Numerical investigation on VIV suppression of marine riser with triangle groove strips attached on its surface

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Abstract

The effects of Triangle Groove Strips (TGS) on Vortex-induced Vibration (VIV) suppression of marine riser are numerically investigated using Computational Fluid Dynamics (CFD) method. The range of Reynolds number in simulations is $4.0 \times 10^5 < \text{Re} < 1.2 \times 10^7$. The two-dimensional unsteady Reynolds-Averaged Navier-Stokes (RANS) equations and Shear Stress Transport (SST) k-ω turbulence model are used to calculate the flow around marine riser. The Newmark-b method is employed for evaluating the structure dynamics of marine riser. The effect of the height ratio ($\epsilon$) of TGS on VIV suppression is evaluated. The amplitude responses, frequency responses, vortex patterns and the flow around the structures are discussed in detail. With the increase of the height ratio of TGS, the suppression effect of TGS on VIV suppression is improved firstly and then weakened. When $\epsilon \leq 0.04$, the suppression effect of TGS is the best. Compared with the VIV responses of smooth marine riser, the amplitude ratio is reduced by 38.9%, the peak of the lift coefficient is reduced by 69% and the peak of the drag coefficient is reduced by 40% when $\text{Re} = 6.0 \times 10^4$. With the increase of Reynolds number, the suppression effect of TGS on VIV suppression is improved firstly and then weakened. When the Reynolds number is $7.0 \times 10^4$, the amplitude ratio can be reduced by 40.1%. As to the large-amplitude vibration cases, the TGS show nice suppression effect on VIV.

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1. Introduction

Vortex-induced Vibration (VIV) is a well-recognized Fluid-Structure Interaction (FSI) phenomena, which especially occurs in ocean engineering, such as bridge, oil pipeline, marine riser and so on (Lou et al., 2017). When the ocean current flows around the marine riser, vortex sheds in the rear of the structure. The vortices apply periodic hydrodynamic forces on the marine riser, which results in VIV (Wong and Kim, 2018). Especially, when the frequency of vortex shedding is close to the natural frequency of marine riser, the large-amplitude vibration will be more severe, which is called the "lock-in" phenomenon (Chen and Kim, 2010; Park et al., 2016). VIV is one of important causes of fatigue damage or structure instability of marine riser. Therefore, VIV suppression has attracted more and more attention in ocean engineering (Chen and Kim, 2012; Gao et al., 2017).

The methods of VIV suppression are divided into active control methods and passive control methods (Zdravkovich, 1981). The active control methods require additional energy input and the design of devices is more complex. The effect of electromagnetic force on VIV suppression had been studied using the experimental method (Artana et al., 2003). The effect of the suction and blowing on VIV suppression had been studied, and the results showed that the amplitude of vibration could be reduced by 70% (Li et al., 2003). The scheme of the rotating cylinder was proposed by Baek and Sung (1998), and the results showed that VIV was well controlled and the drag of marine riser was reduced. Compared with the active control methods, the passive control methods are more simple and many methods have been applied in practical engineering. The scheme of the roughness strips attached on the surface of marine riser was proposed by Park et al. (2016), and the amplitude of VIV responses can be reduced by 30%. The effect of the control rods on VIV suppression had been investigated by Zhu and Yao (2015), and the control effect was the best when the number of control rods was 9. The effect of helical strakes on VIV suppression had been investigated (Sui et al., 2016).
Some scholars have proposed that the separation of boundary layer could be changed by using protuberant structure attached on the surface of marine riser, which contributed to VIV suppression. The effect of the longitudinal wavy surface on VIV suppression had been investigated by Zhu et al. (2018), and the results showed that the vortex shedding could be effectively suppressed when the height of the protuberant structure was larger than a certain value. The effect of the hemispherical structure on VIV suppression had been studied by Assi and Bearman (2018). The scheme proposed in this paper is similar to those of the above methods, but the shape of the protuberant structure is triangle. The triangle protrusion has a great advantages on VIV suppression, compared with the hemispherical protrusion, rectangular protrusion and other kinds of protrusion shapes (Zhu et al., 2018). VIV responses of marine risers with TGS are numerically investigated for Reynolds number ranging from $4.0 \times 10^4$ to $1.2 \times 10^5$. In the present study, the physical model is established in section 2, and the numerical model is established in section 3. In section 3, the numerical model is validated by the experimental results. The effects of the height ratios of TGS on VIV suppression are discussed in section 4. Some conclusions are presented in section 5.

