Research on Optimal Design of Dual Derrick for the 7th Generation Ultra-Deepwater Offshore Platform

Faguang Jiang1, 2, *, Min Zhang1, 2, Xiuju Yang3, Zheng Liang1, 2 and Anyi Wang3

1School of Mechatronic Engineering, Southwest Petroleum University, Chengdu, 610500, China
2Key Laboratory of Oil & Gas Equipment, Ministry of Education, Chengdu, 610500, China
3CNPC Baoji Oilfield Machinery Co, Ltd, Baoji, Shanxi, 721002, China

*Corresponding author e-mail: jiangfg@swpu.edu.cn

Abstract. To solve the problem of small safety factor and heavy structure of dual derrick of the 7th generation ultra-deepwater offshore platform, the optimal design of the dual derrick is studied. Using ANSYS software, the mechanical property of dual derrick under the storm self-storage condition is analyzed. Taking the mass and safety factor of the dual derrick as the target and the beam section parameters as the design variable, after the single factor optimization, the response surface method is used to establish the comprehensive optimization mathematical model of the section parameters. The optimal combination of the section parameters is obtained. The results show that the safety factor of the original design of the dual derrick in the storm self-storage condition is less than 1.67 as required by API Spec 4F, and the bottom leg of the derrick is the most dangerous. Compared with the original scheme, the final optimization scheme of dual derrick reduces the mass by 19.11% and increases the safety factor by 23.81%, which meets the requirements of operating conditions.

1. Introduction

With the deepening of the exploration fields, ultra-deepwater will become the main battlefield of oil and gas exploitation in the future [1]. The 7th generation ultra-deepwater offshore drilling rig has stronger operational capability than the sixth generation, adapting to the operating water depth of 3660 m, and the drilling depth of 15240 m. but its environmental conditions are worse and the damage forms are more complex, which leads to the problems such as too small safety factor and too heavy structure in the operation process of the designed dual derrick. So it is necessary to carry out dual derrick optimization research. However, at present, the optimization research on dual derrick of the 7th generation ultra-deepwater offshore platform is not mature at home and abroad, most of which are land derrick, shallow sea derrick, single derrick or non-7th generation derrick [2-4].

In this study, the dual derrick model of the 7th generation ultra-deepwater offshore platform is established by ANSYS, and the mechanical analysis of the dual derrick in the storm self-storage condition is completed. Combined with single factor and response surface method (RSM), the optimal
functional relations between mass, stress and beam section parameters are established, and the optimal structural parameters of dual derrick are obtained.

2. Establishment of dual derrick model

Fig.1 shows the original designed dual derrick model of the 7th generation ultra-deepwater offshore platform. The beams of the dual derrick are divided into upper leg, middle leg, lower leg and internal support. Standard H-section steel [5] is adopted for the beam, and the material is Q345, with a density of 7850kg/m³, Young's modulus of 206GPa, Poisson's ratio of 0.28 and yield strength of 345MPa. The original designed section parameters are shown in Table 1.

Fig.2 shows the constraint conditions and loads of the dual derrick model. M₀, A, B, C, D, E and F mean respectively mass unit, hook load, wind load, vertical inertial acceleration, horizontal inertial acceleration, acceleration of gravity, and fixed boundary.

![Dual derrick model and section parameters](image1)

**Figure 1.** Dual derrick model and section parameters

**Figure 2.** Constraint conditions and loads

**Table 1.** Original designed section parameters

|          | Height/mm | Width/mm | Flange thickness/mm | Web thickness/mm |
|----------|-----------|----------|--------------------|------------------|
| Upper leg| H₁=450    | B₁=500   | M₁=20              | N₁=30            |
| Middle leg| H₂=450 | B₁=500 | M₂=25              | N₂=40            |
| Lower leg| H₃=450   | B₁=500   | M₃=30              | N₃=50            |
| Internal support| H₄=450 | B₂=450 | M₄=20              | N₄=20            |

3. Optimization design research

Taking the mass and safety factor as the target and the beam section parameters as the design variable, the optimization design of dual derrick is studied. Single factor optimization is carried out firstly, and then multi-objective optimization is carried out on the basis. The final ideal structure can meet the safety requirements and ensure the minimum mass and maximum safety factor of the dual derrick.

3.1. Single factor optimization

Fig.3 shows the variation rules of stress, displacement and mass of different beam section parameters of the dual derrick under the storm self-storage condition. As shown Fig.3 (a) and Fig.3 (b), the maximum stress usually occurs at the contact between the dual derrick bottom and the platform. With the increase of M₁, N₁, M₂, N₂, M₄ and N₄, the lower leg bears more pressure, and the maximum stress increases. With the increase of M₃ and N₃, B₁, H₁ and H₂, the structure of the lower leg became more stable and the maximum stress decreases. When B₂ is less than 350mm, the maximum stress appears at the variable section beam, which decreases with the increase of B₂, because the structure of the variable section beam is more stable. When B₂ is greater than 350mm, the maximum stress increases...
with the increase of $B_2$, which is due to the rapid increase of the wind load caused by the significant increase of the wind bearing area.

