Research on Optimization Design of Dual Derrick for Offshore Platform Based on RSM

Faguang Jiang1,2,* Min Zhang1,2, Xiuju Yang3, Xingchang Zeng1, Zheng Liang1,2 and Dayang Li1,2

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. The structure of dual derrick for offshore platform is optimized in this study. The special arrangement is establishing a mathematical model to minimize the stress and mass of dual derrick. The beam is divided into vertical, horizontal and oblique beam. The beam’s section sizes are design variables. After calculating test point data by ANSYS under operating conditions, the multi-objective optimization method is adopted to solve the optimal section size based on the regression equation of RSM fitting influence factors and response variables. This study will check the safety of the optimized dual derrick under storm self-storage conditions. The result shows that dual derrick meets safety requirements under extreme conditions, the optimized structure’s mass reduced about 21.2%, and the maximum safety factor increased about 8.3%.

1. Introduction
With the development of oil and gas exploration, the semi-submersible platform with dual derrick is the main offshore oil and gas drilling equipment. The dual derrick is different from the single derrick because its drilling load, and the offshore environment load in the deep water field are more complex. The design of dual derrick is excessively satisfied with application conditions, resulting in the safety factor too large, the structure too heavy and other problems. To solve the above problem, the optimum design of dual derrick is put forward [1]. Most of the researches are for the land derrick, shallow sea derrick and single derrick [2–6]. There is less research for dual derrick in the ultra deep-water area.

In this study, the dual derrick is adapted to work in the water depth of 3660m and the drilling depth of 15250m. The experimental site for optimal design of dual derrick is obtained based on the central composite point method (CCD), and the dual derrick model is established by ANSYS. The mechanical analysis of the dual derrick is completed under operating conditions. The functional relationship between impact factors and response variables was fitted based on RSM, the optimal size of the dual derrick is calculated by multi-objective optimization method.
2. Establishment of optimization design model for dual derrick

2.1. Formulation of optimization problem

Eqs. (1) represent the optimization formulation for the dual derrick structure, considering structural performance. The formulation of optimization problem of dual derrick is obtained as follows:

\[
\begin{align*}
\text{Find} & \quad X = [x_1, x_2, x_3, x_4, x_5, x_6]^T = [B_1, H_1, B_2, H_2, B_3, H_3]^T \\
\text{min} & \quad F(X) = W_1 f_1 + W_2 f_2 \\
\text{St} & \quad \min x_i \leq x_i \leq \max x_i \quad i = 1, 2, 3, 4, 5, 6
\end{align*}
\]

Fig. 1 shows that this research classify the dual derrick beam as vertical beam, horizontal beam and oblique beam according to the stress condition. The all of beams are H-shaped steel. Taking the width and height of H-shaped steel as design variables, there are six design variables: vertical beam width \( B_1 \), vertical beam height \( H_1 \), Horizontal beam width \( B_2 \), Horizontal beam height \( H_2 \), oblique beam width \( B_3 \), oblique beam height \( H_3 \).

The dual derrick must meet the safety requirements. The material of the dual derrick beam is Q345. It stipulated that the safety coefficient of the dual derrick ranges from 1.2 to 3, the yield strength ranges from 115MPa to 287.5MPa. According to the range of yield strength, the limit value of the size of dual derrick beams is determined that the upper and lower limit in equation (3). The lower and the upper limit of the the derrick beams size are respectively set at [200, 300, 150, 250, 100, 200]T and [750, 850, 700, 800, 650, 750]T.

![Figure 1. Dual derrick model and design variables](image)

![Figure 2. Constraint conditions](image)

2.2. Numerical model

Fig. 2 shows the constraint conditions of the dual derrick calculation model. A, B, C and D means the fixed boundary, the ultimate hook load under operating conditions, the Marine wind load under operating conditions and the rotation angle acceleration caused by the inertial force of the platform motion. Q345’s material properties are shown as: density is 7800(kg·m\(^{-3}\)), yield strength is 345(MPa), Young's modulus is 2.1×10\(^{11}\) (Pa), Poisson's Ratio is 0.3.
3. Response surface method

3.1. Structure optimization test site design
By using response surface method (RSM) to achieve optimal design, it requires a large number of design variable test points to simulate the size of each beam of the dual derrick. The stress and mass data of the dual derrick are obtained by finite element analysis. The 86 sets of design variable test points are generated by the Central Composite Experiment Design (CCD), and the results are calculated under operating conditions. Finite element results are shown in Table 1.

