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# Pitch Motion Response of an Equipped Semi-Submersible Platform with Tuned Sloshing Dampers

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**ABSTRACT**

Tuned sloshing dampers (TSDs) are applied to dissipate and absorb vibrational energy in structures. They can become an appropriate candidate for damping vibration in rotating offshore structures. In this study, the TSD systems are utilized in a semi-submersible platform in order to suppress its pitch motion response. First, the hydrodynamic behaviors of two different types of vessels are evaluated including a typical GVA4000 semi-submersible rig, and a floating oil storage tank using a finite element analysis. The results are compared with the available data from previous research, which the agreement is good. Subsequently, the semi-submersible platform equipped with four TSDs, which are located inside the bilge of pontoons and filled with 20% water is analyzed. It is analyzed in the frequency domain by considering the effect of internal fluid sloshing of TSDs. The results show that TSDs play a significant role for reducing the pitch motion response of the semi-submersible platform.

## 1. Introduction

Offshore structures are designed and constructed for different purposes which can be applied for oil exploration, production, processing, storage and transportation. Due to the reduced oil resources in shallow water fields, the offshore platforms are developed and moved into the deeper offshore area. One such platform is a semi-submersible which is commonly used for oil exploration in deep waters. The major components of a semi-submersible platform are the hull, mooring system and risers. The hull consists of the pontoons, columns, braces, deck, and topside. The mooring lines anchor this platform to the seafloor with a driven or suction pile. The risers are vertical tubes which are used for pumping seawater into decks, for exchange of heat, and to carry partially processed oil or gas to another place. The semi-submersible platform has six degrees of freedom including surge, sway, heave, pitch, roll, and yaw. The heave, pitch and roll are the most important motions of the semi-submersible platform. These motions can affect the efficiency of platform, threaten its safety and reduce oil production. Therefore, it is necessary to reduce them. One way is application of tuned oscillator systems, which can be commonly classified into passive, active, semi-active, and hybrid systems. Passive systems don't require an external power source. Active systems require a large artificial power source to send energy to the platform. Semi-active systems generally require a small power source. Hybrid systems are constructed from combination of the passive and high performance active systems [1].

Tuned liquid damper (TLD) is a type of passive energy dissipation system which falls into three categories: tuned sloshing dampers (TSDs), tuned liquid column dampers (TLCDs), and controllable TLDs [2].

In general, if the frequency of TLD system is close to one of the natural frequencies of its internal fluid, the large sloshing can be expected. When both frequencies are close to each other, the resonance will be occurred. Adjusting sloshing frequency of TLD to the natural frequency of structure cause a large amount of sloshing and wave breaking at the resonant frequencies of the structure equipped with TLD which, dissipates significant amount of energy [2].

The vibration control of offshore platforms under environmental loading using TLDs is one of the attractive subjects for a number of researchers. Spillane et al. [3] experimentally studied the effect of vertical caisson pairs mounted on the tension leg platform (TLP) columns. Karimi et al. [4] and Luo et al. [5] numerically investigated the efficiency of TLCD with a controllable valve in the motions of spar platform. The results showed that this can strongly reduce its displacements. Utilizing a TLCD in TLP was studied by Lee and Juang [6], analytically and experimentally. The results revealed that TLCD can suppress its dynamic response. A comparative study between TLCD and tuned liquid columns ball damper (TLCBD) in the vibration control of TLP under wave action was carried out numerically by Chatterjee and Chakraborty [7]. It was detected that using TLCBD is better than TLCD for vibration reduction of TLP. The pitch motion response of a spar platform under irregular wave was reduced with installing a semi-active TLCD by Coudurier et al. [8]. The dynamic behavior of a modified spar platform with multilayer tuned liquid damper (TLD) was investigated by Ha and Cheong [9], numerically and experimentally. It was noticed that the multilayer TLD system suppresses a greater amount of the pitch motion response rather than the single layer TLD.

