Numerical study on crosswind stability of spherical structures

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Abstract. Karman Vortex Street will be formed when steady incoming flow flows around square cylinder under a certain Reynolds number. The alternate shedding of Karman Vortex Street will affect the structure of the object which will cause structural vibration, and may even cause structural damage in severe cases. The "world's largest artificial moon" located in Hongguo, Panzhou City, Guizhou Province was selected as the research object in this paper, the flow around characteristics under different crosswind velocity of which are numerically studied by computational fluid dynamics, and then the crosswind stability of the structure is analyzed. Results shows that the vortex shedding mainly occurs in the cylindrical structure, while there is no obvious vortex shedding in the spherical structure and the natural frequency of the artificial moon is much higher than the vortex shedding frequency. There are 3 low-speed regions at different heights on the central section. The lowest velocity appears at the lower part of the leeward side of the spherical structure, and there is even a backflow phenomenon, resulting in a local vortex. Under the same Reynolds number, Karman vortex street is more likely to appear in cylindrical structure than in spherical structure. In addition, as the Reynolds number increases from 8.1×10^5 to 1.6×10^7, except to the increase in overall wind velocity, the characteristics of flow around structure at the rear of the building change little under steady-state condition. The natural frequency of the artificial moon is much higher than the vortex shedding frequency. It means that the crosswind stability of the artificial moon investigated is satisfactory.

1. Introduction
Karman Vortex Street is an important natural phenomenon in fluid mechanics and the study of Karman Vortex Street has always been a hot topic in fluid mechanics. When a stationary inflow flows around some objects under a certain Reynolds number, the two sides of the object will periodically shed double linear vortexes with opposite rotation directions and regular arrangement. After nonlinear action, Karman Vortex Street is formed [1-2]. Karman Vortex Street will affect the structure of the object. Even when the alternating shedding frequency of Vortex Street is similar to or equal to the natural vibration frequency of the object, frequency coupling will occur, causing structural vibration and possibly structural damage [3-6]. There are many factors affecting the characteristics of Karman Vortex Street. Huang ji et al. [7] used CFD software Fluent to study the flow around a binary cylinder with different Reynolds coefficients, and made a detailed analysis of the Karman Vortex Street phenomenon when Re=500, results of analysis showed that when 50<Re<500, Karman Vortex Street began to appear. When Re>500, rule and periodicity of the Karman Vortex Street began to lose. When Re = 5 000 around, tail of the Karman Vortex Street lost regularity. Zhu mengnan et al. [8-9] simulated the flow around two parallel square columns under different Reynolds number conditions, and analyzed the influence of Reynolds number on the Karman Vortex Street formed by the flow.
around the square column, results show that the flow separation Angle around the square column increases with the increase of Reynolds number. As the flow velocity increases, the influence of the square column on the flow wake increases, and the flow becomes more complex. Chen suqin et al. [10] studied the flow field around the staggered square column under low Reynolds number by numerical method, and observed that the flow field near 90° changed from biased toward the upstream cylinder to a bistable flow. It is revealed in the 2D computations that the switching process from the flow pattern that the gap flow is always biased to the side of the upstream cylinder to the flow pattern that the gap flow is unstable and changes the bias direction at irregular time intervals does occur in the neighborhood of 90°, and the computed drag forces agree well with the experimental values. Shen lilong et al. [11] conducted numerical simulation on the flow around the double-row parallel three-square column, and the results showed that the flow around the multi-square column had obvious water-blocking effect of pile group compared with the flow around the single-square column, and the flow field evolution was relatively complicated due to the large variation range of the flow parameters around the multi-square column.

The "world's largest artificial moon" located in Hongguo, Panzhou City, Guizhou Province, which is completed in 2020 was selected as the research object in this paper, the flow around characteristics under different crosswind velocity of which are numerically studied by computational fluid dynamics, and then the crosswind stability of the structure is analyzed.

2. Numerical method

Figure 1 shows the entity and the mesh division situation of simplified geometric model of Panzhou Moon Palace. The height of the main structure is 100m, of which the diameter of the sphere is 40m, and the diameter of the supporting cylindrical structure is 15m. The crosswind enters the calculation area from the left side and is set as velocity inlet, the crosswind entrance is 50m away from the architecture, considering that the height of the building itself and its location is not high, the inlet velocity is assumed to be uniform, and the influence of altitude on wind speed is ignored. According to the local weather conditions, the velocity is set to 1m/s, 5 m/s, 15 m/s, and 20 m/s respectively, corresponding to light air, breeze, and strong breeze, high wind, gale, the main structure of the building is set as wall, and the rest is set as far field. The computational area is divided into unstructured mesh. The number of total elements is 49 8509, the minimum mesh quality is 0.4, just occupied 0.001% of total elements, the mesh quality is also shown in Figure 1.