2. Model description

The marine riser with TGS is presented in Fig. 1, and TGS is distributed symmetrically attached on riser’s surface. As shown in Fig. 1, the main parameters of TGS include the height ($h$). Based on the previous studies (Park et al., 2016; Zhu et al., 2018), the scope of the strips distribution is defined ($\theta_{\text{min}} = 60^\circ$ and $\theta_{\text{max}} = 105^\circ$). The parameter $h$ is reduced as follows:

$$\varepsilon = \frac{h}{D}$$  \hspace{1cm} (1)

The main parameters of VIV system are the same for all simulations, as shown in Table 1. The model specifications of TGS is similar to that in the experiments of Park et al. (2016), who investigated the VIV suppression of bluff body at the University of Michigan. Therefore, the parameters of simulations refers to that of the previous experiments.

The purpose of this paper is to investigate the suppression effect of TGS on VIV responses of marine risers, and the main parameter of TGS is the height ratio ($\varepsilon$). The range of Reynolds number is $4.0 \times 10^4$–$1.2 \times 10^5$. There are 9 cases listed in Table 2.

3. Numerical model

3.1. Equations of motion

VIV of marine riser is a typical fluid-structure interaction

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m^*$</td>
<td>1.725</td>
</tr>
<tr>
<td>$\xi$</td>
<td>0.0158</td>
</tr>
<tr>
<td>$f_0$</td>
<td>1.25</td>
</tr>
<tr>
<td>$K$</td>
<td>1063</td>
</tr>
<tr>
<td>$D$ (mm)</td>
<td>90</td>
</tr>
<tr>
<td>$\rho$ (kg/m$^3$)</td>
<td>$1.0 \times 10^3$</td>
</tr>
<tr>
<td>$\nu$ (m$^2$/s)</td>
<td>$1.0 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
A simple mathematical model.

where $C_{n} = 1$ (Zhu et al., 2018).

The Newmark-$\beta$ method is used to solve the equation of motion, which is an implicit time integration method (Newmark and Veletsos, 1952). The linear acceleration assumption is amended in the Newmark-$\beta$ method. At the time $t + \Delta t$, the parameters $\alpha$ and $\beta$ are introduced in the expression of velocity and displacement. Two basic equations are obtained:

\[
y_{t+\Delta t} = y_{t} + y_{t} \cdot \Delta t + \left[ \frac{1}{2} - \beta \right] \cdot y_{t} + \frac{\beta \cdot y_{t+\Delta t} \cdot \Delta t^{2}}{2}
\]

(8)

\[
y_{t+\Delta t} = y_{t} + \left[ \frac{1 - \alpha}{\beta} \right] \cdot y_{t} + \frac{\alpha \cdot y_{t+\Delta t} \cdot \Delta t}{\beta}
\]

(9)

According to Eq. (8) and Eq. (9), $\dot{y}_{t+\Delta t}$ and $\ddot{y}_{t+\Delta t}$ can be expressed as:

\[
\dot{y}_{t+\Delta t} = \frac{1}{\beta \cdot \Delta t^{2}} \cdot (y_{t+\Delta t} - y_{t}) - \frac{1}{\beta \cdot \Delta t} \cdot \dot{y}_{t} - \frac{1}{2 \beta} \cdot \dot{y}_{t}^{2}
\]

(10)

\[
\ddot{y}_{t+\Delta t} = \frac{\alpha}{\beta \cdot \Delta t} (y_{t+\Delta t} - y_{t}) + \left(1 - \frac{\alpha}{\beta}\right) \cdot \dot{y}_{t} + \frac{\alpha}{2 \beta} \cdot \dot{y}_{t}^{2}
\]

(11)

At the time $t + \Delta t$, Eq. (2) has the following form:

\[
M \cdot \ddot{y}_{t+\Delta t} + C_{\text{total}} \cdot \dot{y}_{t+\Delta t} + K \cdot y_{t+\Delta t} = F_{\text{fluid}}(t)_{t+\Delta t}
\]

(12)

Based on the previous study (Newmark and Veletsos, 1952), the values of $\alpha$ and $\beta$ are 0.5 and 0.25. Considering Eqs. (10) and (11), the items $\ddot{y}_{t+\Delta t}$ and $\dot{y}_{t+\Delta t}$ can be obtained.