Moreover, there are several investigations about the coupling effect of internal fluid sloshing of the tank and vessel on the motion response of vessel, numerically and experimentally. Simulation of the 3D sloshing flow in anti-rolling tank using a finite difference method and ship motion using a time domain panel method were carried out by Kim [10]. The coupling between fluid sloshing of the tanks and motions of ship studied by Kim et al. [11], using the method of impulse response function formulation. Nasar et al [12] experimentally studied the effect of sloshing on the liquid barge tanks under regular beam waves. Zhao et al [13] experimentally showed that sloshing phenomena of inner tank plays significant role in the roll motion of the FLNG vessel. The motion response of a ship with a 3D rectangular container was studied by Mitra et al. [14], in the time domain approach. They studied nonlinear sloshing using a finite element method while the nonlinear ship motion was modeled by a hybrid marine control system. The coupling between sloshing, wave, and ship motion was investigated by Li et al. [15], using Open Filed Operation and Manipulation software. The effect of fluid sloshing inside the tank on the motion response of FLNG was investigated by Hu et al. [16], experimentally and numerically. The numerical modeling was developed by SESAM software. The experimental test carried out in the deep-water offshore basin at Shanghai Jiao Tong University, where good agreement between the results was observed. Liu [17] numerically simulated the floating oil storage tank response with considering the sloshing effect. It was modeled by SESAM software with both frequency domain and time domain approaches. The results showed that the internal liquid sloshing has a significant effect on its surge and especially pitch motion response.

It can be recognized that in literature, there are few attempts to suppress the pitch motion response of the semi-submersible platform with tuned dampers. It seems that using a type of tuned dampers is a suitable approach to improve pitch motion response of the semi-submersible platform. Therefore, in this study, tuned sloshing damper (TSD) is applied for semi-submersible platform.

A TSD plays a significant role to reduce structural vibration. The damping mechanism of the TSD is based on the energy dissipation of the fluid sloshing, to remove the energy from the structure equipped with TSD system, consequently decreasing its response. The significant advantage of TSD is low installation cost, easy to install, applicable to control a different vibration type of multi-degree of freedom system with different frequency for each other, and its natural frequency can be adjusted by water depth and container shape [2].

The TSD can also be classified as deep water and shallow water. If the internal liquid depth of the container relative to its length is less than 0.15, it will be shallow water; otherwise, it will be deep water. Although the effect of damping in shallow water type is significant, it is not appropriate in the large scale for externally excited vibration. Indeed, the analysis of the TSD with shallow water type in the large scale under the externally excited vibration is very difficult, because of the nonlinear behavior of water sloshing in the tank [2].

In this study, a new approach in the form of deep water type TSD is applied in the semi-submersible platform in order to reduce its pitch motion response. The studied platform is Iran Amirkabir semi-submersible rig with four TSDs located inside the bilge of its pontoons. It is represented as an equipped semi-submersible platform. The analysis is performed by using SESAM finite element software. Firstly, the structural model of the platform with TSDs is modeled. Secondly, the hydrodynamic analysis in the frequency domain is carried out by the same software, under the irregular waves. Finally, its motion response is estimated. It is concluded that utilizing TSDs can improve significantly the pitch motion response of the semi-submersible platform.

## 2. Description of the Semi-Submersible

Iran Amirkabri drilling rig is a type of GVA4000M platform that designed and manufactured for drilling oil or gas at water depth of 1000 meters in Caspian Sea, North of Iran. The geometrical form of this platform is simple and consists of two pontoons, four columns, two braces, deck, eight mooring lines and risers. The main hull dimensions of this platform are presented in Table 1[18].

Environmental characteristics of Caspian Sea for a return period of 100 years have also been reported in Table 2 [18]. In this study, waves of head sea ($0^o$ direction) condition, which are the dominant waves, are used to obtain motions response (Table 2). In addition, the water density of Caspian Sea is considered as 1010 $kg/m^3$[18].

