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Optimization for the Outer Windshield of High-Speed Train Based on Numerical Calculation Method of Dynamic Stability About Fluid-Structure Coupling

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Abstract

In this paper, a flutter solving program based on unstructured mesh and mixed mesh CFD solver is developed. Using the high-precision and high-efficiency fluid-structure tight coupling method, and the 145mm outer windshield model of high-speed train is selected as the research object. We have studied and analyzed the influence of intrinsic vibration frequency on the outer windshield structure of high-speed train. The result shows that, the vibration of the outer windshield can be convergent by changing the intrinsic vibration frequency of the structure. At the same time, the relationship between the different operating velocity of high-speed train and the intrinsic frequency of structure is explored, and the optimal outer windshield scheme under the different operating velocity is proposed.

Keywords: the outer windshield, flutter, tight coupling, structural intrinsic vibration frequency, the operating velocity, optimization.

1 Introduction

As an important component of the end connection device of high-speed train, the outer windshield structure can make the transition of the end connection of adjacent vehicles smoothly, thus the noise and aerodynamic drag caused by the aerodynamic load at the end of the train during high-speed running are reduced [1]. With the continuously increasing operating velocity of high-speed train, the influence of the outer windshield on the aerodynamic performance of the high-speed train is also increasing gradually [2].

In recent years, researchs on the outer windshield of the high-speed train is increasing gradually. Kun Zhang et al. [3] introduced types, the present situation of development and production, existing problems and corresponding solutions of the outer windshield about domestic high-speed trains, and prospected the application prospect of the outer windshield. Jun Gao et al. [4] carried out structural analysis and calculation on the outer windshield of high-speed train, and discussed the structural design about the outer windshield at the end of the train from the aspects of material selection, drag reduction effect and sound insulation effect according to relevant standards. Based on a certain type of high-speed train, Jie Gai et al. [5] conducted a simulation analysis and research on the flow field distribution around the outer windshield and the aerodynamic load on the outer windshield when the train is running on the open line with different design forms of the outer windshield structure. Jianming CAI et al. [6] analyzed the inherent dynamic characteristics of U-shaped rubber outer windshield structure through modal finite element calculation and experiment, and studied the influence of the position of the excitation point and response point of the modal test on the modal parameters of U-shaped rubber outer windshield structure. Xiujuan Miao et al. [7] used the three-dimensional numerical method to simulate the flow field around a high-speed freight train under strong crosswind, then explored and analyzed the influence of different windshield schemes on the aerodynamic performance of the high-speed freight train. Based on fluid dynamics and FLUENT software, Dafi Gong et al. [8,9] carried out aerodynamic simulation and drag reduction analysis on the outer windshield of the high-speed train units, and discussed the design technology and design process of the outer windshield structure. Enyu Yang et al. [10,11] studied the influence of different windshields on the aerodynamic force of the high-speed train and the aerodynamic noise of the high-speed train when it is running on the open line by numerical simulation.

With the gradually increasing operating velocity of high-speed train, the mechanical environment of the outer windshield structure becomes more complex, and the vibration deformation of the external components of the train body becomes more frequent caused by the aerodynamic effect of the train. The vibration of the outer windshield of the high-speed train during operation is a complicated fluid-structure coupling problem, which includes three kinds of problems: static aeroelasticity, flutter and buffeting. The static pressure difference between the high-speed moving flow field outside the windshield and the flow field inside the chamber produces stable static aeroelastic deformation. The coupling between the external unsteady flow field and the elastic structure of the windshield causes the vibration of the windshield. When the energy given to the elastic structure by the flow field is greater than the energy dissipated by the elastic structure, the amplitude of the coupling vibration is amplified until it becomes unstable, this is the flutter problem. In other words, flutter represents the dynamic stability of the fluid-structure interaction. Buffeting is mainly manifested as the forced vibration of the windshield under the action of unsteady aerodynamic forces, which is an inevitable phenomenon of the windshield under the action of unsteady aerodynamic forces, and it only affects the structural fatigue strength, but does not affect the stability and safety.

