Research on Numerical Simulation of the Aerodynamic Characteristics of the Three-Cup Anemometer Based on CFD

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Abstract

To research the aerodynamic characteristics of cup anemometer including the dynamic response process and the influence rule of main geometric parameters on the linear response characteristic,a 3D numerical simulation model of the three-cup anemometer was established by ANSYS,with the method of computational fluid dynamics to realize the unsteady numerical simulation of the anemometer's response process.The calculation was based on sliding grid technology to achieve the rotation of the anemometer. The influence of different sizes of the rotation radius and the cup's diameter on the linear characteristic was calculated with the numerical simulation results conformed with the theoretical analysis .The results show that the numerical simulation can accurately predict the the three-cup anemometer's dynamic response process.The linear coefficient increases linearly with the increase of the rotation radius and decreases with the increase of the cups' diameter,of which the rotation radius is the main factor.

Keywords

Anemometer,Aerodynamics,Dynamic Characteristic, Linear response,CFD

1. Introduction

The three-cup anemometers are widely used in wind monitoring and assessment of wind resources because of its accuracy,convenient use, low cost features.Wind speed is measured based on the linear relationship between wind speed and steady revolving speed of the anemometer. The study of the three-cup anemometers began early abroad , but the current common anemometers still adopt the design model before 1970 s, of which the main reason is the high cost of wind tunnel experiments and long design cycle[1-2].What's more, the data of the steady response of the anemometers could be acquired by the wind tunnel experiments but the dynamic response process and the air flow distribution can't be observed effectively.Domestic scholars, Jinzhao Wang[3]and Jihai Jiang [4],have study the static characteristics of the anemometer by the theoretical analysis and experimental research, but there is no in-depth research on the influence of the change of main geometric parameters on the linear response characteristic and the numerical simulation research of the three-cup anemometer is still a blank .In order to study the dynamic response process of the anemometer and the influence law of different gyration radius and wind cup diameter on the linear features, a three-dimensional numerical simulation model is adopted by the method of computational fluid dynamics (CFD) , which provides a new method for the design of the anemometer.

2. Dynamic response equations

The wind speed is changed from u_0 to u_1 in one moment, but the rotating speed of the anemometer can't instantaneous change to steady rotating speed, n_1.The dynamic response equation can be shown to be

$$2\pi I\frac{\mathrm{d}n(t)}{\mathrm{d}t}+B_1n(t)+B_0=D_0u_1{}^2-Cu_1n(t) \tag{2.1}$$

where:

$$D_0=\frac{1}{2}\rho ARa_m \text{ and } C=2\pi\rho AR^2b_m \tag{2.2}$$

where I is the moment of swivel group's inertia, ρ is the air density， A is the front area of the cups，R is cups' center rotation radius， α_m and b_m are the drag coefficients of the cups, B_1n and B_0 are the frictional torque. The frictional torque can be neglected as it is very small in comparison to the aerodynamic torque[4].When the response is steady, the equation can be simplified to the following expression:

$$n_1=\frac{D_0u_1{}^2-B_0}{B_1+Cu_1}\approx\frac{D_0u_1}{C} \tag{2.3}$$

$$A_r=\frac{u_1}{n_1} \tag{2.4}$$

where A_r is the linear coefficient(A_r expressed in m).

The early research showed that A_r is only related to shape structure parameters， so the steady rotating speed n_1 and u_1 is in accordance with proportional relationship. Based on equation(2.1) and (2.3),the dynamic response equation can be simplified to be

$$T\frac{\mathrm{d}n(t)}{\mathrm{d}t}+n(t)=n_1\Rightarrow n(t)=n_1(1-e^{-t/T}) \tag{2.5}$$

where:

$$T=\frac{2\pi I}{B_1+Cu_1}\approx\frac{2\pi I}{Cu_1} \tag{2.6}$$

where T is the time constant(T expressed in s).Equation(2.6) describes the anemometer's step response of the first-order kinetics system. In T ,the anemometer responses 63.2% of the stable value and reaches to 95% of the stable value in $3T$ time. So it is obvious that the smaller time constant , the faster the response speed and the better dynamic performance. As equation(2.6) shows , T is inversely proportional to the wind speed u_1,so we defines distance constant, $L=u_1T$,to measure the dynamic performance of the anemometer.

