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COUPLED DYNAMIC RESPONSE OF A THREE-COLUMN MINI TLP

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Abstract:

For the development of deepwater marginal fields, many new platform concepts and designs are on the anvil. The mini TLP is a proven concept in this regard wherein an optimized conventional TLP system economically and efficiently serves in developing small marginal deepwater reserves. Various new geometric configurations and designs of mini TLPs are reported in the literature. This paper presents a new geometric configuration which could be a better alternative to an existing configuration. A 3-column mini TLP is designed and its platform-mooring coupled dynamic behaviour is investigated and compared with an existing 4-column mini TLP. The numerical investigation is carried out for the 1:56 scaled model using a finite element computer program suitable for compliant offshore platforms. A combination wave force model with diffraction-radiation loading on large members and Morison loading on slender members is adopted for computing the non-linear dynamic response of the structure. The effects of parameters such as pretension in tethers and wave approach angle have been studied. The results obtained are compared with published results of the 4-column mini TLP. It is found that the dynamic responses of the 3-column mini TLP are close to the 4-column mini TLP with relatively higher surge and tether tension. Accounting for this in the design stage, the newly designed structure could be a promising candidate which can be used as an alternative to the 4-column mini TLP. Reducing the number of columns from four to three has added advantages in terms of cost and time during fabrication, installation and maintenance of the platform.

Keywords: Deepwater structures; Coupled dynamics; Finite element method; Mini TLP; Nonlinear dynamic analysis.

1. Introduction

Numerous small oil fields have been discovered in very deep seabeds. New concepts of platform construction, exploration, drilling and production are necessary for economic development of these minimal oil fields situated in deep, remote locations in hostile environment. Mini tension leg platform (mini TLP) is a proven concept towards this objective. It is evident from the literature that the study of structural behaviour and dynamic response of these platform concepts are presently being actively pursued for design optimisation. Several mini TLP designs have been discussed in the literature. These are: a downsized four column mini TLP for 1000 m water depth (Hudson et al. 1996, Hudson and Vasseur 1996); a family of concrete mini TLPs for generic applications (Logan 1996); a three column TLP for 800 m water depth, easily extendable to 1500 m under shorter development schedule with significant reduction in cost (Muren 1996); a mini TLP with vertical cylindrical hull connected to three radially tapered rectangular pontoons called SeaStar (Kibbee 1996 and Kibbee et al. 1999).

The importance of coupled response analysis of offshore compliant structural systems has also been discussed in the literature. Analysis of deepwater compliant structures must address significant hull-tether coupling because the uncoupled method ignores the interaction effects between the platform hull and its tethers. The coupled nonlinear dynamic analysis of the` Seastar mini TLP in the time domain using finite element method has been reported (Sreekumar et al. 2001). The results were compared with the similar calculations based on Morison equation for wave loading as well as with experimental results using a 1:50 scale model.

Kim and Sclavounos (2001) described the fully coupled response simulations of theme offshore structures in water depths of up to 10,000 feet. Bhattacharya et al. (2003) presented a detailed finite element methodology for

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the analysis of coupled dynamics of mini TLPs and the nature of hull-tether coupling and its physical modeling principles have been brought out. Joseph et al. (2004) reported detailed experimental and numerical investigations on the coupled dynamic behaviour of a 4-column mini TLP with special attention to hull-tether coupling. Numerical investigation using several wave force models and validation with experiments identified the best suited wave force model, which is a combination of potential theory based wave loading on the hull-column entity and Morison-type wave loading on the slender cantilevering arms and tethers. Liagre and Niedzwecki (2006) presented the non-linear coupled dynamic response of a deepwater mini TLP considering non-linear stiffness, quadratic damping, surge-pitch and sway-roll coupling. In addition, behaviour of hydrodynamic added-mass and damping coefficient was simulated using an industry standard diffraction-radiation software package. The results obtained were used for modelling the local offshore environment, numerical simulation and model test verification of the platform response characteristics. Chen et al. (2006) compared numerical results with measurements for a mini TLP. They considered only Morison wave loading. Joseph et al. (2007) presented the design details of a 3-column mini TLP based on an existing 4-column mini TLP and carried out its numerical analysis with Morison equation alone for the wave force model

Thus the importance of coupled analysis and combined wave force modelling is underscored in the literature. Several innovative designs and interesting geometrical configurations also are reported aiming towards savings and advantages in terms of material, time and cost, applicable to marginal deepwater sites. Numerous marginal oil fields have been discovered in very deepwater all around the world. For the economic development of these deepwater minimal fields, optimized new platform concepts is necessary. Based on the critical assessment of the literature and the motivation outlined above, the scope of the paper is a new mini TLP design which could have favourable dynamic response along with advantages in terms of cost, material and time.