Static aeroelasticity only affects the aerodynamic drag and aerodynamic noise characteristics of high-speed train, but does not affect the safety and reliability. Buffeting is the inevitable state after the windshield loses stability, the buffeting problem before the windshield loses stability is only related to noise control and fatigue life. Therefore, for the instability problem of the windshield, this paper will focus on the flutter problem, including the influence of structural intrinsic vibration frequency and the operating velocity on the outer windshield of high-speed train. The optimization scheme of the outer windshield of the high-speed train is obtained, which will provide reference for the structure design of the outer windshield of high-speed train.

2 Methods

In this paper, a flutter solving program based on unstructured mesh and mixed mesh CFD solver is developed. The flutter numerical simulation process is shown in Figure 1.

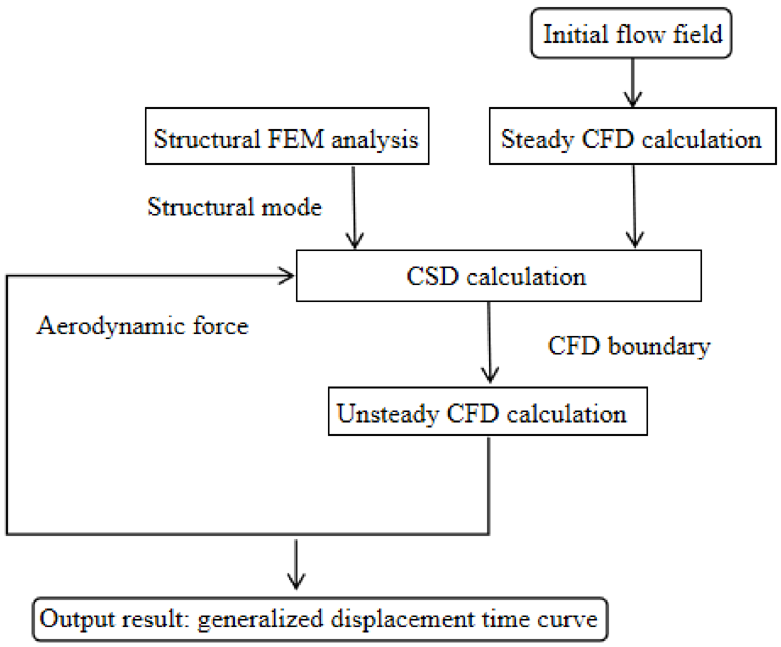


Figure 1: Flow chart of flutter calculation process.

2.1 Computational solid mechanics model

Based on the Rayleigh-Ritz method, the generalized structural equation of motion can be expressed as the following second-order ordinary differential equation:

$$[M]\{\ddot{q}(t)\}+[D]\{\dot{q}(t)\}+[K]\{q(t)\}=\{F(t)\} \tag{1}$$

$$\{w(x,y,z,t)\} = \sum_{i=1}^{N} q_i(t)\{\phi_i(x,y,z)\} \tag{2}$$

$$\{F(t)\} = \sum_{i=1}^{3} \iiint \Delta f_i(x,y,z,t)\phi_i(x,y,z)ds \tag{3}$$

In equations above, $\{w(x,y,z,t)\}$ represents the structural deformation vector of the windshield surface, $\{q(t)\}$ is the generalized displacement, $\{F(t)\}$ is the generalized aerodynamic force, $[M],[D],[K]$ are the generalized mass, damping and stiffness matrix of the structure respectively.

