ICWE 16
August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering

Experimental investigation of the aerodynamic performance of Flettner rotors for marine applications

Wenlong Chen [1], Hanfeng Wang [1,2], Xiyang Liu [3]

[1]*Central South University, Changsha, China, 204801031@csu.edu.cn*
[2]*National Engineering Research Center of High-speed Railway Construction Technology, Changsha, China, wanghf@csu.edu.cn*
[3]*China Ship Scientific Research Center, Wuxi, China, liuxiyang@702sh.com*

SUMMARY:
Flettner rotors are nowadays becoming an alternative wind-assisted propulsion system for marine applications. In this study, the aerodynamic performance of large-scale Flettner rotors with diameter D = 350mm was experimentally investigated with $0 \le \alpha \le 4.5$, $3.5 \le L/D \le 6.0$, $1.0 \le D_e/D \le 2.0$, and $Re = 2.33\times10^5$, where α is the velocity ratio, L is the cylinder span, D_e is the diameter of endplate. Initial area, increasing area, decreasing area, and stable area were defined to describe the variation of mean lift-drag ratio with an increase in α. Both mean aerodynamic performance of Flettner rotors and range of the four areas were influenced dramatically by the L/D and D_e/D. Based on measurement of the aerodynamic forces of tested Flettner rotor under the influence of interfering Flettner rotor with the same α, the effects of the aerodynamic interaction for different wind incidence angle β and spacing ratio S/D were studied in detail.

Keywords: Flettner rotor, Aerodynamic performance, Velocity ratio

1. MOTIVATIONS

The Flettner rotor is a rotating cylinder that generates an aerodynamic lift due to the Magnus effect. In order to reduce the energy efficiency design index (EEDI) of ship, Flettner rotors are currently attracting increasing interest as an effective technology harnessing wind power to generate propulsion for marine applications (Searcy, 2017).

The effects of the velocity ratio α ($\alpha = n\pi D/U_\infty$, where n is the number of revolutions per second of the cylinder, D is the diameter of the cylinder, and U_∞ is the free-stream velocity) and Reynolds number Re on the aerodynamic forces and wake flow of a two-dimensional rotating cylinder in a uniform stream have been extensively addressed over the past years. Considering a rotating cylinder with finite length, the aerodynamic forces and wake flow of it may be more complicated compared with a two-dimensional one. In addition, to increase the fuel-saving potential of the designated vessel, multiple Flettner rotors are often used in practical applications. Due to the aerodynamic interaction effects, the aerodynamic thrust generated by a set of Flettner rotors should not be calculated as the simple arithmetic sum of the thrust produced by each of the installed devices (Gully et al., 2010; Traut et al., 2014). Unluckily, there were little experimental results reported in wind tunnel regarding the interaction effects on the aerodynamic performance of two rotating cylinders with finite length, especially in the condition of high Re.

The present paper reports an experimental investigation on the aerodynamic performance of Flettner rotors with a scale ratio of 1:10. The effects of α, L/D, and D_e/D on the aerodynamic performance of single Flettner rotor were studied. Besides, both wind incidence angle β and S/D were considered to investigate aerodynamic interaction effects on the performance of two Flettner rotors, in order to provide some references for marine applications.

2. METHODS

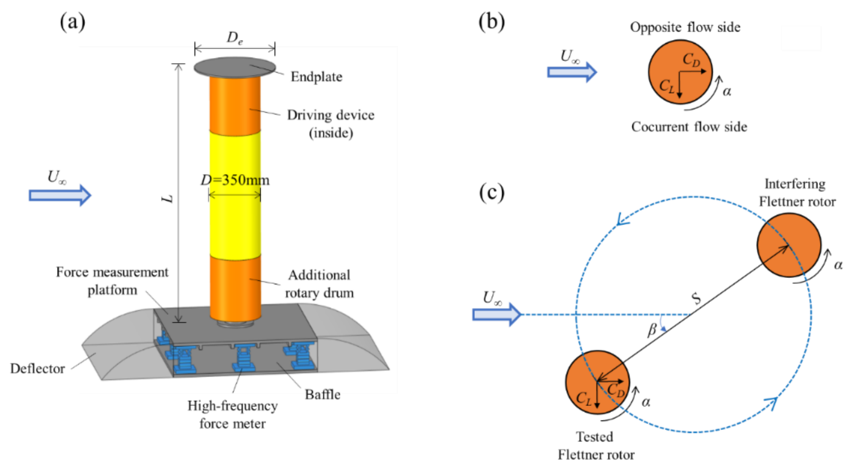


Figure 1. Experimental set-up.

