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Design and fabrication of a Model Jack-Up Rig

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ABSTRACT

The offshore industry has seen the introduction of a new breed of jack-up designs, capable of operating in deep water and harsh environments. In this research, a new design concept of jack-up was introduced. The concept comprises of a chain driven jacking mechanism connected to sprocket gears in the barge and three columnar legs made of galvanized steel equipped with a chain-welded rack and protective collar guides with rollers that support and strengthen the legs. The research is aimed at designing and fabrication of a model mini jack-up rig powered by a battery. The overturning stability of the design was calculated to ascertain its stability. The benefits of the new design concept and its potential application are also outlined.

Keywords: Jack-up, offshore environment, design, model, oil and gas

1. INTRODUCTION

The exploration and development of hydrocarbon is one of the major trends in today's oil and gas industry. Jack-ups were originally designed for use in the relatively shallow waters of parts of the Gulf of Mexico. Jack ups are important in the offshore industry and there has been demand for their use in offshore environments. There is rapid increase in demand for oil and gas. Due to this, many oil and gas industries continue to explore the huge resources deposit at the sea [1]. Jack-up rigs originated from drilling offshore in the Mississippi area in the early 1950s and the first one was designed by R. G. LeTourneau for Zapata Drilling [2]. The ever growing global demand for oil and gas requires more and more wells to be drilled offshore. The majority of these wells are drilled by a fleet of Mobile Offshore Drilling Units (MODUs), consisting of Jack-ups, Semi-Submersibles, Drill ships and Drill Barges. Jack-up rigs are the most common type of drilling rig within the MODU fleet. Jack-up is a marine and offshore structure that has a hull and legs. The hull facilitates their floating and the legs are used to stand on the seabed. They are towed to location where jacking mechanisms drive the legs into the soil and raise the hull above the water surface. The cost benefit of employing jack-ups has led to the introduction of ultra-premium jack-ups which are capable of handling water depths up to 120 meters and beyond in harsh environmental conditions [2]. Jack-ups are popular because they have relatively low building costs and are mobile. The number of jack up rigs used globally has increased significantly. To be confident of their use in these offshore environments, there has been a need for changes in the design and construction analysis of jack-ups to make them more useful, reliable and robust while operating. Before jack-ups are moved to a location, it is assessed to ensure the structure is capable of withstanding the combination of water depth, harsh environment and soil conditions that characterize the specific location. There are also regulatory and operator requirements that the unit has to satisfy prior to operation.

This research is focused on a new design concept of an efficient jack-up which can be able to drill in deep waters of more than 120 meters and harsh environment. It is worthy to note that the development of new concepts is a long-term process that involves a number of specialists in design and construction. Therefore, the scope of this research is limited to some specific issues of the new jack-up design that are relevant for operations in deep waters and harsh environments.

The study reveals the feasibility of the new concept, describe and analyze the main features of the model rig design such as the shape of the legs and the hull, protective collar geometry, drilling through the jack-up leg etc., estimate its applicability in deep waters and harsh environments.

Description of Jack-up Rig Design

The designs of jack-ups vary from mono tower structures (single leg designs) to multiple leg designs. Conventional jack-up design is known to have three legs, each leg normally being constructed of a triangular or square framework [3]. The three leg design gives room for weight reduction of the structure. This design has a big disadvantage such as no jack-up leg redundancy. If drilling is to be performed through one of the legs, the jack-up will lose stability and capsize in case of foundation problems or blowout. Jack-up leg structures are of two types such as open-truss or columnar legs and trussed legs. Open-truss legs are made of tubular steel sections that are crisscrossed, strong and lightweight. Columnar legs are made of huge steel tubes. Fabrication of columnar legs is less expensive than open-truss legs. They usually have stability problems. It cannot be employed in water depth of more than 250 feet deep. In addition to their legs, jack-ups are supported by two different systems of stabilization. Jack-up legs are supported on the sea floor via either mats or spud cans [4]. These support footings provides vertical support and moment restraint at the base of the legs. A fixed rack and pinion jacking system is utilized in the jacking mechanism design. Jacking units are designed to be utilized according to the rack and pinion principle [5-7]. It is responsible for lifting and lowering of the legs of jack-up platforms. Rack and pinion systems are the preferred solution for units with truss legs. Jack-ups are taken to location via self-propelling or towed means.