3. Computing model and mesh grid

3.1 Computing model and mesh grid

The main structure parameters of the 3-cup anemometer are rotation radius, R and cup diameter, D. The structure and the definition of the parameters are shown as figure 1.We can see that the small surfaces and uncorrelated details are very much, which have a bad effect for the meshing. Also, the base part of the cup anemometer has little influence on the flow field, so we just keep the rotation components and improve the details. Establish a cuboid outflow field outside the geometric model, which should be large enough to avoid the effect of boundary on the simulation results. The size of the flow field is $900\times600\times1500$ mm.

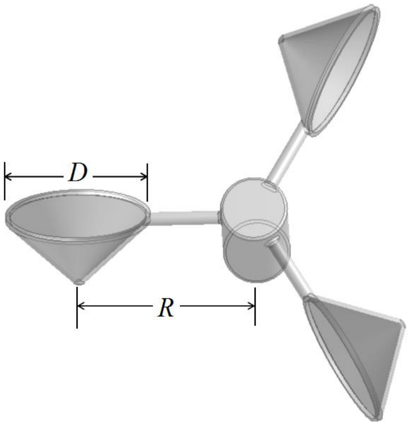


Fig.1 Structure of the Three-Cup Anemometer

In order to simulate the air flow surrounding the wind cup more accurately, the rotating field and the wall of anemometer are set a thinner mesh (Figure 2).Considering the effect of viscous fluid on the boundary layer ,dividing layer mesh for the wall boundary of the anemometer , which has total of five layers. After dividing the grid, the element number is 764479 in the computational domain.

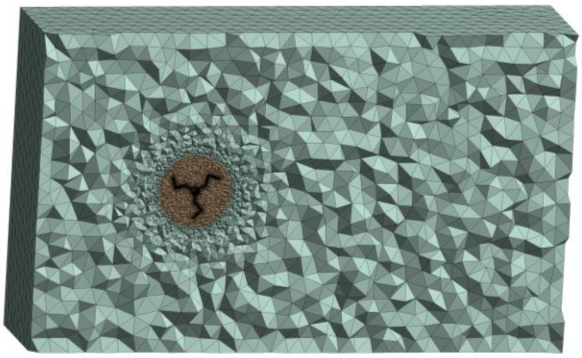


Fig.2 Meshing Grid

3.2 Sliding grid technology and the boundary conditions

In order to get the exact solutions of various physical quantities during the response process, sliding grid technology is used to deal with the problem of multiple reference frame motion. Then the whole computational domain is divided into two parts, static domain as the air outflow field domain and the rotating domain as a sub domain. The anemometer wall area is designated as a rigid body which need to have the moment of inertia and mass. The flow field calculation data is transmitted between static and rotating domains by interface[5].Computing model and boundary conditions are shown in Figure 3.Then set the boundary conditions for the model: inlet—wind speed of 20 m/s, outlet—opening, calculating the turbulence intensity and characteristic length for the inlet and outlet; slipping wall boundary for the four sides of the cuboid; wall of anemometer is defined as no slip wall boundary condition.

