Numerical study for energy harvesting of the tandem wavy cylinders in cross flow

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Abstract. In order to make the bladeless wind turbine better convert wind energy into electric energy, this paper based on the method of passively controlling vortex-induced vibration, by changing the shape of the cylindrical surface, selecting three different parameters of the wavy cylinder (λ/D_m=6, a/D_m=0.15; λ/D_m=2, a/D_m=0.15, λ/D_m=2, a/D_m=0.3), and performing a numerical simulation at Re=100. The results show that the wavy cylinder of λ/D_m=2, a/D_m= 0.15 is more susceptible to induced vibration. Compared to straight cylinders, the wavy cylinder of λ/D_m=2, a/D_m= 0.15 have a wider range of lock-in and a larger amplitude.

1. Introduction

Wind energy as a clean, renewable energy source is a priority alternative energy source both economically and technically, due to the depletion of ore resources and the deteriorating environment. At present, Blade wind turbines are used at home and abroad to convert wind energy into electrical energy. The blade wind turbine has the advantages of cleanliness, good environmental benefit, short construction period and flexible installation scale, but it also has the disadvantages of noise, instability, high cost, affecting organisms, and difficulty in installation and transportation. In view of the shortcomings of blade wind turbines, the adoption and development of bladeless wind turbine can overcome these disadvantages. The principle of bladeless wind turbines for wind power generation is the Karman vortex effect in fluid dynamics. It refers to the flow of certain objects under certain conditions. When some objects are bypassed, the two sides of the object will periodically fall off and rotate in opposite directions. The two-column vortex arranged in a regular manner forms a Karman vortex street after a nonlinear action. Once the vortices are large enough, they can cause structural oscillations. Bladeless wind turbines take advantage of this aerodynamic instability to maximize oscillations and capture mechanical energy, which is then used to generate electricity.

How to strengthen the vortex-induced vibration of the bladeless wind column, promote the vortex vibration/presence excitation in advance, realize the long-lasting generation of vortex vibration and galloping, and thus improve the energy collection efficiency is the primary key to the development of bladeless wind turbines. A large number of researches at home and abroad have focused on passive control techniques[1-2] such as wavy surfaces, surface protrusions, partition plates, and guide vanes, and introduced active control techniques[3-4] such as surface motion, suction/blowing, plasma, and electromagnetic force to reduce the resistance. The vibration is designed to control the flow separation
and suppress the transition of the boundary layer, thereby achieving the drag reduction and vibration suppression, and eliminating the safety hazard of the flexible structure in the wind and rain load. Zou et al. [5] also carried out a series of studies on the passive control of damper flow around the flow and reduce the vibration suppression. In this paper, by changing the surface shape of the wind column, the unsteady aerodynamic control of the wind column and the expansion of the "frequency-locked" region are carried out to effectively increase the vibration, thereby increasing the energy conversion density of the system.

2. Model and numerical method
In the paper we study the effect of wavelength and amplitude on flow structure and the lift and drag coefficient of tandem wavy cylinder under vortex induced vibration. There are three models here: \( \lambda/D_m=6, \alpha/D_m=0.15; \lambda/D_m=2, \alpha/D_m=0.15 \) and \( \lambda/D_m=2, \alpha/D_m=0.3 \).

2.1. Physical model
As is shown in figure 1(a), the geometric model of tandem wavy cylinders is described by the following equation:

\[
D_z = D_m + 2a \cos\left(\frac{2\pi z}{\lambda}\right)
\]

Where \( D_z \) denotes the local diameter of the wavy cylinder. The mean diameter \( D_m \) is defined by \( D_m=(D_{\min}+D_{\max})/2 \), and \( D_{\min} \) is called the “saddle”, while \( D_{\max} \) is called the “node”, \( \lambda \) is the wavelength along the spanwise direction and \( \alpha \) is the amplitude of the curved surface.

2.2. Computational domain and boundary conditions
According to the reference Lam et al. [6], the size of the calculation domain of all the tandem wavy cylinders is determined to be \( 24 D_m \times 36 D_m \times \lambda \). The upstream velocity boundary is \( 12D_m \) from the center of the upstream cylinder, the downstream pressure outlet is \( 24D_m \) from the center of the upstream cylinder, the boundary between the two sides is \( 12D_m \) from the center of the upstream cylinder, and the span height is \( \lambda \), which is a wavelength of the wavy cylinder. The distance between the upstream wavy cylinder and the downstream wavy cylinder is \( 5D_m \).

Figure 1(b) shows the grid distributions. In the calculation domain meshing idea, the whole computational domain is divided into dynamic grid region and static grid region. Meanwhile, the dynamic grid region adopts a tetrahedral unstructured mesh, and the static grid region adopts a hexahedral structural mesh. Considering the reconstruction of the 3D model mesh, if the mesh is too fine, the negative volume is easy to occur, so the number of mesh nodes around the cylinders is 80, and the number of nodes in the X direction of the moving mesh region is 90. The number of nodes in the Y direction is 45.