The k-ε turbulence model based on RNG method can better reflect the complex characteristics of bluff body flow [12-15]. So, the RNG k-ε method is used to simulate the flow. The pressure-velocity
coupling algorithm is solved by SIMPLEC algorithm of finite volume method, and the pressure and momentum are solved by second-order upwind method. Considering the cost of calculation time and accuracy of calculation, the transient iteration step is set to 1s.

3. Results and discussion

3.1. Flow around characteristics

The appearance of Karman vortex is related to Reynold number which is defined as follows:

$$\text{Re} = \frac{\nu l}{\mu}$$

Where \( \nu \) represent velocity, m/s; \( l \) represent the characteristic dimension, m, it is the outside diameter of cylinder or the diameter of sphere in this case; \( \mu \) represent the kinematic viscosity, m²/s. The Reynolds number for the crosswind velocity of 1m/s, 5 m/s, 15 m/s, and 20 m/s is \( 8.1 \times 10^5 \), \( 4.0 \times 10^6 \), \( 8.1 \times 10^6 \), \( 1.2 \times 10^7 \), \( 1.6 \times 10^7 \).

Table 1 shows the diagrammatic drawing of the x-direction velocity distribution at \( Y=0 \) (artificial moon center section) and different height sections \( Z=20m, 40m, 60m, \) and \( 80m \) under different Reynolds number. It can be seen from the figure that there are 3 low-speed regions at different heights on the central section. The lowest velocity appears at the lower part of the leeward side of the spherical structure, and there is even a backflow phenomenon, resulting in a local vortex.

| Reynolds number | Y=0m | Z=20m | Z=40m | Z=60m | Z=80m |
|-----------------|------|-------|-------|-------|-------|
| \( 8.1 \times 10^5 \) | ![Diagram](image1.png) | ![Diagram](image2.png) | ![Diagram](image3.png) | ![Diagram](image4.png) | ![Diagram](image5.png) |
| \( 4.0 \times 10^6 \) | ![Diagram](image6.png) | ![Diagram](image7.png) | ![Diagram](image8.png) | ![Diagram](image9.png) | ![Diagram](image10.png) |
| \( 8.1 \times 10^6 \) | ![Diagram](image11.png) | ![Diagram](image12.png) | ![Diagram](image13.png) | ![Diagram](image14.png) | ![Diagram](image15.png) |
| \( 1.2 \times 10^7 \) | ![Diagram](image16.png) | ![Diagram](image17.png) | ![Diagram](image18.png) | ![Diagram](image19.png) | ![Diagram](image20.png) |
| \( 1.6 \times 10^7 \) | ![Diagram](image21.png) | ![Diagram](image22.png) | ![Diagram](image23.png) | ![Diagram](image24.png) | ![Diagram](image25.png) |

At the same Reynolds number, there is no obvious vortex shedding at the rear of the cylindrical support structure on \( Z=20m \). When the height increases to \( Z=40m \), slight vortex shedding can be observed. As the height continuously increases to \( Z=60m \), significant periodic vortex street shedding appears. However, as the height increase beyond the cylindrical structure to reach the spherical main structure, the vortex shedding phenomenon disappears. It can be seen that under the same Reynolds
number, Karman vortex street is more likely to appear in cylindrical structure than in spherical structure. In addition, as the Reynolds number increases from $8.1 \times 10^5$ to $1.6 \times 10^7$, except to the increase in overall wind velocity, the characteristics of flow around structure at the rear of the building change little under steady-state condition.

3.2. Shedding frequency
The shedding frequency of the Karman vortex street has a great influence on the stability of the structure flow around, when the alternating shedding frequency of Vortex Street is similar to or equal to the natural frequency of the object, frequency coupling will occur, causing structural vibration and possibly structural damage. The natural frequency of an object is not only related to material and shape, but also related to environmental temperature, humidity, medium, etc. Therefore, it is usually determined by experiment or using engineering experience data because there is no definite calculation formula to obtain.

From the analysis of the flow around characteristics, it can be seen that the vortex shedding mainly occurs in the cylindrical structure, while there is no obvious vortex shedding in the spherical structure. The vortex shedding frequency can be obtained by Fourier transform of the lift characteristics of the flow around structure which is monitored during the unsteady state calculation. Table 2 shows the vortex shedding characteristics of the cylindrical structure under different Reynolds number, the period of lift is also listed, where the period is the reciprocal of frequency. It can be seen that the vortex shedding frequency increases with the increase of the Reynolds number.

