown in Table 3.

Table 2. Wave and current dynamic characteristics

Wave Dynamic Characteristics	
Water depth	80 m
Wave height	11.8 m
Mean period	7.8 second
Current speed, Storm generated, Tides included	
Near surface	0.83 m/s
Middle depth	0.27 m/s
Near bottom	0.16 m/s

Table 3. Dynamic characteristics of 5-DOF system of jacket platform

	Level Pile	Level 01	Level 02	Level 03	Level 04
Mass (ton)	220	200	195	130	4850
Stiffness (MN/m)	90	350	210	115	42
$F_{w,c}^*$ (kN)	28.615	133.35	529.27	825.82	111.23

*Maximum amplitude of wave and current forces.

As shown in Fig. 9, each of the platform's peripheral frames has four vertical levels. The SMA dampers have been installed in the 1st, 2nd, 3rd and 4th levels through rigid link supports (Figure 4). To control the platform's vibrations along the x and y axes, it is necessary to have 8 dampers along each (totally 16). The mechanical properties used for SMA, based on DesRoches studies in 2004 [26], are presented in Table 4. Next, the lengths of each damper's SMA

bolts and their required total section area will be found through optimization analyses.

Table 4. Mechanical properties of SMA [26]

	E_{SMA}	ϵ_L	σ_s^{AM}	σ_f^{AM}	σ_s^{MA}	σ_f^{MA}
Values	55	6	420	520	310	240
Units	GPa	%	MPa	MPa	MPa	MPa

5.2. Optimization Analysis

Stiffness and damping are the two main characteristics of an SMA damper and have significant effects on the dissipation of the applied energy and damping efficiency. Hence, bars lengths and areas should be so selected that: 1) the alloy phase transmission from austenite to martensite is achieved and 2) deck displacements are reduced.

To achieve the platform’s optimal dynamic responses, use has been made of the ‘ideal gas molecule movement’ optimization algorithm presented by Varae and Ghasemi in 2017 [27]) which is a new, efficient, population-based and intelligent algorithm and uses the principles and relationships that govern the molecular movement of ideal gases for optimization. This algorithm offers excellent precision and speed in complicated, single/multi-objective optimization problems.

Here, the potential solutions of an optimization problem could be considered equivalent to the gas molecules that are moving and exploring in their chamber i.e. the problem space. The behavioral properties of the gas molecules allow them to rapidly spread throughout the chamber and navigate and search all potential spaces for optimal solutions. During their movement in the problem space, these molecules collide with one another with a certain probability due to which they interact and exchange information. Such information exchange is reflected in the molecules’ velocity variations after they collide and position in a new position at different time steps. Those molecules that do not enter the collision process at any time step, will participate in the general problem search space as free molecules and increase the chance of exploring new spaces and finding suitable solutions. Now, if the information on motions and molecular collisions is used properly (i.e. in the form of an algorithm), it is possible to find the optimal range during these surveys and collisions. The design variables and constraints can be defined after checking how the optimization algorithm operates.

Design variables:

- 1) L
- 2) A

Constraints:

- 1) $L \geq 40 \text{ mm}$
- 2) $x_{max} \leq x_f^{AM}$

Parameters L , A , and x_f^{AM} are the SMAs length, SMAs area, and austenite to martensite finish displacement, respectively.

The main objectives of the optimization of the proposed SMA damper are to minimize the displacements of the deck, reduce the tensions in the jacket members and reduce the SMA’s volume. An SMA damper has both the elastic and damping properties and if the length and area of its SMA alloys are not selected correctly, the damper elasticity may increase and its dissipation capability may decrease. Since the objective functions of this problem cannot be determined easily, optimization has been done based on two different objective functions.

Objective functions:

1. Minimizing v_5
2. Maximizing $A_{hysteresis \ loops}$

Parameters v_5 and $A_{hysteresis \ loops}$ are the displacement of the deck and total area under hysteresis loops of all dampers, respectively. To find the optimal solution, the maximum number of the optimization process cycles (N) and the number of molecules per cycle have been considered to be 100 and 20, respectively. Figures 10, and 11 show the values of each selected objective function and SMA bars total volume calculated in each optimization iteration.

Figure 10 shows the problem optimization solution with the objective of minimizing the deck displacements. As shown, the IGMM method has been able to converge to a displacement of 2.82 cm after 65 cycles (1300 analysis). Figure 11 show the problem optimization solution with the objective of maximizing the area under hysteresis loops of all dampers.

The optimized SMAs geometrical characteristics are presented in Table 5. The SMA dampers are classified to “Design 1” (based on minimizing v_5 objective function) and “Design 2” (based on maximizing $A_{hysteresis \ loops}$ objective function).