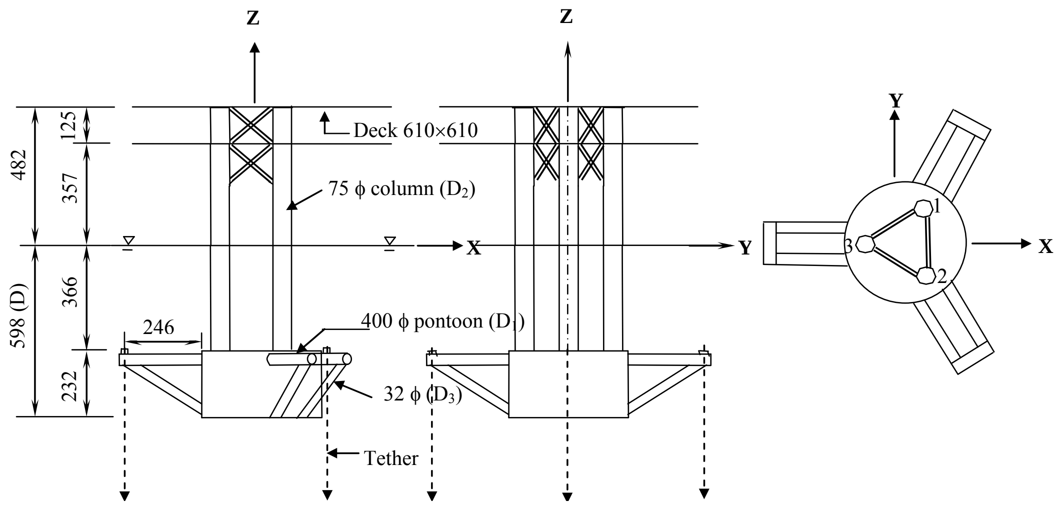
2. Design Details of the Model

The new geometrical configuration is arrived at as a part of a screening of alternative mini TLP concepts. The geometric parameters are designed with reference to the 4-column mini TLP model. The design is done by keeping the draft, the total weight, the weight displacement and the vertical centre of buoyancy same as that of the 4-column model. The model geometry and construction details of the 1:56 scaled model (Froude modeling) of the 3-column mini TLP are given in Fig. 1. Table 1 shows detailed data of both models.

The principal parts of the newly designed mini TLP model are the large pontoon, three slender columns, the upper and lower decks and three cantilevering trusses to which the tendons are attached. The pontoon consists of a 400 mm diameter PVC cylinder of height 232 mm with closed bottom and top ends and provides most of the buoyancy. Three 75 mm diameter columns extend vertically upwards from the top surface of the pontoon to support the lower and upper decks.

The still water level is at the level of the columns (Fig. 1) such that the draft in tethered condition is 598 mm (which is same as that of 4-column TLP model). Therefore the water plane area consists of the three columns (A_{wp}= 3×4418 = 13253 mm^2). The three tendon-supporting cantilevered trusses, each of length 246 mm consisting of two 40 mm diameter horizontal PVC tubes and two 32 mm diameter inclined PVC tubes, extend radially from the pontoon's circumference, at an angle of 120º from each other. PVC flats of size 80 mm × 50 mm × 20 mm (with a 10 mm diameter hole drilled centrally for receiving the tendon assembly) connect the ends of each pair of horizontal truss members. For model tether: Young's modulus is 0.457 × 10^{11} N/m^2, cross-sectional area is 4.04 mm^2, and mass density is 0.0317 kg/m.