Table 1. Site calculation results

| Case | B₁ (mm) | H₁ (mm) | B₂ (mm) | H₂ (mm) | B₃ (mm) | H₃ (mm) | Stress (MPa) | Mass (ton) |
|------|---------|---------|---------|---------|---------|---------|--------------|------------|
| 1    | 200     | 850     | 150     | 250     | 100     | 750     | 143          | 463        |
| 2    | 200     | 850     | 700     | 800     | 650     | 750     | 91           | 1089       |
| 3    | 200     | 300     | 700     | 250     | 100     | 200     | 279          | 537        |
| ...  | ...     | ...     | ...     | ...     | ...     | ...     | ...          | ...        |
| 86   | 750     | 850     | 700     | 250     | 650     | 200     | 42           | 1189       |

3.2. Regression equation fitting
The dual derrick beam size is the influencing factor, stress and mass are the response variables. The regression equation as follows:

\[
\text{Stress} = 728.25564 - 0.86658 \times B₁ - 0.51261 \times H₁ - 0.53870 \times B₂ - 0.12353 \times H₂
\]
\[\quad - 0.017816 \times B₁ + 3.34111 \times 10^{-4} \times B₁ \times H₁ - 8.35295 \times 10^{-5} \times B₁ \times B₂
\]
\[\quad + 1.58608 \times 10^{-4} \times H₁ \times B₂ + 7.69140 \times 10^{-4} \times H₁ \times H₂ + 8.94260 \times 10^{-4}
\]
\[\quad \times B₂ \times H₂ + 5.39799 \times 10^{-4} \times B₂^2 + 4.25655 \times 10^{-4} \times B₂
\]
\[\quad \times H₂^2 \]  
\[\quad = -20.06139 + 0.45536 \times B₁ + 0.15179 \times H₁ + 0.42998 \times B₂ + 0.12899 \times H₂
\]
\[\quad + 0.57945 \times B₁ + 0.14486 \times H₁ \]  

3.3. Regression equation error test
Table 2 shows the errors of the regression equation. The errors are less than 10%. It indicated that the regression equation can express the functional relationship between the influence factor and the response variable accurately. The regression equation can provide reasonable results quickly.

Table 2. Regression equation data error

| Case | ANSYS | RSM | Error |
|------|-------|-----|-------|
|      | Stress/MPa | Mass/t | Stress/MPa | Mass/t | Stress | Mass |
| 1    | 143   | 463  | 134   | 463   | 6.4%   | 0.0% |
| 2    | 91    | 1089 | 102   | 1089  | -12.1% | 0.0% |
| 3    | 279   | 537  | 291   | 537   | -4.3%  | 0.0% |
| ...  | ...   | ...  | ...   | ...   | ...    | ...  |
| 86   | 42    | 1189 | 38    | 1189  | 9.5%   | 0.0% |

3.4. Single factor response curve analysis
The central point values are taken as basic parameters, which are B₁=475mm, H₁=575mm, B₂=425mm, H₂=525mm, B₃=375mm, H₃=475mm. The single factor response of the size to stress and mass are studied in this part.
Fig. 3 shows that the increase of the size of each beam of the dual derrick will reduce the stress of the whole structure. The relationship between the size of each structure and the stress of the dual derrick is: $H_1 > B_1 > B_2 > H_2 > H_3 > B_3$, vertical beam > horizontal beam > oblique beam. Fig. 4 shows the relationship between the size of each beam and the mass of the dual derrick is: $B_3 > B_2 > B_1 > H_3 > H_2 > H_1$, oblique beam > horizontal beam > vertical beam.

### Figure 3. Response curve of section size to stress

### Figure 4. Response curve of section size to mass

#### 3.5. Multi-factor interactive response surface analysis

In order to study the effect of beams to stress, the interactive response surface of interaction factors are shown below. Fig. 5 shows the Interaction between different beam sizes on Von Mises.

![Interaction between different beam sizes on Von Mises](image)

The interactive response surface analysis shows that it is different that the influence of each beam size on the stress. The result provide guidance for size optimization.

### 4. Multi-objective optimization

According to Eqs. (1)-(3), different weighting factors of mass and stress can cause different optimization results. The results of optimization with different weighting factors are shown in Table 3.

#### Table 3. Different weighting factor optimization results

| $W_1/W_2$ | B_1/mm | H_1/mm | B_2/mm | H_2/mm | B_3/mm | H_3/mm | Stress/MPa | Mass/t |
|-----------|--------|--------|--------|--------|--------|--------|------------|--------|
| 1/9       | 200    | 533    | 150    | 398    | 100    | 283    | 196        | 367    |
| 2/8       | 393    | 598    | 152    | 455    | 100    | 350    | 132        | 482    |
| 3/7       | 393    | 598    | 152    | 455    | 100    | 350    | 132        | 482    |
| 4/6       | 393    | 598    | 152    | 455    | 100    | 350    | 132        | 482    |
| 5/5       | 442    | 614    | 198    | 469    | 163    | 366    | 106        | 568    |
| 6/4       | 383    | 850    | 194    | 475    | 100    | 308    | 87         | 531    |
| 7/3       | 475    | 802    | 280    | 500    | 100    | 358    | 70         | 613    |
| 8/2       | 586    | 724    | 351    | 517    | 309    | 405    | 59         | 812    |
| 9/1       | 603    | 850    | 420    | 542    | 296    | 410    | 50         | 865    |
The errors were performed on the different weighting factors. The result is shown in Fig. 6. When the weighting factors are $W_1=0.55$ and $W_2=0.45$, the error is close to zero, so the calculation result under the weighting factor is best size of the dual derrick, the optimal dimensions of the beams of the dual derrick are shown in Table 4.