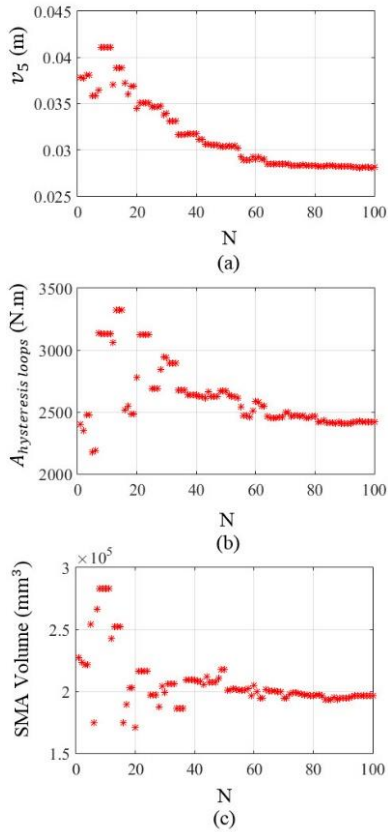


Figure 10. Optimization results based on “minimizing v_5 ” objective function; (a): v_5 (deck displacement), (b): $A_{hysteresis\ loops}$, (c): SMA bars total volume

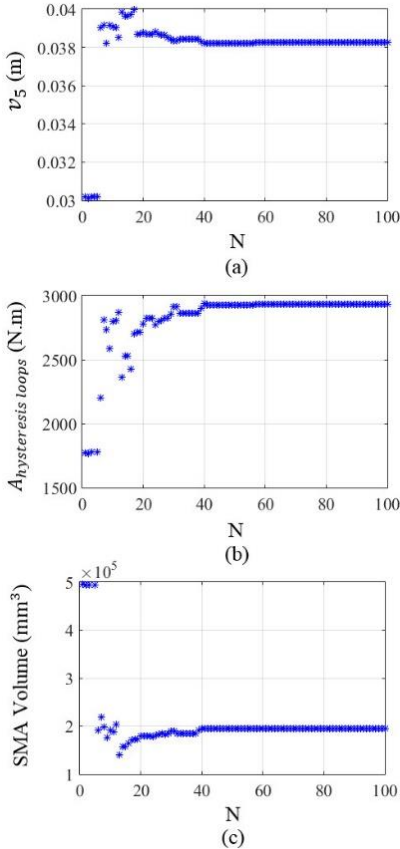


Figure 11. Optimization results based on “maximizing $A_{hysteresis\ loops}$ ” objective function; (a): v_5 (deck displacement), (b): $A_{hysteresis\ loops}$, (c): SMA bars total volume

Table 5. SMA bars geometrical characteristics based on optimization analysis

	Objective Functions			
	Minimize		Maximize	
	v_5		$A_{hysteresis\ loops}$	
	“Design 1”		“Design 2”	
	A	L	A	L
	(mm^2)	(mm)	(mm^2)	(mm)
Level-04	370	40	100	96
Level-03	1300	40	530	103
Level-02	1890	40	1220	65
Level-01	1360	40	1150	45

5.3. Numerical Results and discussions

The optimization analysis results, based on two mentioned objective functions, and dynamic responses of the jacket platform equipped with optimized dampers are presented in Table 6. As is clear, optimization analysis with minimizing v_5 objective function has acceptable results in minimizing deck displacements.

Table 6. Results of optimization analysis and jacket platform dynamic responses

	Objective Functions	
	Minimize	Maximize
	v_5	$A_{hysteresis\ loops}$
v_5 (mm)	28.1	37.8
$A_{hysteresis\ loops}$ (N.m)	2420	2935
SMA volume (mm^3)	196430	194600
\ddot{v}_5 ($mm.s^{-2}$)	59.6	57
Level-01 shear force* (kN)	1644	1720

* Base shear

The time history dynamic responses of jacket platform equipped “Design 1” SMA dampers are displayed in Figures 12 and 13. The results indicate that optimized SMA dampers have significant effects on vibration suppression of jacket platform.

The maximum reduction in the jacket structure dynamic responses and comparison of the two controlled and uncontrolled platform states are presented in Table 7. As is clear, installing “Design 1” SMA dampers on the steel jacket platform can reduce deck displacement and deck acceleration by 47.5 and 56.5 percent, respectively. Furthermore, dampers high efficiency in the dissipation of wave’s energy entry to the jacket structure, cause 59 and 28 percent reduction in level-04 and level-01 shear forces, respectively.

