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Dynamic Response Analysis of Stiffened Triceratops under Regular Waves

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Abstract - *Offshore triceratops is fairly an emerging concept with respect to the structural form that has been tried for ultra-deep waters. It consists of a deck, buoyant leg structures (BLS), ball joints and the platform is position-restrained by tethers. Ball joints connects deck to the positively buoyant BLS units. Ball joint restrains the transfer of rotations between the deck and the BLS as well. Introduction of ball joints between the deck and buoyant leg structure (BLS) makes triceratops different from other offshore structures. In case of a stiffened triceratops, each buoyant leg unit is stiffened using a set of stiffeners joining the three columns and central moon-pool. Stiffeners are added to make the BLS units monolithic and in that way reducing the effect of the encountered wave loads. This study aims to find out the dynamic behavior of the stiffened triceratops under regular and random waves.*

***Key Words*: Triceratops, Buoyant Leg Structure, Central Moon Pool System, Stiffeners.**

1. INTRODUCTION

Since hydrocarbons have started depleting in shallow water, oil exploration is moving towards greater water depths. Offshore structure should be enabled to counteract the lateral force acting on it by its geometric arrangement. There arises the need for new generation offshore platforms to be developed which will be capable of balancing the load acting on it. One among the developing platforms is triceratops. A lot many researchers have studied the response behavior of several innovative structural forms. The concept of Buoyant Leg Structure(BLS) was introduced by Robert W. Copple et al. (1995). The studies have shown that it suits well in deep water and was cost effective. Charles N. White et al. (2005) introduced the concept of triceratops platform. It has evolved its form from BLS, TLP and SPAR as well.

Triceratops is a new generation platform proposed to serve deep water applications. Its main components are deck structure, buoyant leg structures (BLS), ball joints that connect buoyant legs with deck, tethers and a foundation system. Deck structure is equipped to serve topside facilities like providing space for crew quarters and for other production facilities. BLS is a positively buoyant system. The BLS unit resembles a SPAR due to its deep draft, while the restraining system makes it act more like a TLP. Deck is partly isolated from the buoyant legs by ball joints. Ball joints are special components that transfer displacements from BLS to deck structure and restricts the transfer of rotations. Comfortable working environment is guaranteed to the people on board by restraining transfer of rotation to the deck. Since the BLS are not interconnected to each other, each one of them have the freedom to move independently, this independent motion essentially in terms of rotation, will not be transferred to the hull because of the ball joint. Similarly, when the hull starts activating or rotating because of the aerodynamic force, the wind action is not transferred to the BLS. Ball joint makes the structure different from other platforms. Restraining system can be either a restraining leg or tether. If depth of water is less than 1500 m, restraining legs will be employed and if it is greater than 1500 m, tethers act as a restoring system. The restoring system will be under high pretension. Excess buoyancy ensures high initial pre-tension of tethers. Foundation system can be a suction pile, multiple driven piles or a gravity base structure.

Buoyant legs are designed as stiffened cylinders since they have to resist both axial stress and bending moment caused by lateral forces. Stiffeners are welded to the shell, this enhances their lateral resistance. In addition to ring stiffeners, longitudinal stiffeners called as stringer stiffeners are also provided at equal spacing, both externally and internally. The operational advantages of the structural configuration include its reduced deck response and good re-centering capability.

