Design and Verification of the Real-time Monitoring System for Offshore Structures

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Abstract: The SCR installation system, a typical offshore structure, is designed to solve the problem that S-lay vessel cannot install the SCR independently. Because of the harsh environment of deep-sea, offshore structures will always withstand great compound load such as pressure, bending and torsion. In this paper, as a typical offshore structure, the SCR installation system is introduced first, and then combining with the characteristic of the system, the real-time monitoring programs are presented and the corresponding monitoring systems are developed to monitor the operation states of the system. In addition, the model test is carried out to verify the safety of the designed system and the function of the proposed monitoring system. The test results show that the monitoring system can monitoring the SCR installation system conveniently and real-timely. This paper provides the method and lays the foundation for monitoring offshore structures. Copyright © 2013 IFSA.

Keywords: SCR installation system, Monitoring system, Stress-strain measuring & analysis technique, Model test.

1. Introduction

Because of the length of the S-lay vessel stinger, it is difficult to get close to FPU, so the S-lay vessel cannot install SCR independently. Meanwhile, many risky factors and potential difficulties exist in both S-lay and J-lay methods because there are many underwater operations and difficulties in tension conversion. For these reasons above, the novel device named SCR installation system is developed to install the SCR [1-3].

The motions of pipe-laying vessel are affected by the marine environment such as wind, wave and current. And the large amplitude motion not only affects the stability of vessel, but also may result in the failure of the structure installed on the vessel. So the motoring system needs to be developed to monitor the motions of vessel and the security of structures should also be concerned.

In this paper, the designed SCR installation system is presented, and the measuring technique for its components such as A&R Wire limiting device, SCR fixture, connect legs is also proposed. During the installation process, the A&R wire should bear the whole weight of SCR, so attentions should also need to be paid to the tension changes of A&R wire. And the tension monitoring system is also designed. In order to verify the security of the SCR installation system and the function of the real-time monitoring system, the model test is carried out, and corresponding results are obtained and presented in this paper.
2. SCR Installation System

The overall dimension of the designed SCR installation system is 8.03 × 6.07 × 11.07 m. The gross weight of the system is 97.6 t. As shown in Fig. 1, the system includes: main tower, quick connector, SCR fixture and A&R wire limiting device. The main tower is designed as a truss structure, whose five legs are welded on the deck and they support all the weight of the tower. During the fixed process of SCR, the weight of it is also supported by these legs [4-5].

![Fig. 1. SCR installation system.](image)

The SCR fixture device is used to reduce the underwater operation time, which can improve operating reliability. The taper cylinder with a certain dip angle is consistent with the SCR installation angle. During the fixed process of SCR, all the weight of SCR is held by the fixture and because of the dip angle, it can also withstand torsional deformation and bending caused by the pressure.

Since the swing of the A&R wire is inevitable under the circumstances of wind–wave, the potential factors of insecurity are existed. To guarantee the stability of the A&R wire during the SCR installation process, a limiting device is designed to restrict the large amplitude swing of the A&R wire. The swing of the A&R wire will cause it to hit against the protection card of the limiting device and the collision force may result in the damage of it.

In addition, the dynamic amplifier factor (DAF) determined by hydrodynamic and other factors may significantly reduce the bearing capacity of the A&R wire. For Example, if the maximum capacity of A&R wire is 800 t and the DAF is 2, the maximum weight that the A&R wire can bear is 400 t.

Because of the reasons mentioned above, the force status of the components such as A&R limiting device, A&R fixture and the main tower should be concerned.

3. Development of the Monitoring System

During the SCR installation process, the factors that should be monitored are as follows: motion of the pipe-laying vessel, tension of the A&R wire, stress& strain of the A&R wire limiting device, A&R fixture and main tower.

3.1. Monitoring Programs of Vessel Motion

Three uppermost parameters of the ship attitude monitoring are roll, pitch and heave. And more attention should be paid to the heave of the pipe-laying vessel. The developed monitoring system contains the ship attitude measuring sensor, monitoring system (Fig. 2), attitude analysis system, and some accessories, such as UPS and industrial panel computer, etc.

The sensor is used to measure the attitude of the pipe-laying vessel, the developed monitoring system is used to monitor the status of the vessel in real-time and the analysis system is used to analyze the obtained data and characteristic of the vessel.

![Fig. 2. Vessel motion monitoring system](image)

1. UPS battery pack, 2. UPS (unpaused power supply), 3. Linear voltage converter, 4. Wave motion sensor, 5. Industrial panel computer.