The weight of model (W) without ballast (additional weight) is 17.882 kg (= W_{min}). At design draft of 598 mm, the weight displacement (Δ) of the model is 37.84 kg. Two tether pretension levels were used in experiments, T_t/Δ = 0.26 (T_t = $\Delta - W$ = 9.84 kg; W = 28 kg, ballast = 10.06 kg, W/T_t = 2.85) and T_t/Δ = 0.17 (T_t = $\Delta - W$ = 6.43 kg; W = 31.41 kg, ballast = 13.47 kg, W/T_t = 4.88). Steel ballast weights could be used to achieve desired model weight. The condition with W/T_t ratio of 2.86 is in the range of typical TLP designs. The two tether pretension levels can be achieved by varying the weight of the model, by inserting the ballast in the three columns. The percentage difference of weight displacement of the present model from that of 4-column model is 1.96. The percentage difference of the water plane area is 5.9 and that of the total weight of the model is 0.65. All these values are sufficiently low so that results of the present model could be compared with published results of the 4-column mini TLP.



(a) Elevation X-Z (b) Elevation Y-Z (c) Plan

Fig. 1. Three-column mini TLP model (scale 1:56)

Table 1: Model Data

Parameter		3-column mini TLP	4-column mini TLP
Displacement (Δ)		37.84 kg	38.6 kg
Weight (W)	T_t/Δ=0.26	28.6 kg	28 kg
	T_t/Δ=0.17	32 kg	31.41 kg
Total tether pretension (T_t)	T_t/Δ=0.26	10 kg	9.84 kg
	T_t/Δ=0.17	6.56 kg	6.43 kg
Water depth		4.3 m	4.3 m
Draft		598 mm	598 mm
Height of pontoon		232 mm	232 mm
Diameter of cylindrical pontoon		400 mm	400 mm
Water plane area of hull (A_{wp})		13253 mm^2	12469 mm^2
Moment of area of water plane (I_{wp})		53.37×106 mm^4	140.5×106 mm^4
Diameter of columns		75 mm	63 mm
Length of tether (L_t)		3.6 m	3.6 m
Vertical centre of gravity (VCG) from keel	W = 18 kg	429 mm	450 mm
	W = 28.6 kg	295 mm	310 mm
	W = 32 kg	280 mm	292 mm
Vertical centre of buoyancy		159 mm	157 mm

The tethers of the present model is taken as the same as that for the 4-column model. They are strand type twisted steel wire ropes of 3 mm outer diameter comprising of six strands of seven threads each (i.e. a total of 42 threads). Diameter of each thread is 0.35 mm and hence its c/s area is 0.0962 mm^2. On this basis, the cross section area (A) of the steel wire is 42×0.0962 = 4.04 mm^2. Mass density of the tether (ρ_t) is 0.0317 kg/m, so that the total mass of one tether is 0.0317×3.6 = 0.114 kg, which is negligible compared to the platform mass. The value of Young's modulus is E = 0.457×10^{11} N/m^2.

The damped natural periods of vibration of the mini TLP model (Table 2) reveal that the surge, sway and yaw (soft modes) frequencies lie much below while the heave, roll and pitch (stiff modes) frequencies lie above the practical range of wave frequencies.

Table 2: Comparison Natural periods of vibration and damping ratios of the mini TLP model (T_t/Δ = 0.26, θ = 0°)

Degree of freedom	Natural period (s)	Damping ratio
Surge, sway	10.600	0.040
Heave	0.115	0.129
Roll, Pitch	0.130	0.118
Yaw	3.630	0.274

3. Coupled Response Analysis

The dynamic response of the model is investigated using nonlinear finite element method in the time domain. The underwater hull of the mini TLP comprises of three sets of slender columns and cantilevering arms as well as a hydro-dynamically compact pontoon with a slender tether system providing the compliance. So a wave force model with diffraction-radiation loading on the pontoon-column unit and Morison loading on slender members was adopted for computing the non-linear dynamic response of the structure. For evaluating wave forces on hydrodynamically transparent (slender) members, Morison equation is generally used. Depending on the Keulegan-Carpenter (*KC*) numbers of various members, drag coefficient (C_d) values ranging from 0.5 to 0.76 and inertia coefficient (C_m) values ranging from 2.2 to 2.3 were selected from experimental values given in Chakrabarti (1987). The hydrostatic parameters used in the numerical analysis are heave stiffness = 43.34 N/m, pitch stiffness (= roll stiffness) = 0.01524 Nm/rad.