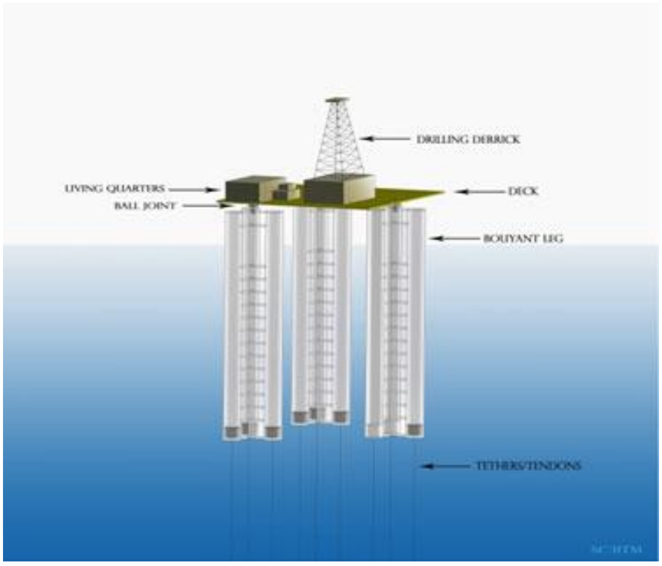

Fig 1: Conceptual view of a Stiffened Triceratops

Ball joint carries the entire weight of the deck and holds the equally spaced buoyant leg structures (BLS). Faults in this element as a result of corrosion, fatigue, fabrication errors, etc. can probably lead to the breakdown of this structure. Any defect on each of the ball joint will impose more load on other bearing ball joints on the structure that can eventually cause the entire structure to collapse.

1.2 Advantages

The structural form of offshore triceratops is less complex than that of TLPs and Spar. It only requires simpler station maintenance systems. The installation and decommissioning of the platform contribute to a significant reduction in spending, making it more affordable. The risers are positioned in a protected environment making them laterally supported. This contributes to additional safety.

Common types of offshore deep-water structures have rigid connections. This leads to the production of more stress on the members, when they are subjected to environmental loads. Triceratops reduces the severity of environmental loads encountered under its new structural form and design. The advantages of triceratops are as follows:

(i) Simplicity of the structure, simpler station keeping system and simpler restraining system

(ii) Easy to install and decommission;

(iii) Reusable and re-locatable;

(iv) Forces acting on the platform is reduced due to the reduction in the exposed fraction of the structure

(v) Risers are protected from lateral forces since they are situated inside the moon pool.

(vi)Reduced deck response offer better working environment to the workers

2. STIFFENED TRICERATOPS

A finite number of stiffeners are used to connect three columns of single BLS unit to the central moon-pool. This makes the structure a stiffened triceratops. These stiffeners make the BLS units monolithic and henceforth decrease the effect of the wave loads on the structure.

3. PRELIMINARY DESIGN

The triceratops is proposed at a water depth of 896 m at Mississippi Canyon, Gulf of Mexico. Configuration is chosen similar to an existing TLP at the same place. Geometric details and structural properties are given in the table 1 and 2. The triangular deck supports the same payload carried by the MARS TLP. Single BLS unit consist of three cylinders and a central moon pool. These three cylinders are connected to the moon pool with the help of stiffeners.

Table 1: Mass properties of triceratops

Description	Quantity
Payload	7200 ton
Ball joint	1013 ton
Leg weight	15633 ton
Ballast weight	15738 ton
Pretension	6248 ton
Total displacement	45832 ton

Table 2: Geometric properties of triceratops

Description	Quantity
Water depth	896 m
Density of steel	7850 kg/m³
Density of sea water	1025 kg/m³
Total length of leg	155 m
Draft	125 m
Freeboard	30 m
c/c distance b/w legs	70 m
Outer diameter of cylinder	9.5 m
Thickness of cylinder	40 mm
Outer diameter of moonpool	5 m
Thickness of moonpool	25 mm
Vertical COG of BLS	44.74 m
Metacentric height	16.668 m
Length of tether	771 m
Stiffness of tether	203 MN/m

4. NUMERICAL MODELING AND ANALYSIS UNDER REGULAR WAVES

The numerical analysis was carried out using the finite element software ANSYS AQWA. Deck is modelled and its weight and payload is assigned at the mass center of deck. BLS units are modelled as line elements in ANSYS AQWA, as they qualify for the Morison region ($\pi D/\ell < 0.5$). Mass center of each group of legs is assigned with buoyant leg mass and ballast loads. TUBE elements are used to model the buoyant legs. BLS unit is connected to the deck by means of ball joints. Ball joints are modelled to transfer all translations and no rotation to the deck. Tether which extends from keel of each buoyant leg to the seafloor is modelled as cable elements with suitable axial stiffness and the initial tension is imparted to the cable by stretching it.