All experiments were conducted in a smooth flow at the test section of the wind tunnel laboratory of Central South University. The test section was 12 m wide, 3.5 m high, and 18 m long. The free-stream velocity U_∞ could be continuously adjusted from 0 to 20 m/s, with a turbulence intensity lower than 1%. In this study, 1:10 was chosen as the appropriate model scale to meet the requirements. As shown in Fig. 1, the diameter of the test Flettner rotor (D) was 350 mm, and its aspect ratio (L/D) was controlled by changing the additional rotary drum with different length at the bottom of the rotor. The endplate was screwed at the top of the rotor, and the number of revolutions per second of the rotor was determined by driving device. In the present experiment, the U_∞ was 10 m/s, which corresponded to a Re value of 2.33×10^5. The lift and drag forces of the rotor were measured using eight high-frequency force meters with a measurement range of 1000 N, which were placed inside the force measurement platform under the rotor (Fig. 1(a)). The sampling frequency of the high-frequency force meters was 1200 Hz, and the sampling duration was 60 s for each tested case.

3. RESULTS OF THE SINGLE FLETTNER ROTOR

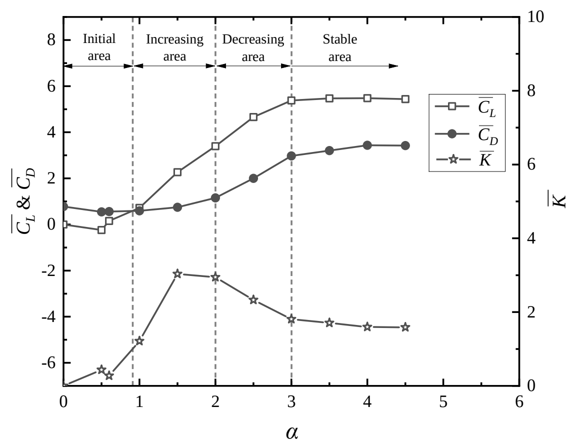
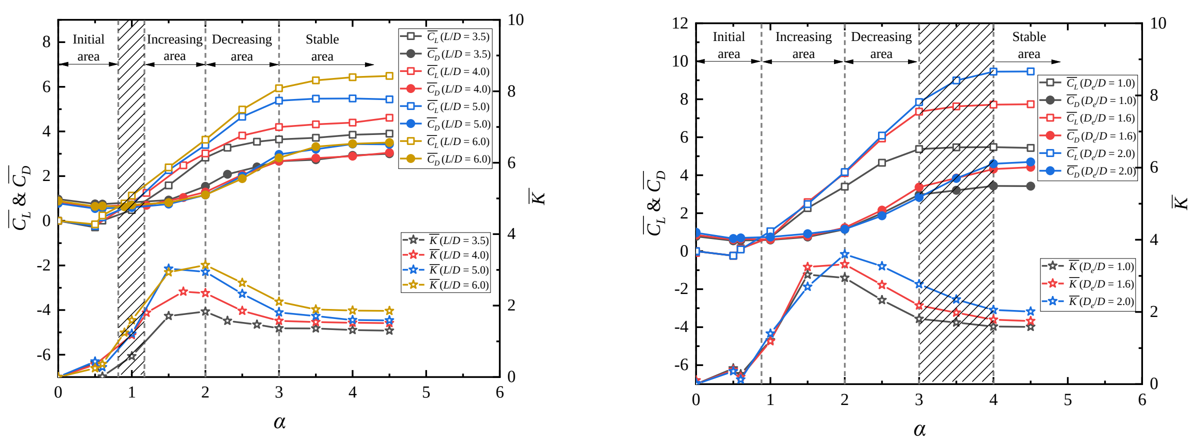


Figure 2. Variation of $\overline{C_L}$, $\overline{C_D}$, and $\overline{K}$ with α for a single Flettner rotor.

Fig. 2 shows the variation of the time-averaged lift coefficient $\overline{C_L}$, drag coefficient $\overline{C_D}$ and the lift-drag ratio $\overline{K}$ ($\overline{K} = \overline{C_L}/\overline{C_D}$) with α for a single Flettner rotor with L/D = 5. The corresponding Re was 2.33×10^5, which was in the subcritical range. Four typical areas, that is, the initial ($0 < \alpha < 0.9$), increasing ($0.9 < \alpha < 2$), decreasing ($2 < \alpha < 3$), and stable ($\alpha > 3$) areas are observed in the variation of $\overline{K}$ with increasing α for a Flettner rotor. For $0 < \alpha < 0.5$, the value of $\overline{C_L}$ was negative because of inverse Magnus effect. This inverse Magnus effect can be observed in a certain range of the Re and at a low α (Seifert, 2012). The origin of the negative Magnus force is attributed to different locations of the transition points on both sides of the rotating cylinder, where the laminar flow either turns to turbulent flow or separates (Kim et al., 2014). The separation point on the opposite flow side moved upstream with the increase in α from 0.5 to 0.6, and the wake flow deflected to the opposite flow side. In the initial area, the variation of $\overline{C_D}$ with α was effected by both the negative pressure region in the wake flow of the rotor and the deviation of Magnus force.