Finally, Eq. (12) is simplified as:

\[
[K] \cdot (y_{t+\Delta t} - y_{t}) = [F]
\]

(13)

where $[K] = K + \frac{1}{\beta \cdot \Delta t^{2}} M + \frac{\alpha}{\beta \cdot \Delta t} C_{\text{total}}$.

\[
[F] = F_{\text{fluid}}(t)_{t+\Delta t} + \left[ \frac{1}{\beta \cdot \Delta t^{2}} \cdot (y + \frac{1}{2} \cdot \dot{y}_{t}) + \left(1 - \frac{\alpha}{\beta}\right) \cdot \dot{y}_{t} + \frac{\alpha}{2 \beta} \cdot \dot{y}_{t}^{2} \right] \cdot M + \frac{\alpha}{\beta \cdot \Delta t} \cdot \dot{y}_{t} + \left(1 - \frac{\alpha}{\beta}\right) \cdot \dot{y}_{t} + \frac{\alpha}{2 \beta} \cdot \dot{y}_{t}^{2} \right] \cdot C_{\text{total}}
\]

The solution of the above equations (Eqs. (10), (11) and (13)) are realized by the C language, and the algorithms are embedded in UDF. Firstly, hydro-force exerts on the riser surface and the flow velocity is constant. Then, the force and the torque imposed on marine riser are by calculated by solving 2D-RANS equations. According to the force and the torque, UDF calculates the displacement, velocity and acceleration of motion at time $t + \Delta t$. Finally, the mesh is updated based on the displacement of motion. The process of VIV is realized by the above methods, as shown in Fig. 3.

### 3.2. Computational domain

The entire computational domain is divided into three regions, including Sub-Domain, Slipway and External Flow Field, as shown in Fig. 4. Due to the amplitude of motion may be high, the lengths of computational domain in x-direction and y-direction are 60D and 40D. The entire domain includes four kinds of boundaries, which are inlet, outlet, wall and riser-wall. Because k-\omega SST turbulence model is adopted, the mesh resolution of the riser-wall is used with $y^{+}$, which is about 1. And the $y^{+}$ is defined as (Zhu and Yao, 2015):

\[
y^{+} = 0.172 \cdot \frac{\Delta x}{D} \cdot Re^{0.9}
\]

(14)

Where $\Delta x$ is the height of the first layer mesh. The mesh is shown in Fig. 5.

The Layer-Method is adopted in Fluent for updating mesh. Moving Layer are located at the top and the bottom of Sub-Domain for solving the motion in y-direction. The different mesh regions are merged using the Interface. The Sub-Domain and Riser-wall move up and down together (Ding et al., 2015).
3.3. Model validation

The density of the mesh can affect the accuracy of the numerical model. Therefore, the grid independence validation is conducted using different grid density, including $1.5 \times 10^5, 1.6 \times 10^5, 1.7 \times 10^5, 1.8 \times 10^5$. As shown in Table 3, results show that the amplitude responses are almost the similar. The percentage differences between the two grids of M4 and M3 is 0.37%, which is less than 1%. Based on the previous study (Gao et al., 2018), the grids of M4 can be adopted when the percentage difference between M3 and M4 is less than 1%.

Because the transient CFD method is adopted, the time-step has an effect on the accuracy of the simulation.

Time-step independence is validated using four kinds of time-steps, including 0.002s/step, 0.003s/step, 0.004s/step and 0.006s/step. The amplitude of VIV are presented in Fig. 6. For 0.002s/step and 0.004s/step, the results are almost similar. Finally, 0.003 s/step is selected in the present study.

Before the numerical simulation is carried out, the accuracy of numerical model must be verified by the experimental results and other CFD results (Khalak and Williamson, 1996; Gao et al., 2017). The VIV response of the cylinder is numerically simulated in the range of $2 < U^* < 14$ and the surface roughness is same, as shown in Fig. 7. The frequency of vibration is calculated by Fast Fourier Transform (FFT) of the displacement, and the displacement of vibration is the maximum values in the stable region. In general, the numerical results are in excellent agreement with the experimental data, despite some differences remain. The possible reason is the difference of VIV system parameters, such as the spring stiffness per unit length and the added mass. Based on the amplitude response and the frequency response, the response region is divided into three branches, including the initial branch (I), the upper branches (U), and the lower branches (L) (Khalak and Williamson, 1996). The vortex patterns are different in the different branches. The vortex pattern is 2S mode in the initial branch, 2P mode in the upper branch and no synchronized mode in the lower branch (Khalak and Williamson, 1996). 2S means that two vortices shed during one cycle with different sign rotating, and

