Study on flow field characteristics of undulating member bar in engineering

Ruochen Zhao¹, Meng Zhao²*, Zhen Liu², Tiemei Jia¹ and Fanguang Kong¹

¹ Engineering Management Department, Inner Mongolia Honder College of Arts and Sciences, Hohhot, Inner Mongolia, 010070, China
² College of Energy and Power Engineering, Inner Mongolia University of Technology, Hohhot, Inner Mongolia, 010051, China

*Corresponding author’s e-mail: mzhao_imut@163.com

Abstract. Aiming at the undulating member bar, three kinds of wavelength models are established. The flow characteristics of the undulating member bar with space angle of attack are analyzed by the large eddy simulation method under high Reynolds number, its velocity and pressure distribution with different wavelengths are studied, and the time and frequency domain characteristics of circumferential pressure coefficient, resistance and lift are discussed. The results suggest that the greater the fluctuation of the outer surface of the wave member, the greater the time difference between the maximum and minimum cross-sections; the greater the surface inclination, the greater the change in surface pressure. While the smaller the wavelength, the larger the amplitude of the rod resistance coefficient and the range of the main peak; the larger the wavelength, the slower the attenuation rate of the amplitude peak of the rod resistance and lift coefficient. Combined with the characteristics of the flow field, when the incoming flow has a space angle of attack, the wave cylinder of can achieve a better effect of drag reduction and vibration reduction. Finally, the research results provide important significance and value for the research and application of the flow characteristics of undulating member bar.

1. Introduction
Under the premise of meeting the requirements of strength and stiffness of all kinds of members in engineering, the shape of members is changed from the aspects of limiting the development of wake area and reducing the intensity of wake vortex, and the eddy current at the tail is controlled to reduce the longitudinal vibration of members. For example, wave cylinders can effectively improve the stability of the flow around. Scholars at home and abroad have done a lot of research. Experiments have proved that the wave-shaped bar studied by Wang Fenghao[1] has a small pulsating lift coefficient and has the effect of reducing fluid-induced vibration. Zou Lin et al. [2] reveal that under the subcritical Reynolds number, the vortex shedding occurs far downstream of the wave cylinder, so as to achieve the purpose of drag reduction. Lam K et al.[3] have studied that the wave-like rod symmetrical along the axis has a good effect of reducing drag and vibration, and has a certain control effect on the flow field. Lee S et al. [4] report that the wave type can achieve a good effect of drag reduction and vibration reduction in the subcritical zone. Under the condition of a certain Reynolds number, Wang Wei et al. [5] claim that the surface of the ridge structure can not only reduce the surface resistance of the member, but also effectively control the pulsating lift of the member and delay the separation of the boundary layer. However, in the current research, the analysis of the space...
angle of attack in the inflow and the horizontal inflow is still a great challenge. The effect of space angle of attack and transverse flow on the flow field is enhanced, especially when there is a hinge connection in the structure, the influence of the transverse force is obvious, and the longitudinal vibration law changes, such as the upper and lower arms of the pantograph of the high-speed train. Therefore, a three-dimensional wave cylinder model with space angle of attack is established to analyze its flow characteristics.

2. Calculation model and method

2.1. Calculation model
The model of the wave cylinder is established. \( D_{\text{max}} \) and \( D_{\text{min}} \) are the diameters of the largest and smallest section of the wave cylinder in the axis direction, respectively. The average diameter of the wave cylinder is \( D_m \), \( D_m = \sqrt[3]{2(D_{\text{max}} + D_{\text{min}})} \), \( \alpha \) is the amplitude of the sinusoidal curve on the surface of the wave cylinder, and \( \lambda \) is the wavelength. In order to facilitate comparison, the average diameter \( D_m \) is selected as the average diameter of the upper arm of the pantograph, and all scales are taken as a reference of \( D_m \). With reference to the relevant parameters of the upper arm under the pantograph attitude of the high-speed train, the bar models of three wavelengths are established.

The wave crest number, amplitude and wavelength of the wave cylinder under the three working conditions are shown in Table 1. Taking \( D_m \) as the average diameter of the upper arm of the pantograph, the influence of the parameters of the wave cylinder model on the characteristics of the flow field is discussed.

| working condition | the number of wave crests | \( \alpha/D_m \) | \( \lambda/D_m \) |
|-------------------|--------------------------|----------------|----------------|
| I                 | 7                        | 0.34           | 5.5            |
| II                | 13                       | 0.34           | 3.26           |
| III               | 17                       | 0.322          | 2.45           |

The geometric model of the wave cylinder and the calculation domain are shown in figure 1, and the length, height and width of the calculation domain are 60D, 10D and 28D, respectively.

Figure 1. Geomery model and control domain of wavy cylinder.
The area near the wall is solved by the wall function method, and the surface boundary layer area and wake area of the wave cylinder are encrypted, and the number of grids is 9.76 million.

