Vehicle contact network based on fluid coupling analysis of load of operational status detection device

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Abstract. Based on the analysis of aerodynamic load and structural strength of the vehicle contact network monitoring device, the distribution of aerodynamic moments and surface pressure of the monitoring device is calculated by means of fluid-solid coupling. The calculated load is applied to the surface of the device for structural analysis, mainly to investigate the maximum deformation and maximum equivalent stress of the device. The study found that air flow separation occurred above the ear region when driving forward, the pressure was higher, and the air flow below the ear region flowed around the ear region. The pressure difference between the upper and lower ears produced a downward force of about 150N in a single ear region, and produced a large rolling moment, after checking its connection strength with the central body to meet the requirements for use.

1. Introduction

The coupling phenomenon between structure and fluid is common in transportation, ship, energy, construction, machinery manufacturing, aerospace and other engineering fields, sometimes causing structural damage. In 1940, Tacoma Narrows Bridge in the United States experienced fluid structure coupling vibration in the wind, and finally collapsed [1]. In 2006, the blade of an axial-flow compressor developed fluid structure coupling vibration, which induced high cycle fatigue and resulted in blade fracture [2]. In 2010, Lockheed Martin's demonstrator broke the wing due to the flutter induced by the fluid structure coupling effect between the wing and the air [3]. Therefore, fluid structure coupling has become the focus of researchers. Mao Guodong [4] studied the effect of fluid structure coupling on the wind-induced vibration response of membrane structures. Wang Zheng [5] calculated the fluid structure coupling response of compressor blades based on CFD / CSD technology and predicted the flutter boundary. In recent years, with the rapid development of high-speed railway in China, more and more attention has been paid to the influence of aerodynamic load on the structural reliability [6]. The online monitoring device for the operating state of the vehicle contact net of the EMU (hereinafter referred to as the device) is an optical and infrared monitoring device for the operating status of the pantograph network installed on the top of the vehicle. Therefore, the interior needs more space. The detection device is generally designed as a thin shell structure. When the train is running at high speed (the speed can be as high as 350–400 km/h), the aerodynamic load (force and moment) of the device is relatively large and its structural strength needs to be considered. In this paper the fluid-structure interaction method was adapted. Through aerodynamic and structural analysis, the structural strength of the device under aerodynamic load is checked to meet the engineering requirements.
2. Computational model and conditions

The calculation involves a device of type C inverted buckles + the shape of the left and right raised ears, with glass observation windows and lighting holes at the front, and optical and infrared monitoring instruments installed in the glass windows. The lighting hole mainly provides the lighting of the pantograph during the night and in the tunnel, and the rear has an entry hole. There are small grooves on the back and ears to facilitate the heat dissipation of the device. The schematic diagram of the model device is shown in Figure 1.

![Figure 1. Profile of the device.](image1)

![Figure 2. Models and computational mesh.](image2)

The normal speed of the train is about 200km/h to 400km/h. Therefore, this project considers the situation where the train is subjected to aerodynamic force when driving at the highest speed. That is, the speed is 400km/h, and no special circumstances such as natural winds, train crossings, tunnels, etc. are considered. Taking the observation window facing the direction of the air flow as the positive direction of the train, the aerodynamic characteristics of the configuration device during the train's direct and reverse driving are investigated, and the six-component aerodynamic power/moment and surface pressure distribution of the device's shape are mainly calculated. The aerodynamic load results are used for the static structural strength analysis of the outer shell of the device.

