Research on The Installation Window of Deepwater Subsea Xmas Tree

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Abstract. The purpose of this paper is to determine the safe operating window of subsea tree installation through analysing the sensitivity of multiple environmental parameters. In this paper, the wave height, period, phase angle and the sea surface current speed are taken as the evaluation factors of the marine environment, and a sensitivity ranking of these four factors is obtained by orthogonal analysis. The lateral offset and axial velocity of the tree, the axial deformation and von-Mises equivalents stress of the pipe are taken as constrain factors in sensitivity analysis. Results show that the wave height and period are the most significant affecting factor in sensitivity analysis. Finally, based on the given installation evaluation criteria, the installation operation window of the tree under different sea conditions are studied.

Keywords: Operation Window, Subsea Xmas Tree, Drill pipe, Orthogonal test, Sensitive parameters.

1. Introduction

With the rapid development and exploration of offshore oil and gas from shallow water to deep water regions, the subsea Xmas tree (hereafter referred to as the tree) is a key piece of equipment in the subsea production system and is widely used in deep water [1]. From shallow to deep water, the cost of the underwater equipment has not significantly increased, but the installation cost and risk have risen rapidly due to the complex combination of wave and current [2]. Therefore, it is necessary to analyze the installation operation window of the tree, which is important to improve safety and reliability of the tree underwater installation. In this paper, we choose to lower the tree with drill pipe (hereafter referred to as the pipe).

The installation model of the tree can be viewed as a slender cylinder with concentrated mass at the end, and many scholars have studied the mechanical behaviours of a slender structure in deep water. Patel [3] presented a theoretical and experimental investigation of the lateral dynamics of free-hanging marine drilling risers. Gosse [4] established a mathematical model of the riser under working conditions and derived the vibration equation. Sheng et al. [5] discussed the riser in hang-off modes under typhoon conditions in the South China Sea in which the both soft and hard riser hang-off configurations for storm events were assessed. Hu et al. [6] analysed the dynamic characteristics of the riser in the time domain throughout the entire installation operation (from the vessel to the wellhead).
and took the launch velocity as a variable parameter. This research supplied a new method for study of
the variable-length riser. Considering the water depth, riser size, BOP weights and weather conditions,
Wang et al. [7] analysed the static behaviour and lateral vibration of the riser during installation
process. Qin et al. [8] analysed many factors that affect the installation process, such as wave phase,
current speed, wave height, pipe size and towing speed.

Although the mechanics of marine structures has been fully studied, few references refer to
engineering operation window. S. Chen [9] had done some studies to find more suitable operating
environments for drilling operating of the riser system, so as to increase drilling operation time and
reduce the operating downtime. Soørensen et al. [10] proposed that the angle of the riser relative to
the well-head and the top joint was the most limiting factors. On the contrary, Rustad et al. [11]
considered that the traditional limits for vessel offset were too conservative. They suggested that the
upper angle can be excessive within a limited time, so that the operation can last longer and an
unnecessary disconnection can be avoided. Wang et al. [12] researched the installation window of riser
based on mechanics analysis and actual marine environment, they believed that the maximum
equivalent stress, relative to the fleet angle, is the main factor to determine the installation operation
window.

Previous studies focused mainly on the effects of environment parameters on mechanical properties,
however there is little research on the weight of those parameters. In this paper, the platform-drill
pipe-subsea tree system is taken as the research object, and the wave height, period, phase angle and
the sea surface current velocity are taken as the evaluation factors of marine environment, and a
sensitivity ranking of these four factors is obtained by orthogonal analysis.

2. Sensitivity analysis of parameters

2.1. Analysis method

The main purpose of this paper is to determine the safe installation operation window under a given
marine environment parameters. From the perspective of the pipe mechanical properties, the Xmas
tree lowering operation window is defined as a specific environmental parameter; if a certain
environmental factor changes, resulting in evaluation parameters exceeding the evaluation criteria, it
does not meet the requirement of the operation window. Two mechanics analysis of the pipe in both
vertical and horizontal directions are described below:

Lateral analysis: in both static and dynamic research, the deflection and stress distribution of the
pipe under the combined action of wave and current should be considered. In this analysis, the key
parameters are the offset of the tree and the maximum von-Mises equivalent stress at the critical
section of the pipe.