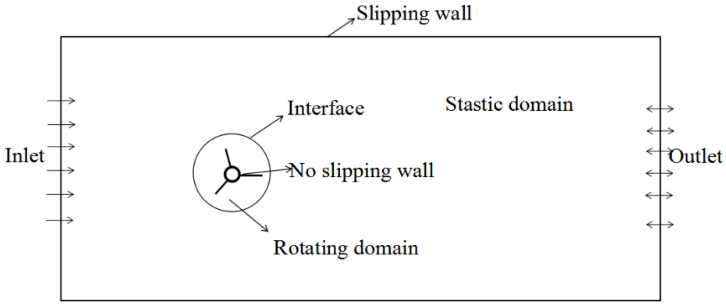


Fig.3 Computing Domain and Boundary Conditions

3.3 Solver options

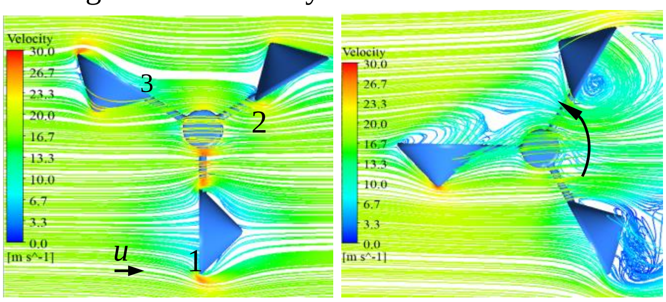
Numerical simulation is based on improved RNG k - epsilon turbulence model[6] instead of the standard k-epsilon turbulence model .High solution mode is set to control the overall solving accuracy, and set five iteration in each time step.The residual error convergence criteria for convergence solution is 1×10-5.Reasonable time step can speed up the convergence, so set 0.001s as the time step and set 2s as the total computation time.If the rotary achieve stability is stopped manually to solve ahead of time.If the rotating achieves stability before the deadline, stop the solving manually.

4. Analysis of the simulation results

4.1 The distribution of flow field

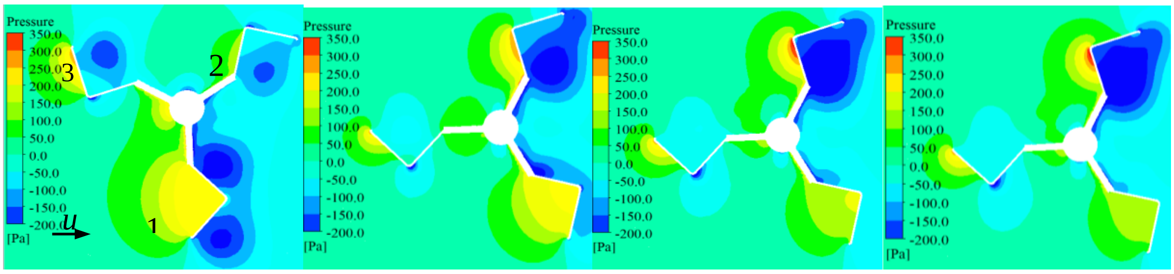
When the initial speed is zero, the velocity distributions of the flow line of the rotating components at different times are shown in Fig.4,and their stress nephograms are shown in Fig.5.In Figure 4 (a), the anemometer is still in the initial state, and it can be seen that the wind speed is obviously decreased due to the blocking effect of the wind cup. Hence, the flow of the air still keeps its original flow direction. While the Fig.4(b) shows the streamlines around the anemometer after a period of time for response, air trajectory obviously changes because of the rotation of the wind cup. Especially there are more than one significant swirls at the lee sides of cup 1 and 2 , but the turbulence is limited just around the cup.

In the stationary flow, the lower fluid flow rate, the greater the pressure. Then the pressure distribution shown in Fig.5(a) is consistent with the Bernoulli equation. The effective frontal area of cup 1 is big, so the airflow produces larger driving moment. While the effective frontal area of cups 2,3 are smaller, and they bear partial pressure, so the overall driving torque is greater than the resistant moment, and the cup has higher acceleration. From the 0.059s to 0.243s, the pressure of cup 1 at the windward decreases, while the pressure of cup 2 rises and its center of pressure moves outside. Resultant moment is decreased. From 0.243s to 0.429s, the pressure field around three cups changes a little which can be judged that anemometer rotating is close to steady state.



(a) t=0.019s (b) t=0.429s

Fig.4 Speed of Flow Figure



(a) t=0.019s (b) t=0.059s (c) t=0.243s (d) t=0.429s

Fig.5 Stress Nephogram

4.2 The analysis of the response process

Response angular velocity of the anemometer varying over time in ANSYS is shown in Figure 6.

The dynamic response process of the anemometer is consistent with the results of the analysis of the flow field. The angular acceleration of the anemometer decreases to zero when it reaches stable state of rotation. The fluctuation of the angular velocity is result from the fact that the resultant moments of the three cups are constantly changing during the rotation. The angular velocity reaches 63.2% of the stable value at T=0.109s and 95% after 0.312s, which is nearly consistent with Formula (2.5). Also, $L = uT = 2.18m$,in the range of 2~3.5m based on the international standard for the small cup anemometers[1].

