Study on Vortex-induced Vibration Characteristics of Large Slenderness Ratio Tandem Risers

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Abstract. The fluid mechanics software-Fluent was used to simulate vortex-induced vibration (VIV) of flexible tandem risers with large slenderness ratio. In this paper, VIV of a single riser and the flexible tandem risers with large slenderness ratio at a spacing of 2-16 times were numerically simulated, which was based on slicing principle for 2-DOF vortex-induced fluid-structure coupled vibration. The ratio of vibration frequency between upstream and downstream risers, dimensionless amplitude and the effects of reduced speed of the risers were discussed under different spacing conditions. The preliminary results show that the VIV characteristics of the upstream riser is similar to the single riser, “lock-in” occurs obviously, the frequency ratio of lift force and drag force is 1:2 over the entire reduced velocity range, and there is no obvious “lock-in” in the downstream riser due to the influence of the wake of upstream riser. The maximum cross-flow amplitude reaches 0.9 times the diameter of the riser, and complex coupling phenomena such as the 1:1.5 times frequency ratio and double “8” track were observed.

Introduction

Due to various factors such as economy and flexibility, the group tube (column) system has been widely used in risers and submarine pipelines. The risers are closely arranged and interact with each other, making the VIV situation more complicated. Therefore, scholars have carried out many researches on the fluid-structure coupling between multiple risers[1-3]. Vinh-Tan[4] used numerical research methods to analyze the wake induced vibrations of cylinders in tandem arrangement at subcritical Reynolds numbers and there was a very good consistency in the response of the downstream riser; Jian[5] analyzed the VIV of a series of elastically mounted cylinders by numerical analysis. It was confirmed for the first time that there was an asymmetric vibration mechanism—an anomalous biased oscillation regime, and the main existence range of the biased oscillation zone was determined; Guo Xiao-ling [6] found the interference between the tandem cylinders by studying the series double cylinders with low Reynolds number (Re=150) with numerical simulation method; Ming Zhao[7] based his study on the finite element method to solve the N-S equation, and found the spacing between series risers has a significant effect on the response; Zhang[8] used two-dimensional numerical simulation to study the VIV of two bluff bodies with different cross sections arranged in a certain diameter interval, and found that the amplitude ratio curve and cross section of the downstream cylinder has no relationship with shape, but it changes regularly with the spacing. In addition, HaiSun, Tamimi etc.[9,10] also conducted related research in this area and achieved some results.

In this paper, the computational fluid dynamics method is used to numerically simulate the VIV of large slenderness flexible riser. According to slicing principle, the fluid domain is divided into several two-dimensional planes along the longitudinal direction of the riser, and the two-dimensional flow field calculation is performed separately, and the fluid force is applied to the riser model by the UDF function to solve the newmark-β to obtain the dynamic response. The VIV of the single riser and the
tandem riser under uniform flow is numerically simulated and the differences of VIV characteristics are studied.

**Numerical Calculation and Experimental Model**

Computational model and meshing

In this paper, the fluid area is set to a rectangular area of \((40D+xD)\times20D\) (D is the diameter of the cylinder, x is the ratio of the distance between the two risers to the diameter of the riser), the left side is the speed entrance, and the right is the pressure outlet, the upper and lower boundaries are free-sliding walls (as shown in Figure 1). The grid is divided by gambit software, and the manual encryption process is performed around the riser to meet the calculation accuracy and speed requirements (as shown in Figure 2).

![Figure 1](image1.png)

**Figure 1. Computational domain geometry**

![Figure 2](image2.png)

**Figure 2. Tandem riser calculation domain meshing and detail around the riser wall.**

The structural parameters of the riser model are shown in Table 1. The first-order natural frequency is 1.0487 Hz. The fluid is water.