To carry out linear diffraction-radiation analysis of the scaled model a cylindrical fluid domain of diameter approximately five times that of the larger diameter (400mm) hull is selected. The finite element mesh of the fluid domain with horizontal seabed boundary has 12702 nodes and 11442 eight-noded brick elements. The diffraction-radiation analysis is carried out using a finite element code which has been extensively used in a variety of problems yielding frequency-dependent added mass and radiation damping coefficients and first order wave forces (Sathyapal, 2001). Second order dampers have been used at the radiation boundary. In the context of the nonlinear dynamic analysis, the added mass matrix is modeled by a 3D global coupled mass element and the radiation damping matrix is modeled by a 3D global coupled damper element, locating both at the CG of the hull.

To carry out the nonlinear dynamic analysis, a finite element code for the nonlinear time domain simulation of dynamic response based on updated Lagrangian formulation considering both hull-tether coupling and coupling between six platform degrees of freedom is used. The dynamic equilibrium equation is solved in the time domain using the incremental-iterative Newmark-Beta algorithm (Sreekumar**,** 2001). The finite element model is presented in Fig. 2. It comprises of 39 nodes, 62 beam elements, 3 spring elements, 7 mass elements and 180 equations. There are 4 beam elements per tether, 16 in pontoon, 2 each per cantilevering truss, 3 in columns below SWL, and 15 above the SWL representing the columns and the upper and lower decks. Table 3 shows the diameters for hydrodynamic calculations for the different sets of elements (1 to 7 marked in the basic FE model in Fig. 2).

The three dimensional beam elements are modelled such that (i) the mass distribution should match with the overall mass of 17.882 kg of the mini TLP model (ii) the VCG should match with 450 mm, as in the case of the 4-column mini TLP model. Six 3D coupled mass elements (at the top and bottom nodes of the pontoon column elements) model the ballast (lumped mass) for varying the pretension values. Effect of two tether pretensions of 26 % and 17 % and two wave approach angles 0º and 60º are studied. The tether nodes at the seabed are given fixed boundary conditions. Being a compliant structure, the large displacements are of interest than the structural deformation of the platform. So the elastic tethers are modelled as beam elements with their true stiffness while arbitrarily high values are used for the rigid platform.

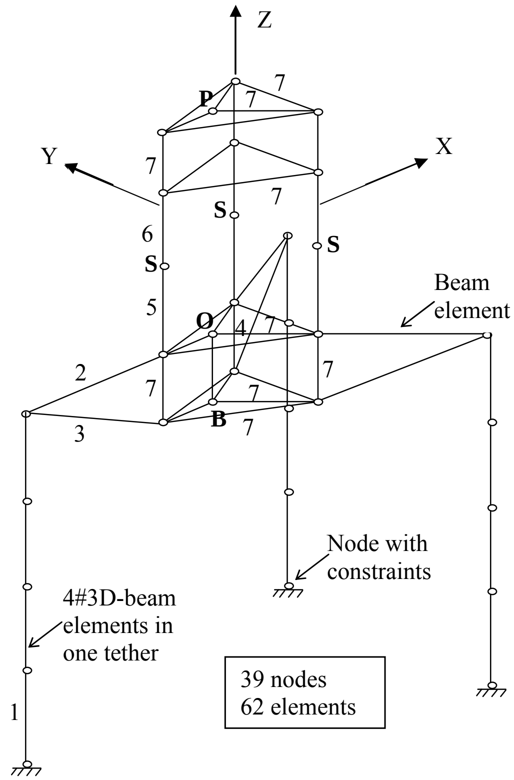


Fig. 2. Finite element model of mini TLP

Table 3: Diameters of beam elements for hydrodynamic calculation

Element set	Description of member	Diameter (m)	Structural area of cross section (m^2)
1	Tether	0.003	4.0409×10^{-06}
2	Horizontal cantilevering arm	0.0566	8.5038×10^{-04}
3	Sloping cantilevering arm	0.0453	3.4457×10^{-04}
4	Pontoon - central member	0	4.0362×10^{-03}
5	Submerged column	0	2.077×10^{-03}
6	Column above SWL	0.075	6.7858×10^{-04}
7	Deck and other pontoon members	0	1.25096×10^{-03}

4. Results and Discussion

The results of the diffraction-radiation analysis are added mass [μ], radiation damping coefficients [β], diffraction force components {F} and their phases for unit wave amplitude. The analysis is carried out for frequencies ranging from 0.36 Hz to 2.5 Hz.