Equation of motion for free oscillation studies is as follows:

$$[M + Ma]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{0\} \qquad \text{[Ref 3]}$$

where [M] is the mass matrix, [Ma] added mass matrix, [C] damping matrix, [K] stiffness matrix of the platform, $\{X, \dot{X}, \ddot{X}\}$ displacement, velocity and acceleration of the structure.

Mass matrix is given by,

$$[M] = \begin{bmatrix} M_{11}+M_{a11} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & M_{22} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & M_{33}+M_{a33} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 & 0 & 0 & 0 \\ M_{a51} & 0 & M_{a53} & 0 & M_{55} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & M_{77} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & M_{88} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & M_{99} \end{bmatrix}$$

Stiffness matrix is given by,

$$[K]=\begin{bmatrix} k_{11} & 0 & 0 & 0 & k_{15} & 0 & 0 & k_{18} & 0 \\ 0 & k_{22} & 0 & k_{24} & 0 & 0 & k_{27} & 0 & 0 \\ k_{31} & k_{32} & k_{33} & k_{34} & k_{35} & k_{36} & k_{37} & k_{38} & k_{39} \\ 0 & k_{42} & 0 & k_{44} & 0 & 0 & k_{47} & 0 & 0 \\ k_{51} & 0 & 0 & 0 & k_{55} & 0 & 0 & k_{58} & 0 \\ 0 & 0 & 0 & 0 & 0 & k_{66} & 0 & 0 & k_{69} \\ 0 & k_{72} & 0 & k_{74} & 0 & 0 & k_{77} & 0 & 0 \\ k_{81} & 0 & 0 & 0 & k_{85} & 0 & 0 & k_{88} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & k_{99} \end{bmatrix}$$

The coefficients, *kij*, of the stiffness matrix of the triceratops are derived as the reaction in the degree of freedom *i* due to unit displacement in the degree of freedom *j*, keeping all other degrees of freedom restrained.

Numerical analysis is performed on the model of triceratops by solving equation of motion under lateral loads as given below:

$$[M + Ma]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{f(t)\}$$

where {f(t)} is the force vector

To estimate the wave force exerted by waves added mass and drag coefficient of 1.05 and .75 are assigned respectively. The wave force is calculated using Morison equation:

$$df = 0.5\rho_w DC_d(\dot{u}_f - \dot{x}_s)|\dot{u}_f - \dot{x}_s| + \rho_w AC_m\ddot{u}_f - \rho_w A(C_m - 1)\ddot{x}_s$$

where C_d is the drag coefficient, C_m is the inertia coefficient, D is the characteristic drag diameter, $\dot{u}_f$ is the fluid velocity in the transverse direction, $\dot{x}_s, \ddot{x}_s$ are the structural velocity and acceleration respectively in the transverse direction of BLS, A is the cross-sectional area, ρ_w is the mass density of the fluid and $(\dot{u}_f - \dot{x}_s)$is the instantaneous relative velocity in the considered direction.
Regular waves are simulated in ANSYS AQWA software. Time history analyses are performed under unidirectional regular waves for different wave heights and for different wave heading angles (0, 120 and 180°) by solving the equation of motion at each time using the numerical integration scheme. Nonlinear analysis is carried out in time domain under regular waves. Airy's wave theory is used for evaluating the water particle kinematics for the assessment of hydrodynamic forces on buoyant legs.

5. RESULTS AND DISCUSSIONS

The triceratops has been analyzed for three different wave heights (8 m, 12m,15m) to find out the variation of response with wave height. Fig 2 shows the wave heading towards the triceratops when the wave heading angle is 0°. Triceratops has also been analyzed for regular wave loading by varying the wave heading angles (0°, 120° and 180°). In the case of regular waves, the amplitude of structural response is generally normalized with reference to the amplitude of wave. For linear systems these normalized responses are invariant to the wave amplitude at a frequency and these are referred to the response amplitude operator (RAO). Response Amplitude Operator (RAO) is plotted for the comparison of response in various degrees of freedom. For a wave height of 8 m, the wave period chosen is 7 s to 17 s. Time history response for a time period of 14 s is shown in fig 3, 4 and 5