Making $\vec{S} = \{q(t), \dot{q}(t)\}$, The second-order ordinary differential equation (1) can be rewritten as a system of linear equations:

$$\frac{d\vec{S}}{dt} = \vec{P} = \begin{bmatrix} 0 \\ \{F(t)/[M]\} \end{bmatrix} - \begin{bmatrix} 0 & -1 \\ [K]/[M] & [D]/[M] \end{bmatrix} \vec{S} \tag{4}$$

We construct equation (4) into the following sub-iterative format:

$$\begin{bmatrix} 1 & -\phi^i \Delta t \\ \phi^i \Delta t [K]/[M] & 1+\phi^i \Delta t [D]/[M] \end{bmatrix} \Delta\vec{S} = -\phi^i \left\{ (1+\phi)\vec{S} - (1+2\phi)\vec{S}^n + \phi\vec{S}^{(n-1)} + \Delta t \vec{P}^p \right\}$$

$$\Delta\vec{S} = \vec{S}^{(p+1)} - \vec{S}^p, \phi^i = \frac{1}{(1+\phi)} \tag{5}$$

Equation (5) is a second-order time-precision format when $\phi = 0.5, p \to \infty$, If the flow field calculation is also constructed with the sub-iterative format, the tightly coupled format is obtained by solving both the flow field and the structural deformation at each sub-iterative step. When the sub-iterative step approaching infinity, the time precision of the whole calculation is second order.

2.2 Computational fluid dynamics model

The equation of the three-dimensional N-S equation in the rectangular coordinate system can be expressed as:

$$\partial_t Q + \partial_x E + \partial_y F + \partial_z G - \partial_x E_v - \partial_y F_v - \partial_z G_v = S_{GCL} \tag{6}$$

Among them, S_{GCL} is a geometric conservation term caused by mesh deformation. In this paper, a DP-LUR time advancing scheme with sub-iteration is constructed:

$$\begin{aligned} D^{-1}\Delta Q = -\phi^i \{ & (1+\phi)Q^p - (1+2\phi)Q^n + \phi Q^{n-1} \\ & -\Delta t(\delta_x E^p + \delta_y F^p + \delta_z G^p) + \Delta t(\delta_x E_v^p + \delta_y F_v^p + \delta_z G_v^p) \} \end{aligned} \tag{7}$$

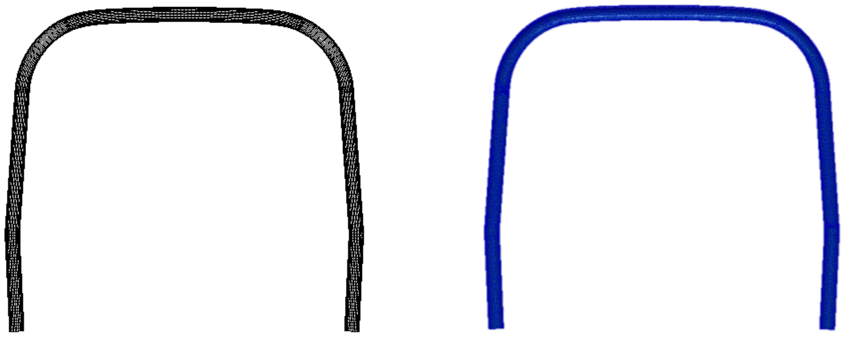
Unlike the standard DP-LUR, a variable ϕ^i is contained in the expression, which is:

$$D=\bar{\rho}I+\phi^{i}\Delta t\sum_{j(i)}A_{ij}$$
$$\bar{\rho}=1+\phi^{i}\Delta t\sum_{j(i)}\bar{\rho}_{ij}$$
$$\phi^{i}=1/(1+\phi),\Delta Q=Q^{p+1}-Q^{p}$$

In the sub-iteration process, equations (5) and (7) are solved at the same time, and the tight coupling calculation format of fluid-structure coupling is obtained. The non-viscous term is discretized by the modified HLLEW format, and the viscous term is discretized directly by the second-order center format. The modified HLLEW format is automatically recovered to the upwind difference flux splitting Roe format in the isentropic flow field, and to the standard HLLEW format in the flow field with large entropy change. This not only overcomes the non-physical oscillation phenomenon that may occur when simulates the shock flow in the Roe format, but also overcomes the shortcoming that is too viscous in the continuous flow field in the HLLEW format. Thus, the overall calculation accuracy of the flow field is improved.