2.2. Calculation methods and calculation conditions
The wave cylinder with high Reynolds number belongs to compressible turbulent flow, and the small unsteady state can be obtained by large eddy simulation method in complex fluid flow. The N-S equation is filtered by box filter function by using large eddy simulation method, and the control equation is obtained as follows [6].

\[
\frac{\partial \overline{\rho u}}{\partial t} + \frac{\partial \overline{\rho u_i u_j}}{\partial x_j} = \frac{1}{\rho} \frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_i \partial x_j} + \frac{\partial \overline{\tau_{ij}}}{\partial x_j} \quad (1)
\]

Where, \(\rho\) is the density, \(u\) is the velocity, \(\overline{\tau_{ij}}\) is the sub-grid scale stress; In the formula, the filter scale, box filter and Reynolds stress model can be found in reference [7].

3. Results and analysis

3.1. Pressure distribution
It should be known that the low-pressure center of wake zone in the working condition III is farther away from the rear wall of wave cylinder than that of the working condition I, but the negative pressure value of wake low-pressure center is smaller in the working condition II. If the center of low pressure is far away from the wall, the pressure difference between the front and back surfaces of the wave cylinder will obviously decrease, as shown in Figure 2.

![Figure 2. Low pressure centres of wake field in three conditions.](image)

At the maximum cross section of the working condition III, the pressure around the wave cylinder facing wall is larger than the working conditions I and the working condition III, the pressure variation along the two side walls is larger than other working conditions, and the negative pressure center range at the tail is also larger. In three working conditions, the pressure field is basically positive pressure except near the wall, as shown in figure 3.

![Figure 3. Pressure nearby the wall surface of wavy cylinder.](image)

Figure 4 to figure 6 show the pressure coefficients of the maximum and minimum sections under three working conditions. The pressure coefficient at the smallest cross-section is smaller than that at the largest cross-section under three working conditions. The minimum pressure at the smallest cross-section is about 65°, and the minimum pressure at the largest cross-section is about 75°. The smaller the difference between the pressure coefficient in the back flow area and the pressure coefficient on the front face of the wave bar, that is, the smaller the pressure difference between the front and back faces, the more obvious the effect of drag reduction. The wave cylinder surface
pressure distribution is related to the surface inclination. The greater the surface inclination \( \frac{a^2}{(\lambda D_m)} \), the greater the change of the surface pressure of the wave bar.

![Figure 4. Circumferential pressure of condition I.](image)

![Figure 5. Circumferential pressure of condition II.](image)

![Figure 6. Circumferential pressure of condition III.](image)

3.2 Resistance characteristics

When the incoming flow has a space angle of attack, the time-history variation laws of wave cylinder resistance coefficient and lift coefficient change compared with the direct working condition. Table 2 shows the time-history variation of resistance coefficient under three working conditions. The average value and amplitude of the resistance coefficient are the largest under the working condition III, and the maximum value and minimum value are larger under the working condition I, while the average value and amplitude are the smallest under the working condition II.

| \( \lambda / D_m \) | Maximum value | Minimum value | Average value | Maximum amplitude |
|---------------------|---------------|---------------|---------------|-------------------|
| \( =5.5 \)          | 0.1742        | 0.1693        | 0.1718        | 0.0025            |
| \( =3.26 \)         | 0.1572        | 0.1482        | 0.1489        | 0.0083            |
| \( =2.45 \)         | 0.2322        | 0.1375        | 0.1931        | 0.0556            |

3.3 Lift characteristics

The lift coefficient of wave cylinder in time-history variation is shown in table 3 when the incoming flow has space angle of attack. The average value and amplitude of lift coefficient are larger in the working condition III, and the periodic variation law is obvious, while the average value and amplitude of lift coefficient are smaller in the working condition II.
Table 3. Lift coefficient.

|                          | $\lambda / D_m = 5.5$ | $\lambda / D_m = 3.26$ | $\lambda / D_m = 2.45$ |
|--------------------------|------------------------|------------------------|------------------------|
| Maximum value            | 0.0526                 | 0.0393                 | 0.0741                 |
| Minimum value            | 0.0484                 | 0.0357                 | 0.0524                 |
| Average value            | 0.0503                 | 0.0369                 | 0.0623                 |
| Maximum amplitude        | 0.0023                 | 0.0024                 | 0.0118                 |

The distribution ranges of lift coefficient amplitude peaks are basically the same in the working condition I and working condition III, and the frequency ranges corresponding to the main peaks are basically the same in the three working conditions. The attenuation rate of amplitude peaks is the fastest in the working conditions III. Combining the time-domain and frequency-domain characteristics of wave cylinder with space angle of attack, we can get better drag reduction and vibration reduction effects by comprehensively comparing the three working conditions.

4. Conclusion
(1) The two side walls of the wave cylinder in the section face backward to form an obvious symmetrical vortex; the greater the fluctuation of the outer surface of the wave member, the greater the time difference between the maximum and minimum sections in velocity separation.

(2) The greater the surface inclination ($\alpha$), the pressure coefficient at the smallest cross-section is smaller than that at the largest cross-section under three working conditions. The minimum pressure at the smallest cross-section is about 65°, and the minimum pressure at the largest cross-section is about 75°.

(3) The average value and amplitude under the working condition III are the largest, and the main peak value of the frequency spectrum is wider; The average value and amplitude of the resistance coefficient under the working condition II are the smallest. Comprehensive analysis shows that under the condition of space angle of attack, the working condition II can get better drag reduction and vibration reduction effect.

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