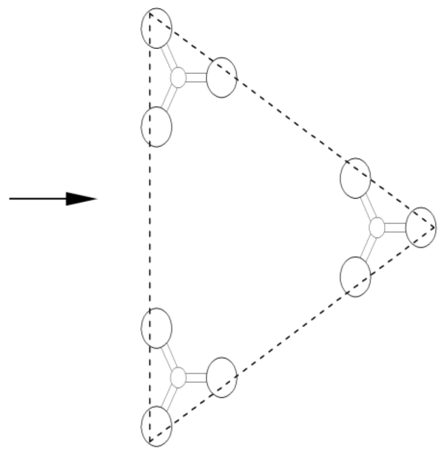

Fig 2: Direction of wave.

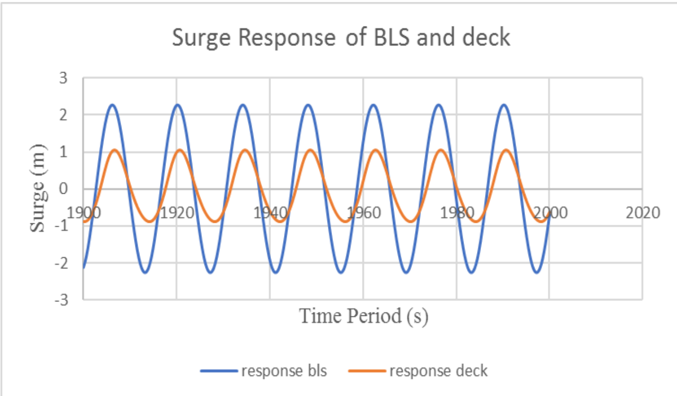

Fig 3: Surge Response of BLS and deck

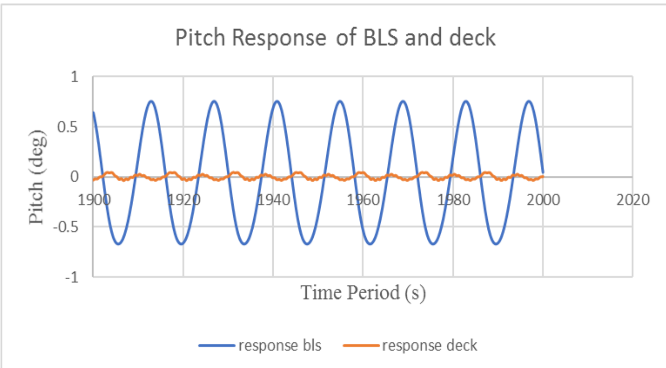

Fig 4: Pitch Response of BLS and deck

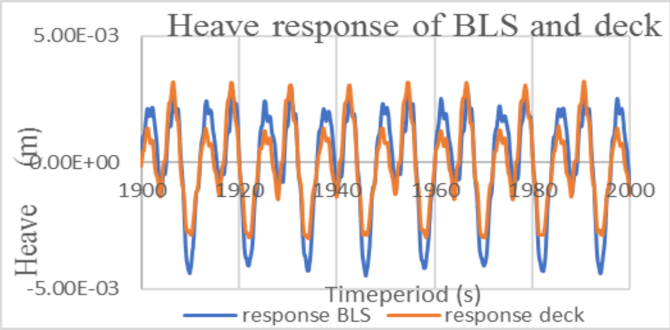

Fig 5: Heave Response of BLS and deck

Time history response show that the deck response in all active degrees of freedom is reduced with respect to the BLS. In case of pitch the motion of deck is almost negligible.

RAO of deck and that of a single bls is plotted in surge, heave and pitch degrees of freedom for different wave height.