3 Results

The outer windshield model of the high-speed train selected in this paper is 145mm windshield, the pneumatic mesh uses the mixed form, and the structural finite element model uses 10-node tetrahedral solid elements, as shown in Figure 2.



(a) Pneumatic mesh. (b) Structural finite element mesh.

Figure 2: Mesh models about the outer windshield of high speed train.

3.1 The influence of structural intrinsic vibration frequency

Taking the Fuxing high-speed train as an example, the operating velocity of 350km/h as a typical working condition, and the flutter boundary is searched by the method of variable structural stiffness. The numerical simulation result shows that the coupling divergence appears in the original structural state of the outer windshield of high-speed train. Results are shown in Figure 3 and 4, which respectively shows the generalized displacement curve of the first 30 modes and individual order modes under the original structural state of the outer windshield of high-speed train.

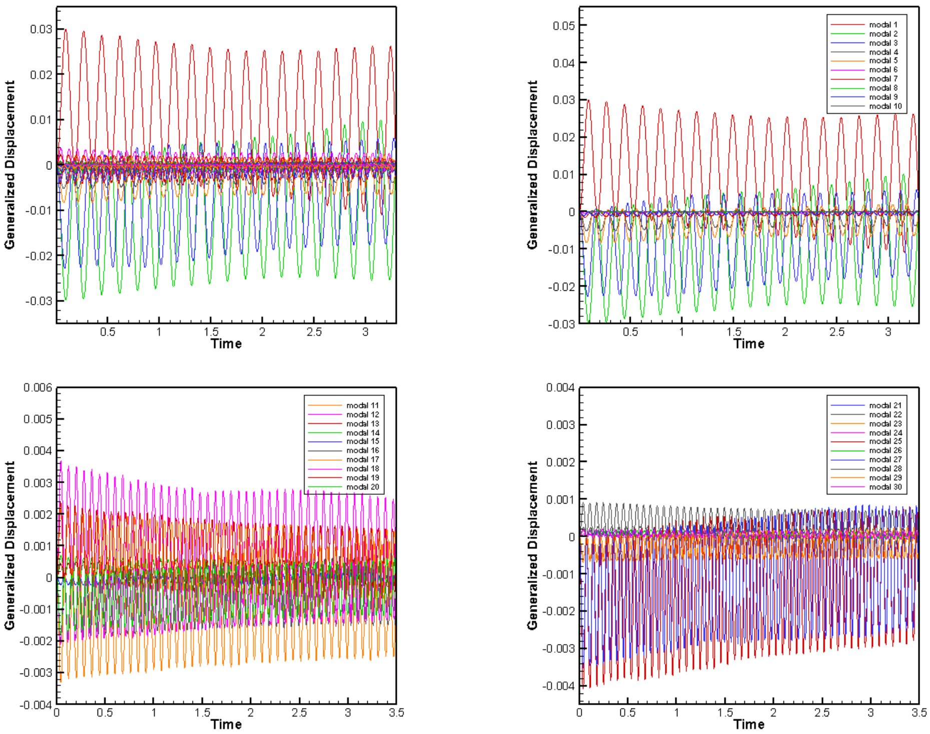


Figure 3: The generalized displacement curve of the first 30 modes when the intrinsic vibration frequency of the structure is multiplied by the coefficient 1.00.

