Open Access Journal

Journal of Power Technologies 94 (1) (2014) 42–49

journal homepage:papers.itc.pw.edu.pl

Dynamic Analysis of a Tension Leg Platform for Offshore Wind Turbines

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Abstract

The design for a floating offshore wind turbine tension leg platform (FOWT-TLP) is economical, technically feasible and experiences less motion compared to other floating structures, especially in deep water. In this paper, the conceptualization of a floating offshore wind turbine tension leg platform (HIT-FOWT-TLP) is proposed and discussed, and compared with the traditional NREL-TLP model. A concrete ballast model is arranged underneath the spoke bottom plane to serve as permanent ballast. Much of the water ballast can be considered as a single column. Its center of gravity can be adjusted freely by moving water, to obtain a dynamic feature. It can be assembled more easily than ballasts based on other concepts. The spoke part is considered to have dimensions and mass. The new model has only 49% of the displacement, and only 27% of the mass of the NREL-TLP model. The hydrodynamic characteristic parameters and the RAO values are compared with the NREL-TLP model under similar environmental conditions. The results show that, in roll, sway and pitch motions, the model proposed in this paper performs better.

Keywords: Offshore wind turbine, Floating foundation, Tension leg platform, Spar structure

1. Introduction

In China, the United States, Japan and many other countries, there are large offshore wind energy systems in deepwater operation (depths of approximately 60 m to 900 m). At these depths, traditional monopile, tripod and jacket systems are limited in application, because they are not cost-effective and suffer from low performance. Even at intermediate-water depths of 30 m to 60 m, a floating structure can support a viable alternative instead of a traditional structure. An essential requirement for a deep-water, floating, offshore wind turbine is a reliable and viable floating-platform support structure. After considering the variety of mooring systems, tanks, and ballast options that are used in the offshore oil and gas industries [1] and are based on achieving the static concept, three types of floating structures are used: a shallow drafted barge achieving pitch restoration by water plane area moment, a ballasted spar buoy with pitch restoration by ballasting, and a tension leg platform with pitch restoration by a mooring system. The shallow drafted barge is costly compared to the other two types of offshore floating systems when the ballast material is not concrete [2, 3]. Extensive studies have been conducted on spar and TLP floating structures. The advantages and disadvantages of these structures are well known. The spar structure, which has a small single cylinder, needs deep ballast and requires a deepwater harbor for assembly and the water depth in this application perhaps exceeds 50 m [2, 3]. The amount of ballast needed also increases the costs, Denis reports that the spar structure in terms of fatigue ratios indicates improve-

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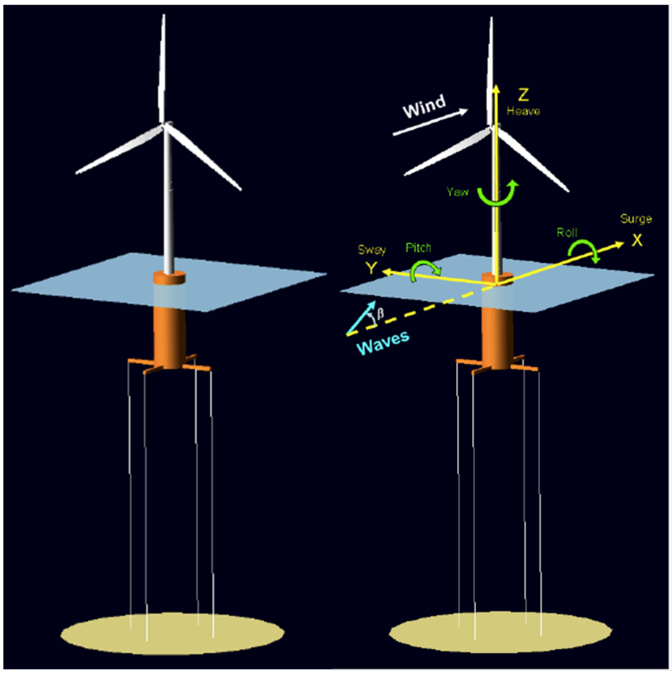