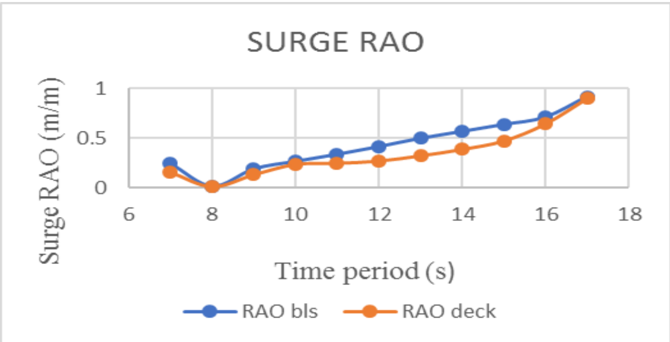

Fig 6: Surge RAO for 8 m wave

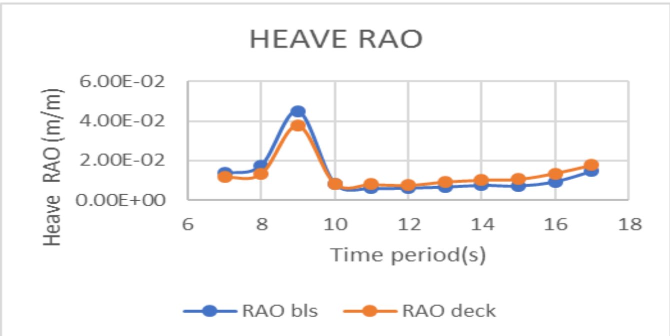

Fig 7: Heave RAO for 8 m wave

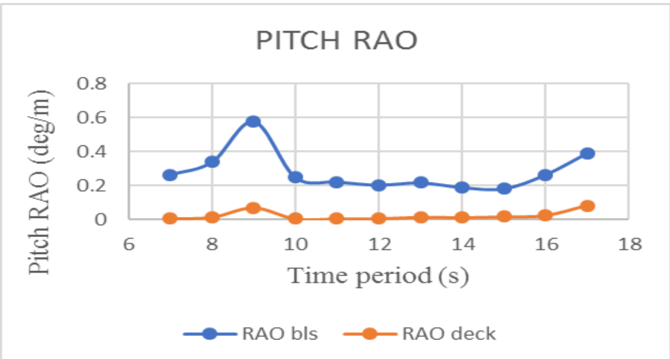

Fig 8: Pitch RAO for 8m wave

From fig 6, RAO in surge degree shows that the deck response is slightly less than the bls response. Fig 7 shows the heave RAO of the bls unit and the deck. The deck response seems to be slightly more than the bls response after 10 s. The rotations of the deck can also induce heave forces (contribution of k_{36}, k_{37} and k_{38}) Pitch RAO of the deck and bls is shown in fig 8. From the RAO it is clear that the deck response is much lesser than the bls response. This is mainly due to the presence of ball joint. This makes it clear that the ball joint is effective in restraining rotations to the deck.