During installation, the hull structure of the jack-up is elevated to a predetermined height above the water level and the spud is penetrated through the soil until it has sufficient bearing capacity to carry the load. The ballast tanks are emptied and the hull is jacked/elevated to a predetermined operational height. The jack-up will remain there until the operation activities is completed, before it is jacked down and taken to another location [8-10]. Jack-ups have relatively high failure rates when compared to fixed platforms [11]. [11] Analyzed accident data for both platform types over an interval of 20 years.

2. MATERIALS AND METHODS

The new design concept in this research represents a self-propelled jack-up that is battery powered. Major components of the Jack-up system are mild carbon steel plate, galvanized steel, chain rack and pinion, chains, DC electric motor, wires, sensors and stopper switches and battery. In this development of jack up system, the equipment and instruments used for fabrication of jack up are arc welding machine, centre punch, measuring tape, electrodes, chalk, drilling machine, cutting machine, filing machine and hammer.

The Hull of the Jack Up Rig

The jack-up deck house has a rectangular geometry that can break an ice. The front and back of the keel of the hull have a crushing surface inclined at an angle with ice-breaking capabilities. The jacking legs and jacking system are placed inside the jack-up hull. Design of the hull of the jack up is illustrated in Figure 1.

Figure 1 Design of the hull of the jack up

Legs Design of the Jack Up

The jack-up has three legs with spud cans and a support-protective leg collar guide placed inside the hull [12-15]. Tubular or cylindrical leg design was used instead of open-truss design because such structure will allow jack-up legs to withstand some external loads [16]. The duplex chain leg design of the model jack up is shown in Figure 2.

Figure 2 Duplex Chain Leg Design

The Collar Guides of the Jack up legs

To protect the jack-up legs from drift, support-protective collar guides with rollers are used. They are placed and fastened to the hull at the spots where the legs will be placed. The guides add to strengthening of the legs and its jack-up stability.

The Jacking System

A chain welded fixed rack and pinion jacking system is used. The pinion is connected to a shaft and a bearing bracket fastened to the hull. This jacking system concept involves the application of the principle of chain and gear drive connected to a motor and a battery. Figure 3 & 4 is use to show a Jacking System.

Figure 3 Jacking System

Design Theory and Calculation

Design Data

a) Reactions due to self-weight and onboard variable loads, at the jacking system level are:

Aft legs: 2500 N each

Bow leg: 2200 N

Apparent weight of legs: 380 N each

Number of legs = 3

Natural period = 3.5s

Cross sectional area of each leg: 0.088 m^2

Inertia of each leg: 0.11786 m^4

Equivalent Young Modulus of legs: 160 X 10^{-6}GPa,

Distance of spud cans from lower level of hull: 1.52m

Distance from bow leg to axis of aft legs: 0.553m,

b). The wave period in extreme conditions considered is T = 7s

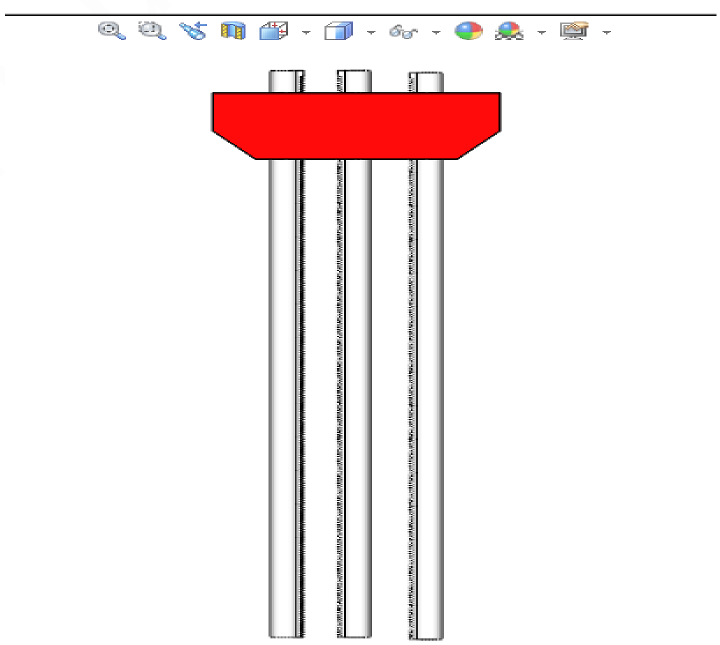

Figure 4 Model of Jack up Leg

Calculation of Restoring Moment

a) Assuming a rigid structure, the restoring moment is the product of the reaction under the least loaded leg (bow) multiplied by the distance from this leg to the axis of the two other legs:

$$M_{so} = (2200 + 380) \text{ x } 0.553 = 1426.74 \text{ Nm}$$

b) Average load per leg is:

At top: $\frac{2500 + 2500 + 2200}{3} = 2400 \text{ N}$

At Bottom: 2400 + 380 = 2780 N

The average load (P) considered is 2590 N

c) The critical Euler load is obtained by the following calculations. All formulas are obtained from referenced materials.

Radius of gyration of the leg:

$$\rho = \sqrt{\frac{I}{s}} = \sqrt{\frac{0.11786}{0.088}} = 1.1573\, m$$

Slenderness of the leg:

$$\lambda = \frac{2\, x\, l}{\rho} = \frac{2\, x\, 1.52}{1.1573} = 2.6268$$

Euler's critical stress:

$$\sigma_{\epsilon} = \frac{\pi^2\, E}{\lambda^2} = \frac{\pi^2 \times 160{,}000}{2.6268^2} = 228857.8\, Pa$$

Hence, P_E = 0.088 x 228857.8 = 20140 N.

d) The reduction of the restoring moment due excursion (0.0018 m, displacement at top platform) of the platform (P.Δ effect) and to the buckling risks of the legs is given by the equation:

$$\frac{nP\,(e_0 + e)}{1 - \frac{P}{P_E}} = \frac{3\, x\, 2590\, x\, 0.0018}{1 - \frac{2590}{20140}} = 16.050\, Nm$$

e) Taking account of the excursion of the platform and the buckling of the legs, the final restoring moment is:

Ms = 1426.74 – 16.050 = 1410.69 Nm

The Calculation of Overturning Moment

a) The dynamic amplification factor is:

$$\boldsymbol{k} = \frac{\mathbf{1}}{\mathbf{1} - \left(\frac{T_o}{T}\right)^2} = \frac{\mathbf{1}}{\mathbf{1} - \left(\frac{3.5}{7}\right)^2} = 1.333$$

If overturning moment due to wind is 250 Nm, and the overturning moment due to wave and current varies from -100 Nm to +700 Nm (deep water > 50m).Then,

b) Average Moment due to wave and current is:

(700 – 100) / 2 = 300 Nm

c) Amplitude of the Moment due to wave and current is:

(700 + 100) / 2 = 400 Nm

d) The total overturning moment is therefore:

Moment due to wind is 250 Nm and the Moment due to wave and current is 300 Nm

Dynamic amplitude moment due to wave
and current is: 400 x 1.333 = 533.2 Nm

This result shows that the restoring moment of the jack-up which is calculated to be 1410.69 Nm is higher than the moment which will try to overturn the jack-up structure in deep waters which is 533.2 Nm. Therefore, the structure is stable to withstand external loads in harsh environments.

Response Calculation of Jack-Up

To find the forces acting on the platform, the given parameters of the Jack up below can be utilized.