Figure 1. The physical model and grid distributions
3. Results and discussion

3.1. Analysis of flow characteristics of the tandem wavy cylinder fixed flow

The tandem wavy cylinders of the selected three different parameters are calculated in a fixed flow, and the straight cylinders are also calculated for comparison calculation results, as shown in Table 1. It is known that the drag of the upstream and downstream of the three wavy cylinders are much smaller than the straight cylinder, which indicates that the three wavy cylinders have a certain drag reduction effect. The drag of the wavy cylinder with \( \lambda/D_m=2, \alpha/D_m=0.15 \) is less than the wavy cylinder with \( \lambda/D_m=2, \alpha/D_m=0.3 \), but the lift of the wavy cylinder with \( \lambda/D_m=2, \alpha/D_m=0.15 \) is bigger. This indicates that the ability of \( \lambda/D_m=2, \alpha/D_m=0.15 \) wavy cylinder to reduce drag is stronger than that of \( \lambda/D_m=2, \alpha/D_m=0.3 \) wavy cylinder, but it is easier to vibrate than of \( \lambda/D_m=2, \alpha/D_m=0.3 \) wavy cylinder.

Table 1. Three Scheme comparing.

| Cylinder parameter | \( C_d_{1,mean} \) | \( C_d_{2,mean} \) | \( C_l_{1,r.m.s} \) | \( C_l_{2,r.m.s} \) | \( St_1 \) | \( St_2 \) |
|--------------------|--------------------|--------------------|--------------------|--------------------|----------|----------|
| \( \lambda/D_m=6, \alpha/D_m=0.15 \) | 1.3313 | 0.8288 | 0.0023 | 0.0090 | - | - |
| \( \lambda/D_m=2, \alpha/D_m=0.15 \) | 1.1263 | 0.0994 | 0.0048 | 0.0029 | 0 | 0 |
| \( \lambda/D_m=2, \alpha/D_m=0.3 \) | 1.1878 | 0.1863 | 0.0200 | 0.1561 | 0 | 0.1289 |
| \( \lambda/D_m=2, \alpha/D_m=0.3 \) | 1.2225 | 0.2413 | 0.0012 | 0.0055 | 0 | 0.0945 |

As shown in Figure 3, for \( \lambda/D_m=2, \alpha/D_m=0.15 \) wavy cylinder, the shear layer of the upstream cylinder pulsates and reattaches to the front surface of the downstream cylinder, and there is obvious vortex shedding in the downstream cylinder wake. From the flow structure of \( \lambda/D_m=2, \alpha/D_m=0.3 \) wavy cylinder, there is no obvious vortex formation behind the downstream cylinder, and there are two stable vortices in the upstream and downstream cylinders of the Node section. The center of the vortex is closer to the cylinder. But there is no vortex between the upstream and downstream cylinders of the Saddle section. This may be the reason why the lift of the upstream and downstream of the wavy cylinder with \( \lambda/D_m=2, \alpha/D_m=0.15 \) is larger than the wavy cylinder with \( \lambda/D_m=2, \alpha/D_m=0.3 \), and the drag is reduced.

3.2. Numerical simulation of vortex-induced vibration of the tandem wavy cylinder

For \( \lambda/D_m=2, \alpha/D_m=0.15 \) wavy cylinder, when the reduced velocity is \( U_r<7.2 \), the amplitude of the downstream wavy cylinder increases with the increase of the flow velocity, and the maximum value (0.791D_m) is obtained at \( U_r=7.2 \). Then, if the reduced velocity increases again (\( U_r>7.2 \)), the amplitude of the downstream cylinder begins to decrease again. This means that the downstream cylinder start to enter the "lock-in" when the reduced velocity \( U_r=2.4 \), and gradually exit the "lock-in" when the reduced velocity \( U_r=7.2 \). At the same time, it can be clearly seen that the "lock-in" range of \( \lambda/D_m=2, \alpha/D_m=0.15 \) of wavy cylinder is much larger than the "lock-in" range of the straight cylinder. At most of the reduced velocity \( U_r \) (except \( U_r=8.4, 9.6 \)), the amplitude of the wavy cylinder with \( \lambda/D_m=2, \alpha/D_m=0.15 \) is greater than the amplitude of the straight cylinder at the same reduced velocity. In addition, the locking range
of the wavy cylinder with $\lambda/D_m=2$, $\alpha/D_m=0.3$ is similar to that of a straight cylinder, and the locking range of the wavy cylinder with $\lambda/D_m=6$, $\alpha/D_m=0.15$ is much smaller than that of a straight cylinder. This shows that only the wavy cylinder with $\lambda/D_m=2$, $\alpha/D_m=0.15$ is more likely to induce vibration.

![Figure 3. Amplitudes of downstream wavy cylinder at different wavelengths and amplitudes](image)

4. Conclusion
The numerical simulation of tandem wavy cylinders with three different wavelengths and different amplitudes shows that the wavelength and amplitude affect the lift and drag of the cylinder. Among them, the wavy cylinder with $\lambda/D_m=2$, $\alpha/D_m=0.15$ is most easily induced to vibrate, which can transform wind energy into mechanical energy better; the wavy cylinder with $\lambda/D_m=2$, $\alpha/D_m=0.3$ is second. Conversely, the wavy cylinder with $\lambda/D_m=6$, $\alpha/D_m=0.15$ has the effect of reducing vibration.

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