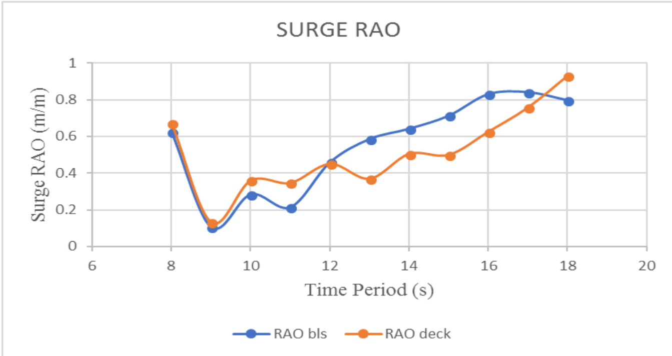

Fig 9: Surge RAO for 12 m wave

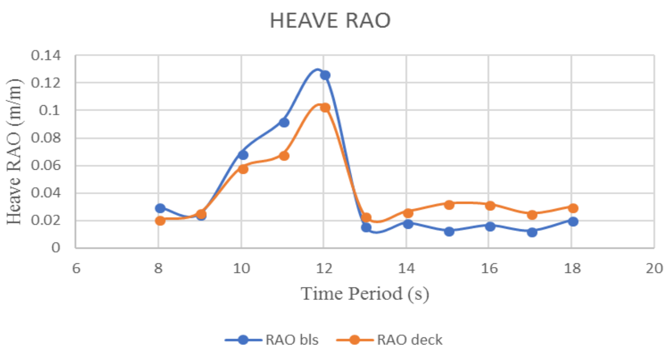

Fig 10: Heave RAO for 12 m wave

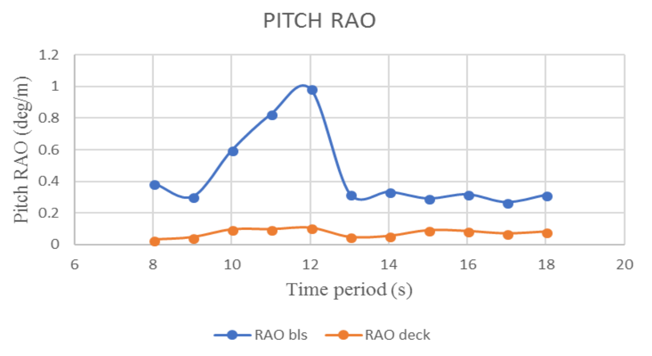

Fig 11: Pitch RAO for 12 m wave

RAO for 12 m wave height is shown in fig 9, 10 and 11. The pattern followed is almost same. But the response has increased.

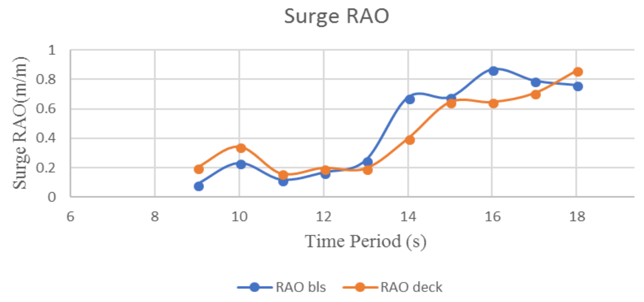

Fig 12: Surge RAO for 15 m wave

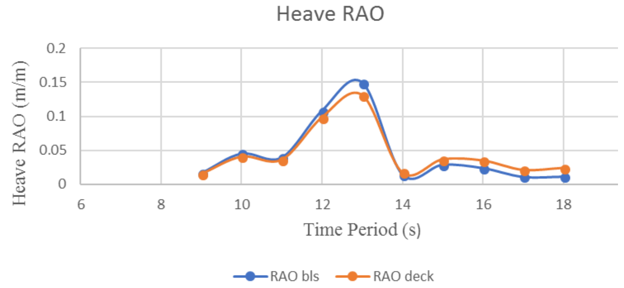

Fig 13: Heave RAO for 15 m wave

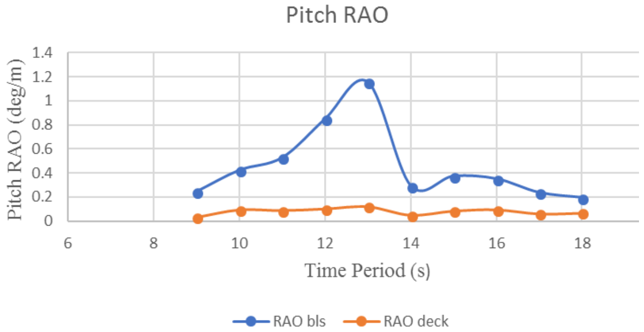

Fig 14: Pitch RAO for 15 m wave

RAOs in fig 12, 13 and 14 shows the response at 15 m wave height for time period varying from 9 to 18 s.

By comparing the response of triceratops with varying wave height, it is seen that the response of deck and BLS increases with increase in wave height.

The response of the fore bls is found out for various wave heading angle (0°, 120° and 180°) and plotted as RAOs.