Refer to the natural frequency data of the large-diameter single pile foundation of offshore wind power with the similar structures and materials, the natural frequency of the artificial moon investigated is about 0.5~0.8HZ [16], which is much higher than the vortex shedding frequency. It means that the crosswind stability of the artificial moon investigated is satisfactory.

| Vortex shedding characteristics | Reynolds number |
|---------------------------------|----------------|
|                                 | $8.1 \times 10^5$ | $4.0 \times 10^6$ | $8.1 \times 10^6$ | $1.2 \times 10^7$ | $1.6 \times 10^7$ |
| Frequency (HZ)                  | 0.078           | 0.01            | 0.019           | 0.04            | 0.045           |
| Period (s)                      | 129             | 96              | 52              | 25              | 22              |

4. Conclusions
The flow around characteristics under different crosswind velocity of the "world's largest artificial moon" is numerically studied by computational fluid dynamics, and then the crosswind stability of the structure is analyzed.

(1) There are 3 low-speed regions at different heights on the central section. The lowest velocity appears at the lower part of the leeward side of the spherical structure, and there is even a backflow phenomenon, resulting in a local vortex.

(2) Under the same Reynolds number, Karman vortex street is more likely to appear in cylindrical structure than in spherical structure. In addition, as the Reynolds number increases from $8.1 \times 10^5$ to $1.6 \times 10^7$, except to the increase in overall wind velocity, the characteristics of flow around structure at the rear of the building change little under steady-state condition.

(3) The natural frequency of the artificial moon is much higher than the vortex shedding frequency. It means that the crosswind stability of the artificial moon investigated is satisfactory.
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References
[1] Wang Z D 2014 Von Karman and Karman Vortex Street[J]. Chinese Journal of Nature, 2014(4): 243-245
[2] Min L Q 2009 Numerical simulation of Karmen vortex street with low Reynolds number[J]. Journal of Sichuan Ordnance, 2009, 11, 30(11):81-83
[3] Hu J P, Luo S 2019 Comparative analysis of numerical simulation methods for turbulence around a square column [J]. Scientific and Technological Innovation, 2019(2)
[4] Chen S J, Wang Z 2008 Comparative analysis of numerical simulation method for flow turbulence around a square column [J]. Journal of China Three Gorges University (Natural Sciences), 2008, 10, 30(5): 18-21
[5] Duan Z Q 2012 An Numerical Investigation on Fluid Flow Past a Circular Cylinder with Splitter Plate at Low Reynolds Number[D]. Chongqing: Chongqing University
[6] Yng J W, Fu X L 2008 Research progress on circular flow around cylinder [J]. China Water Transport, 2008(5): 156-158
[7] Huag J, Lu H G, Lin C B, et al. 2015 Study on Two-Dimensional Around A Circular Cylinder Flow Reynolds Coefficient Based on Fluent[J]. Journal of Guangdong Ocean University, 2015(4): 81-86
[8] Zhu M N, Cao Y, Zhao J J, et al. 2017 Numerical simulation of flow around two parallel square columns[J]. China Wind Transport, 2017, 7, 17(7): 252-255
[9] Zhu M N, Cao Y, Zhao J, et al. 2017 The simulation of flow around square cylinder[J]. Water Sciences and Engineering Technology, (5): 20-24
[10] Chen S Q, Gu M, Huang Z P 2004 Numerical Computation of Low Reynolds Numbers Flow around Two Square Cylinders in Staggered Arrangement [J]. Journal of Tongji University, 2004, 11, 32(11): 1466-1470
[11] Shen L L, Liu M W, Lu Q B, et al. 2014 Numerical Simulation of the Flow around Double-row Tied for Three Square Cylinders [J]. Science Technology and Engineering, 2014, 8, 14(32): 135-139+163
[12] Li X X, Wan S L, Zuo L L, et al. 2020 Investigation on the characteristics of wind field around buildings at different wind direction angles[J]. Building Structure, 2020, 50(S2): 112-116
[13] Yang W, Gu M 2003 Numerical Simulation of Steady Flow around a 3D High-rise Building[J]. Journal of Tongji University (Natural Sciences), 31(6): 647-651
[14] Wang Y C, Wu W Q 2004 Numerical simulation of flow around blunt bodies using RNG k-ε turbulence model[J]. Journal of University of Shanghai for Science and Technology, 26(6): 519-523
[15] Li L, Li Y L 2000 Numerical Simulation of Turbulent Flow around Bluff Bodies Using the RNG k-ε Turbulent Model[J]. Advances in Water Science, 2000(04): 357-361
[16] Sun X F, Ma D, Su G Y, et al. 2021 Numerical Analysis of Influencing Factors on Natural Frequency of Large-diameter Single Pile Foundation of Offshore Wind Power [J]. Ship and Ocean Engineering, 50(01): 99-103.