Figure 1: NREL-TLP model and the coordinate system

ment in tower strength or the control system [1]. The TLP floating structure design is expensive as regards the tension leg mooring system and anchors. There are advantages however alongside the disadvantages. The spar structure has a simple anchor system, small drag force because of the volume, and its natural frequency lies outside of rich energy wave spectra. Due to the tension in the line, the TLP structure has good dynamic heave, roll and pitch natural periods and motions, and small mean surge and sway displacement [4].

The author earlier proposed a new TLP concept called the MIT-TLP model, combining the traditional TLP and spar structures [5]. The advantage of this system is that without the moorings, this design is stable in calm sea when the turbine is not operating. When anchored to the seabed, most of the restoring action is still provided by the mooring system. The platform would be considered additionally water-ballasted during towing. Fig. 1 shows the shape for this type of structure. In [1], Denis modified the MIT-TLP model spoke length and corrected the faults to obtain better motion by using FAST software, and renamed it the NREL-TLP model. Interesting aspects of this research are that the dimensions of spoke mass are not considered and the effect on motion is not decided. In the MIT-TLP and NREL-TLP models, the concrete is filled inside the column, so that the column volume left is limited for use of water ballast, the spoke is too long and building it is not easy, the large pitch motion causes a large moment in the tower base, and yaw instabilities occur [1]. The coordinate system is also shown in Fig. 1 in order to compare it with the older one.

Based on the MIT-TLP and NREL-TLP concepts, this paper attempts to propose an HIT-FOWT-TLP system to overcome the disadvantages inherent in them and induce some motion responses. In the same input situation, an attempt is made to compare the NREL-TLP dynamic feature with HIT-FOWT-TLP in the time domain in order to test this concept. Analysis software ANSYS AQWA is used for computing hydrodynamic properties. NREL (the National Renewable Energy Laboratory) FAST simulation software for wind turbines and platforms is used to do the combined dynamic analysis.

2. Input information

The NREL 5 MW offshore wind turbine is used in this study. The preliminary concept was designed by Jonkman. The disadvantage of using this type of wind turbine is that it was adopted as a reference in earlier research [6–8]. The environmental conditions are kept the same as those in [1] and [5]: 11 m/s hub-height wind speed, 10 m significant wave height, and the wave peak spectral period of Tp is 17.64 s.

This platform is named the HIT-Floating Offshore Wind Turbine-Tension Leg Platform (HIT-FOWT-TLP) in order to distinguish it from the MIT/NREL TLP and other types of platform. It is similar to the models mentioned, but underwent modifications to obtain much better motion characteristics. The unique features of the HIT-FOWT-TLP are: a single-column with four pontoons and a 5 m high bevel shaped free board. Fig. 2 shows the whole structure. The biggest difference between this platform and other types is that concrete is at the bottom of the steel column, and the space inside the steel column can be used for water ballast. The HIT-FOWT-TLP structure can obtain much more free ballast space at minimal cost. Larger diameters are considered for the spoke, and the connection between the spoke and

Figure 2: HIT-FOWT-TLP assembly

column is welded. The concrete ballast part is at the bottom. This type of design easily adjusts to the gravity and buoy center by using water ballast, as shown in [5]. It can be designed on a stable station for transportation.

3. Dynamic process analysis and results

3.1. Hydrodynamic properties

ANSYS AQWA software is used for computing hydrodynamic properties, including excitation force, added mass, and damping matrix. It is similar to WAMIT. Both use a 3-D panel method for wave loads, which is based on potential flow theory. It neglects flow separation. All the coefficients in this section are made dimensionless according to formulas in chapter 3 of WAMIT 7.0 user's manual.