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Number of elements</th>
<th>$A^*$</th>
<th>The percentage difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>150000</td>
<td>0.721</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>160000</td>
<td>0.781</td>
<td>8.33%</td>
</tr>
<tr>
<td>M3</td>
<td>170000</td>
<td>0.802</td>
<td>3.85%</td>
</tr>
<tr>
<td>M4</td>
<td>180000</td>
<td>0.799</td>
<td>0.37%</td>
</tr>
</tbody>
</table>

![Fig. 3. The procedures of the numerical calculation.](image3)

![Fig. 4. The entire computational domain.](image4)

![Fig. 5. The mesh (a) the mesh of entire domain; (b) the mesh around the riser.](image5)

![Fig. 6. The time-step independence validation.](image6)
the intensity of vortices are almost the same. 2P means that two vortices shed during each half cycle with different sign rotating, and the intensity of the first shedding vortex is stronger. There are many advantages in displaying vortex pattern, wake interaction, velocity distributions and frequency characteristics using numerical model. Therefore, the numerical model is available in the present study.

4. Results and discussions

4.1. Hydrodynamic coefficients

Fig. 8 shows the hydrodynamic coefficients versus the height ratio. Both the mean drag coefficient ($C_d$) and the root mean square of lift coefficient ($C_L$) decrease firstly and then increase. When $\varepsilon = 0.04$, $C_d$ and $C_L$ are all the smallest value, which means that the suppression effect is the best. When $\varepsilon = 0.10$, $C_d$ and $C_L$ are bigger than that of $\varepsilon = 0.00$, which means that the VIV response is strengthened. So $\varepsilon$ can not be too big. The $C_d$ decreases from 2.7819 (T1) to 1.9701 (T4), which reduces by 29.2%. The mean drag coefficient has a nearly threefold increase over a stationary cylinder case, which is consistent to the test result of Khalak and Williamson. (1996). The $C_L$ decreases 0.4295 (T1) to 0.1521 (T4), which reduces by 64.6%. The periodic lift is the fundamental cause of VIV. So the VIV response is suppressed when lift is decreased.

The hydrodynamic coefficients of T1 and T4 are compared in Fig. 9. The drag coefficient ($C_d$) and lift coefficient ($C_L$) of T4 become more stable compared with that of T1. The peak of the drag coefficient decreases from 4.5 (T1) to 2.7 (T1), which is reduced by 40%. The peak of the lift coefficient decreases from 1.3 (T1) to 0.4 (T4), which reduces by 69%. The possibility of fatigue damage and structural instability of marine riser is reduced.

4.2. Amplitude responses and frequency responses

Fig. 10 shows the amplitude ratios and frequency ratios versus the height ratio. The amplitude ratios ($A^*$) decrease firstly and then increase. When $\varepsilon = 0.04$, the amplitude ratio is the smallest value, which means that the control effect is the best. When $\varepsilon = 0.10$, the amplitude ratio is bigger than that of $\varepsilon = 0.00$, which means that the VIV response is strengthened. The amplitude ratio decreases from 1.0 (T1) to 0.61 (T4), which reduces by 38.9%. The frequency ratios increases slightly, which increases from 1.0 (T1) to 1.05 (T3,T4,T5,T6,T7 and T8). When $\varepsilon$ is 0.03 - 0.08, the frequency ratio is stable. Therefore, the TGS show stable suppression effect on VIV.

The amplitudes of T1 and T4 are compared in Fig. 11. The peak of

![Fig. 7. Numerical model validation (a) Comparisons of amplitude and (b) Comparisons of frequency.](image)

![Fig. 8. The hydrodynamic coefficients versus the height ratios (Re = 6.0 \times 10^4).](image)

![Fig. 9. Comparison of hydrodynamic coefficients of T1 and T4 (Re = 6.0 \times 10^4).](image)
the amplitude decreases from 0.09 m (T1) to 0.055 m (T1), which is reduced by 38.9%. The possibility of fatigue damage and structural instability of marine riser is reduced.

4.3. Effect of Reynolds number

The suppression effect of TGS on VIV suppression may be changed with the increase of Reynolds number. The amplitude ratios of T1 and T4 are compared when Reynolds numbers are $4.0 \times 10^4$, $6.0 \times 10^4$, $7.0 \times 10^4$, $8.0 \times 10^4$, $1.0 \times 10^5$ and $1.2 \times 10^5$, as shown in Fig. 12.

