Displacement response analysis of the SCR rigid body rotation under the wave and X direction motion of the riser hanging point effects based on Cable3D

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Abstract. The steel catenary riser has a rigid body swing around the top suspension point and the bottom touch down point. The effect of rigid body oscillation on the displacement response of the transverse flow is not negligible. It is very important to calculate the swing displacement response of structural rigid body. The structure was imposed the wave action and the X direction action of the top suspension point that makes the rotation axes change. Based on the slender beam with large deflection model, wave model and the rigid body swing model, the influence of rigid body swing to the structure is studied. Calculation shows that structure under wave loading and X direction action, the percentage of rigid body swing impact on the structural is about 10%, increasing as the radius vector S, while decreasing with the decrease of the S. The trend is different from the waves and the top action decreasing with increasing of the depth of water. It is hoped that the above research can provide some reasonable and practical suggestions to the calculation of steel catenary riser.

1. Introduction

Owing to the axis of the rigid body swing system of SCR model[1][2] is the connection between the top hanging point and the touch down point. The change of the top hanging point and the bottom of the touch down point will make the SCR rotation model axes change. It will further make the swing radius of the motion change, such as, in turn, affecting the performance of SCR rigid body swing mode.

Wei Wang and Luyun Chen[3] proposed the calculation method of the complex prestress distribution of the riser when only the top platform lifting and sinking is considered. The parametric vibration of the pretensioning tube was calculated by Luyun Chen[4] and and Kelon Wei. The results show that the welding residual stress affects the resonance of the structure. Yun Gao et.al.[5] studied the dynamic response SCR. Feifan Li et.al.[6] studied the VIV of a flexible riser. Zunru Yang et.al.[7] studied the collision between serial risers. Dongyang Chen et.al.[8] calculated the VIV of composite riser. Luyun Chen et.al.[9] analyzed pre-stress force distribution of VIV. Yun Gao et.al.[10] studied the trajectory performance of riser.

In this paper, the influence of rigid body swing on the structure is studied under the influence of top X direction motion and wave motion.
2. SCR Large Deflection Slender Beam Model

2.1. Basic Equations

According to conservation theorem of momentum and theorem of momentum, the equilibrium equation of beam is obtained. Further according to Bernoulli-Euler theory, the motion equation[1][2] of the long beam with large deflection can be deduced:

$$\rho \ddot{y} + (Br^*)'' - (\lambda \dot{r})' = q$$

(1)

The vibration control equation of the riser can be obtained after the expression of the load gravity, static pressure and hydrodynamic load, inertial force, drag force and f-k force on the structure. and the equation can be deduced:

$$M\ddot{r} + (Br^*)'' - (\lambda \dot{r})' = q_F$$

(2)

$q_F$ - the distribution force of unit length on the beam; $\rho$ - the quality of beam unit length; $M$ the beam quality matrix; $B$ the beam stiffness matrix; $\lambda$ the Lagrangian.

2.2. SCR Rigid Rotation Model.

SCR rigid body rotation model[1] is shown in figure 1. A is fixed point. B is touch down point (TDP). O is hanging point. Riser is around the OB rotation axis. S is radius vector.

$$m_{am} s^2 \ddot{\alpha}_r + c_a s^2 \dot{\alpha}_r + m_a g \dot{s}_r = q_z \sqrt{s_1^2 + s_2^2} + q_x c_2 s_3$$

(3)

$m_{am}$ - the per unit length quality of SCR and the added mass, $c_a$ - the additional damping coefficient, $q_x$, $q_z$ - environmental load projection for riser $\alpha$, $\dot{\alpha}_r$, $\ddot{\alpha}_r$ - riser angular displacement, angular velocity and angle acceleration.

When formula (3) is added to formula (2) as a coupling term, the following equation can be obtained:

$$M\ddot{r} + (Br^*)'' - (\lambda \dot{r})' = q_F + mg - (m + m_a)\ddot{r}_r - c_a \dot{r}_r$$

(4)

2.3. Wave Force Model

The Morison equation[3] is a formula to calculate the wave load of the rigid cylinder perpendicular to the bottom of the sea. If it is a cylinder, velocity $\dot{x}$ and the acceleration $\ddot{x}$, the equation is as follows:

$$f_H = \frac{1}{2} C_D \rho A (u_x - \dot{x}) |u_x - \dot{x}| + C_M \rho \frac{\pi D^2}{4} \dot{u}_x - C_w \rho \frac{\pi D^2}{4} \ddot{x}$$

(5)
\( A \) is the projection area perpendicular to the wave direction. \( \rho \) is the density of sea water; \( V_0 \) is the volume of drainage; \( C_m \) is the additional mass coefficient; \( C_M \) is the mass coefficient for SCR; \( C_D \) is the drag force coefficient for SCR; \( u_x \) the horizontal velocity water quality.

After adding formula (5) as the coupling term to formula (4), it can be obtained:

\[
M\dddot{r} + \left(Br^*\right)'' - (\lambda r')' = q_f + mg - (m + m_a)\dddot{r} - c_a r_L + f_{ll}
\]  
(6)

2.4. SCR motion boundary.

Fixed constraint is adopted at the bottom of SCR, and top X direction affects the riser’s movement. When calculation and analysis, the file calculated by the X direction is superposition of rigid body swing effect. Transverse flow characteristics of the structure amplitude is studied at the top suspension point under the X direction motion and the rigid body rotation.