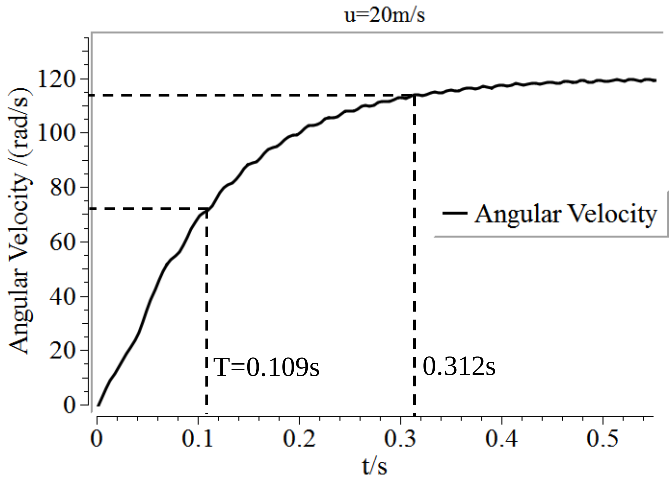
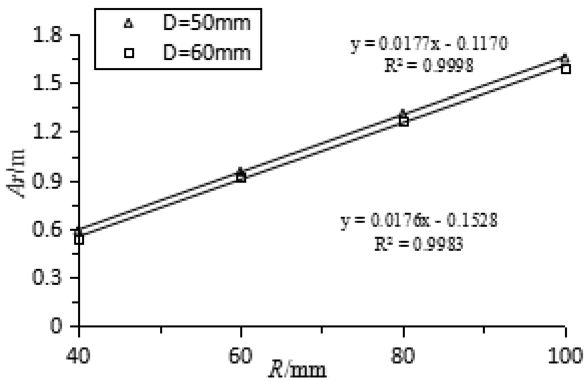


Fig.6 Response Angular Velocity of the Anemometer Varying over Time

4.3 The influence of the main geometrical parameters on the linear coefficient

With changing the rotation radius and cup's diameter, the simulation results are shown in Fig.7. As the figure shows, the linear coefficient increases linearly with the increase of the rotation radius when the cup’s diameter is constant. What’s more, the slope of the linear coefficient has nothing to do with the cup’s diameter. Simulation results for only changing the cup's diameter are shown in Fig.8. The linear coefficient decreases with the increase of the cup's diameter, but there is no clear linear relationship between them. With respect to the rotation radius, the change of the cup's diameter has little influence on the linear coefficient.

As to the 3-cup anemometers, the output wind speed is equal to the input signal of rotation speed multiplied by the linear coefficient. In this way, if the measured wind speed is too high, we can reduce the rotation speed by increasing the rotation radius reasonably to make the measurement of wind speed close to the actual value.



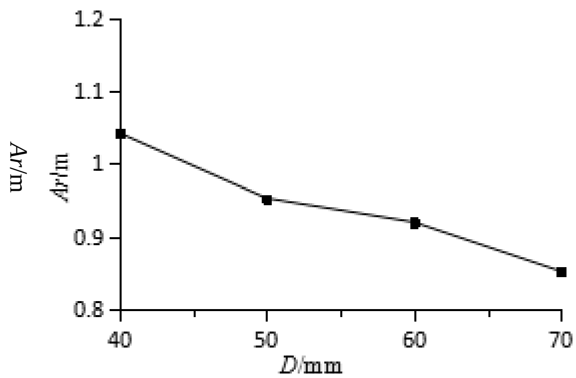


Fig.7 Linear Coefficient Changing with the Cup’s Diameter

Fig.8 Linear Coefficient Changing with the Rotation Radius

5. Conclusion

In the present study, the dynamic response characteristics and the influence of the main geometrical parameters on the linear coefficient have been analyzed by the numerical simulation based on computational fluid dynamics .The major conclusions resulting are:

Firstly, through the comparison between numerical simulation results and the theoretical formulas, the feasibility and accuracy of the simulation have been proved, which provides a new method to study the dynamic response of three type anemometer and reduces the cost of wind tunnel experiment conspicuously. Secondly, the linear coefficient increases linearly with the increase of the rotation radius and decreases with the increase of the cup's diameter, of which the rotation radius is the main factor. Thirdly, the little high measurement of the wind speed can be amended by increasing the rotation radius properly.

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