As shown Fig.3(c) and Fig.3(d), the maximum displacement usually occurs at the top of the dual derrick, which increases with the increase of $M_1, N_1$ and $B_2$, and decreases with the increase of $M_2, N_2, M_3, N_3, M_4, N_4, B_1$ and $H_1$. When $H_2$ is less than 350mm, the maximum displacement appears at the variable section beam, which decreases significantly with the increase of $H_2$. When $H_2$ is greater than 350mm, the maximum displacement decreases slowly as $H_2$ increases.

As shown Fig.3 (e) and Fig.3 (f), the mass increases linearly with the increase of section parameters.

Combined with the above analysis, under the condition of ensuring maximum safety factor, minimum mass and minimum displacement, optimization parameters are obtained: $M_1=10$mm, $N_1=10$mm. The stress on the left of the stress minimum point is too large, and the mass on the right is too large, so it is taken as optimization parameter: $H_1=350$mm, $B_2=350$mm. Therefore, preliminary optimization results are obtained, as shown in Table 2. Compared with the original plan, the mass of the optimized dual derrick is reduced by 15.92% and the safety factor is increased by 6.80%.

**Table 2.** Single factor optimization results

| Beam section parameter/mm | Mass /ton | Safety factor |
|---------------------------|-----------|---------------|
| $M_1$ | $N_1$ | $M_2$ | $N_2$ | $M_3$ | $N_3$ | $M_4$ | $N_4$ | $B_1$ | $H_1$ | $B_2$ | $H_2$ |            |       |
| Original derrick         | 20        | 30          | 25        | 40        | 30        | 50        | 20        | 20        | 500        | 450        | 450        | 450        | 785        | 1.47     |
| Optimized derrick        | 10        | 10          | 25        | 40        | 30        | 50        | 20        | 20        | 500        | 350        | 350        | 450        | 660        | 1.57     |
| Comparison               | Mass is reduced by 15.92% | Safety factor is increased by 6.80% |
3.2. Multi-objective optimization

Based on the results of single factor optimization, multi-objective optimization is carried out for the dual derrick. According to Fig.3, $M_4$ and $N_4$ have a greater impact on mass, and $M_3$ and $N_3$ have a greater impact on stress. Therefore, taking $M_3$, $N_3$, $M_4$, and $N_4$ as the design variables, a mathematical optimization model is established.

$$\begin{align*}
\text{Find } X = [x_1, x_2, x_3, x_4]^T = [M_3, N_3, M_4, N_4]^T \\
\min \ f_1(x) = \text{mass} & \quad \max \ f_2(x) = \text{security factor}
\end{align*}$$

(1)

Fig.3 shows that the larger $M_3$ and $N_3$ are, the smaller the stress of the dual derrick. When $M_3$ and $N_3$ are greater than 70mm, the stress is basically constant. So the minimum value of $M_3$ and $N_3$ is the initial value, and the maximum value is 70mm. $M_4$ and $N_4$ have little influence on stress, so the value range of $M_4$ and $N_4$ is within 30mm of the initial value when only considering the mass. Therefore, the lower and upper limits of the design variables are $[30, 30, 10, 10]^T$ and $[70, 70, 30, 30]^T$ respectively.

RSM is used for multi-objective optimization, which requires a large number of experimental points to simulate the operating conditions of dual derrick. 30 test points of design variables are generated by Central Composite Experimental Design (CCD) method, and 30 finite element models of dual derrick are analyzed. The results are shown in Table 3.

| Case | $M_3$/mm | $N_3$/mm | $M_4$/mm | $N_4$/mm | Mass/ton | Stress/MPa |
|------|-----------|-----------|-----------|-----------|----------|------------|
| 1    | 50        | 50        | 20        | 20        | 682      | 190        |
| 2    | 50        | 70        | 20        | 20        | 688      | 189        |
| …    | …         | …         | …         | …         | …        | …          |
| 30   | 30        | 60        | 15        | 15        | 569      | 212        |

By fitting the site calculation results, the optimization function expressions between mass, stress and design variables are obtained:

$$\text{Mass} = 131.76667 + 1.0875M_3 + 0.3125N_3 + 14.80833M_4 + 9.20833N_4$$

(2)

$$\text{Stress} = 425.3203 - 2.39115M_3 - 0.12917N_3 - 8.23333M_4 - 3.14167N_4 - 0.06375M_3M_4$$

$$+ 0.1125M_4N_4 + 0.028203M_3^2 + 0.16781N_4^2$$

(3)