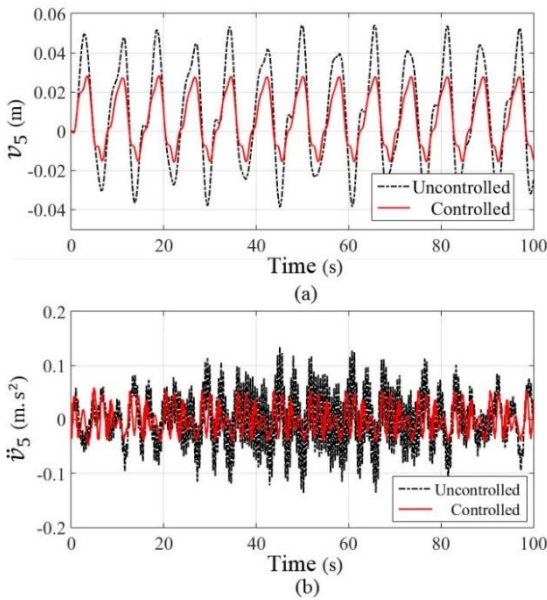


Figure 12. Time history responses of the controlled (with “Design 1” dampers) and uncontrolled states; (a): v_5 (deck displacement), (b): \dot{v}_5 (deck acceleration)

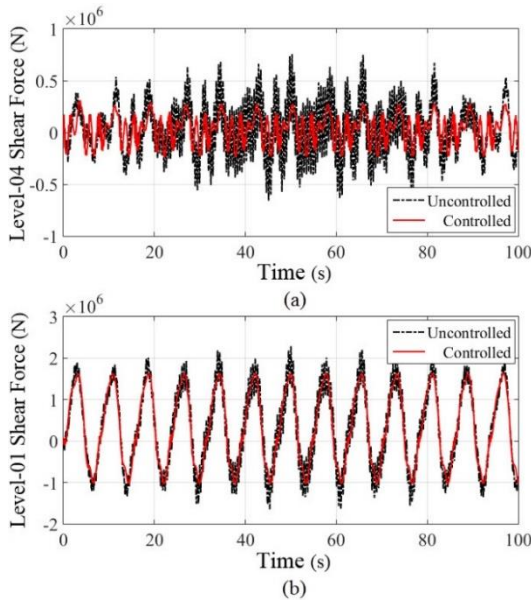


Figure 13. Time history responses in the controlled (with “Design 1” dampers) and uncontrolled states; (a): level-04 shear force, (b): level-01 shear force (base shear)

Table 7. Maximum dynamic responses of controlled (design 1 dampers) and uncontrolled jacket platform

	Uncontrolled	Controlled	Reduction
v_5 (mm)	54	28.3	47.5 %
\dot{v}_5 (mm.s ⁻²)	136.5	59.6	56.5 %
Level-04 shear force (kN)	755.5	311.6	59 %
Level-01 shear force (kN)	2290.6	1644	28 %

According to the performed optimization analysis and dynamic responses of equipped-SMA dampers jacket platform, the following results could be achieved:

1. In comparison with the uncontrolled jacket platform, both mentioned optimization analysis has significant effects on deck acceleration and

base shear (Level-01) suppression (Tables 6 and 7).

- In the above two optimized cases, the differences between deck displacements are significant and the difference between SMA bars total volume is negligible. Therefore, it can be concluded that the optimization of minimizing deck displacement, according to mentioned constraints, has had acceptable results (Table 6).
- To perform a more realistic comparison, the hysteresis loops of optimized SMA dampers are shown in Figures 14 and 15. Maximum restoring forces of “Design 2” dampers are less than “Design 1” dampers and make them easier to install on the jacket platforms. This characteristic is of great importance in retrofitting projects of aging jacket platforms.

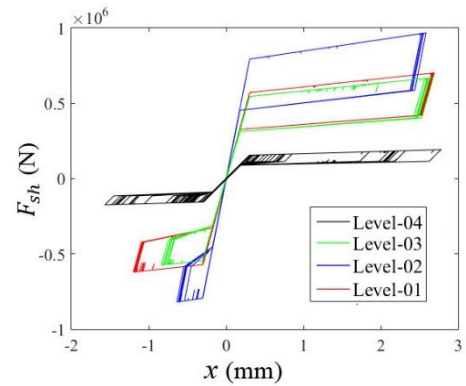


Figure 14. Hysteresis loops of “Design 1” SMA dampers

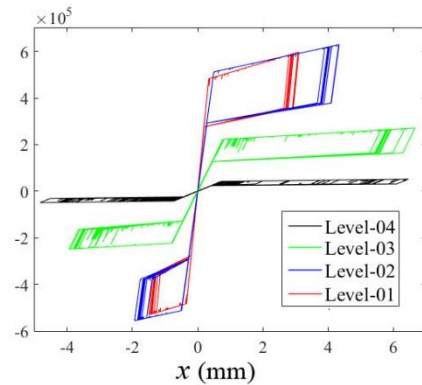


Figure 15. Hysteresis loops of “Design 2” SMA dampers

- Hysteresis loops of optimized SMA dampers shown in Figures 14 and 15, indicate that SMAs displacements did not reach to x_f^{AM} . Hence, full phase transition from austenite to martensite does not lead to optimum responses.