**Table 1. Dimensions of Iran Amirkabir Platform**

| Characteristic | Value | Unit |
|---|---|---|
| Diameter of Columns | 12.9 | m |
| Diameter of braces | 2 | m |
| Transverse and Longitudinal distance of columns | 54.72 | m |
| Height to upper deck | 36.5 | m |
| Height to lower deck | 28.5 | m |
| Height to pontoon | 7.5 | m |
| Length of pontoon | 80.56 | m |
| Breadth of pontoon | 18.68 | m |
| Displacement at operational draught | 28621 | ton |
| Operation draught | 20.5 | m |

**Table 2. Environmental characteristics of Caspian Sea [18]**

| Orientation relative to north direction (degree) | Probability of occurrence (%) | Height of nominal wave (m) | Period (s) | Suitable Spectrum |
|---|---|---|---|---|
| 0 | 24 | 10.50 | 16.25 | JONSWAP |

## 3. Theory of the floating motion and Sloshing

Sloshing means any motion of the free liquid surface inside its container. Depending on the type of disturbance and container shape, the free surface can create various types of motions includes simple planer, nonplanar, irregular beating, symmetric or asymmetric, quasi-periodic. The basic problem of liquid sloshing is to estimate its hydrodynamic performances such as pressure distribution, forces, reactions, moments, and its natural frequencies. Also, these parameters can significantly influence on the dynamic behavior and performance of a moving structure supporting this container [19].

For a rigid body with six degrees of freedom, the governing equation of motion is expressed in the form of Eq. (1)[20].

$$\left[M_{ij} + m_{ij}(\omega)\right]\ddot{\varepsilon} + C_{ij}(\omega)\dot{\varepsilon} + K_{ij}\varepsilon = F(\omega) \qquad (1)$$

where, $M_{ij}$ is the mass matrix of floating platform, $m_{ij}(\omega)$ is the hydrodynamic added mass matrix, $C_{ij}(\omega)$ is the hydrodynamic damping matrix, $\varepsilon$ is the related rigid body motion, $K_{ij}$ is the hydrostatic restoring matrix and $F(\omega)$ is the vector of exciting wave force.

When the TSD is installed inside the floating structure, the internal fluids free surface moves according to the tank motions. Consequently, the coupling effect of sloshing phenomena and floating container will be occurred. Therefore, the motion equation of rigid body will be modified as Eq. (2) [2].

$$\left[M_{ij} + m_{ij}(\omega) + m_{ij-\tan k}(\omega)\right]\ddot{\varepsilon} + \left[C_{ij}(\omega) + C_{ij}^{*}\right]\dot{\varepsilon} + \left[K_{ij} + K_{ij-\tan k}\right]\varepsilon = F(\omega) \qquad (2)$$

where, $m_{ij-\tan k}(\omega)$ is the added mass due to the internal liquid motion, $C^{*}$ is the linear equivalent damping coefficient and considered as viscous damping and $K_{ij-\tan k}$ is the hydrostatic restoring matrix of the tanks.

In this paper, the studied floating structure is a semi-submersible platform equipped with TSD systems. It is analyzed by using SESAM software. It is a robust finite element software where is widely applied in offshore engineering. It is used for analyzing of fix as well as floating structures, mooring and riser systems, and pipelines [21].

## 4. Numerical Modeling

Before the investigation on the hydrodynamic behavior of the equipped semi-submersible platform, the accuracy of the applied software must be verified in the modeling process as well as in the calculation of the coupling effect of sloshing and vessel motions.

### 4.1. Validation of the numerical modeling

In order to verify the numerical modeling process, a similar platform without TSD is modeled (Fig 1). This platform is a GVA4000 type drilling rig platform with geometrical dimensions illustrated in Fig. 1 and 2. The experimental heave and pitch RAOs data of this platform are available which was performed over a model with scale 1:81 in a wave flume with length of 80m, width of 4m and water depth of 1.5 m under the rogue and monochromatic waves. Its behavior was studied under random waves with JONSWAP spectrum, significant wave height of 11.92 m and zero-up crossing period of 10.8 s with a maximum height of 25.63 m and crest elevation of 18.5 m [22].

Figs. 3 and 4 illustrate both numerical modeling and experimental data of the heave and pitch RAOs, which indicates suitable agreement.