Table 4. Optimal design scheme

| $B_1$/mm | $H_1$/mm | $B_2$/mm | $H_2$/mm | $B_3$/mm | $H_3$/mm | Stress/MPa | Mass/t |
|----------|----------|----------|----------|----------|----------|------------|--------|
| 450      | 600      | 200      | 450      | 200      | 400      | 106        | 594    |

5. Comparison of optimized derrick and derrick before optimization

5.1. Calculation and evaluation under self existence condition of the storm

The test point data of dual derrick optimization design were calculated under the operating condition, but the dual derrick will encounter actually more serious work-condition. The optimized design model must be checked in the most dangerous working condition of self existence condition of the storm.

Fig. 7 shows that the maximum stress of the dual derrick is 233MPa, the maximum displacement is 106mm, the displacement of the upper part of the derrick is large, and the maximum stress is the contact
between the bottom and the platform. The mechanical characteristics are consistent with the optimization and the safety factor is 1.48, which meets the safety requirements.

5.2. Comparison of mechanical analysis of optimized derrick and derrick before optimization

In order to study the effect of optimized dual derrick on mechanical properties, the mechanical properties of the optimized derrick and derrick before optimization are calculated. The size of the dual derrick optimized design and original design were shown in Table 5.

| Designing scheme   | Beam size /mm | Mass /t |
|--------------------|----------------|---------|
|                    | B1  | H1  | B2  | H2  | B3  | H3  |       |
| Original derrick   | 550 | 650 | 300 | 500 | 300 | 400 | 754   |
| Optimized derrick  | 450 | 600 | 200 | 450 | 200 | 400 | 594   |

Table 5. Comparison between optimized design and original design

The comparison results are shown in Table 6. The safety factor is 3.25, and the maximum displacement is 47 mm. The Mass is reduced about 21.2%, the safety factor is increased about 8.3%.

| Original derrick | Optimized derrick | Safety factor increase | Mass decline |
|------------------|-------------------|------------------------|--------------|
| Safety factor    | Mass /t           | Safety factor          | Mass /t      |
| 3                | 754               | 3.25                   | 594          |

6. Conclusion

(1) The influence between the beam size and the stress as follow: H1>B1>B2>H2>H3>B3, vertical beam>horizontal beam>oblique beam. The influence between the beam size and the mass as follow: B3>B2>B1>H3>H2>H1, oblique beam>horizontal beam>vertical beam. In particular, the beam width has the greatest influence to the mass.

(2) The error of the regression equation is within 10%. The optimal size of dual derrick beams were solved with regression equation. The result of optimal size is: B1=450mm, H1=600mm, B2=200mm, H2=450mm, B3=200mm, H3=400mm.

(3) The maximum stress of the optimized dual derrick is 233MPa, and the safety factor is 1.48 under the self existence condition of the storm, which meets the safety requirements in the extreme condition. By comparing with the optimized derrick and derrick before optimization, the optimized structure’s mass reduced about 21.2%, the safety factor increased about 8.3%.

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] X. Xu, G. Liu, H. Wang, Y. Wang, Z. Liu, X. Zhang, and L. Zhang, Mechanical analysis of a dual derrick, INTERNATIONAL JOURNAL OF MODELLING IDENTIFICATION AND CONTROL, 28 (2) (2017) 135-143.
[2] J. Zhu, L. Zou, and H. Fu, Feasibility Design of Derrick Anchor Pile Piling Position Based on ANSYS Optimization, Advanced Materials Research, 694-697 (2013) 246-250.
[3] 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.
[4] X. P. Xu, L. Wang, X. Zhang, Optimal design of dual derricks, International Journal of Modelling,
Identification and Control, 1 (1) (2012): 61-67

[5] F. Wang, W. Xiao, J. Liu, L. Xu, X. Yang, and Y. Geng, Research on layout optimization of drilling rig system of semi-submersible platform based on modified particle swarm optimization, Journal of China University of Petroleum (Natural Science Edition), 40 (2) (2016) 123-128.

[6] F. Guan, C. Zhou, S. Wei, W. Wu, X. Z. Yi. Load-Carrying Capacity Analysis on Derrick of Offshore Module Drilling Rig, The Open Petroleum Engineering Journal, (2014) 29-40.