Fig.4 verifies the fitting results. The mass error and stress error are within 0.2% and 1.5% respectively, indicating that RSM can reliably and quickly predict the response value of other data combination points and provide reasonable optimization results.
3.3. Optimization results and validation
The influence of different weighting factors on the optimization results of the dual derrick is analyzed. Literature [2] is used to obtain the optimization results under three weighting factors \((W_1/W_2=0.7/0.3, 0.5/0.5\text{ and } 0.4/0.6)\), as shown in Table 4. The error of the optimization results is compared with that of the derrick optimization results in literature [2]. It can be seen from Fig.5 that the error of the three weighting factors is smaller than that in literature [2], so as to verify the reliability of the optimization method combining single factor with response surface.

### Table 4. Optimization results with different weighting factors

| \(W_1/W_2\) | \(M_3/\text{mm}\) | \(N_3/\text{mm}\) | \(M_4/\text{mm}\) | \(N_4/\text{mm}\) | ANSYS Mass/ton | Safety factor | Mass/ton | Safety factor |
|-------------|-----------------|-----------------|-----------------|-----------------|--------------|-------------|-----------|-------------|
| 0.7/0.3     | 57              | 50              | 19              | 10              | 582.41       | 1.70        | 582.82   | 1.73        |
| 0.5/0.5     | 63              | 50              | 22              | 10              | 634.71       | 1.82        | 633.77   | 1.86        |
| 0.4/0.6     | 65              | 50              | 24              | 10              | 667.42       | 1.87        | 665.56   | 1.94        |

3.4. Comparison before and after optimization
The proportion of mass and safety factor is taken to equally important \((W_1/W_2=0.5/0.5)\). The results before and after optimization are compared, as shown in Table 4. Before optimization, the safety factor of dual derrick under storm self-storage condition is less than 1.67 specified by API Spec 4F. After optimization, the mass of the dual derrick is reduced by 19.11% and the safety factor is increased by 23.81%, which is greater than 1.67 as required by API Spec 4F and meets the safety requirements.

### Table 5. Comparison before and after optimization

| Beam section parameter/mm | Mass/ton | Safety factor |
|---------------------------|----------|---------------|
| \(M_1\) | \(N_1\) | \(M_2\) | \(N_2\) | \(M_3\) | \(N_3\) | \(M_4\) | \(N_4\) | \(B_1\) | \(H_1\) | \(B_2\) | \(H_2\) | Original derrick |
|---------------------------|----------|---------------|
| 20 | 30 | 25 | 40 | 30 | 50 | 20 | 20 | 500 | 450 | 450 | 785 | 1.47 |
| Optimized derrick | Mass is reduced by 19.11% | Safety factor is increased by 23.81% |
|---------------------------|----------|---------------|
| 10 | 10 | 25 | 40 | 63 | 50 | 22 | 10 | 500 | 350 | 350 | 450 | 635 | 1.82 |

4. Conclusion
Under the storm self-storage condition, the safety factor of the original design of the dual derrick of the 7th generation ultra-deepwater offshore platform is less than 1.67 as required by API Spec 4F, and the bottom leg of the derrick is the most dangerous. Therefore, the reinforcement of the lower leg should be considered when designing dual derrick.

The safety factor of the optimized dual derrick is 1.82 under the storm self-storage condition, which meets the safety requirements. Comparing with the original structure, the optimized structure’s mass reduced about 19.11%, the safety factor increased about 23.81%.

Acknowledgements
This work was financially supported by the Ministry of Industry “The seventh generation of ultra-deepwater drilling platform (boat) innovation special-drilling bag integration and some key equipment application research” (Ministry of Industry [2016] No. 24)
References

[1] Infield S L. Deep and ultra-deepwater capex to continue growing to 2017 [R]. America: Infield Systems Ltd, 2013: 1-2.

[2] J. Lee, J. Jeong, and P. Wilson, A study on multi-objective optimal design of derrick structure: Case study, INTERNATIONAL JOURNAL OF NAVAL ARCHITECTURE AND OCEAN ENGINEERING, 10(6) (2018) 661-669.

[3] Xu, X P, Wang L, Zhang X. Optimal design of dual derricks [J]. International Journal of Modelling, Identification and Control, 2012, 1(1): 61-67.

[4] X. Xu, G. Liu, H. Wang, Y. Wang, Z. Liu, X. Zhang, and L. Zhang, Mechanical analysis of a dual derrick [J]. INTERNATIONAL JOURNAL OF MODELLING IDENTIFICATION AND CONTROL, 28(2) (2017) 135-143.

[5] GB/T 11263-2017, Hot rolled H and cut T section steel [S]. Masteel (group) holding co. LTD, 2017.