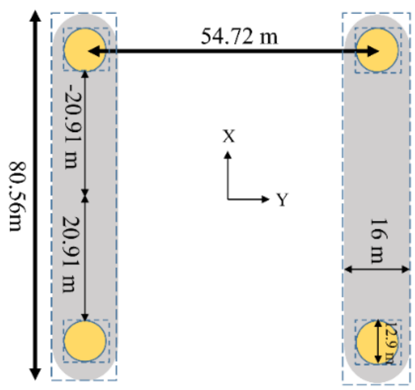


**Figure 1. The Top side of the studied GVA4000 semi-submersible drilling platform.**

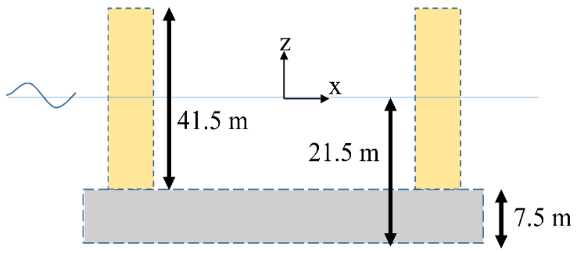


**Figure 2. The front side of the studied GVA4000 semi-submersible drilling platform.**

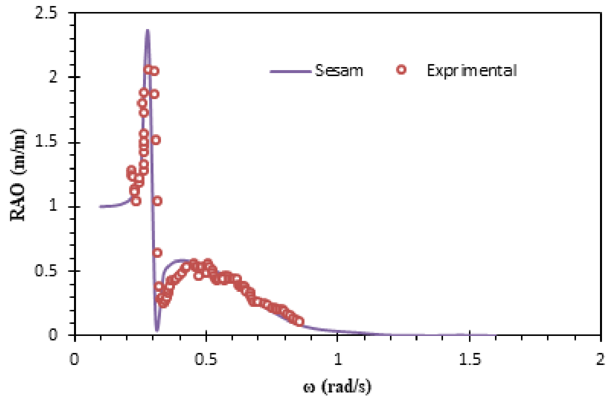


**Figure 3. Comparison of the numerical and experimental heave RAO under the head sea waves**

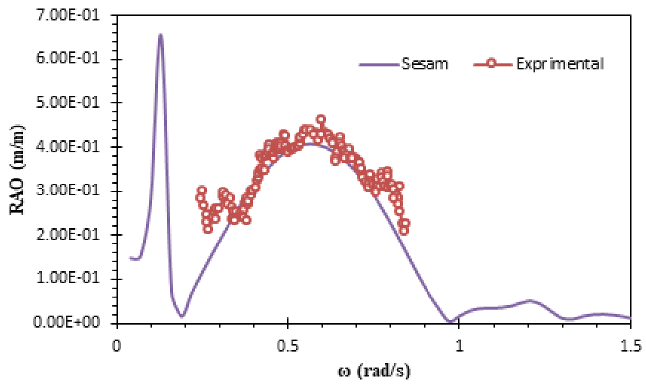


**Figure 4. Comparison of the numerical and experimental pitch RAO under the head sea waves**

## 4.2. Validation of the Effect of Sloshing

In the next step, the coupling effect of the internal fluid sloshing of the tank with the vessel motions is verified. For this purpose, a type of floating oil storage tank (FOST) is considered. The FOST is contained from an external rectangular tank and internal cylindrical with dimensions of 35m x 35m x 20m, which designed to store diversity oil products. It is located in the near-shore area around Singapore with the water depth of 30m. The density of water is 1025 kg/m$^3$ and oil is 870 kg/m$^3$ [2].

The structural model of FOST which is filled up to 40% with oil is simulated (Fig. 5 and 6) and then the coupling effect of liquid sloshing and FOST motion is investigated in the frequency domain.

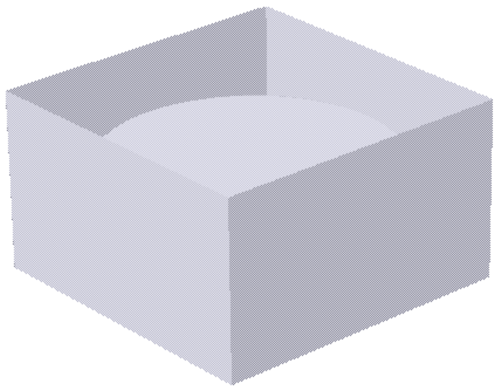

**Figure 5. Structural modeling of FSOT**

**Figure 6. The FSOT with 40% oil filled**

The comparison of the heave and pitch RAOs of modeled FOST and the results of Liu's study [2] have been illustrated in Figs 7 and 8. The results are close enough to be considered acceptable. Moreover, the comparison of FOST filled up to 40% with oil and the empty one shows the applied method can simulate the coupling between the sloshing and FOST motions. It is notable the effect of the sloshing is more visible in the pitch motion of FOST.