3.2. Monitoring Tension of A&R Wire

As shown in Fig. 3, the tension of A&R wire is measured by S-sharp tension sensor, and each end of it is connected with the A&R Wire.

The tension of A&R wire can be displayed on the screen in real-time. And the tension variation range can be obtained by analyzing the data which is acquired from the vessel motion monitoring system, and the safety operation range of A&R wire under each sea-state can also be got.
3.2. Monitoring Tension of A&R Wire

3.2.1. Monitoring the Security of A&R Wire Protection Device

The A&R wire will impact the protection card of A&R wire limiting device under the influence of wave-current. And both the size and direction of the impact force are unknown. So the monitoring plan should not only consider the size of the force, but also the direction of it. For above reasons, the rosette gauge technique is used to monitor the size and direction of the impact force. However, the main stressed area is unknown and the FEM method is used to estimate the position. The position where rosette gauges are arranged is based on the calculation results of Abaqus. The measuring programs are shown in Fig. 4.

The red region is the monitoring focus, and through comparison, it can be seen that the protection card bears the largest impact force. So it is the most important monitoring part. Because the rosette gauge is easily damaged by the wire, it needs special treatment to avoid this damage. The monitoring principles are illustrated below:

The rosette is composed by three strain gauges. The angles between gauges and the X axis are 0°, 45°, and 90° respectively, and the corresponding strains are $\varepsilon_x$, $\varepsilon_y$, and $\varepsilon_{\theta}$. So the following equations can be got:

\begin{align*}
\varepsilon_0 &= \varepsilon_x, \\
\varepsilon_{xy} &= \frac{1}{2}(\varepsilon_x + \varepsilon_y) + \frac{1}{2}\varepsilon_{\theta}, \\
\varepsilon_{\theta} &= \varepsilon_y.
\end{align*}

According to the relationship of strain-stress, the equations can be expressed as:

\begin{align*}
\sigma_x &= E \left(1 - \mu^2\right) \left(\varepsilon_x + \mu \varepsilon_y\right), \\
\sigma_y &= E \left(1 - \mu^2\right) \left(\varepsilon_y + \mu \varepsilon_x\right), \\
\tau_{xy} &= \frac{1}{2}(\sigma_x - \sigma_y) = \frac{E}{2(1+\mu)}(\varepsilon_x + \varepsilon_y - 2\varepsilon_{xy}),
\end{align*}

By adopting the extreme way to obtain the direction and size of principle stress, so following equations can be expressed as:

\begin{align*}
\sigma_1 &= \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}, \\
\tan 2\alpha &= \frac{2\tau_{xy}}{\sigma_x - \sigma_y}.
\end{align*}
From Eq. (1) - (8), the size and direction of the principle stress is:

\[
\frac{\sigma_i}{\sigma_i} = \frac{E(\varepsilon_{\theta} + \varepsilon_{90})}{2(1-\mu)} \pm \frac{E}{2(1+\mu)} \sqrt{(\varepsilon_{\theta} - \varepsilon_{90})^2 + (\varepsilon_{\theta} + \varepsilon_{90} - 2\varepsilon_{45})^2},
\] (9)

\[
tg 2\alpha = \frac{2\varepsilon_{45} - \varepsilon_{\theta} - \varepsilon_{90}}{\varepsilon_{\theta} - \varepsilon_{90}},
\] (10)

where \(\alpha\) is the included angle between the principle stress and the x-axis, and the counterclockwise direction is positive.

The strain of three gauges is measuring in real-time, and then the size and direction of the principle stress can be monitored real-timely by the measuring device.

### 3.2.2. Monitoring the Security of SCR Fixture

During the fixed process of the SCR, the whole weight of the SCR is supported by the fixture. If the fixture fails, the SCR may fall into the sea-bed. So it is very important to monitor the key bearing parts of the SCR fixture. The selection of measuring point is also based on the calculation results from Abaqus in Fig. 5.

By comparing the FEM calculation results, it can be seen that the upper support plate and the taper cylinder are the main measuring parts. Because the direction is known, the gauges are used to measure the strain of these regions. The measuring point is shown in Fig. 5(b), and the monitoring principle is illustrated below:

By Adopting the half-bridge measure form, \(R_a\) is arranged in the axial direction and \(R_b\) is perpendicular to \(R_a\). \(R_c\) and \(R_d\) are constant resistances as shown in Fig 6. The stress of the measuring point can be calculated by the following equation:

\[
\sigma = \frac{E}{1+\mu} \varepsilon_{d},
\] (11)

where \(\sigma\) is the stress of measure point, \(E\) is elasticity modulus, \(\mu\) is poisson ratio and \(\varepsilon_{d}\) is the value measured by the device.