3. SCR wave rigid body oscillation response under linear motion.

The linear motion simulating floating platform response of X is applied to the top suspension point of the SCR model. This section only considers wave action, regardless of the effect of ocean current, and the wave incidence direction is X direction. Table 1 shows the top motion parameters in each working condition.

| Condition | Amplitude(m) | Cycle(s) | Frequency(Hz) | Angular Frequency(Hz) |
|-----------|--------------|----------|---------------|-----------------------|
| 1         | 3.0          | 10.8     | 0.093         | 0.581                 |
| 2         | 2.0          | 9.90     | 0.101         | 0.634                 |
| 3         | 1.0          | 9.00     | 0.111         | 0.698                 |

![Figure 2. The 10th node response of the riser when working condition 1](image)

![Figure 3. The 80th node response of the riser when working condition 1](image)
Figure 4. The 140th node response of the riser when working condition 1

Figure 5. The 200th node response of the riser when working condition 1

Figure 6. The 10th node response of the riser when working condition 2

Figure 7. The 80th node response of the riser when working condition 2

Figure 8. The 140th node response of the riser when working condition 2

Figure 9. The 200th node response of the riser when working condition 2
Figure 10. The 10th node response of the riser when working condition 3

Figure 11. The 80th node response of the riser when working condition 3

Figure 12. The 140th node response of the riser when working condition 3

Figure 13. The 200th node response of the riser when working condition 3

Table 2. Node Response of the Riser

| Condition | Node | Cab(m) | Csw(m) | Growth Rate(%) |
|-----------|------|--------|--------|----------------|
| 1         | 10th | 0.139  | 0.138  | -0.42          |
| 1         | 80th | 0.074  | 0.078  | 5.46           |
| 1         | 140th| 0.051  | 0.055  | 8.59           |
| 1         | 200th| 0.028  | 0.024  | -16.99         |
| 2         | 10th | 0.120  | 0.120  | -0.02          |
| 2         | 80th | 0.070  | 0.074  | 6.03           |
| 2         | 140th| 0.051  | 0.053  | 3.99           |
| 2         | 200th| 0.031  | 0.027  | -13.68         |
| 3         | 10th | 0.098  | 0.098  | 0.52           |
| 3         | 80th | 0.064  | 0.068  | 7.45           |
| 3         | 140th| 0.046  | 0.049  | 6.00           |
| 3         | 200th| 0.035  | 0.028  | -18.53         |

*Cab responds to wave and top X direction motion response.
*Csw responds to the wave and top X direction motion response superimposed rigid body.
Figure 2-5, 6-9 and 10 to 13 are calculation for working condition 1-3. Each diagram, figure 2-5, in conditions 1, results calculated for node 10th, 80th, 140th and 200th are 0.13884m, 0.07412m, 0.05063m and 0.02849m. It showed with the increase of the node number, namely the increase of the depth of the water, the transverse responses of structure under wave action and X direction are in reduced, as shown in figure 14-16. Without considering the effect of ocean current, as the water depth increases, the response value decreases under the wave load and the top movement.

In waves and the top movement superposition of the rigid body oscillating movement, results calculated for node 10th, 80th, 140th and 200th are 0.13826m, 0.07817m, 0.05498m, 0.02365m. It showed with the increase of water depth, cross flow responses of structure on the top of the wave and movement superimposed structure rigid body action are in reduced, as shown in figure 14-16. It is important to note that structural response trend are similar after the superposition of rigid body swing, and only under the action of waves and the top movement. The structural response affected by rigid body swing does not exceed the waves and the top movement load effects.

The effect of the swing effect of rigid body with the wave and the top movement is simply seen as linear superposition, the node 10th, 80th, 140th and 200th calculation increases to -0.42%, 5.46%, 8.59% and -16.99%. As the water depth increases, the swing effect of rigid body increases first and then decreases, that is, with the increase of the radius of the axis of rotation, it increases and in turn decreases. The remaining working conditions have similar trends, as shown in figure 6-9, 10-13 and table 2.

![Figure 14. The response of the structure in Working condition 1](image1)

![Figure 15. The response of the structure in Working condition 2](image2)

![Figure 16. The response of the structure in Working condition 3](image3)

![Figure 17. The structure response of node 10th varies with the working condition.](image4)
Figure 18. The structure response of node 80th varies with the working condition.

Figure 19. The structure response of node 140th varies with the working condition.

Figure 20. The structure response of node 200th varies with the working condition.

Contrast between node 10th, 80th, 140th and 200th for condition 1-3 figure 17-20 shows that with the decrease of the motion amplitude, structural response is reduced, oscillation amplitude considering the rigid body oscillation for the top 10th and touchdown 200th and the amplitude regardless of the rigid body oscillation appeared different. The reason may be that the response of the top and bottom is complex. In the middle node amplitude considering rigid body oscillation is greater than that regardless of the rigid body oscillation.

The motion frequency applied at the top is not the same as the wave frequency, and the response is not the sinusoidal motion.

4. Conclusion
It is an important issue to calculate the transverse flow direction displacement of the structure, which is caused by the wave action. This paper does not consider the effect of water flow, and the complex response of the structure is studied from the perspective of the wave load and the linear motion of the top X direction.

Under the action of wave load, the response of the structure decreases with the depth. After coupling the top X direction, with the increase of the depth of the water, the phenomenon of the response decreases with the increase of the depth still exists. It explains the influence of top X direction linear motion on structures is not more than wave loading effects.

The structure is affected by rigid body sway and usually increases in response to the transverse flow response of the structure. In this article, the linear superposition of X direction movement, structural response performance for the top suspension point and the bottom the touch location area, structural response is not same to increase like the middle of SCR. In the middle of the SCR, response is usually increasing with the increase of the depth.
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