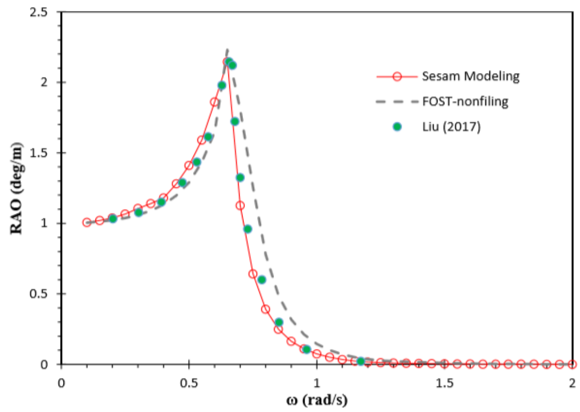


**Figure 7. Comparison of the results modeled FOST and Liu [2] for heave RAO under the head sea waves**

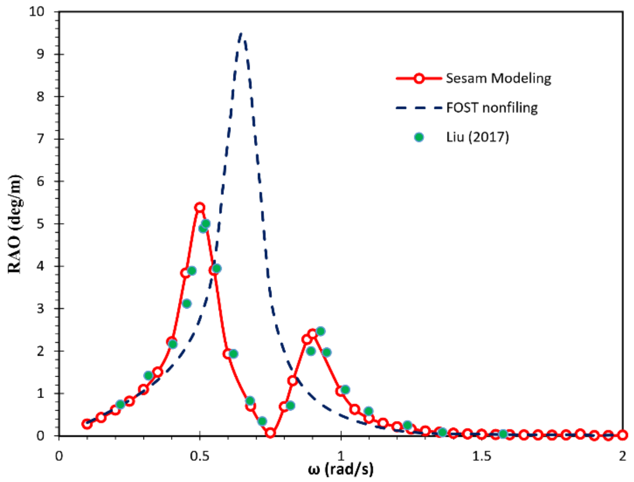


**Figure 8**. **Comparison of the results modeled FOST and Liu** [2] **pitch RAO under the head sea waves**

### 4.3. Modeling of Equipped Semi-Submersible

In the next step, the structural model of Iran Amirkabir semi-submersible platform is simulated with different parts such as pontoons, columns, bracings, and deck (Fig. 9). Four semicircular TSDs are placed inside the bilge of pontoons (Fig. 10). The radius of TSDs is 9.34 m and its height is 7.5 m.

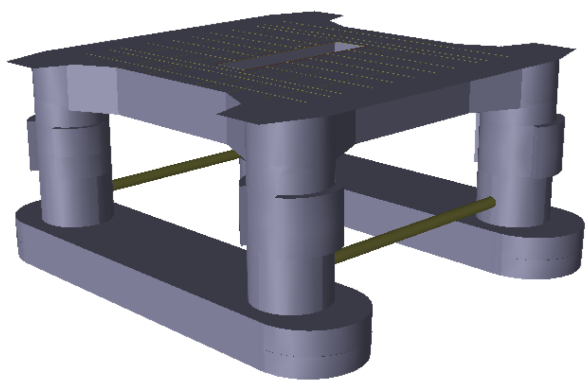

**Figure 9. The developed model of Iran-Amirkabir**

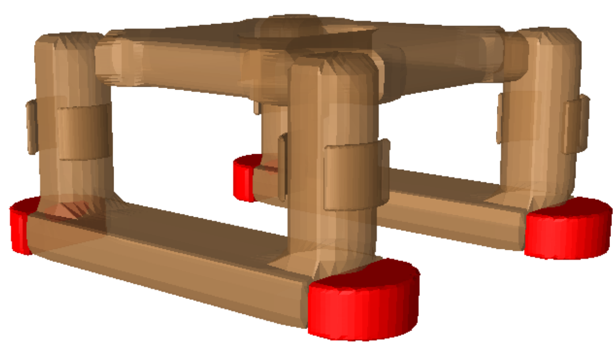

**Figure 10**. **Semicircle TSDs placed inside the bilge of pontoons of the semi-submersible platform.**

### 4.3.1 Hydrodynamic Behavior of Equipped Semi-Submersible

To determine the effect of TSD on the semi-submersible motions, the TSD's fluid properties such as filling fraction and fluid density are defined and associated with the structural model. The filling fraction includes 20% water by assuming the deep water type and density of 1010 kg/m$^3$ (Fig. 11).

