Experimental on the vortex induced motion suppression of floating spar-type wind turbine

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Abstract—To investigate the suppression performance of the spar-type wind turbine vortex induced motion (VIM) with the addition of splitter plate, VIM model tests were carried out in a circulating water channel. Two different splitter plates width conditions were tested. In all the conditions, the cylinder was free to oscillate with one DOF. Results regarding response amplitudes and characteristic frequencies were presented and discussed. There was no obvious lock-in phenomenon on the vortex excitation motion of the cylinders with splitter plate, only some synchronization was observed. \(W/D=0.2\) has better suppression performance than \(W/D=0.4\) in vortex induced motion.

1. Introduction
The deteriorating natural environment has led us to look at offshore wind energy, and the complex marine environment of the deep sea has caused difficulties in the installation and operation of our wind turbine platforms.

Vortex-induced motion (VIM) is one of the major concerns in design problems of offshore wind turbine. As the current passes by the offshore wind turbines, it generates vortices in the wake of the structure. The vortex shedding leads to an alternate pressure on the platform, exciting the system, which triggers the VIM phenomenon which can disrupt the fatigue life of mooring and riser systems.

In the past few decades, researchers have proposed many control methods to suppress vibrations of bluff body. Cui et al.\textsuperscript{[1]} conducted a two-dimensional numerical simulation study of the one-degree-of-freedom vortex induced motion of square and rectangular columns with a length-to-diameter ratio of 0.5. Sahu et al.\textsuperscript{[2]} investigated the two-degree-of-freedom vortex induced motion of a cylinder with a rigid separation disk over a large range of folded velocities (1 \(\leq U_r \leq 70\)) and explored the performance of suppression with different mass ratios and different lengths of the splitter plate, which showed the effectiveness of this passive suppression measure and discussed the galloping phenomenon generated by this device. Narendran et al.\textsuperscript{[3]} studied the suppression of vortex motion on a semi-submersible platform by incorporating a near-wake jet and this active control technique resulted in an approximate 30% reduction in fluid forces and response amplitudes.

The height of the plate is an important influencing factor for measures of suppression, such as spoilers, splitter plates, and new cross-sectional shapes. It is found that too low height negatively affects the suppression of vortex induced motion, and too high height requires better structural strength. Feng\textsuperscript{[4]} first investigated experimentally the vibration displacement of a 3-inch diameter
cylinder and a D-section cylinder in a wind tunnel. Bearman\textsuperscript{[5]} conducted similar experiments in a water channel and developed a mathematical model to predict the vortex induced vibration performance of the cylinder. In recent years, researchers have studied the vortex induced motion of columns in greater depth, and the current model tests on vortex induced motion are mainly carried out in towing tanks or circulating water channels. Goncalves et al.\textsuperscript{[6]} performed experiment on the vortex induced motion of small aspect ratio cylinders in water channel and discussed the behavior of vortex induced motion of cylinders with eight different aspect ratios in the range of 0.2 ≤ L/D ≤ 2. Liu\textsuperscript{[7]} carried out an experiment on the vortex induced motion of a deep draft semi-submersible platform in a towed tank to study the response characteristics under different flow angles and different draft conditions, and the displacement curves of the column were measured by an optical motion capture system Qualisys in the experiments. Carlson et al.\textsuperscript{[8]} conducted an experimental study on the flow induced vibration of a Spar-type wind turbine platform, and the experiment used a high-speed camera to record the displacement response of the system and synchronized with a Panasonic Lumix DSLR camera on the side to record the lifting and sinking motion.

In this paper, the study of vortex induced motion experiments was carried out in a circulating water channel. Two different conditions of splitter plate width were tested, and the displacement response of the cross-flow motion of the spar-type wind turbines is recorded by a laser rangefinder. The results regarding response amplitudes and characteristic frequencies were presented and discussed.

2. Experiment set-up

The experiment is carried out in the circulating water channel at Zhejiang Ocean University. The effective size of the channel is 17.13m long, 0.5m wide and 0.8m high, and the flow grid was installed on both sides to make the flow stable. Flow velocity is the key factor affecting the response of vortex induced motion, therefore, the control and measurement of current speed are especially important. The water current speed was controlled by a circulating submersible pump flow generation system. A vectrino high-precision acoustic doppler point flow meter was used to measure the X-Y-Z three-dimensional current speed of a water stream. The maximum current speed is up to 0.8m/s to meet the test requirements.

The response amplitude is the key characteristic of vortex induced motion\textsuperscript{[9-10]}. The one degree-of-freedom (DOF) motion (Cross-flow direction) was captured using a laser rangefinder in present work.