In order to verify the process of obtaining, the hydrodynamic properties, the process in [1] is repeated with Ansys and WAMIT, and the results were compared for accuracy. The two models are shown in Fig. 4. The WAMIT model is obtained from paper [1, 9]. Fig. 3 is the HIT-FOWT-TLP AQWA model. It is evident that the spoke part considered in this study is in the mesh step. Following Figs. 5 to 8 are the results obtained. A comparison of these results shows that they are very consistent. This proves the success of the process. As space in this paper is limited, only part of the figures is selected. The added mass resulting from NREL TLP is larger than that of the present TLP. That is due to smaller displacement in the current model. But the results for NREL TLP in WAMIT and AQWA are in good agreement.

Table 1: Model dimension

	Variant	MIT/NREL TLP	HIT-FOWT-TLP
1.	Platform diameter	18 m	14 m
2.	Platform draft	47.89 m	30 m
3.	Total displacement	12,179 m^3	5,950 m^3
4.	Platform mass	8,600,000 kg	2,327,460 kg
5.	Distance between fairleads	54 m	48 m
6.	Concrete (ballast) mass	8,216,000 kg	1,923,250 kg
7.	Spoke diameter and mass	Not considered	Considered
8.	Concrete height	12.6 m	5 m
9.	Water depth	200 m	200 m

Damping in the yaw direction of the proposed model is higher than in the NREL TLP model. The reason for this is that the spoke effect was ignored in the NREL model. The model proposed in this paper uses a larger spoke dimension and its effect on the damping is considered. In a limited zone from 0.7 rad/s to 1.8 rad/s damping is evident, as shown by Fig. 6. In this area the wave energy is concentrated between 0.25 rad/s and 1.25 rad/s. Future research should look to develop a method to improve yaw damping and make it cover all energy zones by using the spoke dimension. In the exciting force of zero

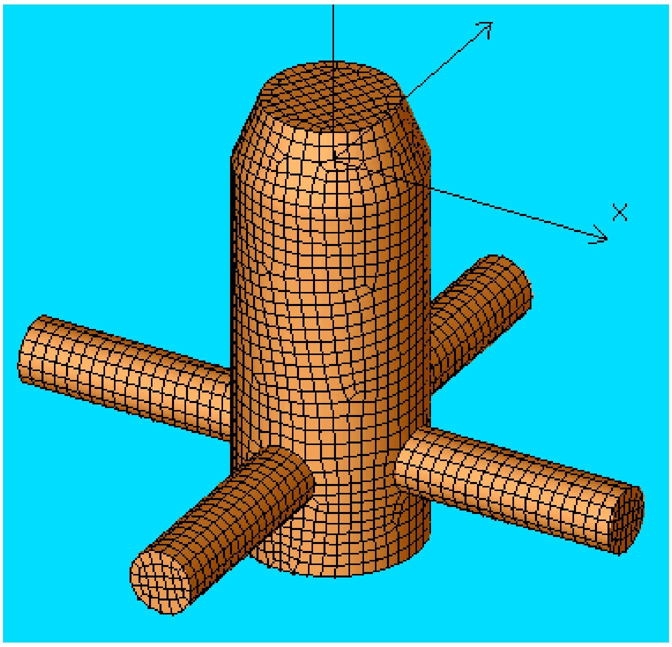

Figure 3: HIT-FOWT-TLP AQWA model

degree, the direction of roll, sway, yaw and heave is selected, as in other directions the exciting forces are similar and coincide better. In roll, sway and yaw, the exciting force is not zero, which results in obvious vibration. In order to research this situation, another degree of incident wave is considered. Fig. 8 is a result for the exciting force of the twentieth degree, in which coincidence with each other is better, except for in the yaw direction. This type of floating structure with the incident wave in the vertical incident holds promise. As earlier publications overlooked the spoke effect, the phenomenon was not noticed and this subject accordingly requires more research in future.