Modeling is carried out in the frequency domain with considering the dynamic behavior of the TSDs' fluid, under the environmental characteristics of Caspian Sea. Finally, the results of its motions are processed. The corresponding numerical simulation results and their comparison with the original semi-submersible platform have been given in Figs. 12-14.

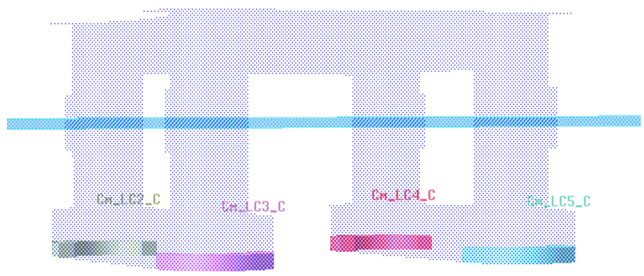

**Figure 11**. **Iran Amirkabir platform equipped with TSDs filled up to 20% with water**

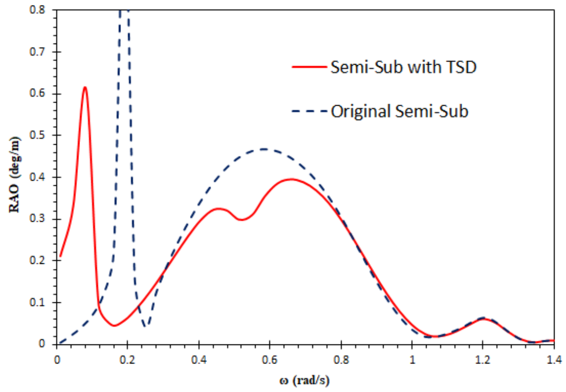


**Figure 12**. **Comparison of pitch RAO of equipped semi-submersible platform with original case under the head sea waves**

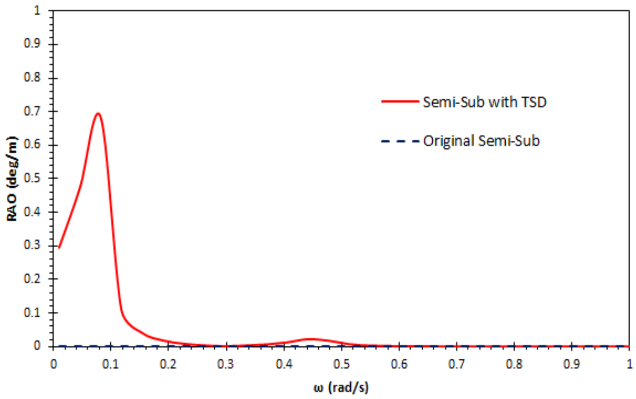


**Figure 13**. **Comparison of roll RAO of the equipped semi-submersible platform with its original case**

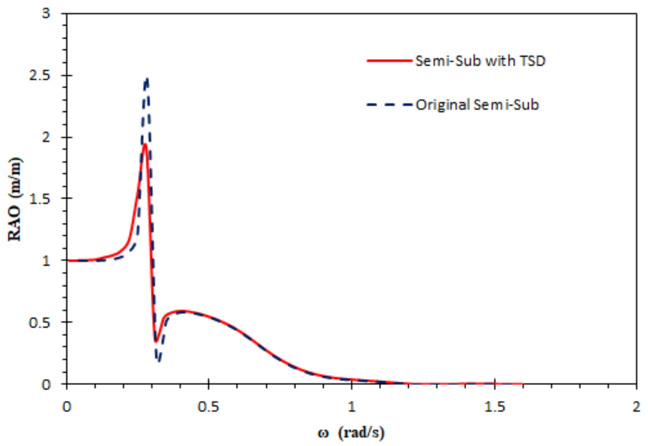


**Figure 14**. **Comparison of heave RAO of the equipped semi-submersible platform with original case**

## 4.3.2. Motion Response Spectrum

In order to determine the effect of TSDs on the motion response of the semi-submersible platform, the value of the motion response must be evaluated which is calculated using Eq. (3).