2.1. Aerodynamic numerical calculation method

The train’s operating speed is \(V=400\text{km/h}\) on the railway with an ambient temperature \(T=300\text{K}\). Compressible complete gas model was used in this study. The Mach number is 0.32, which belongs to the subsonic speed flow region. The Reynolds number corresponding to the airflow and characteristic length with \(L_{ref}=0.5\text{m}\) is approximately 3.54 million. Due to the irregular shape of the device, we use unstructured grids to divide the flow field area, and at the same time simplify the shape of the device, mainly filling the small grooves on the back of the configuration and at the two ears. All configurations were filled with screw holes and back pits. The calculation of the model grid division is shown in Figure 2. The influence of the lateral wind is not considered in the calculation. In order to save the calculation resources, a semi-model calculation is used. Symmetric boundary conditions are used on the symmetric surface, and non-slip wall fixation conditions are used on the connection surface of the train. The far field boundary is taken as more than 100 times the reference length. The compressible Reynolds average Navier-Stokes equation was adopted as control equation. The control equation can be written in the following form [7].

\[
\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} = \frac{\partial E_{r}^{+}}{\partial x} + \frac{\partial F_{r}^{+}}{\partial y} + \frac{\partial G_{r}^{+}}{\partial z}
\]

(1)

SST turbulence model with two-equation turbulent model with good accuracy and applicability in engineering problems that is suitable for simulating boundary layer flow under moderately complex outflows and pressure gradients. The closed N-S equation uses the turbulent energy viscous transport equation. The specific form of SST turbulence model can be referenced [8]. The finite volume method
is used to discrete the RANS equation. The finite volume method is a common method used in practical CFD software. It can well guarantee the conservation of quality, momentum and energy. In order to ensure the spatial second-order accuracy of discrete equations, the equation is discrete in Roe format and viscous term discrete in center format [9] [10]. Considering that the shape of the model is relatively complex, the leeward surface will have a large range of separated flows, the flow field structure is complex, and the flow shows obvious unsteady regularity. This term is calculated using unsteady calculations, and the time is discrete using the implicit format of the two-time step., the time step length 0.0001s, Iterative calculation of 1000 time steps, the time to obtain flow field parameters is much greater than the characteristic time \( V=0.0045 \) S.

![Figure 3. Surface pressure on test models.](image)

3. Results and analysis of aerodynamic forces

Figure 3 gives a cloud diagram of the surface pressure distribution of the calculation model under various working conditions, Figure 4 and Figure 5 give the flow chart near the surface of the calculation model under the corresponding working conditions. From the pressure cloud map, there is a high-pressure area on the windward side of the device. This is due to the fact that the air flow is hindered by the device, the speed is reduced, the pressure is increased, and at the same time, it can be seen in the streamline diagram that there is a small flow below the windward side. Area; There is a low pressure band on the shoulder of the device, which is formed by the rapid acceleration of the high-pressure air flow that decelerates on the windward side when bypassing the shoulder; Due to the fact that the air flow around the shoulder of the device is too fast and the pressure is low, an inverse pressure gradient is formed with the higher pressure on the leeward side. The surface air flow of the device will be separated at a certain position on the leeward side, forming a large leeward side. Reflow area. Due to the separation of the airflow, the airflow pressure on the leeward side was not fully restored, and the pressure difference between the windward side and the leeward side of the device was the main source of drag to the device.

As shown in Figure 4, the area of the windward pressure area is relatively large and is mainly distributed in the two observation windows and the lower half of the windward side of the ears. The calculation results show that the two-ear part provides about 1/3 of the total drag. Regardless of other design requirements, the windward area of the two ears can be appropriately reduced, such as increasing the inclination of the two ears, which can significantly reduce the drag to driving. As shown in Figure 5, there are three large vortices on the leeward side of the driving direction. After the leeward side of the ear, the upper leeward area of the inlet and the inlet, the three vortices constitute a large area of reflux. area. Therefore, there is greater drag to positive driving. When driving in the
opposite direction, the pressure distribution is basically similar to that of positive driving. The area of the high pressure area of the two ears is significantly reduced compared to the working conditions. The separation point is relatively backward, and the reflux area on the leeward side is also smaller. Therefore, the overall drag is significantly reduced when driving in a positive direction, which is about 1/2 of that when driving in a positive direction.