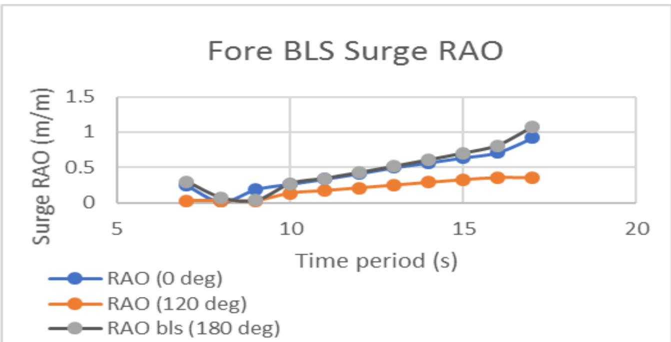

Fig 15: Surge RAO of fore BLS under various wave heading angle

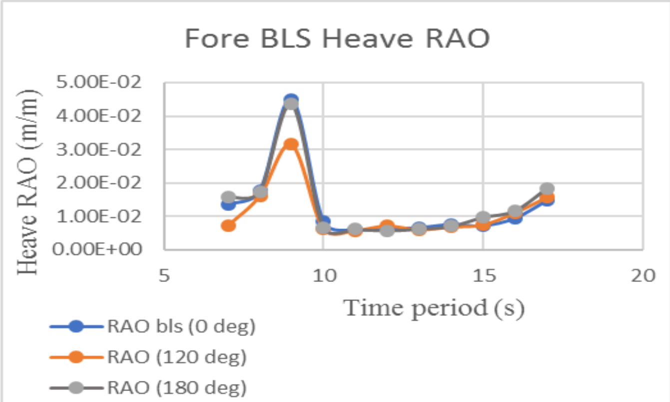

Fig 16: Heave RAO of fore BLS under various wave heading angle

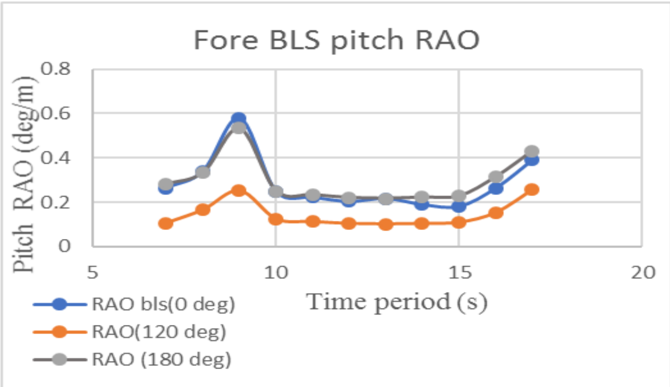

Fig 17: Pitch RAO of fore BLS under various wave heading angle

Fig 15, 16 and 17 shows the surge, heave and pitch RAOs respectively of fore BLS under 0°, 120° and 180° wave heading angle. From the RAO it is observed that the response for 0° and 180° wave heading angle remains almost the same but the response for 120° heading angle is reduced. This may be because of the reduction in wave forces at the point of application. This reduction in wave force can be accounted due to the angle of inclination of wave force .

4. SUMMARY AND CONCLUSIONS

Structures in deep and ultra-deep water will be subjected to loads of higher intensities and they should be designed to withstand the loads acting on it. Offshore triceratops is an emerging platform which has been proved suitable for deep waters. A triceratops has been designed for a water depth of 896 m. the selected site is located at Mississippi Canyon, Gulf of Mexico. Numerical studies have been conducted on triceratops under unidirectional regular waves. The structure is stiff in heave degrees of freedom. Thus makes it more adaptable to deep waters. Studies done by varying the wave heights have shown that the response of deck and BLS increases with increase in wave height. Studies have also been done by varying the wave heading angles (0°, 120° and 180°).RAOs are plotted for comparing the results. Responses obtained for 120° wave heading angle in surge, heave and pitch degrees of freedom is lesser than 0° and 180° and this is because of the reduction in wave forces. The rotational response of the deck is almost negligible when compared to the bls response. This is mainly because of the presence of ball joint. The deck remains almost horizontal. Reduction in deck response contributes to a safe and comfortable working environment to the workers on board. The study shows that triceratops offers numerous operational benefits and better motion characteristics when put next to alternative offshore platforms.

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