$$S_s(\omega) = RAO^2 \times S_{JONSWAP},$$
$$m_{0s} = \int_0^\infty S_s(\omega) d\omega, \quad (3)$$
$$(2S)_s = 4\sqrt{m_{0s}}$$

Irregular waves based on JONSWAP spectrum [23] is applied.The characteristics of Caspian Sea waves (Table. 2) are used. The results of the pitch, roll and heave motions are compared with the original platform in Figs. 15-17. Moreover, the reduction percentage relative to the original platform are presented in Table 3. As shown, the pitch motion has reduced more than 30% whilst slight changes are observed in heave and roll motions. As a result, using TSD system is a way appropriate for improving pitch motion response of the semi-submersible platform without making considerable change in the heave and roll motion response.

**Table 2. Comparison of the maximum pitch motion response of the equipped semi-submersible platform with original case**

| Motions of equipped semi-sub | Value of motion response of original case | Value of motion response of equipped semi-sub | Percentage of reduction |
|---|---|---|---|
| Pitch (deg) | 1.58 | 1.10 | 30.37 |
| Roll (deg) | 0 | 1.2E-6 | - |
| Heave (m) | 1.865 | 1.805 | 3.217 |

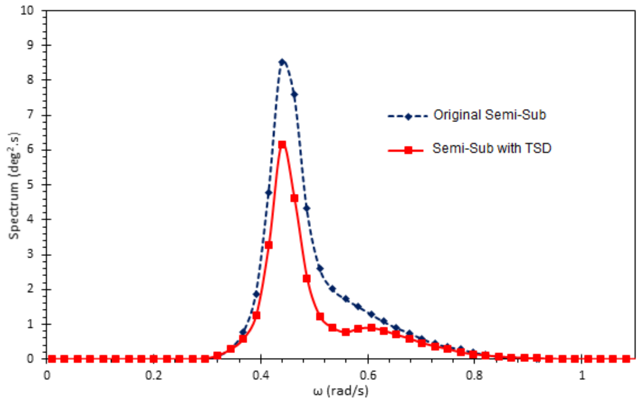


**Figure 15**. **Comparison of pitch motion response of the equipped semi-submersible platform with original case**

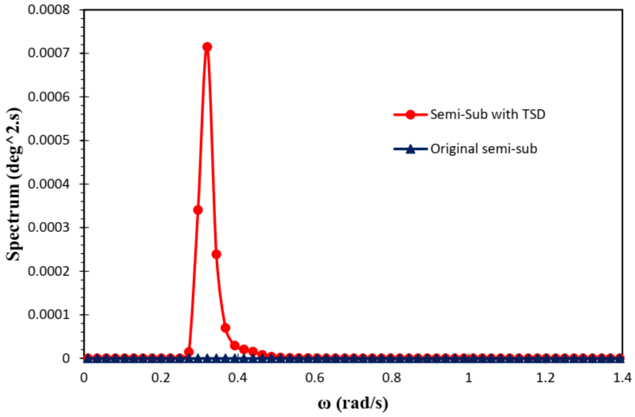


**Figure 16**. **Comparison of roll motion response of the equipped semi-submersible platform with original case**

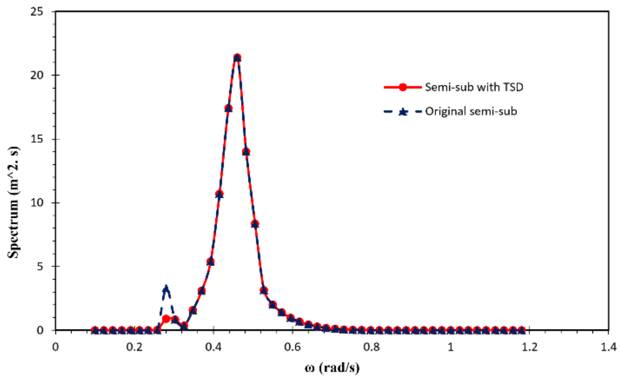


**Figure 17**. **Comparison of heave motion response of the equipped semi-submersible platform with original case**

## 4.4. Effect of the Filling Fraction

The pitch motion response of the equipped semi-submersible is studied with different filling fraction for TSD including 20%, 40%, and 60%. The corresponding results for pitch RAO are given in Fig. 18. Furthermore, the pitch motion response spectrum is illustrated in Fig. 19. Obviously, by decreasing water filling fraction, the pitch motion response would be more suppressed (Table 3). Therefore, TSD with 20% water filling fraction is more suitable.