5.4. Different Sea States

To check the efficiency of the optimized SMA dampers in Table 5 (“Design 1” dampers), the platform was placed under two other regular waves the dynamic characteristics of which are; Case I: wave height 10 m, wave period 7.3 s and Case II: wave height 8.4 m, wave period 6.8 sec and the water

current velocity is the same given in Table 2. Compared to the initial selected wave, these two waves are less intense and cause less displacement in the platform deck and vertical levels. Figures 16 and 17 show the dynamic responses of the deck displacements and SMA dampers hysteresis loops in the controlled and uncontrolled state.

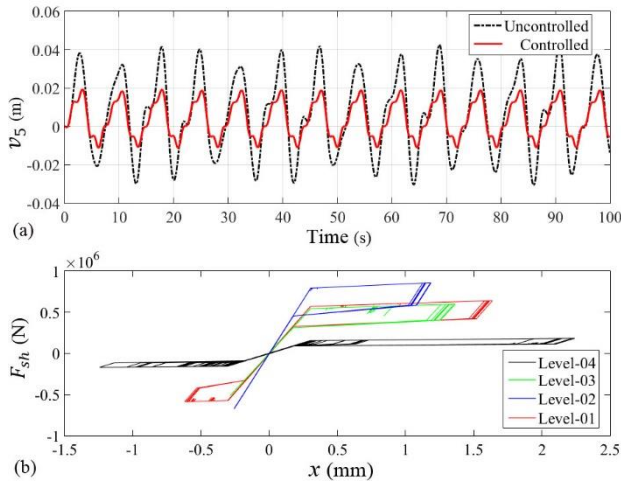


Figure 16. Dynamic response of jacket platform in controlled and uncontrolled state (Case I); (a): Deck displacements, (b): SMA dampers hysteresis loops

As shown in Figure 17, SMA dampers of level-02 and level-03, work linear with zero area in their hysteresis behavior. Decrease in the wave energy decreases the jacket drifts and hence the SMA dampers phase transition does not occur. To eliminate this limitation, use can be made of semi-active dampers capable of adjusting the stiffness of the SMA bolts.

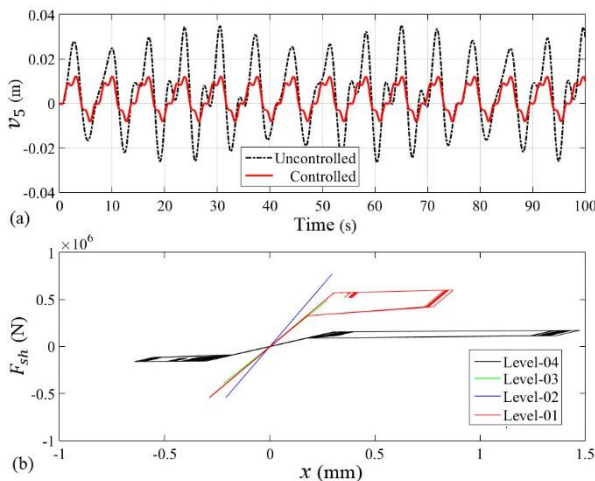


Figure 17. Dynamic response of jacket platform in controlled and uncontrolled state (Case II); (a): Deck displacements, (b): SMA dampers hysteresis loops

6. Conclusions

In this study, effort has been made to evaluate the effects of mounting optimized SMA dampers on the improvement of the dynamic behavior of no-damper jacket platforms under the action of regular sea waves.

As a case study analysis, the dynamic responses of a 90 m height jacket platform equipped with SMA dampers and modeled as an equal 5-DOF system has been carried out.

To optimize the SMA elements geometry and obtaining the optimum dynamic responses of jacket platform under the action of extreme wave, an optimization analysis was done with two different objective functions. In the optimization analysis performed with the IGMM algorithm, the best results (“Design 1” SMA dampers) were obtained with use of the “deck displacements minimization” objective function. Although, joining optimized “Design 1” SMA dampers to jacket platform caused a significant reduction in deck displacement by 47.5 percent, deck acceleration by 56.5 percent and base shear of the structure by 28 percent, these two important results were obtained:

- SMA dampers hysteretic behavior was unsymmetrical in two states of tension and compression. Hysteresis loops area in the negative region was much less than positive region. Therefore, in the opposite direction of sea wave, an appropriate energy dissipation didn't occur in platform oscillations.
- In jacket platforms equipped with optimized SMA dampers, a decrease in the wave intensity will decrease the damper efficiency. Therefore, it is proposed to use active or semi-active SMA dampers with tunable stiffness SMA elements in the vibration suppression of jacket platforms induced by different waves and sea states.

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