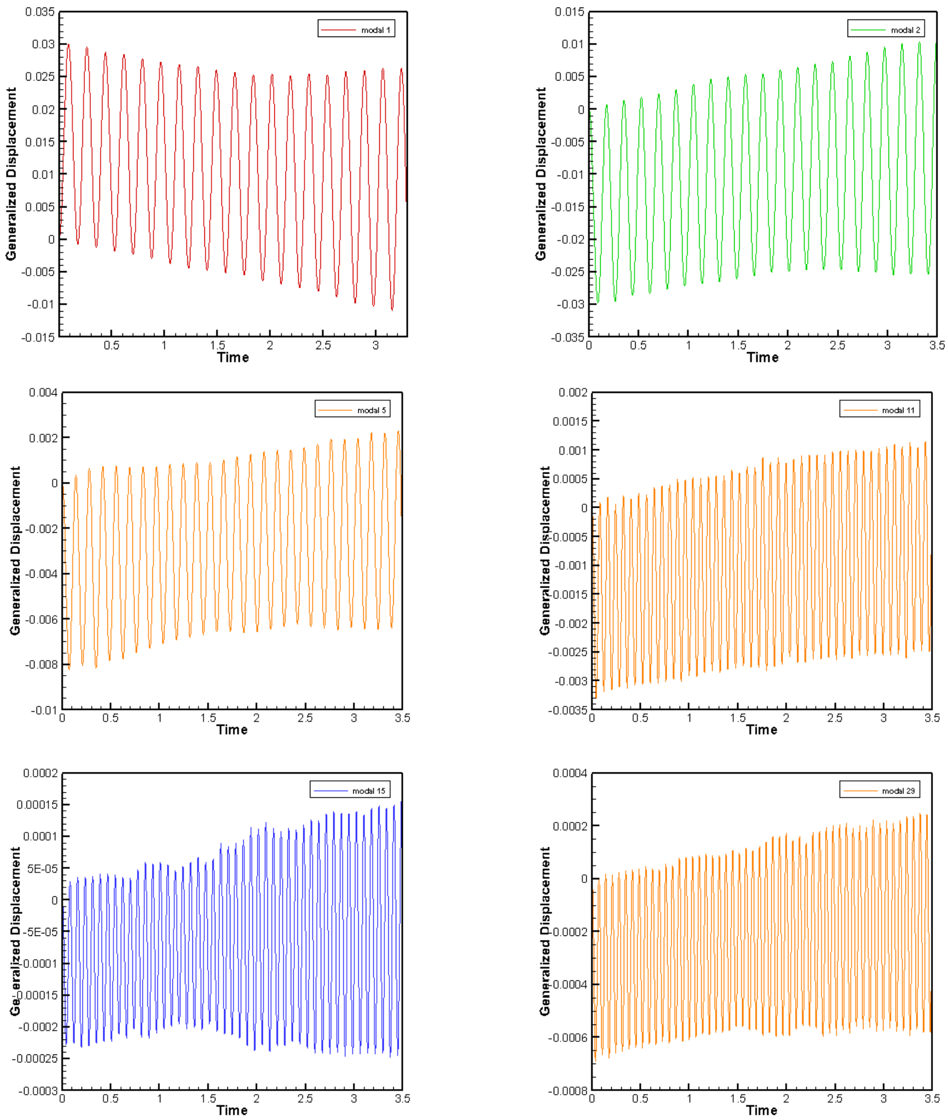


Figure 4: The generalized displacement curve of individual order modes when the intrinsic vibration frequency of the structure is multiplied by the coefficient 1.00.

After multiplying the intrinsic vibration frequency of the original structure of the outer windshield of the high-speed train by a coefficient of 1.10, numerical simulation results are shown in Figure 5 and 6. Results show that the generalized structure displacement of the outer windshield of the high-speed train appears constant amplitude oscillation and just reaches the flutter boundary.