Diameter of leg, d = 0.007m

Thickness of leg, t = 0.0025m
Sea depth, D = 0.6m
Normal wave height, H = 0.3m
Wave Period, T = 8sec

Wave number, K = 0.01
Slamming wave height, $Ɛ_b$= 0.5m
Slamming coefficient, C_s = 1.3
Inertial coefficient, C_m = 1.5
Drag coefficient, C_d = 1.1
Roughness factor, C_A = 3
Mean wind speed, U = 3 m/s

ρ_w = 1025 kg/m^3
ρ_a = 1.22 kg/m^3
Assuming coiling factor, ƛ = 0.4
Yield strength of legs material (pipe) = 210 MPa
Area of topside = 0.6m^2
The total force acting on the structure is:
F_{Total} = $F_D + F_I + F_s + F_w$
Fs = C_s ½ ρ C_b^2 D (ƛ Ɛb)
C_b = L/T
L = 2π/K = 2 x 3.142/ 0.01 = 628.4
C_b = 628.4/8 = 78.55
F_s = 1.3 x 0.5 x 1025 x 78.55^2 x 0.6 x 0.4 x 0.5 = 493 kN (one leg)
For all 3 legs = F_sx 3 = 493 x 3 = 1479 kN
F_w= F_{avg}+ F_5
F_{avg}= ½ ρ C_A A U^2 (Platform)
= 0.5 x 1.22 x 3 x 0.6 x 3^2
= 9.9 x 10^{-3} kN
F_5 = ½ ρ C_A A U^2 (Platform legs)
Since A is not given, A = π d L/2
A = (3.142 x 0.007) x ½ = 0.011m^2
Area for all 3 legs = 0.011 x 3 = 0.033m^2
F_5 = 0.5 x 1.22 x 3 x 0.033 x 3^2
= 5.44 x 10^{-4}kN
For the 3 legs, F_5 = 5.44 x 10^{-4} x 3
F_5 = 1.63 x 10^{-3} kN
F_D = ½ ρ C_D D U^2
To get U, check if it is deep or shallow water
If D/L < 0.5 (shallow water)
D/L > 0.5 (deep water)
D/L = 0.6/628.4 = 0.001

Therefore, since D/L is less than 0.5, we shall use the shallow water equation to demonstrate its response:

U = $Ɛ_0$ g K/ω
$Ɛ_0$ = H/2 = 0.3/2 = 0.15
ω = 2π/T = 2 x 3.142/8 = 0.786
U = 0.15 x 9.81 x 0.01/0.786 = 0.0187 m/s
F_D = 0.5 x 1025 x 1.1 x 0.007 x 0.0187^2
= 0.0014 N/length
To convert to newton, multiply by H

F_D = 0.0014 x 0.3 = 0.00042 N
F_D = 4.2 x 10^{-7} kN
For the 3 legs, F_D = 4.2 x10^{-7} x 3
= 1.26 x 10^{-6} kN
$F_I = \rho_w C_M (\frac{\pi D^2}{4}) U_x$
$U_x = \mathcal{E}_0$ g K
= 0.15 x 9.81 x 0.01
= 0.0147 m/s
F_I = 1025 x 1.5 x $\frac{\pi \text{ x } 0.007^2}{4}$ x 0.0147
= 8.7 x 10^{-7} kN
For the 3 legs, F_I = 8.7 x 10^{-7} x 3
= 2.61 x 10^{-6} kN
$F_w = F_{avg} + F_5$
= 9.9 x 10^{-3} + 1.63 x 10^{-3}
= 0.01153 kN
$F_{Total} = F_D + F_I + F_S + F_w$
= 1.26 x 10^{-6} + 2.61 x10^{-6} + 1479 + 0.01153 = 1479.011 kN