According to the Eq. (11), the relationship between strain and time can be converted to that between stress and time. So the stress of dangerous part can be monitored real-timely through the computer.
3.2.3. Monitoring the Security of the Tower

The main tower is the complex structure with huge size, so it is impossible to monitor all the parts of it. But the SACS can be used to find out the dangerous part of the tower. In the analysis, the influence of the vessel motion on the tower has been considered. The model is shown in Fig. 7.

The analysis results show that the legs which are connected with the deck of the vessel are the main forced components. The legs withstand pressing, bending and torsional loads simultaneously and the monitoring scheme should take all these factors into account. The scheme is shown in Fig. 8. And the monitoring principles are illustrated in the following part a-c [6].

3.2.3.1. Monitoring Scheme of Pressure

The designed measuring bridge circuit is shown in Fig. 9.

The relationship between the change rate of the resistance and the strain of each gauge is:

\[
\frac{\Delta R_a}{R_a} = K (\varepsilon_m + \varepsilon_N + \varepsilon_P), \quad (12)
\]

\[
\frac{\Delta R_b}{R_b} = K (-\varepsilon_m - \varepsilon_N + \varepsilon_P), \quad (13)
\]

\[
\frac{\Delta R_c}{R_c} = K (-\varepsilon_m + \varepsilon_N + \varepsilon_P), \quad (14)
\]

\[
\frac{\Delta R_d}{R_d} = K (\varepsilon_m - \varepsilon_N + \varepsilon_P), \quad (15)
\]

where \( \frac{\Delta R}{R} \) is the change rate of the gauge’s resistance, \( K \) is the sensitivity coefficient and \( \varepsilon_m, \varepsilon_N, \varepsilon_P \) represent the strain induced by bending moment, torque and pressure respectively.

It can be seen that the strain caused by bending and torque can be eliminated by connecting four gauges as Fig. 9.

From the generalized Hook’s law, the following equations can be got:

\[
\varepsilon_{ap} = \frac{1}{E} (\sigma_a - \mu \sigma_b) = \frac{P}{2EA} (1 - \mu), \quad (16)
\]

\[
\varepsilon_{bp} = \frac{1}{E} (\sigma_b - \mu \sigma_a) = \frac{P}{2EA} (1 - \mu), \quad (17)
\]

where, \( \varepsilon_{ap}, \varepsilon_{bp} \) are the strain of Ra and Rb which induced by pressure, and \( \sigma_a, \sigma_b \) are the stress in Ra and Rb direction, \( P \) is pressure, \( E \) is elasticity modulus, \( \mu \) is poisson ratio and \( A \) is cross-sectional area of the leg.

From Eq. (16) and Eq. (17), it can be seen that the strain of each gauge induced by pressure is the same.
The calculation formula of pressure is illustrated in Eq. (18)

\[ P = \frac{EA}{(1 - \mu)} \varepsilon_p, \quad (18) \]

### 3.2.3.2. Monitoring Scheme of Torque

Similarly, the designed measuring bridge circuit of torque is shown in Fig. 10.

![Fig. 10. Torque measuring bridge circuit.](image)

According to the generalized Hook’s law, the following equations can be got:

\[ \varepsilon_{x1} = \frac{1}{E} (\sigma_{x1} - \mu \sigma_{y1}), \quad (19) \]
\[ \varepsilon_{y2} = \frac{1}{E} (\sigma_{y2} - \mu \sigma_{x1}), \quad (20) \]

As \( \sigma_1 = -\sigma_2 = \tau \), so the Eq. (19) and (20) can be rewritten as follows:

\[ \varepsilon_{x1} = \frac{\tau}{E} (1 + \mu), \quad (21) \]
\[ \varepsilon_{y2} = -\frac{\tau}{E} (1 + \mu), \quad (22) \]

where \( \varepsilon_{x1}, \varepsilon_{y2} \) is the tangential and normal stress.

From (21) and (22) both the torsional and the shearing strength can be got:

\[ \tau = \frac{T}{W_p} = \frac{E}{1 + \mu} \varepsilon_{x1} = \frac{E}{1 + \mu} \frac{\varepsilon_p}{4}, \quad (23) \]

where \( W_p = \frac{\pi D^4}{32} \left[ 1 - \left( \frac{D}{D}' \right)^2 \right] \).