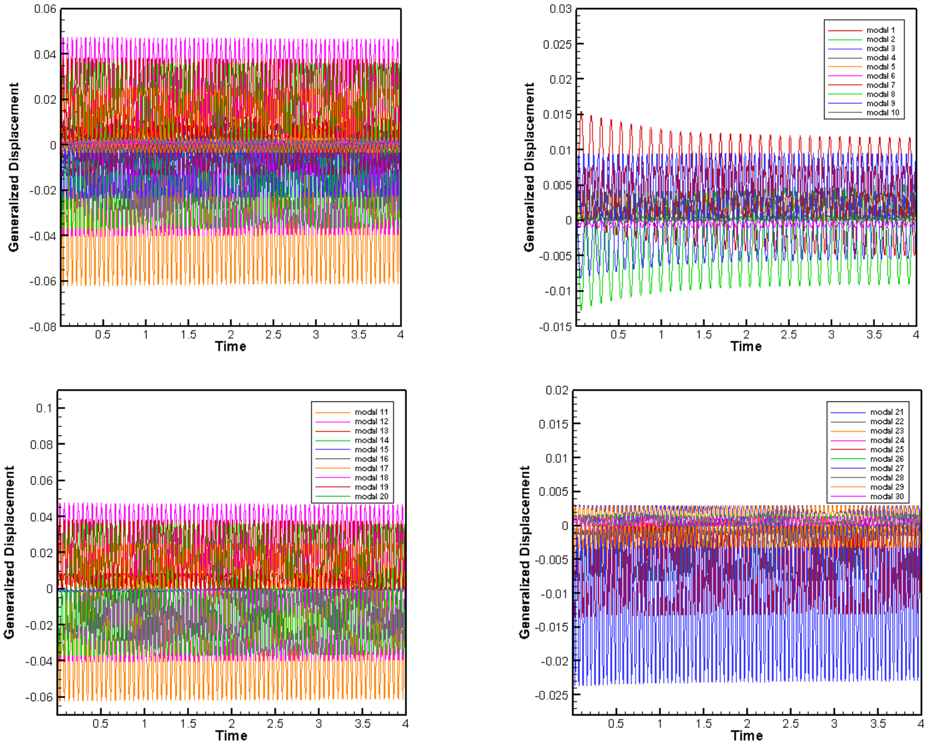


Figure 5: The generalized displacement curve of the first 30 modes when the intrinsic vibration frequency of the structure is multiplied by the coefficient 1.10.