Shear Force
ΣX = 0
ΣY = S F = 0.0184 + 1479 + 5.4 x 10^{-4} + 9.9 x 10^{-3}
S F = 1479.03 kN
At point 1
S F = 1479.03 kN
At point 2
S F = 1479.03 – 0.0184 = 1479.01 kN
At point 3
S F = 1479.03 – 0.0184 + 1479 = 0.028 kN
At point 4
S F = 1479.03 – 0.0184 + 1479 + 5.4 x 10^{-4} = 0.011 kN
At point 5
S F = 1479.03 – 0.0184 + 1479 + 5.4 x 10^{-4} + 9.9 x 10^{-3}
= 0 kN

Bending Moment
Σfx = 0
Σfy = 0
At point 1 = 0
At point 2
B M = 1479.03 x 0.65 = 961.37 kNm
At point 3
B M = (1479.03 x 1.15) – (0.0184 x 0.5)
= 1700.875 kNm
At point 4
B M = (1479.03 x 1.65) – (0.0184 x 1) – (1479 x 0.5)
= 1700.881 kNm
At point 5
B M = (1479.03 x 1.65) – (0.0184 x 1.35) – (1479 x 0.85) – (5.4 x 10^{-4} x 0.3)
= 1700.885 kNm
$Ƶ = \frac{m}{\sigma}$

$\sigma = \frac{m}{Z}$

m = 1700.885 kN

$Z = \left(\frac{\pi D_o^4 - \pi D_i^4}{32 D_i}\right)$

D_o = 0.007m

$D_i = D_o - 2t$

= 0.007 -2 x 0.002

= 0.003m

$Z = \left(\frac{(3.142 \text{ x } 0.007^4) - (3.142 \text{ x } 0.003^4)}{32 \text{ x } 0.003}\right)$

$Z = 7.592 \text{ x } 10^5$ m

$\sigma = \frac{m}{Z}$

$= \frac{1700.885}{7.592 \text{ x } 10^{-5}}$

$= 22.4 \text{ x } 10^3$ MPa

Since the yield strength is 210 MPa and bending stress is 22.4 x 10^3MPa, the condition that bending stress is greater than the yield strength, the design will not fail is met.

The Design Power of the Jack up

Design power = Rated power x Service factor (Ks)

Service factor (Ks) is the product of various factors K_1, K_2 and K_3. The values of these factors are taken as follows:

