Study on the influence of turbulence intensity on vortex signal

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Abstract. Numerical simulation software FLUENT was used to compare the turbulence intensity of the fluid at the outlet of the linear shrinkage tube and curvilinear shrinkage tube. Through the detection points behind the bluff body in the measurement segment, the static pressure distribution is obtained, and the frequency and intensity of the vortex street signal are analysed. The results show that the fluid turbulence intensity in the curvilinear contraction tube is small, and the vortex signal intensity of the measurement segment is higher and the noise signal is less, which is favourable to the measurement of the vortex signal.

1. Introduction
Vortex flow meter, as a new-type velocity flow meter, has been widely used in industrial production. The theoretical shrinkage ratio of vortex street flowmeter can reach 100:1, but it can only reach 15:1 in practical applications. The reason is that vortex street flowmeter has a higher bottom boundary [1]. From the principle of Karman vortex signal generation, the vortex sensor output signal is weak at low velocity. Experts and scholars have found that vortex street signals tend to be aliased and even submerged by noise signals at low flow velocities, resulting in low signal-to-noise ratios for vortex street signals. To improve the performance of vortex flow meters at low velocity, the simplest method is to increase the fluid velocity. The solution adopted in industry is to add linear shrink tube in front of the vortex flow meter.

According to the Fluid Continuity Theorem, the linear shrink tube can significantly increase the fluid velocity, but it has been found in long-term use that the structure increases the fluid turbulence while increasing the fluid velocity, which in turn causes measurement error of the vortex flow meter. Then, a curvilinear shrink tube appeared, and to some extent improved the problem of the linear shrink tube increasing the fluid turbulence, which improved the measurement characteristics of the vortex flow meter. However, there are few theoretical and experimental studies on the Influence of fluid turbulence on vortex signal.

This article will use the computational fluid dynamics simulation software to model the straight pipe, the linear contraction pipe, the curve contraction pipe three kinds of different fluid pipes, takes the straight pipe as the reference, studies and analyses the change of fluid turbulence and the influence of turbulence on vortex signal in linear shrinkage tube, the curve shrinkage tube. The result indicates that low turbulence intensity has a positive effect on vortex signal.

2. Turbulence formation theory
Reynolds experiments show that the fluid has two flow patterns: laminar flow and turbulent flow; the two flow states not only have different fluid particle trajectories, but also their internal structures are...
completely different. However, as the flow velocity changes, the two flow states can convert to each other. Taking the transition from laminar flow to turbulent flow as an example, we analyse the conditions and reasons for its transformation.

From Reynolds experiments, the indispensable conditions for the laminar flow to turn into a turbulent flow is that the formation of a vortex and the vortex are separated from the original stratum and incorporated into the adjacent flow stratum. An important prerequisite for vortex formation is fluid viscosity. The distribution of flow velocity on the actual fluid flow cross-section is not uniform, thus promoting internal friction shear stress between the flow layers. For a certain stratum, the shear stress exerted on it by the faster flow layer is in the forward flow direction, and the shear stress exerted on it by the slower flow layer is in the reverse flow direction. Therefore, the shear stress experienced by the selected flow layer tends to promote the generation of the vortex.

When the vortex formed, the velocity distribution near the vortex changes. The rotation direction of the vortex is the same as the direction of the faster flow layer and is opposite to that of the slower flow layer. This leads to an increase in the velocity, and decrease in the pressure of the faster flow layer and a decrease in the velocity, an increase in the pressure of the slower flow layer. As a result, there is a pressure difference between the two sides of the vortex, forming a lateral force. This force will prompt the vortex to disengage from the original stratum and into the faster flow zone. When the vortex body departs from the original stratum and enters the new stratum, the laminar flow becomes turbulent flow [2].

In the shrinkage tube, the flow near the tube wall is greatly increased due to compression, and the fluid velocity at the centre of the tube changes slowly. Shrink tubes increase the difference of flow velocity in different fluid layers. The flow velocity in the linear shrink tube is always increased and the vortex body is always formed. At the outlet of the straight shrink tube, the turbulence intensity of the fluid is maximized. The flow velocity in the curvilinear shrinkage tube increases slowly, then increases rapidly, and then slowly increases. In the whole process, the vortex body most easily forms when the flow velocity increases rapidly, and the fluid turbulence intensity reaches the maximum in this section. The outlet of the curvilinear shrinkage tube is relatively flat and the turbulence intensity of the fluid at the outlet is relatively small.

3. The simulation experiment

3.1. Modelling and Meshing

This paper uses modelling software ICEM CFD to establish three models [3], as shown in Figure 1. The linear tube (Fig. 1a) has a length of 600mm and a diameter of 50mm; the linear shrinkage tube (Fig. 1b) has a length of 600mm, a large diameter of 100mm, a small diameter of 50mm, a shrinkage ratio of 4; and a curvilinear shrinkage tube (Fig. 1c) has a length of 600mm, a large diameter of 100mm, a small diameter of 50mm, and the shrinkage ratio is 4. Trapezoidal bluff body is used in all three types of pipes. The length of the trapezoidal bluff body is 16mm, the width of the inflow plane is 14mm, and the entrance distance is 360mm. To ensure the same velocity in the measuring section, the inlet velocity of the linear shrinkage tube and the curvilinear shrinkage tube is set to 0.4m/s 1.8m/s, 1.5m/s; the inlet velocity of the linear tube is set to 1.6m/s, 3.2m/s, 6.0m/s.