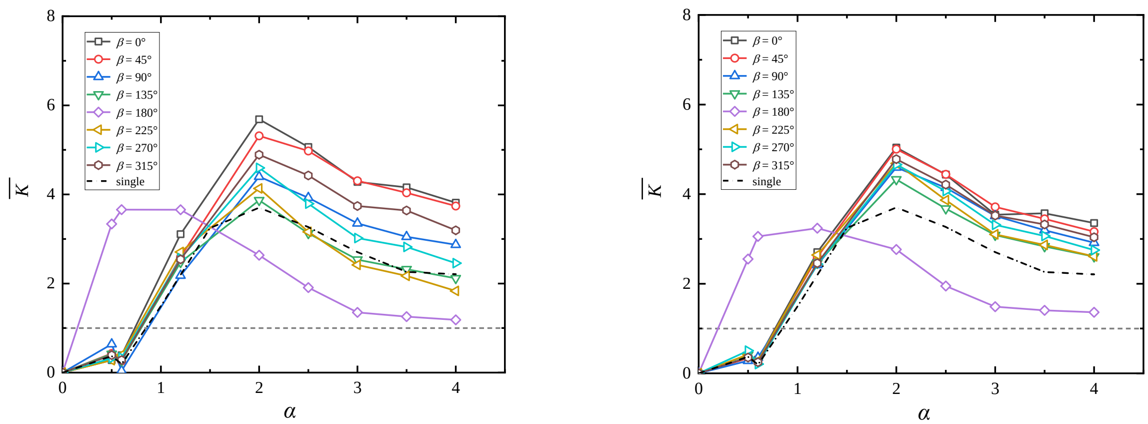


(a) effect of L/D (b) effect of D_e/D

Figure 3. The effects of L/D and D_e/D on the aerodynamic performance of Flettner rotor.

Fig. 3 shows the variation of $\overline{C_L}$, $\overline{C_D}$ and $\overline{K}$ with α for a single Flettner rotor at different L/D and D_e/D values. The D_e/D had a similar effect on the $\overline{K}$ as the L/D for $\alpha > 2$, that is, the value of $\overline{K}$ increased with increasing either the L/D or D_e/D. However, the effects of the L/D and D_e/D on the $\overline{K}$ occur at $\alpha > 0.5$ and $\alpha > 1.5$, respectively.

4. RESULTS OF TWO FLETTNER ROTORS



(a) S/D = 5 (b) S/D = 10

Figure 4. The effects of β and S/D on the aerodynamic performance of two Flettner rotors.

Fig. 4 shows the variation of $\overline{K}$ with α for two Flettner rotors at different β and S/D values. The $\overline{K}$ presented its extrema at α = 0.6–1 for β = 180°, while presented its extrema at α = 2 for the other wind incidence angle. In addition, the aerodynamic performance of Flettner rotor was optimum at β = 180° for $\alpha < 1.3$, while it was optimum at β = 0° for $\alpha > 1.3$. Moreover, the larger the S/D, the smaller the difference in the aerodynamic performance of the rotor at different values of β.

5. CONCLUSIONS

This paper reports an experimental investigation on the aerodynamic performance of Flettner rotors with large-scale. Initial area, increasing area, decreasing area, and stable area were defined to describe the variation of mean lift-drag ratio with an increase in α. Both mean aerodynamic performance of Flettner rotors and range of the four areas were influenced dramatically by the L/D and D_e/D. Due to the aerodynamic interaction effects on the performance of two Flettner rotors, the influence of the wind incidence angle β and spacing ratio S/D can not be negligible.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the Shanghai Municipal Science and Technology Commission (Grant No. 22dz1207702).

REFERENCES

Gully, B.H., Webber, M.E., Seepersad, C.C., 2010. A comparative analysis of wind propulsion systems for ocean-going vessels. ASME 2010 International Mechanical Engineering Congress and Exposition, pp. 1077-1085.

Kim, J., Choi, H., Park, H., et al., 2014. Inverse Magnus effect on a rotating sphere: When and why. Journal of Fluid Mechanics 754.

Searcy, T., 2017. Harnessing the wind: A case study of applying Flettner rotor technology to achieve fuel and cost savings for Fiji's domestic shipping industry. Marine Policy 86, 164-172.

Seifert, J., 2012. A review of the Magnus effect in aeronautics. Progress in Aerospace Sciences 55, 17-45.

Traut, M., Gilbert, P., Walsh, C., et al., 2014. Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. Applied Energy 113, 362-372.