<table>
<thead>
<tr>
<th>Outer diameter (D_1)</th>
<th>Inner diameter (D_2)</th>
<th>Length (l)</th>
<th>Density (\rho)</th>
<th>Elastic Modulus (E_1)</th>
<th>Poisson's ratio (\nu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03[m]</td>
<td>0.027[m]</td>
<td>2[m]</td>
<td>7850[kg/m(^3)]</td>
<td>1.0e8[pa]</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Simulation method reliability verification

In order to verify the reliability of the numerical simulation, the flow around the cylinder with \(Re=20000\) is analyzed, and the time history curve of the lift and drag coefficient is obtained in Figure 3. In this case, the lift coefficient \(Cl\) of the cylinder is about 0.69, and the drag coefficient \(Cd\) is approximately 1.1. Comparing the results with the existing results of cylindrical flow (as shown in Table 2), it can be seen that the simulation results are similar to the existing classical results. Therefore, it is proved that the meshing and turbulence model selection in this paper meets the requirements, that is, the numerical simulation has reliability.
Table 2. Comparison of results of cylinder flow around Re=20000 compared with the existing results.

<table>
<thead>
<tr>
<th>Re=20000</th>
<th>Cd Mean</th>
<th>Cl Amplitude</th>
<th>Cl Mean square error</th>
<th>St</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lu</td>
<td>1.30</td>
<td>0.60</td>
<td>/</td>
<td>0.201</td>
</tr>
<tr>
<td>BaiZhining</td>
<td>1.17</td>
<td>1.18</td>
<td>0.71</td>
<td>0.21</td>
</tr>
<tr>
<td>Yokuda</td>
<td>1.20</td>
<td>/</td>
<td>/</td>
<td>0.21</td>
</tr>
<tr>
<td>Results of this article</td>
<td>1.10</td>
<td>0.97</td>
<td>0.69</td>
<td>0.206</td>
</tr>
</tbody>
</table>

**Results Analysis**

Spectrum analysis

When the motion frequency is close to the natural frequency of the riser, the transverse flow direction of the riser does not increase with the increase of the reduction speed, but approaches the natural frequency of the riser, this phenomenon is called the "lock-in". The range of reduced speeds is called the "locked area". Figure 4 shows the lift frequency as a function of the reduction rate for a single riser and tandem risers at different pitch ratios. The lift force frequency of the upstream riser and the single riser at each interval is basically the same as the reduction speed: the lift frequency is horizontal when the reduction speed is 5-8, and it is basically maintained near the natural frequency of the structure. At this time, the "lock-in" occurs; under different spacing conditions, the range of the reduction speed of the upstream riser "lock-in" is basically the same, indicating that the spacing has no effect on the speed range of upstream riser. The lateral force frequency of the downstream riser always increases linearly with the increase of the reduction speed, and no obvious "lock-in" occurs.

Figure 4 is a frequency spectrum diagram of lift of each riser at a pitch ratio of 8D and different reduction speeds. It can be seen from the figure that in the non-locking zone (for example, Ur=2, as shown in Figure 5a, b), the ratio of the two directions of force to the upstream and downstream risers is 1:2. Due to the horizontal and downstream flow response frequency of the riser, the response frequency ratio is basically the same as the force frequency ratio. The trajectory of the centroid of the upstream riser is a regular "8" shape. The movement of the downstream riser is affected by the vortex of the upstream riser, and the movement trend of the downstream riser changes to a more complex double "8" shape (as shown in Figure 6a, b). When the riser enters the lock zone (taking Ur=7 as an example, as shown in Figure 5c, d), the two-way force-coupling relationship between the upstream and downstream risers becomes complicated: the upstream riser has a distinct secondary peak frequency in both the transverse and...
downstream directions, and the ratio of the main peak frequencies is 1:2, and the ratio of the secondary peak frequencies is approximately 1:2; the main peak of the downstream riser to the force frequency is in a 2:1 relationship with the cross flow direction, and the frequency of the cross flow direction is approximately the secondary peak frequency value of the 1:1 relationship. Although the coupling relationship between the force and frequency of the two risers in the locked zone is complicated, the motion trajectories of the two centroids are still relatively regular "8" shape (as shown in Figure 6c, d). In the over-locking zone (for example, \( Ur=12 \), as shown in Figure 5e, f), the ratio of the two-way force of the upstream riser changes back to the regular 1:2 relationship, while the downstream riser is affected by the wake of the upstream pipe, and the lift shows the flow force is approximately 1:1 with the secondary peak frequency.