### 3.2.3.3. Monitoring Scheme of Bending Moment

The bending moment measuring bridge circuit is shown in Fig. 11.

![Fig. 11. Bending moment measuring bridge circuit.](image)

According to the generalized Hook’s law, the following equations can be got:

\[ \varepsilon_{a,M} = \varepsilon_{b,M} = \frac{1}{E} (\sigma_a - \mu \sigma_b) = \frac{M}{2EW} (1 - \mu), \quad (24) \]
\[ \varepsilon_{c,M} = \varepsilon_{d,M} = \frac{1}{E} (\sigma_c - \mu \sigma_b) = -\frac{M}{2EW} (1 - \mu), \quad (25) \]

where \( \varepsilon_{a,M}, \varepsilon_{b,M} \) are the strain of Ra and Rb which induced by bending moment, and \( \sigma_a, \sigma_b \) are the stress in Ra and Rb direction, \( M \) is the bending moment, \( E \) is elasticity modulus, \( \mu \) is the poisson ratio and \( W = \frac{\pi D^4}{32} \left[ 1 - \left( \frac{D}{D'} \right)^2 \right] \).

From Eq. (24) and (25), the calculation formula of bending moment can be got:

\[ M = \frac{EW}{(1 - \mu)} \varepsilon_p, \quad (23) \]

The pressure, torque, and bending moment can be got by solving Eq. (18), (23) and (26) respectively. From the derived equations, the relationship between the bending moment, torque, pressure and time can be obtained and the stress of dangerous part can be monitored real-timely though the computer.

### 4. Model Test

To verify the proposed monitoring scheme, the model test is carried out. The SCR installation system is scaled by 1:10 and the model and the testing scheme are shown in Fig. 12. The devices contains: 6-DOF platform, SCR model, SCR installation system model and boundary conditions apply system. The 6-DOF is used to simulate the motions of the vessel and the boundary conditions apply system replaces the weight of the SCR [7, 8].

The HYSY201 is selected as the target vessel and the following sea-state is adopted: wind speed is 16 m/s, significant wave height is 3 m, wave period is 9 s and the wave spectrum is Jonswap. The corresponding motion parameters of the vessel are shown in Table 1.
Table 1. Motion parameters of the vessel.

<table>
<thead>
<tr>
<th>Sea state</th>
<th>Period (s)</th>
<th>Heave (m)</th>
<th>Roll (°)</th>
<th>Pitch (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>2.38</td>
<td>2.73</td>
<td>0</td>
</tr>
</tbody>
</table>

4.1. Monitoring the Tension of A&R Wire

The tension of A&R wire is shown in Fig. 13. The applied weight is about 4000 kN, and it can be seen that the range of tension is between 3000-5000 kN, and then a dynamic amplifier factor can be obtained. Under this sea state, the DAF is about 1.23, which means the HYSY201 with a winch of 400 t has ability to install the structures whose weight is less than 320 t. It provides the criteria for Subsea production facilities installation [9-16].

4.2. Monitoring of SCR Fixture

As shown in Fig. 14, the stress of the fixture changes with time. The blue line is the maximum allowable working stress, and the red line and dot line represent the measuring value. So the stress of the fixture can be monitored real-timely.

4.3. Monitoring of the Tower

As shown in Figs. 15 - 17, the pressure, torque and bending moment of the legs will change with time.
Fig. 15. Supporting leg pressure time history curve.

Fig. 16. Supporting leg torque time history curve.

Fig. 17. Supporting leg bending moment time history curve.
It can be seen that the pressure on five supporting legs is almost the same. And both of them are within the permissible stress range. The test results also show that the torque of five legs is very small and can be ignored during the monitoring programs. Meanwhile, the bending moment of five legs is also small, but it bigger than the torque because the fixture has a 10° dip angle. Therefore, the bending moment of the supporting legs should also be considered in the monitoring programs.

6. Conclusions

The designed monitoring system could monitor the stress of dangerous part of SCR installation system, the tension of A&R wire and the motions of the pipe-laying vessel real-timely. The model test can provide the novel method to estimate the maximum capacity for the winch to install subsea production system. Because the motions of the vessel are known, the corresponding capacity of the winch can be obtained through the test. In addition, the monitoring programs can also be applied in other offshore complex structures with huge size.

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