The load factor (K_1) for variable load with heavy shock = 1.5

The lubrication factor (K_2) for drop lubrication = 1

The rating factor (K_3) for 16 hours per day = 1.25

∴ Service factor, Ks = K_1 x K_2 x K_3 = 1.5 × 1 × 1.25 = 1.875

Design Power = 18 x 1.875 = 33.750 kW

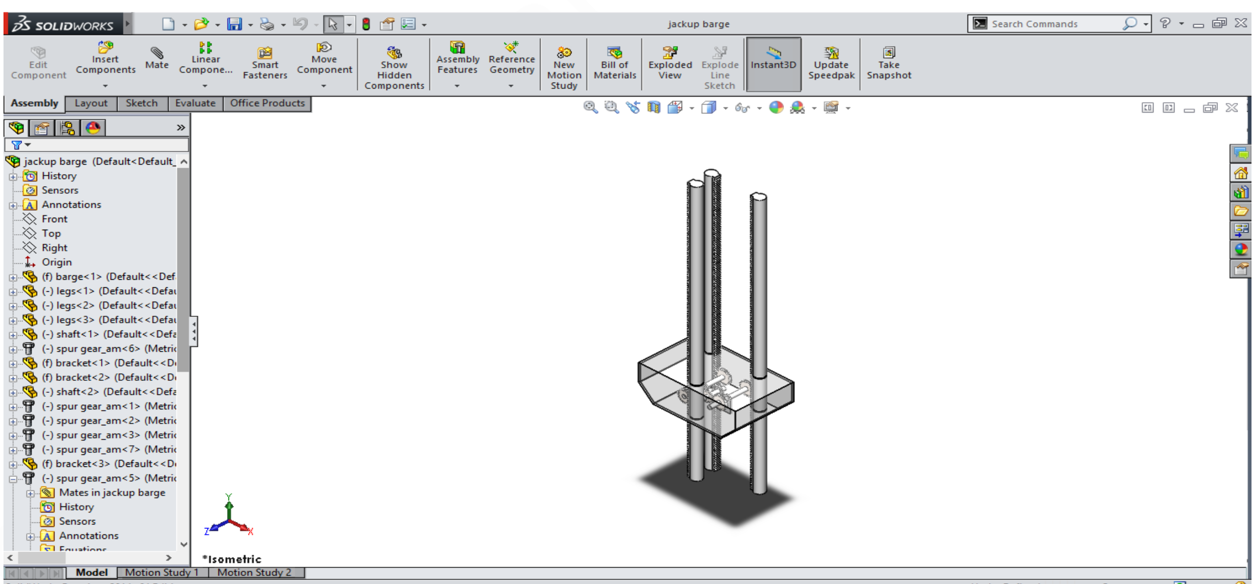

Figure 5 Isometric View of Jack-Up

Engineering Properties of the Model Mini Jack-Up

The model mini jack-up was designed to have the components such as hull, chain and sprocket, jacking system, columnar legs, collar guides, bearings, chain rack and motor. The criteria for selection of materials for the various components of the plant was based on the type of forces, pressures, and stresses that the system will be subjected to, the functions they are expected to perform, the environmental condition in which they will function, their relevant physical and mechanical properties, the cost, the strength of the materials and their availability in the local market. During the design process, standard principles that are well expounded in a number of machine design texts were employed. The legs of the jack-up structure are made of galvanized steel, while most of the basic components of the model mini jack-up are made of mild steel due to the reasons such as ductility, strength, heat resistivity, high carrying capacity and availability in the local market. The aforementioned design components of jack-up highlighted above are assembled as presented in Figure 5 while the fabricated view is presented in Figure 6.

Figure 6 Fabricated Jack-Up Structure

3. RESULTS AND DISCUSSIONS

Design analysis and calculations were carried out to assess the stability of the jack-up structure. The apparent weights of the legs are 380 N each, while the average load on the legs of the structure is 2590 N. The distance from bow leg to the axis of aft legs is 0.553 m. The natural period and the wave period considered are 3.5 seconds and 7 seconds respectively. The restoring moment of the jack-up unit was calculated to be 1410.69 Nm while the overturning moment due to environmental loads acting on the structure is 533.2 Nm. The result shows that the jack-up have a restoring moment greater than the overturning moment due to extreme environmental loads.

The model mini jack-up rig was tested and evaluated. The performance evaluation of the system was analyzed using both physical testing and solid works simulation to outline where the system would undergo strains and stresses. The jack-up was loaded with 25kg of weighting rod on the deck of the hull of design structure. The time taken for the system to jack-up was 1hr. From the calculation, the shear force and the bending moment due to external loads acting on the structure were calculated after solving for the drag force = 1.26×10^{-6} kN, slamming force = 1479 kN, inertia force = 2.61×10^{-6} kN, wind force = 0.01153 kN and the total force acting on the system = 1479.011 kN. Also, the condition that the bending stress is greater than the yield stress (22.4×10^{3}MPa> 210 MPa) was satisfied so the design will not fail.

4. CONCLUSION

A model mini jack-up rig was successfully designed and fabricated that can withstand extreme environmental conditions in the offshore deep waters. In the research, a new concept of a jack-up rig for exploration was introduced. The new jack-up design comprises of a strengthened barge shaped hull with icebreaking capabilities, a chain driven jacking system connected to a DC motor and three tubular legs placed inside the hull with protective collar guides. The potential slamming wave loads on the jack-up legs during operations was calculated to be 1479 kN. The restoring moment of the jack-up structure was found to be far higher than the overturning moment which tends to collapse the offshore structure.

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