**Table 3. Comparison of pitch motion response of the equipped semi-submersible platform with different filling fraction for TSD**

| Filling ratio | Pitch Motion Response (degree) | Percentage of reduction for Pitch motion response |
|---|---|---|
| Original | 1.58 | - |
| 20% | 1.10 | 30.37 |
| 40% | 1.234 | 21.8 |
| 60% | 1.285 | 18.6 |

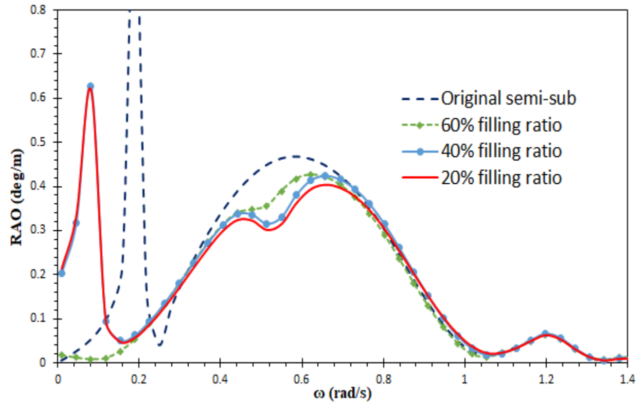


**Figure 18**. **Comparison of pitch RAO of equipped semi-submersible platform with 20%, 40%, and 60% water filling fraction under the head sea waves**

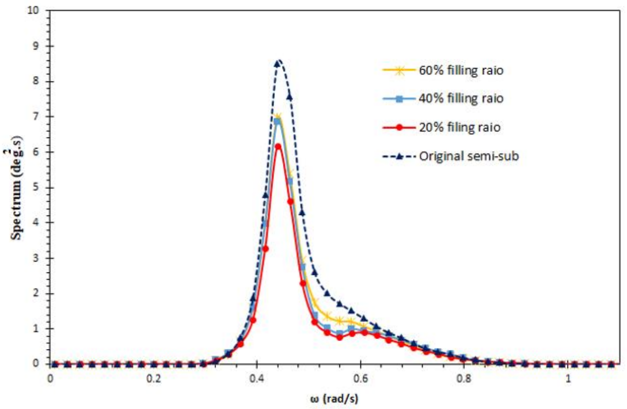


**Figure 19**. **Comparison of pitch motion response of the equipped semi-submersible with 20%, 40%, and 60% water filling fraction under the head sea waves**

## 5. Conclusion

Offshore platforms are unique structures that pose many challenges in their development and conceptual design. A semi-submersible platform is the category of offshore platform which commonly used for gas and oil exploration in deep waters. The heave, pitch or roll motion response of the conventional semi-submersible platforms are relatively significant. This can often limit their operability especially for drilling rigs or even can damage to its risers and mooring system. In this paper, it was focused on the pitch motion response of Iran-Amirkabri semi-submersible rig with four TSDs. It was named as an equipped semi-submersible platform. A finite element software was applied to simulate its hydrodynamic behavior. The results of the equipped semi-submersible platform was calculated and compared with original case. The following conclusions were obtained:

- The pitch motion response has two separate peaks: one close to the peak wave frequency and the other at the sloshing natural frequency.
- The pitch motion response of the equipped semi-submersible platform is decreased by about 30% relative to its original case.
- The heave and roll motion response of the equipped semi-submersible platform is slightly changed relative to the original case.
- The value of the filling fraction of TSD can be effective for reducing the pitch motion response of the semi-submersible platform.

It is summarized that TSDs are an appropriate device to suppress pitch motion response of the semi-submersible platform. Moreover, this study can make significant contribution to the more economical and more efficient design of semi-submersible oil and gas drilling platforms.

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