Figure 3 shows that the surge added mass for the 3-column mini TLP is 12.5 % lower than that of 4-column mini TLP (for a wave frequency of 1.2 Hz). The sway added mass for the 3-column mini TLP is 11 % lower than that of 4-column mini TLP (for a wave frequency of 1.2 Hz). The heave added mass for the 3-column mini TLP is 10 % lower than that of 4-column mini TLP (for a wave period of 1.6 Hz). Roll added inertia of the 3-column mini TLP is 10 % higher and Pitch added inertia of 3-column mini TLP is 9 % higher than that of the 4-column mini TLP (for a wave frequency of 1.2Hz).

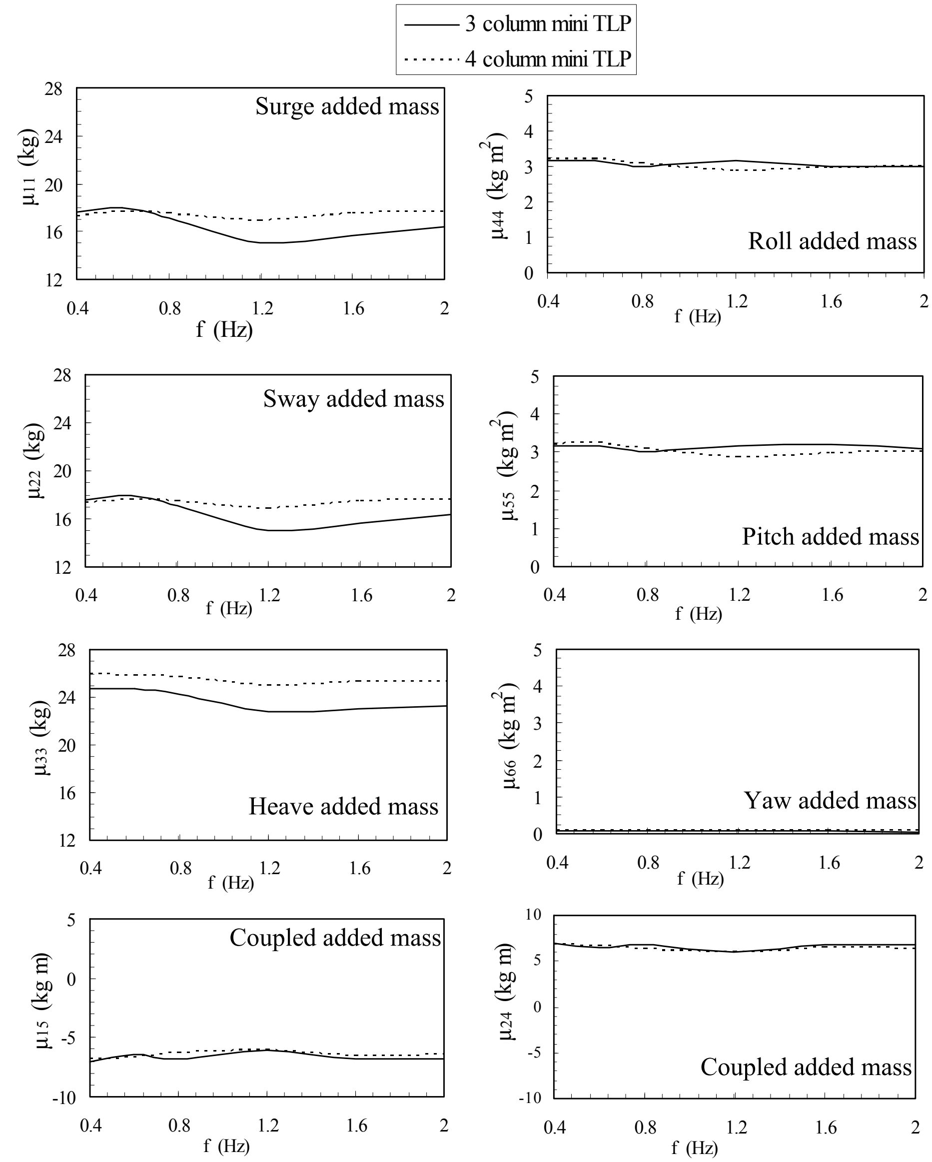


Fig. 3. Comparison of added mass of mini TLP models.