The wall curve of the curvilinear shrinkage tube is the Witozinsky curve, and its equation is as follows:

\[
 r = \frac{R_2}{\sqrt{1 - \left(1 - \frac{R_2}{R_1}\right)^2 \left(\frac{1 - \frac{3x^2}{a^2}}{1 + \frac{x^2}{a^2}}\right)^2}}
\]  

(1)

In the formula, \( R_1 \) is the inlet radius of the shrinkage tube, \( R_2 \) is the outlet radius of the shrinkage tube, \( r \) is the cross-sectional radius of the shrinkage tube at the axial distance \( x \), \( a = \sqrt{3}L \), and \( L \) is the length of the shrinkage tube.
The ICEM CFD software is used to divide the established model into grids. Because the model structure is simple, the structured grid is used to divide the model. After meshing, the model is imported into FLUENT for calculation.

(a)  
(b)  
(c)  

Figure 1. Three different types of fluid pipes.

3.2. Calculation Models and Algorithm Selection

The results obtained by different numerical models in FLUENT differ in the accuracy and speed of calculations, and appropriate calculation methods should be selected for specific problems to obtain accurate results [4].

This paper selects the RNG k-\(\varepsilon\) turbulence model. This model is an improved model of the standard k-\(\varepsilon\) model, and its improvement measures mainly include the following aspects:

1. An additional term is added to the \(\varepsilon\) equation, making it more accurate when calculating flow fields with large velocity gradients.
2. The model considers the rotation effect, so the calculation accuracy for strong rotational flow is also improved.
3. The model adds an analytical formula for calculating the turbulent Brandt number.
4. The model can calculate the low Reynolds number effect after proper treatment of the near wall area.

The above measures make the model more suitable for calculating turbulence, and its calculation accuracy and speed are greatly improved.

To control the calculation process and improve the accuracy of the calculation, it is necessary to set the corresponding value in the solver. The settings mainly include algorithms and discrete formats.

In this paper, the SIMPLE form of pressure-velocity correlation algorithm is selected. SIMPLE has good stability and high precision and is used for the calculation of steady flow. The second-order upwind style in the discrete format is selected. The second-order upwind style can be seen as a special case of the flow field variable in the control point of the upstream grid unit. It retains the first and second terms of the Taylor series, and the calculation accuracy is higher.

Considering the calculation accuracy and the calculation speed, the fluid flow field of three different pipeline structures was simulated and analysed using RNG k-\(\varepsilon\) turbulence model, SIMPLE pressure-velocity coupling algorithm and second-order upwind discrete format.
4. Analysis of simulation results

4.1. Comparison of Vortex signal strength

The detection point behind the bluff body in the measurement segment records the periodic variation of the pressure. The vortex frequency measurement is performed by using the Fourier Transform (FFT). The following figures show the pressure change curve and frequency diagram of the post-body detection points of the line tube, curvilinear shrinkage tube, and line shrinkage tube at different velocity.

![Figure 2. Pressure curve and frequency diagram when velocity is 1.6m/s.](image)

![Figure 3. Pressure curve and frequency diagram when velocity is 3.2m/s.](image)
It can be seen from the time domain waveform that the vortex signal is a sine wave, which reflects the vibration characteristics of the fluid caused by the periodic vortex. Due to the change of the pipeline structure, the pressure value at the detection point deviated from the sine law, and the pressure value of linear shrinkage pipe deviated the most. The signal peak-to-peak value corresponds to the magnitude of the pressure fluctuation generated by the vortex. The larger the peak-to-peak value, the stronger the corresponding vortex signal. The comparison shows that the vortex signal intensity is the highest when the flow velocity is 6.0 m/s. The peak value in the frequency domain map corresponds to the frequency of vortex signal, and as the velocity increases, the frequency value also increases accordingly. At the same velocity, the spectral density of the curvilinear tube is greater. Among the three types of pipes, the frequency components of the linear shrink tube are complex and there are many noise signals, which is also the reason for the poor measurement characteristics of the vortex flow meter in actual measurement.

4.2. **The comparison of turbulence intensity**

Turbulence is an eigenvalue that reflects the turbulence intensity and is the ratio of the root mean square of the pulsation velocity to the corresponding mean velocity [5]. The greater the turbulence intensity, the more vortices are present inside the fluid and the vortex signal collected in the measurement section will have a lot of noise signals. Therefore, low turbulence intensity has a positive effect on the collection and processing of vortex signals. Based on the principle of turbulent flow formation and experience in practical application, the turbulence intensity of the fluid in the linear shrinkage tube at the same velocity is higher than that of the curvilinear shrinkage tube. At different velocity, the turbulent intensity of the linear shrinkage tube and the curvilinear shrinkage tube are almost the same. As shown in the figure below.
The figure shows that the turbulence intensity in the line shrinkage tube at the same velocity is greater. At different velocity, turbulence intensity changes little. It shows that the turbulence intensity is more affected by the structure of the shrinkage tube, and the turbulence intensity of the fluid in the curvilinear shrinkage tube is smaller than the turbulence intensity of the fluid in the linear shrinkage tube.

5. Conclusion
In this paper, FLUENT simulation software is used to simulate the flow field of straight pipe, straight shrink pipe and curved shrink pipe. The following conclusions are obtained:

1. At the same flow velocity, the frequency of the vortex street signal is the same; the frequency and intensity of the vortex street signal increase with the increase of the flow velocity.

2. The turbulence of the fluid in the linear shrink tube is greater than that of the curved shrink tube. At different velocity, the degree of turbulence in the fluid did not differ significantly. Turbulence is more affected by the structure of the shrink tube.

3. The fluid in the linear contraction tube structure is more disordered, and there are more noise signals in the measurement section, which are consistent with the phenomenon in practical application.

According to the above simulation results, compared to the straight shrink tube, the fluid turbulence in the curve shrink tube is smaller, the noise signal in the measurement section can be reduced, the vortex signal is easier to measure, and the static characteristics of the vortex flow meter are improved.

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