3.2. Response amplitude operators (RAO) analysis

The equations of motion that control the linear dynamic motion of the system are summarized in Eq. 1 [10]:

$$\left[-\omega^2 (M + A(\omega)) + \hat{i}\omega B(\omega) + C\right] \Xi(\omega) = X(\omega) \tag{1}$$

For the translational modes of motion, the RAO is given by Eq. 2 [10]:

$$RAO_{trans\,modes}(\omega) = \frac{|X_k(\omega)|}{A_{wave}} \tag{2}$$

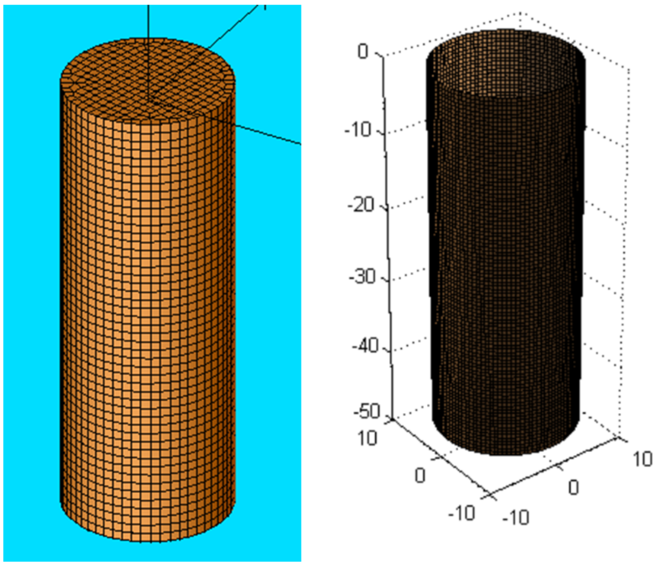

Figure 4: AQWA and WAMIT models [1]

For the rotational modes of the motion, the RAO is given by Eq. 3 [10]:

$$RAO_{rot\,modes}(\omega) = \frac{X_k(\omega)}{\frac{A_{wave}}{L}} \tag{3}$$

A_{wave} represents the wave amplitude, and L is the cylinder radius.

In order to compare the results with each other, some input data are kept the same. An *RAO* represents the non-dimensional response of a system to an incident wave unit-amplitude period in the direction of the X coordinate axis. The graph in red is for the data obtained with FAST and the NREL TLP model described in [1]. The *RAO*s of the rotation degree are normalized by the platform length. The length of the platform is 9 m. The energy is concentrated between 0.25 rad/s and 1.25 rad/s [1]. The results obtained are shown in Fig. 8. The present TLP represents the HIT-FOWT-TLP model.

In the new model, the surge *RAO* value is higher for values of ω in the range of 0.4 rad/s to 1.38 rad/s, and then it is reduced from 1.38 rad/s to 2 rad/s. The trend on the graph is different from the NREL model. The NREL TLP model has a similar ratio for reducing its *RAO* value, but it is found to increase. The roll *RAO* value is similar in the energy concentrated zone for both of these two models, but in the zone for ω from 1.3 rad/s to 1.6 rad/s, the *RAO* value is higher than that for the NREL TLP model. There-