Axial analysis: this section focuses on the dynamic characteristics of the tree hanging at the end of
the pipe. There are two kinds of constrain states on the top of the pipe while the tree is being lowered,
hard suspension and soft suspension. Generally, the dynamic response calculated by hard suspension
is bigger than that calculated by soft suspension. Therefore, the rigid suspension model with the pipe
top fixed on the vessel is taken as example in this paper. If the axial velocity of the tree and axial
deformation of the pipe are too large, collision damage will occur when the tree is connected with
subsea wellhead.

In this paper, the wave phase angle, wave height, wave period and sea surface velocity are selected
as the marine environmental evaluation factors, which can directly affect the mechanics properties in
both lateral and axial directions. Furthermore, the lateral offset and axial velocity of the tree, the axial
deformation and von-Mises equivalents stress of the pipe are considered as constrain factors
respectively to explore the sensitivity order of the environmental factors mentioned above.

2.2. Orthogonal experiment set

According to the literature [8], the pipe bending deformation and stress are affected by the current
speed, wave height, wave period, and wave phase angle. Therefore, a four-factor and four-level
orthogonal experiment is designed to reveal the order of these factors, the four factors are listed in Table 1.

**Table 1. Four factors and four levels orthogonal test.**

| Test number | wave phase angle (°) | wave height (m) | wave period (s) | current speed (m/s) |
|-------------|----------------------|-----------------|-----------------|---------------------|
| 1           | 0                    | 1               | 10              | 0.1                 |
| 2           | 30                   | 4               | 15              | 0.4                 |
| 3           | 60                   | 7               | 20              | 0.7                 |
| 4           | 90                   | 10              | 25              | 1.0                 |

Table 2 shows an L16(45) orthogonal test table, where sensitivity analysis was carried out for the process of tree lowering with mass of 30t, 50t and 60t, respectively.

**Table 2. Design of orthogonal test scheme.**

| Group | wave phase angle (°) | wave height (m) | wave period (s) | current speed (m/s) |
|-------|----------------------|-----------------|-----------------|---------------------|
| 1     | 0                    | 1               | 10              | 0.1                 |
| 2     | 0                    | 4               | 15              | 0.4                 |
| 3     | 0                    | 7               | 20              | 0.7                 |
| 4     | 0                    | 10              | 25              | 1.0                 |
| 5     | 30                   | 1               | 15              | 0.7                 |
| 6     | 30                   | 4               | 10              | 1.0                 |
| 7     | 30                   | 7               | 25              | 0.1                 |
| 8     | 30                   | 10              | 20              | 0.4                 |
| 9     | 60                   | 1               | 20              | 1.0                 |
| 10    | 60                   | 4               | 25              | 0.7                 |
| 11    | 60                   | 7               | 10              | 0.4                 |
| 12    | 60                   | 10              | 15              | 0.1                 |
| 13    | 90                   | 1               | 25              | 0.4                 |
| 14    | 90                   | 4               | 20              | 0.1                 |
| 15    | 90                   | 7               | 15              | 1.0                 |
| 16    | 90                   | 10              | 10              | 0.7                 |

2.3. **Experimental results**

According to the table 2, Orcaflex software was used to conduct dynamic simulation of three different weight tree lowering processes, and the dynamic response of the pipe under the coupling effect of four environmental factors was obtained, as shown in Table 3, Table 4 and Table 5 respectively.
Table 3. Dynamic response of drill pipe for 30t subsea tree.

| Group | Lateral deflection (m) | Axial deflection (m) | Von-Mises Stress (MPa) | Velocity (m/s) |
|-------|------------------------|----------------------|------------------------|---------------|
| 1     | 1.33                   | 0.13                 | 166.23                 | 0.18          |
| 2     | 20.53                  | 1.86                 | 465.27                 | 0.78          |
| 3     | 61.55                  | 4.64                 | 818.12                 | 1.15          |
| 4     | 123.95                 | 10.45                | 1298.26                | 1.23          |
| 5     | 59.06                  | 1.66                 | 551.02                 | 0.20          |
| 6     | 122.73                 | 6.82                 | 1386.91                | 0.89          |
| 7     | 1.69                   | 3.35                 | 220.35                 | 0.88          |
| 8     | 21.46                  | 4.98                 | 637.87                 | 1.55          |
| 9     | 120.39                 | 6.91                 | 961.90                 | 0.16          |
| 10    | 60.03                  | 3.20                 | 570.86                 | 0.50          |
| 11    | 22.88                  | 3.52                 | 1553.26                | 2.76          |
| 12    | 2.07                   | 4.94                 | 679.04                 | 2.08          |
| 13    | 19.35                  | 0.50                 | 206.89                 | 0.13          |
| 14    | 1.62                   | 1.90                 | 204.92                 | 0.65          |
| 15    | 124.09                 | 9.03                 | 1149.47                | 1.49          |
| 16    | 64.23                  | 7.89                 | 3735.67                | 4.86          |