The object is a simplified cylindrical model of a single-cylinder with splitter plate which is made of Plexiglas, and the cylinder is a hollow structure to control the draft depth by adding ballast to it. The floating cylinder was elastically supported by a set of four springs with the same stiffness parameter, \( k=11 \text{N/m} \). The springs were fixed in the model above 20 mm from the waterline with an angle of 45 degrees between adjacent, as can be seen in Fig. 1 and Fig.2. The main scale parameters of the model are described in Tab.1.

| Parameters          | Unit | Value |
|---------------------|------|-------|
| Height(\(L\))      | mm   | 400   |
| Diameter(\(D\))    | mm   | 100   |
| Draft depth (\(T\))| mm   | 250   |
| Width of splitter plate(\(W\)) | mm   | 20-40 |
| Spring stiffness(\(k\)) | N/m | 11    |
3. **Data processing**

The reduced velocity is used to characterize the dimensionless current velocity, \( U_r = \frac{u}{f_n D} \). \( f_n \) is the natural frequency of the structure which is determined by the sway free decay test. \( A_y \) denote the non-dimensional displacement in cross-flow direction with \( D \). The measurement results were evaluated using the Fast Fourier Transform Method (FFT) and plotted in a color graph as a function of the reduced velocity.

First, we conducted a hydrostatic decay test on the floating cylindrical model, the decay test results and conditions are shown in Tab.2.

| \( W/D \) | \( U \) (m/s) | \( f_n \) (Hz) | \( U_r \) | \( Re \) |
|----------|--------------|---------------|----------|--------|
| 0.2      | 0.18→0.69    | 0.56          | 3.2→12.3 | 17914→68670 |
| 0.4      | 0.18→0.69    | 0.56          | 3.2→12.3 | 17914→68670 |

### 3.1. Response amplitude

Fig.3 shows the response amplitudes of one degree of freedom VIM with increasing \( U_r \) for two cylinders with splitter. As shown in Fig.3, the classical four branches (initial excitation branch, upper branch, lower branch, and decoherence) cannot be observed. In other words, they exhibit different response amplitudes. For \( W/D=0.2 \), the response amplitude at a lower value as \( 3.2 \leq U_r \leq 6.96 \). This stage is the initial excitation. As the reduced velocity increases, the amplitude increases sharply and reaches a maximum at \( U_r = 8.52 \). A rapid decrease in amplitude ratio from \( U_r = 8.52 \) to \( U_r = 11.6 \) is observed.
For $W/D=0.4$, the response amplitude increases with increasing reduced velocity before $U_r=6.28$ and the response amplitude reaches a maximum of $0.2D$. The response amplitude tends to stabilize in the range of $6.28 \leq U_r \leq 9.46$. There was no resonant behaviour in this time in combination with Fig.6. Hence this amplitude stabilization phenomenon is what we call synchronization. The response amplitude then continues to increase and reaches a maximum at $U_r=10.17$. We cannot analyse the behaviour of the vortex excitation motion at a larger reduced velocity with $W/D=0.4$ due to the limitation of the current velocity. Fig.4 and Fig.5 show the time history of response displacement on the cylinder with splitter plate $W/D=0.2$ and $W/D=0.4$. 

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**Fig.3** Response amplitudes of VIM with increasing $U_r$ for two cylinders with splitter plate

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**Fig.4** Time history of response displacement on the cylinder with splitter plate $W/D=0.2$

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**Fig.5** Time history of response displacement on the cylinder with splitter plate $W/D=0.4$
3.2. Characteristic frequency

In Fig. 6, non-dimensional frequency \((f/f_n)\) as a function of reduced velocity is plotted for the two different cylinders. The characteristic frequency increases linearly with the reduced velocity at a lower reduced velocity. For \(W/D = 0.4\), the characteristic frequency is close to 1 which demonstrates the resonance of the motion in this reduced velocity range, \(8.52 \leq U_r \leq 9.46\). Thereafter, the response frequency returns to growth. For \(W/D = 0.4\), there is no significant lock-in can be observed here and a small range of synchronization phenomena are observed at \(5.98 \leq U_r \leq 6.96\). The response frequency shows a linear variation with the increase of reduced velocity.

4. Conclusion

The present work was motivated by the VIM studies on the spar-type offshore wind turbines with two different width splitter plate and their suppression performance.

Hence, vortex induced motion experiments were carried out in a circulating water channel at Zhejiang Ocean University. Two different splitter plate width conditions were tested. In all the conditions, the model of offshore wind turbine was free to oscillate with one DOF. Results regarding response amplitudes and characteristic frequencies were presented and discussed.

There was no obvious lock-in phenomenon on the vortex excitation motion of the cylinders with splitter plate, only some synchronization was observed. The response amplitude grows with the reduced velocity to a maximum value and then immediately decreases, no lock-in range appears here for \(W/D = 0.2\). In case of \(W/D = 0.4\), the synchronization phenomenon occurs in the range of \(6.28 \leq U_r \leq 9.46\). After that, the amplitude continues to increase. Considering the response amplitudes and characteristic frequencies, it is concluded that \(W/D = 0.2\) has better suppression performance than \(W/D = 0.4\) in vortex induced motion.

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