The following conclusions can be obtained from Fig. 10. With the increase of Reynolds number, the amplitude ratio of marine riser (T1) increases firstly and then decreases, and the amplitude ratio is close to 1 when Reynolds number is 60000–70000. With the increase of Reynolds number, the suppression effect of TGS on VIV suppression is strengthened firstly and then weakened. When the Reynolds number is 7.0 $\times$ $10^4$, the amplitude ratio can be reduced by 40.1%. As to the large-amplitude vibration cases, the TGS show nice effect on VIV suppression. When $Re > 1.0 \times 10^5$, the amplitude ratio of T1 decreases because it is far away from the resonance region. Therefore, even if the suppression effect of TGS is weakened, the amplitude ratio is low as to the high Reynolds number cases.

4.4. Flow field around the structure

When VIV response is strengthened, there will be more vortices shedding in one cycle. On the contrary, there will be less vortices shedding in one cycle. As shown in Fig. 13, the TGS has a obvious effect on the vortex pattern. Based on the vorticity contours of T1, the wake pattern is 2P mode in the upper-branch (2P mode is explained in section 3.4). With the increase of $\varepsilon$, the wake pattern changes from 2P mode to 2S mode, and then changes from 2S mode to 2P mode. When the $\varepsilon = 0.04$ (T4), the wake pattern is a stable 2S mode. Therefore, the TGS show nice suppression effect on VIV when $\varepsilon = 0.04$.

Fig. 14 shows the relative pressure contours of VIV responses. As shown in Fig. 14, the TGS has a obvious effect on the flow around the structure. Based on the pressure contour of T1, there is low-pressure vortex shedding behind the marine riser, and the strength of vortex is about $\sim 1.5$. With the height ratio of TGS, the strength of vortex increases firstly and then decreases. The strength of vortex is about $\sim 0.9$ for T4 ($\varepsilon = 0.04$). Therefore, the formation of vortex is destroyed and the strength of vortex is controlled. With the increase of $\varepsilon$, the pressure increases at the starting position of TGS, which means that VIV response is strengthened and the drag of marine riser increases. Therefore, the height ratio of TGS can not be too high. When the height ratio of TGS is low, the suppression effect of TGS is limited. So the TGS show the best suppression effect on VIV when the height ratio of TGS is at a certain value.

Fig. 15 shows the wall pressure distribution of marine riser. The pressure distribution of riser' wall is changed. The pressure of T1 decreases from 700 pa to $\sim 1.6$ pa along the direction of flow. However, the pressure of T4 decrease from 250pa to $\sim 0.9$ pa. The pressure difference of riser' wall is reduced. The pressure difference is the bigger, the vortex shedding is the stronger. The wall pressure distribution is changed dramatically at the location of TGS distribution.

5. Conclusions

Marine riser with Triangle Groove Strips (TGS) attached on its surface are numerically investigated. The two-dimensional unsteady RANS equations and k-ω Shear Stress Transport (SST) turbulence model are used to calculate the flow around the structure. The Newmark-β method is employed for evaluating the structure dynamics of marine riser. The effect of the height ratio ($\varepsilon$) of TGS on VIV suppression is evaluated. The numerical model is verified by others experimental results. The Reynolds number range of
simulations is $4.0 \times 10^4 < \text{Re} < 1.2 \times 10^5$. The amplitude responses, frequency responses and vortex patterns have been discussed in detail. Based on the above researches, the following conclusions can be obtained:

(1) With the increase of $\varepsilon$, the effect of TGS on VIV suppression is improved firstly and then weakened. When $\varepsilon = 0.04$, the suppression effect of TGS is the best. The peak of the lift coefficient can be reduced by 69%. When $\varepsilon = 0.04$, the peak of the drag coefficient can be reduced by 40%.

(2) The peak of amplitude is 0.055 m for $\varepsilon = 0.04$. Compared with T1 (the peak of amplitude is 0.09 m), the peak of amplitude can be reduced by 38.9%.

(3) With the increase of Reynolds number, the effect of TGS on VIV suppression is improved firstly and then weakened. When Re = 70000, the amplitude ratio can be reduced by

![Fig. 13. Vorticity contours of VIV responses when Re = 6.0 \times 10^4.](image1)

![Fig. 14. Comparisons of relative pressure of VIV responses (Re = 6.0 \times 10^4).](image2)
40.1%. As to the large-amplitude vibration cases, the TGS show nice suppression effect on VIV.

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References