Table 4. Dynamic response of drill pipe for 50t subsea tree.

| Group | Lateral deflection (m) | Axial deflection (m) | Von-Mises Stress (MPa) | Velocity (m/s) |
|-------|------------------------|----------------------|------------------------|---------------|
| 1     | 1.15                   | 0.30                 | 237.75                 | 0.18          |
| 2     | 10.41                  | 1.42                 | 544.94                 | 0.79          |
| 3     | 28.47                  | 3.26                 | 809.61                 | 1.15          |
| 4     | 55.60                  | 5.76                 | 1187.11                | 1.24          |
| 5     | 25.16                  | 0.49                 | 503.93                 | 0.21          |
| 6     | 53.84                  | 2.22                 | 1387.11                | 0.89          |
| 7     | 2.44                   | 3.01                 | 369.06                 | 0.87          |
| 8     | 13.49                  | 4.54                 | 759.03                 | 1.56          |
| 9     | 50.89                  | 0.27                 | 789.96                 | 0.16          |
| 10    | 26.28                  | 1.84                 | 528.45                 | 0.50          |
| 11    | 13.88                  | 3.10                 | 1985.62                | 2.19          |
| 12    | 2.83                   | 4.62                 | 1027.38                | 2.11          |
| 13    | 8.29                   | 0.49                 | 220.96                 | 0.13          |
| 14    | 1.68                   | 1.55                 | 298.27                 | 0.64          |
| 15    | 56.79                  | 4.44                 | 1070.94                | 1.52          |
| 16    | 36.38                  | 5.99                 | 3596.02                | 3.70          |
Table 5. Dynamic response of drill pipe for 60t subsea tree.

| Group | Lateral deflection (m) | Axial deflection (m) | von-Mises Stress (MPa) | Velocity (m/s) |
|-------|------------------------|----------------------|------------------------|----------------|
| 1     | 1.06                   | 0.24                 | 237.48                 | 0.19           |
| 2     | 8.51                   | 1.25                 | 580.65                 | 0.79           |
| 3     | 22.76                  | 3.00                 | 829.65                 | 1.12           |
| 4     | 44.21                  | 5.14                 | 1169.50                | 1.24           |
| 5     | 19.87                  | 0.46                 | 498.85                 | 0.21           |
| 6     | 42.69                  | 1.62                 | 1338.72                | 0.90           |
| 7     | 2.24                   | 2.84                 | 443.25                 | 0.88           |
| 8     | 11.48                  | 4.37                 | 819.92                 | 1.56           |
| 9     | 40.17                  | 0.49                 | 751.70                 | 0.16           |
| 10    | 20.84                  | 1.56                 | 532.88                 | 0.50           |
| 11    | 11.62                  | 3.00                 | 2036.27                | 2.20           |
| 12    | 2.28                   | 4.52                 | 1146.73                | 2.12           |
| 13    | 6.56                   | 0.52                 | 236.60                 | 0.13           |
| 14    | 1.12                   | 1.40                 | 336.91                 | 0.64           |
| 15    | 45.3                   | 3.86                 | 1090.30                | 1.53           |
| 16    | 30.05                  | 5.75                 | 3873.49                | 3.70           |

2.4. Range analysis

2.4.1. Lateral deflection. Tables 6 shows the range analysis of the maximum lateral offset in the lowering process of 30t, 50t and 60t subsea tree. It can be seen from the range value that the sensitivity order of lateral offset to the four factors is ocean current speed, wave height, wave period and phase angle. And the influence of current speed on the lateral offset of the pipe is very significant.