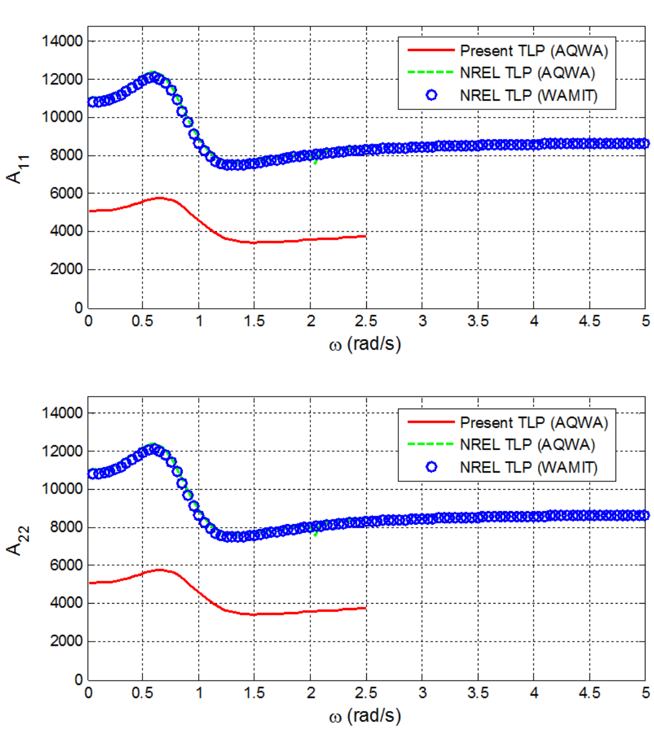

Figure 5: Added mass

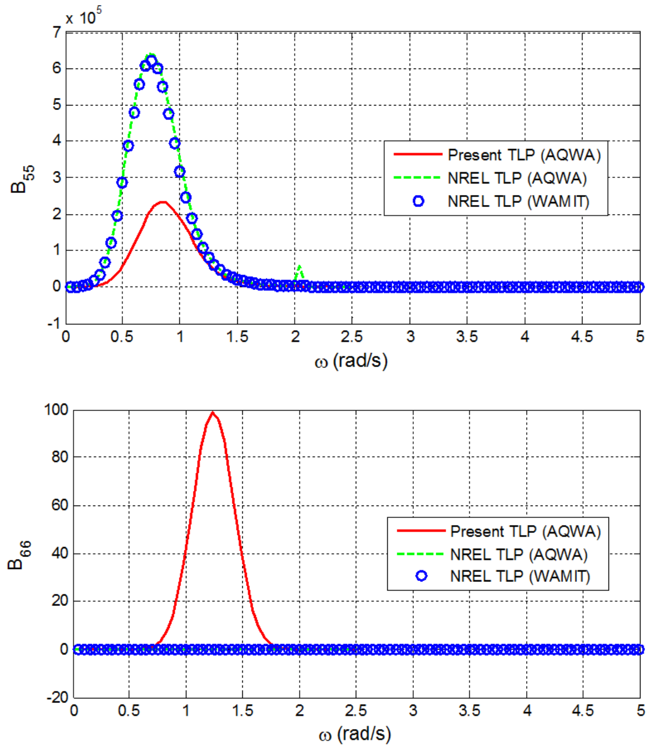

Figure 6: Damping

fore the new TLP model is better for roll motion. For the sway and pitch *RAO*, the new TLP model is also obviously better. The value is zero compared to the result from the NREL TLP model. The heave RAO trends are different for the NREL TLP model. At some points the value given by the NREL TLP model changes too much and to increases in ω. However, for the present model the heave *RAO* value always decreases with ω. The yaw *RAO* for the present model is lower for ω from 0.7 rad/s to 2 rad/s, but for ω from 0.25 rad/s to 0.7 rad/s the value is higher than that for the NREL TLP model. Above all, the new TLP model has better motion in the roll, sway and pitch direction. The trends in surge and heave RAO value induce more quickly than the NREL TLP model. It is better in the yaw motion at high frequency. Heave and surge in the new model changes more quickly than that in the NREL model. If it can be moved from high frequency to a lower frequency, it would be very useful.

4. Conclusions

In this paper, a new HIT-FOWT-TLP system is proposed, and under similar conditions, the hydrodynamic properties and *RAO* values for this model are compared with those for the NREL-TLP model. In earlier reported research, the spoke is kept small and its mass is considered insignificant. The work reported in this paper considered the effect of the spoke attached to the column. The final results can be summarized as follows:

1. The new model has much more space to accommodate free ballast, which offers scope to adjust centers of gravity and buoyancy to obtain dynamic features.
2. In the preliminary calculations, the spoke effect on the wind turbine and TLP system is considered. It is found that the spoke effect should not be neglected, and that it might cause vertical incident wave exciting force. The displacement and mass of the HIT-FOWT-TLP model are only 49% and 27% respectively of those of the NREL-TLP model. The dynamic features of the new model with respect to roll, sway and pitch *RAO*, are superior to those of the NREL model. At some point, the yaw motion in high frequency can be improved. The effect of the spoke dimension on the TLP and wind turbine

system dynamics should be subject to further detailed research to establish a method to control the yaw motion, and to induce sway, roll and pitch response amplitude operators. It would also be useful to find a method to induce the heave and surge initial point and *RAO* value in this type of structure. These issues merit future research.