Figure 5. Upstream and downstream risers vibration spectrum diagrams at different reduction speeds.
Displacement response analysis

Figure 7 shows the mean square error curve of the cross-flow response of a series of double risers with a single riser and different spacing ratios as a function of the reduction rate. Comparing the single riser with the upstream riser in a diagram, it can be seen that in the case of each spacing, the change of the cross-flow response of the upstream riser with the reduction speed is similar to that of the single riser: after the VIV enters the locking zone, a significant resonance occurs. And the maximum response of the upstream riser in the whole reduction speed range is basically equal under the interval. However, when the pitch is small (6D), the resonance speed of the resonance is wider, and after crossing the lock zone, the cross-flow response of the front tube in the 6D state is slightly larger than the other pitches, indicating that 6D is a dangerous interval for the upstream riser; the transverse flow response of the downstream riser under each spacing ratio does not show obvious vortex-induced resonance, but when the speed reaches 7, there is a surge, and after that, the high-vibration state is maintained. After the reduction speed is greater than 9, the cross-flow response of the downstream riser is much larger than the single riser when it was out of locked area, and at this stage, the response at 8D spacing is mostly the largest of each interval, indicating that 8D is a more dangerous spacing for the downstream riser.

Figure 8 shows the mean square deviation curve of the flow direction of the tandem risers in the case of single riser, 6D, 8D, and 12D. It can be seen from the figure that the forward displacement response curve of the upstream riser under different spacing ratio conditions is similar to that of a single riser: the “lock-in” starts from Ur=3 and ends to Ur=7. When the reduction speed reaches 8, the upstream riser forward displacement response value at each pitch increases again, and decreases when
the reduction rate is about 11. There is no obvious resonance in the downstream movement of the
downstream riser. The response value in the locking zone is basically smaller than that of the single
riser. Especially when the reduction rate is 4, the displacement ratio of the larger spacing ratio (8D,
12D) decreases. When the lock zone is exceeded, the downstream response of the single riser is
greatly reduced, while the downstream riser is keeping continuously increasing. Therefore, after \( Ur=7 \),
the downstream flow response is much larger than the single riser.

![Displacement vs. Ur for tandem risers](image)

**Figure 8. The flow displacement of tandem risers.**

**Summary**

In this paper, the VIV characteristics of a single riser and the flexible tandem risers are numerically
simulated by slicing principle. The reliability of the simulation method is verified by the flow around
the cylinder, and the simulation results are analyzed from the force of the riser, the spectrum and the
trajectory of the centroid. Here are some preliminary conclusions:

1) The upstream riser is similar to the single riser in terms of force and response; due to the
influence of the upstream riser wake vortex, the downstream direction of the downstream riser and
the transverse flow response amplitude are much larger than the upstream riser when the flow velocity
is large, and the coupling of the two-direction force frequency is more complicated, indicating that if
the classical VIV analysis method for analyzing a single riser is used, it is not accurate enough for the
downstream riser and it is dangerous when the flow rate is large.

2) The distance between the two risers has an influence on the response amplitude of the riser:
under most reduced speed conditions, the 6 times riser diameter spacing is the dangerous spacing of
the upstream riser, and the 8 times diameter spacing is the dangerous spacing of the downstream riser.
There is basically no difference between the force frequency and the centroid motion trajectory of the
two risers at different intervals.

3) When the VIV is in the unlocked zone, a relatively complicated double "8" shaped trajectory is
observed in the downstream riser at each pitch.

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