Table 6. Range analysis of lateral offset.

| msss  | 30t                  | 50t                  | 60t                  |
|-------|----------------------|----------------------|----------------------|
|       | phase angle (°)      | wave height (m)      | wave period (s)      | current speed (m/s) |
|       | Average 1            | 51.84                | 50.03                | 52.79               | 1.68               |
|       | Average 2            | 51.24                | 51.23                | 51.44               | 21.06              |
|       | Average 3            | 51.34                | 52.55                | 51.26               | 61.22              |
|       | Average 4            | 52.32                | 52.93                | 51.26               | 122.79             |
|       | Range                | 1.09                 | 2.90                 | 1.54                | 121.11             |
|       | Average 1            | 23.91                | 21.37                | 26.31               | 2.03               |
|       | Average 2            | 23.73                | 23.05                | 23.80               | 11.52              |
|       | Average 3            | 23.47                | 25.40                | 23.63               | 29.07              |
|       | Average 4            | 25.79                | 27.08                | 23.15               | 54.28              |
|       | Range                | 2.32                 | 5.71                 | 3.16                | 52.25              |
|       | Average 1            | 23.91                | 21.37                | 26.31               | 2.03               |
|       | Average 2            | 23.73                | 23.05                | 23.80               | 11.52              |
|       | Average 3            | 23.47                | 25.40                | 23.63               | 29.07              |
|       | Average 4            | 25.79                | 27.08                | 23.15               | 54.28              |
|       | Range                | 2.32                 | 5.71                 | 3.16                | 52.25              |

2.4.2. Axial deflection. Tables 7 shows the range analysis of the axial tensile deformation of the pipe during the installation of three different weight subsea tree. It can be seen that the axial tensile deformation is very sensitive to the change of wave height. In addition, when the 30t subsea tree is lowered, the current speed also plays a vital role in the axial deformation.
2.4.3. Von-Mises Stress. Tables 8 is the rang analysis of von-Mises Stress of the pipe with three different weight subsea tree. The sensitivity order of the four factors in these three tables are wave period, wave height, current speed and wave phase angle. Compared with the wave phase angle, the other three factors play an obvious role, and their weights are basically equal. However, as the weight of the tree increases, the influence of the current velocity on the maximum equivalent stress of the pipe gradually decreases.

Table 8. Range analysis of von-Mises stress.

| mass | phase angle (°) | wave height (m) | wave period (s) | current speed (m/s) |
|------|-----------------|-----------------|-----------------|--------------------|
| 30t  | Average 1       | 686.97          | 471.51          | 1710.52            | 317.64             |
|      | Average 2       | 699.04          | 656.99          | 711.2              | 715.82             |
|      | Average 3       | 941.27          | 935.3           | 655.70             | 1418.92            |
|      | Average 4       | 1324.24         | 1587.71         | 574.09             | 1199.14            |
|      | Range           | 637.27          | 1116.2          | 1136.43            | 1101.28            |
| 50t  | Average 1       | 694.85          | 438.15          | 1801.63            | 483.12             |
|      | Average 2       | 754.78          | 689.69          | 786.80             | 877.64             |
|      | Average 3       | 1082.85         | 1058.81         | 664.22             | 1359.50            |
|      | Average 4       | 1296.55         | 1642.39         | 576.40             | 1108.78            |
|      | Range           | 601.70          | 1204.24         | 1225.23            | 876.38             |
| 60t  | Average 1       | 704.32          | 431.16          | 1871.49            | 541.09             |
|      | Average 2       | 775.19          | 697.29          | 829.13             | 918.36             |
|      | Average 3       | 1116.90         | 1099.87         | 684.55             | 1433.72            |
|      | Average 4       | 1384.33         | 1752.41         | 595.56             | 1087.56            |
|      | Range           | 680.01          | 1321.25         | 1275.93            | 892.63             |

2.4.4. Axial velocity. According to Table 9 that the range analysis on amplitude velocity at the end of the pipe, the axial vibration of the pipe is most affected by the wave height, followed by the wave period, and other two factors have less influence.
3. Analysis of operation window

In this section, the 50t subsea tree is used as the research object. Based on the OracFlex software and the installation model, the simulation results about the stress and amplitude velocity of the pipes in the lowering stages would be discussed.