Figure 4 shows that all damping coefficients, except heave, are higher for the 3-column mini TLP model. Surge and sway damping coefficients are 60 % higher, heave damping coefficient is 55 % lesser, and roll as well as pitch damping coefficients are 45 % higher for the 3-column mini TLP (for a wave frequency of 1.2 Hz) compared to the 4-column mini TLP. The reduction in the case of 4-column mini TLP could be attributed to the cancellation by interference from the reflected waves from the four columns and supporting frames, whereas for a 3-column mini TLP, the interference is only from three columns and supporting frames resulting in an increase of waves passing out of the radiation boundary thus increasing the radiation damping.

In Fig. 5 the diffraction force components as well as their phases for unit wave amplitude (for $\theta = 0°$) are compared with that of 4-column mini TLP. Surge force is 13 % and heave force is 21 % higher for 3-column mini TLP (for a wave frequency of 0.8 Hz). Pitch moment is almost same for both the models For both the models, sway force, Roll moment and yaw moment vanish for θ equal to 0° and hence not shown.. The plots show that the phase angles in surge and sway are independent of wave approach angle. Also, the phases of surge and sway are identical for both 3-column and 4-column mini TLPs.

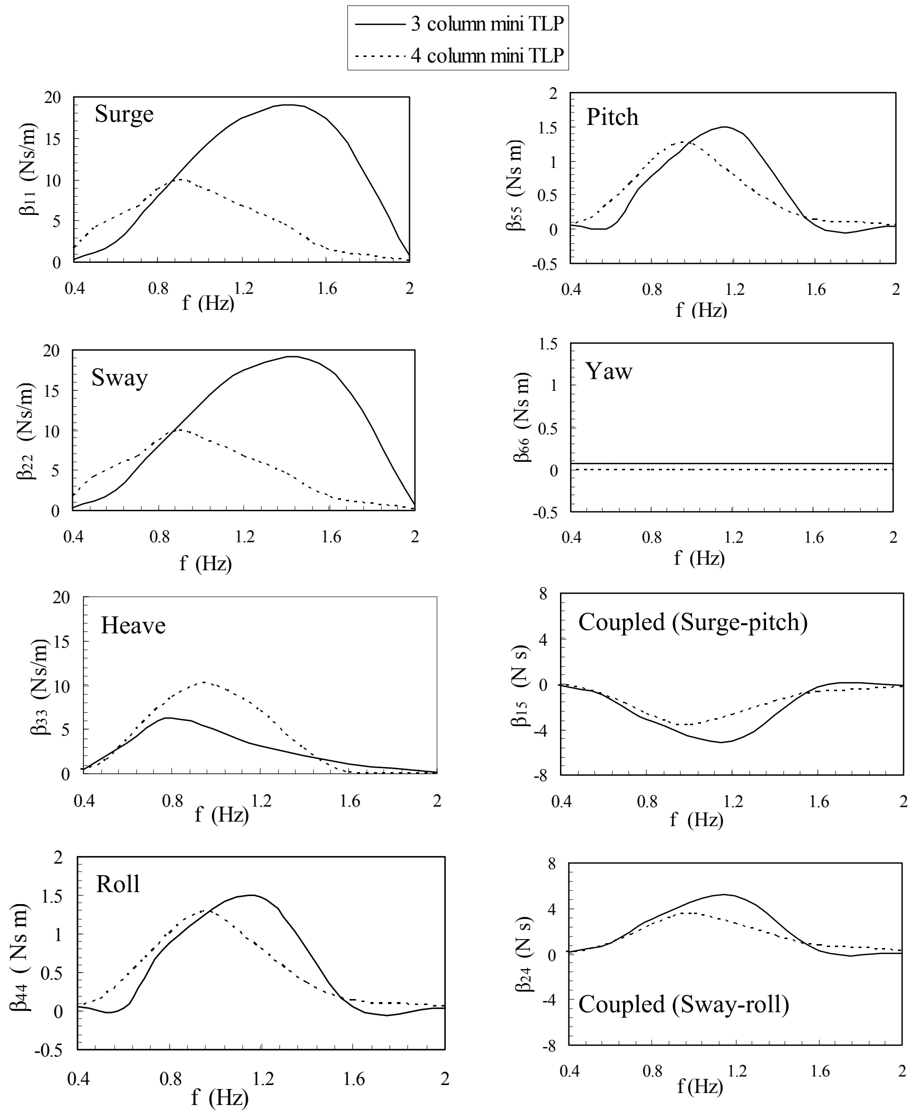


Fig. 4. Radiation damping coefficients of mini TLP models.