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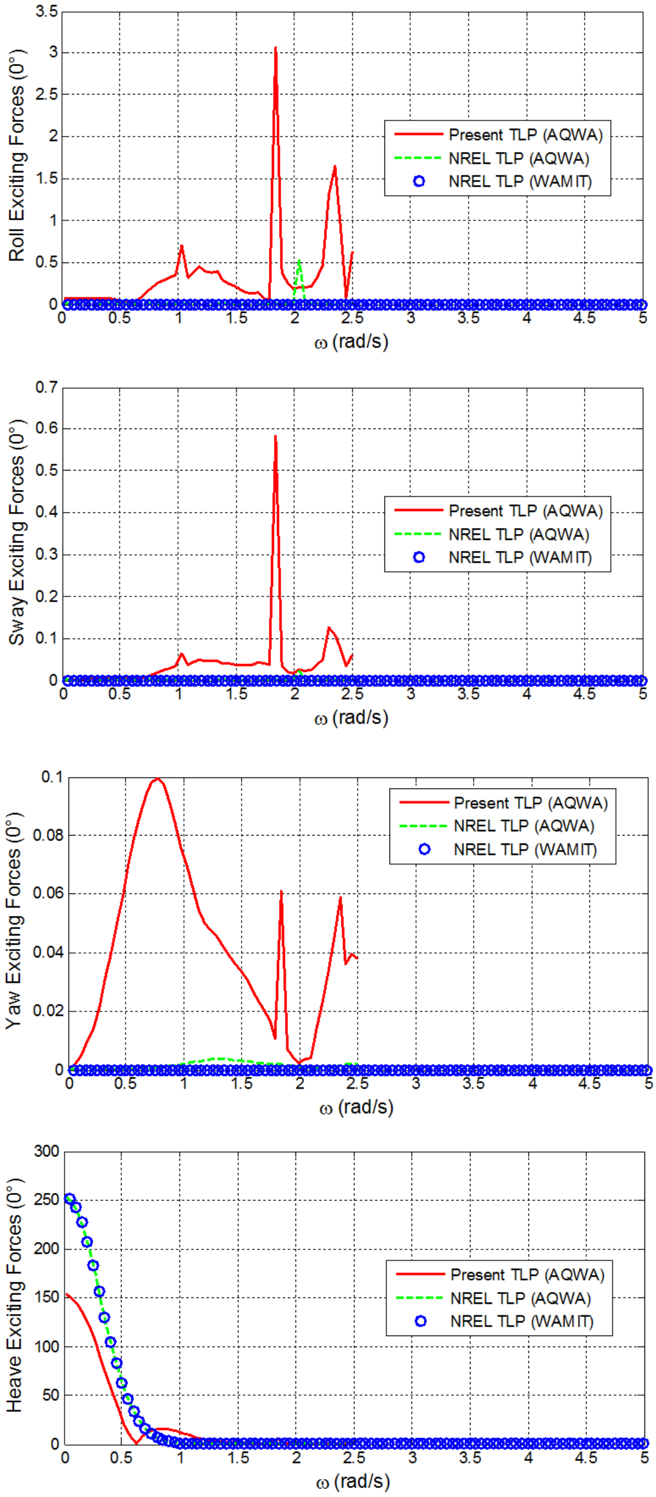