3.1. Criteria condition

Taking the maximum Von-Mises equivalent stress of the pipe and axial velocity of the tree as constrain factors, the criteria to determine installation window is shown in Table 10.

| Operation mode         | Mises equivalent stress (MPa) | Dynamic velocity(m/s) |
|------------------------|-------------------------------|-----------------------|
| Normal installation    | $0.67 \sigma_y$               | 0.5                   |
| Carefully installation | $0.8 \sigma_y$                | 0.3                   |
| Forbid to install      | $>1 \sigma_y$                 | $>1$                  |

$\sigma_y$ means the minimum yield strength of the material, which is 862MPa

3.2. Operation window

Through the sensitivity analysis about the four factors, it is determined that the main factors affecting the von-Mises Stress at the top of the pipe and the amplitude velocity at the end of the pipe are the wave period and wave height. Table 11 and 12 respectively show the stress and vibration velocity under the combined action of wave height and period.
Table 11. von-Mises Stress (MPa) of the pipe.

| Period(s) | 10     | 12     | 16     | 20     | 24     | 28     |
|-----------|--------|--------|--------|--------|--------|--------|
| height(m) | 0.5    | 486.39 | 464.71 | 449.64 | 443.55 | 440.37 |
|           | 1      | 564.47 | 510.51 | 472.70 | 458.75 | 451.79 |
|           | 2      | 777.84 | 619.49 | 528.36 | 492.33 | 476.74 |
|           | 3      | 1000.85| 749.80 | 591.20 | 529.66 | 503.76 |
|           | 4      | 1082.40| 892.18 | 661.21 | 600.13 | 533.57 |
|           | 5      | 1409.83| 1046.69| 736.12 | 617.93 | 566.43 |
|           | 6      | 1549.59| 1205.92| 917.86 | 663.49 | 599.54 |
|           | 7      | 1711.54| 1364.29| 1032.76| 715.25 | 636.70 |

Table 12. Amplitude velocity (m/s) of the tree.

| Period(s) | 10     | 12     | 16     | 20     | 24     | 28     |
|-----------|--------|--------|--------|--------|--------|--------|
| height(m) | 0.5    | 0.15   | 0.13   | 0.10   | 0.08   | 0.07   |
|           | 1      | 0.31   | 0.26   | 0.20   | 0.16   | 0.14   |
|           | 2      | 0.62   | 0.53   | 0.44   | 0.32   | 0.27   |
|           | 3      | 0.93   | 0.79   | 0.64   | 0.48   | 0.40   |
|           | 4      | 1.27   | 1.06   | 0.84   | 0.63   | 0.51   |
|           | 5      | 1.79   | 1.52   | 1.23   | 0.95   | 0.78   |
|           | 6      | 2.28   | 1.95   | 1.60   | 1.09   | 0.79   |
|           | 7      | 2.84   | 2.29   | 1.89   | 1.31   | 0.91   |

As shown in Figure 1, the limit operating window of stress and vibration velocity were obtained based on the subsea tree lowering criteria which is recommended by DNV-RP-C205. When the 50t subsea tree is lowered, the maximum wave height is 6.21m, and the window widens as the wave period increases.

Figure 1. Limit operating window, (a) Stress limit condition, (b) velocity limit condition.

3.3. Operation window

The variation of the pipe deflection and von-Mises stress with sea surface velocity (which ranges from 0.1 m/s to 1 m/s) for four different speeds is shown in Figure 2. As the current speed increases, the
displacement of the tree and the maximum von-Mises stress of the pipe increase significantly. Therefore, the increase of current speed will narrow the operating window due to the stress criterion.

![Figure 2](image-url) Variations of pipe deflection with current velocity, (a) Stress limit condition, (b) velocity limit condition

4. Conclusions
This paper studies the safe lowering operation window of subsea Xmas tree through analysing the sensitivity of multiple factors. Several conclusions are given as follows.

1) In order to research the weight of multiple parameters in the tree lowering operation, a four-factor and four-level orthogonal experiment is designed to reveal the order of these factors.

2) The sensitivity order of four environmental parameters are given respectively for the 30t, 50t and 60t subsea Xmas tree.

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