The results of the non-linear dynamic analysis are presented in Fig. 6 and Fig. 7 in the form of response amplitude operators (RAO). From Fig. 6 it is seen that the surge response, which is the only major motion response is more for the 3-column mini TLP i.e., a maximum of 20 % increase (for a wave period of 1.5 s, $T_t/\Delta = 0.17$). The heave response is small and is almost same for both the structures. The maximum value is less than 2 mm for wave amplitude of 1 m. The pitch response also is small but higher for 3-column model. The maximum value is less than 0.17^{o} against 0.11^{o} per unit wave amplitude for the 4-column mini TLP.

It is evident from Fig. 7 that the dynamic tether tension is higher for the 3-column model, the maximum being 94 N per unit wave amplitude (for a wave period of 1.5 s, $T_t/\Delta = 0.17$) against 60 N for the 4-column mini TLP.

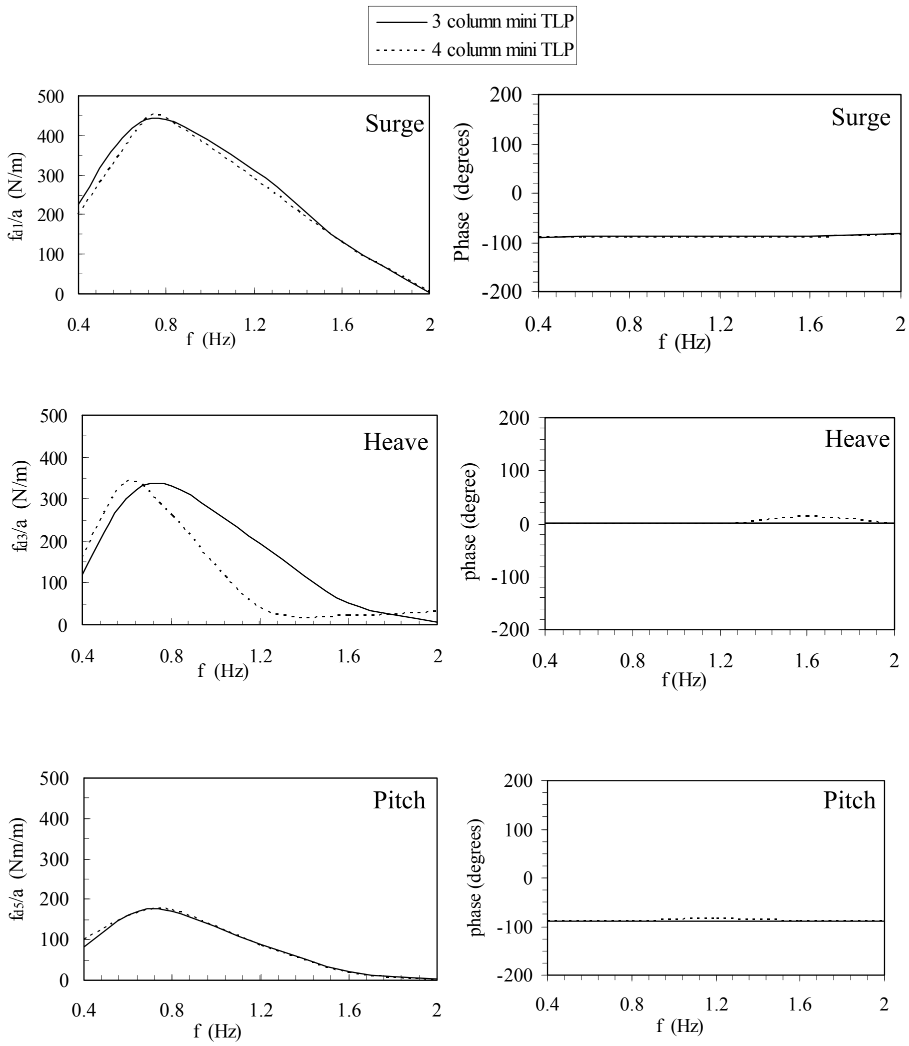


Fig. 5. Diffraction force components and their phases.

Parametric studies reveal almost similar observations for tether pretension values of $T_t/\Delta = 0.17$ and 0.26 which show that the chosen pretension levels which are in the practical range do not affect the dynamic response appreciably. For a change of wave approach angle from 0º to 60º, it is observed that there is considerable decrease in responses for surge and pitch while, the heave and tether responses shows little change. But the resultant horizontal displacement in the direction of the wave is the same as that for $\theta = 0º$.