Figure 7: Exciting force of zero degree

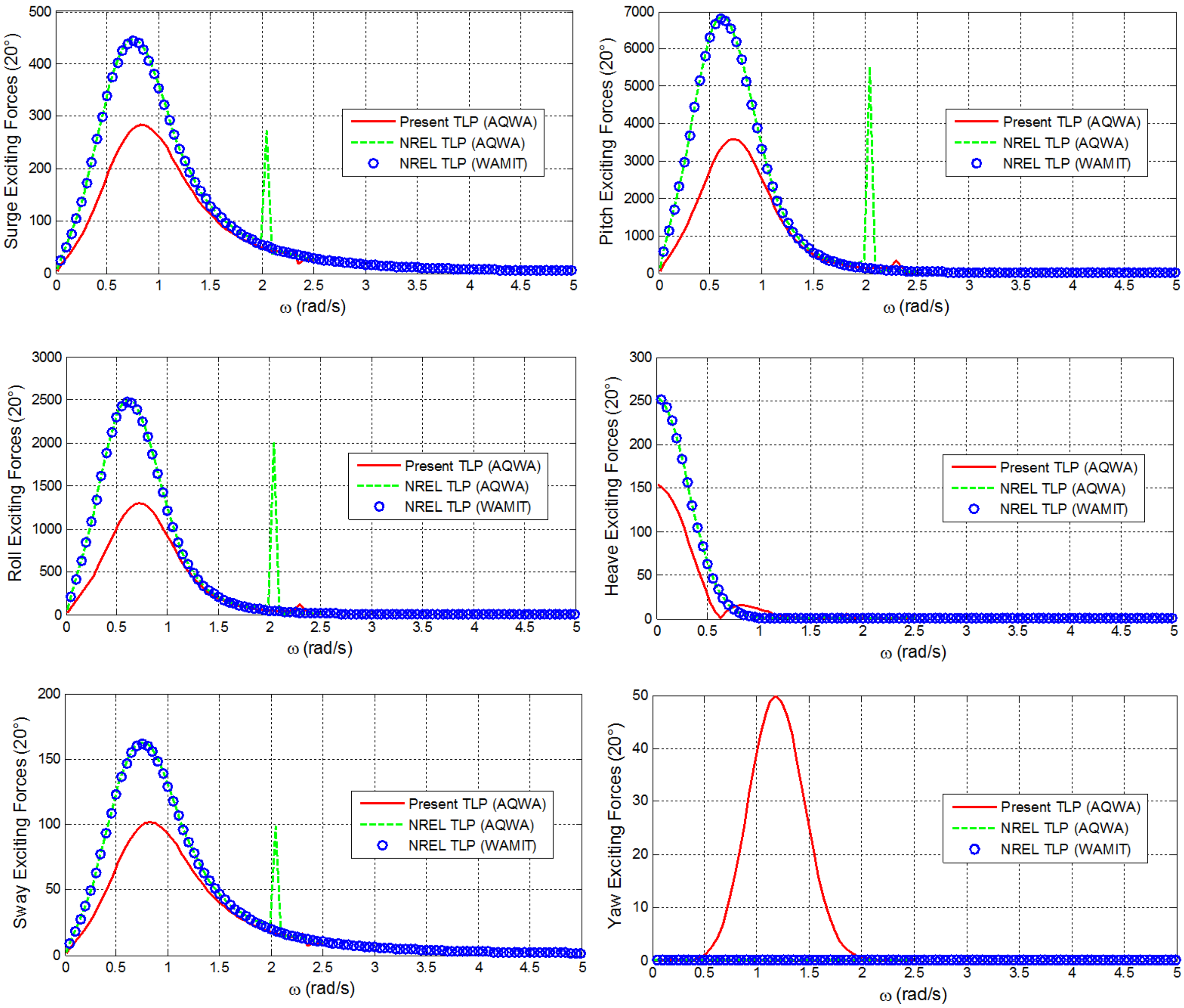

Figure 8: Exciting