It is worth noting that the ear has received a greater negative lift while driving in a positive direction. This is because of the separation of air flow above the ear, the pressure is higher, and the air flow below the ear flows around the ear, the pressure is lower, and the pressure difference between the upper and lower ears produces a downward force of about 150N in a single ear, and produces a large rolling moment. Special attention should be paid to the connection strength of the ear during intensity checking. The details of the six-component aerodynamic forces / moments of each part and the whole of the forward and reverse driving are shown in Table 1.

| conditions       | parts   | Fx(N) | Fy(N) | Fz(N) |
|------------------|---------|-------|-------|-------|
| Drive straight.  | body    | -125.4| 167.0 | 235.1 |
|                  | ear     | -78.1 | 308.7 | -150.3|
|                  | total   | -203.5| 475.7 | 84.8  |
| Drive backwards. | body    | 78.3  | 112.8 | 196.7 |
|                  | ear     | 30.7  | 246.0 | -14.3 |
|                  | total   | 109.0 | 358.8 | 182.3 |

4. Structural strength analysis
According to the product design objectives, the configuration of the device must meet the following requirements under the driving conditions of the vehicle:

A. Static strength: The maximum Von Mises stress in the shell structure and the working stress of the fastener are not greater than 1/3 of the material yield stress $S$, i.e., the safety factor $M.S \geq 3$.

B. Stiffness: The maximum allowable deformation of the structure $U \leq 1\, \text{mm}$ is proposed by the designer.

The strength calculation uses the Fluid Flow (FLUENT) and Static Struggle modules in the ANSYS Workbench platform to perform one-way fluid-solid coupling calculations. The aerodynamic load is passed through the fluid-solid coupling surface (i.e., the device removes all outer surfaces of the
base surface). Grid point interpolation. The observation window material is also set as an aluminum alloy material. Since the yield strength and elastic modulus of the observation window glass are generally higher than that of aluminum alloy, this is conservative in engineering. The bottom surface of the device is set to the fixed condition, and binding contact is used between the components of the outer shell. The overall deformation and stress cloud diagram is shown in Figure 6. It can be seen from the figure that the maximum deformation is about 0.02 mm, which is much less than 1 mm; The maximum Von Mises stress is 1.925 MPa, which is much smaller than the yield stress of the material 280 MPa, which satisfies the design requirements. The overall deformation amount is calculated by the following formula

\[ U_{total} = \sqrt{U_x^2 + U_y^2 + U_z^2} \]  

(a)Drive straight  
(b)Drive backwards

**Figure 6.** Deformation of the model on aerodynamics.

deposition in the X, Y, Z directions, respectively. The device adopts 6(configuration 1) to 8(configuration 2, 3, 4, 5) M10 screws connected to the moving roof base to overcome the aerodynamic force and moment of the device. It can be seen that the aerodynamic loads under the operating conditions of the full mode are mainly composed of \( F_x \), \( F_z \), and \( M_y \). Where \( F_x \) produces shear stress on the screw, \( F_z \) produces tensile stress, and \( M_y \) produces tensile stress. As shown in Figure 6, the \( Z \) coordinate vertical paper faces outward, when \( M_y \) is the positive 4# screw load maximum, and when \( M_y \) is the negative 3# screw load maximum. Take configuration 1 as an example to check the strength of the 4# position M10 screw. Under the condition of reverse driving, the force acting on No.4 screw is bigger 20.

5. Conclusions

The numerical model of fluid structure coupling analysis for catenary monitoring device of EMU established in this paper can effectively simulate the influence of aerodynamic load effect on the deformation of monitoring device shell and connecting device. Firstly, through the flow field simulation analysis, it is found that the most influential part of the flow field on the monitoring device is two lugs, and then the aerodynamic load on the surface of wind turbine obtained from the flow field analysis is taken as the external load. The static analysis of the monitoring device shell shows that the deformation of the shell and the strength of the connecting structure meet the design requirements.

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