5. Conclusion

The study thus shows that there is no drastic change in the dynamic response of the proposed 3-column mini TLP compared to the 4-column mini TLP. The increase in the case of surge and tether tensions is expected as the number of tethers is reduced to three from four, and can be taken into account while designing the structure. As its dynamic responses are found to be close, the 3-column structure can be considered as an alternative to the 4-column mini TLP. Reducing the number of columns from four to three has added advantages in terms of cost and time during fabrication, installation and maintenance of the platform.

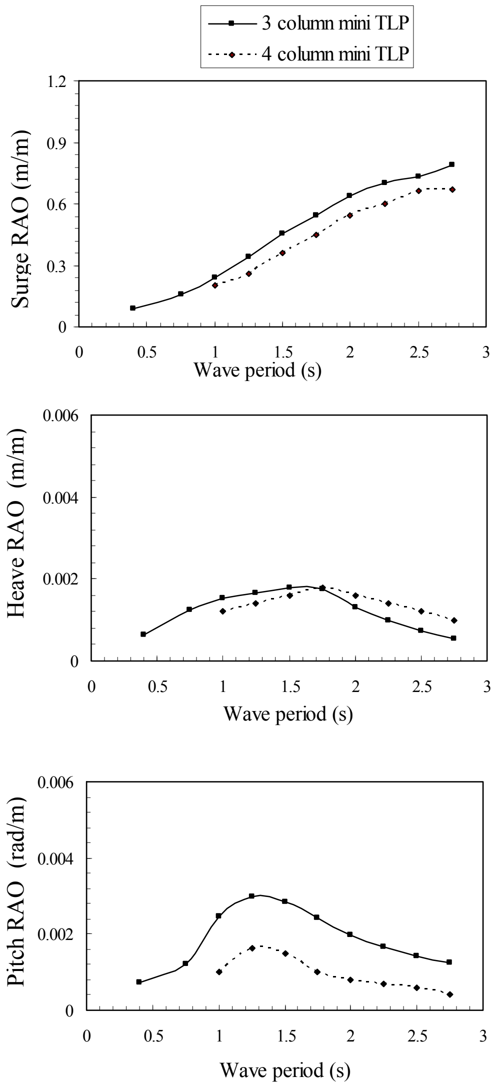


Fig. 6. Surge, heave and pitch responses.

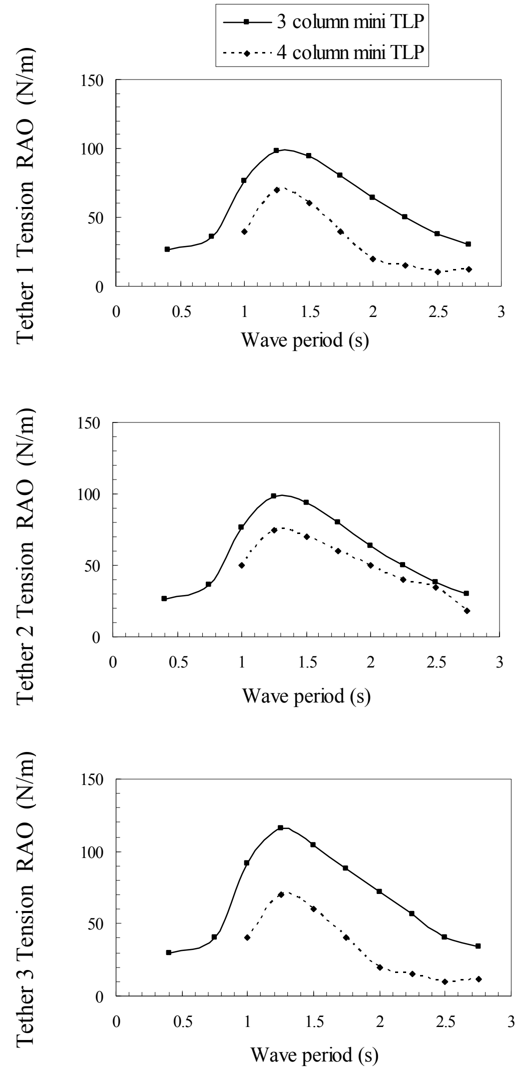


Fig. 7. Dynamic tether tension responses.

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