force of twentieth degree

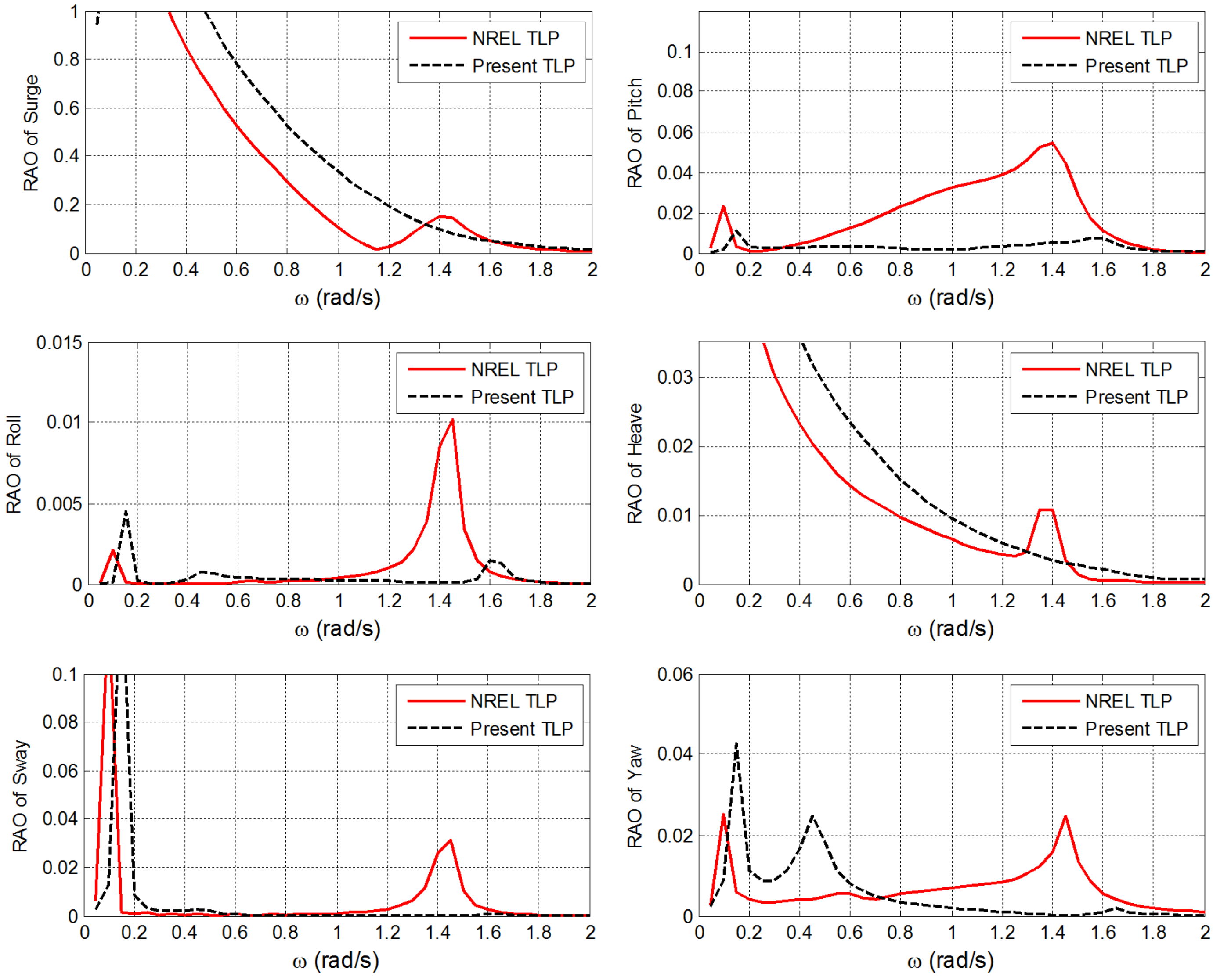

Figure 9: Different values of *RAO*