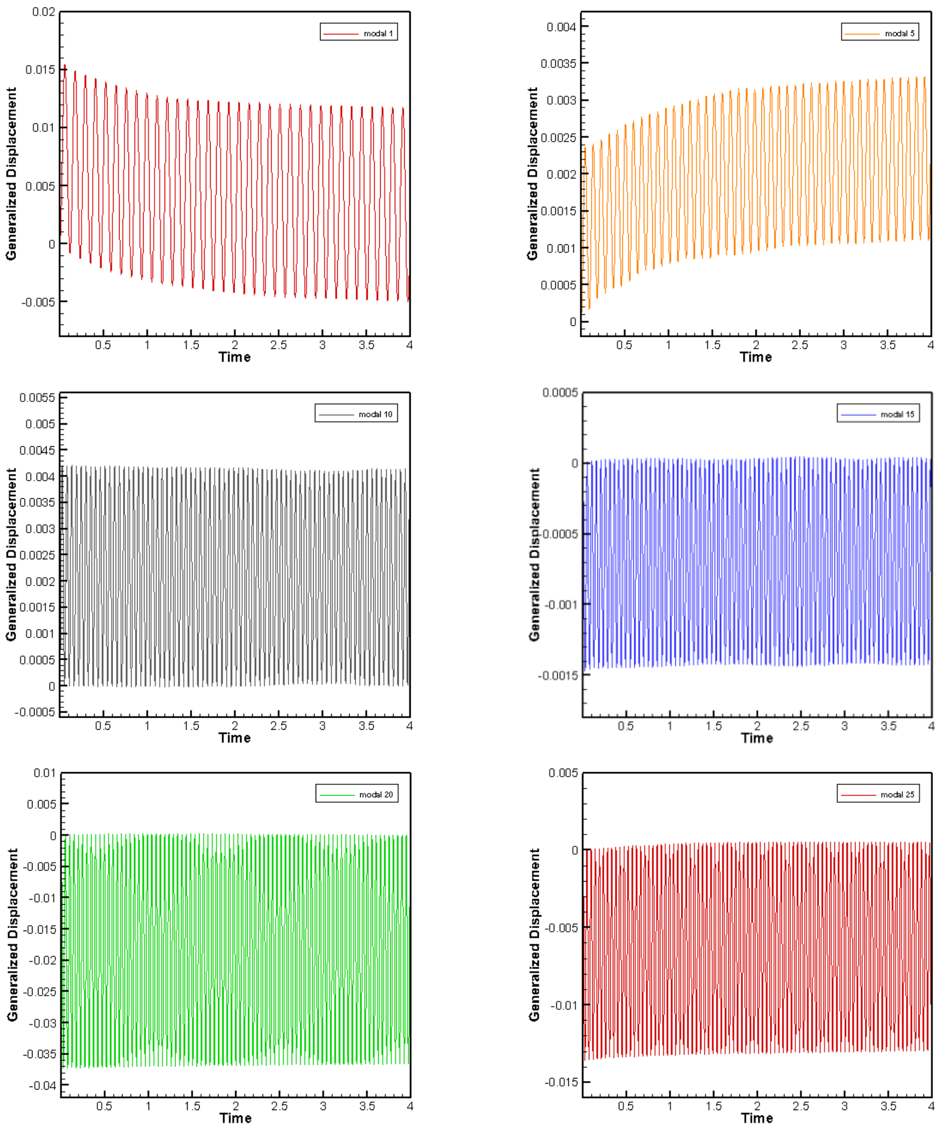


Figure 6: The generalized displacement curve of individual order modes when the intrinsic vibration frequency of the structure is multiplied by the coefficient 1.10.

With the increase of the structural stiffness coefficient, the generalized displacement of the outer windshield of the high-speed train converges, and the structure tends to the dynamic stability state of the fluid-structure coupling. Figure 7 and 8 are generalized structural displacement curves when the intrinsic vibration frequency of the original structure of the outer windshield of the high-speed train is multiplied by the coefficient 1.50.

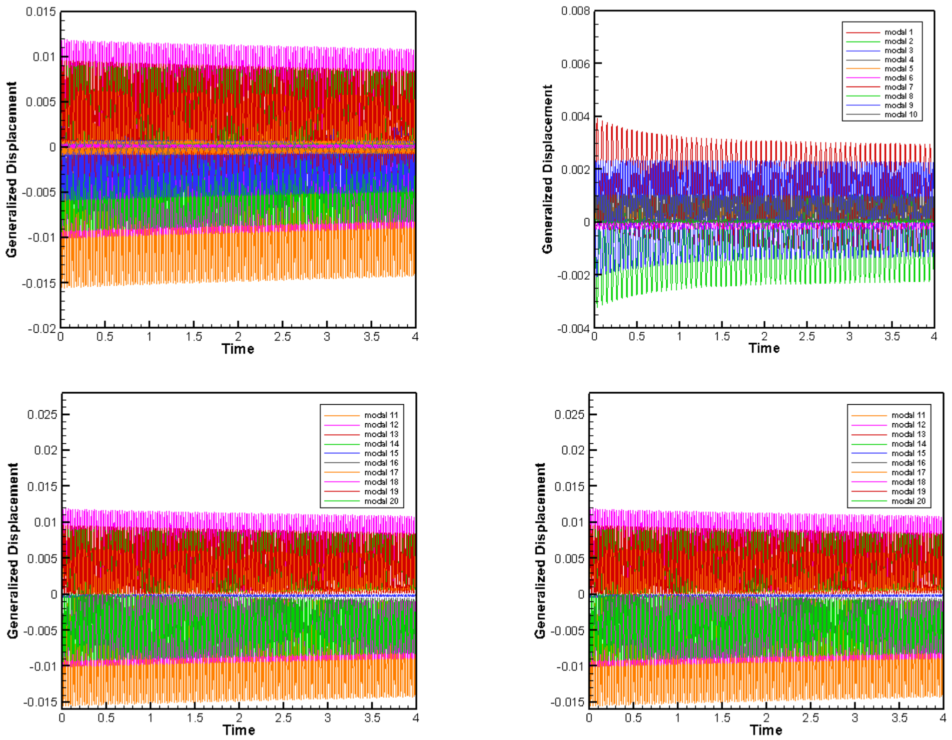


Figure 7: The generalized displacement curve of the first 30 modes when the intrinsic vibration frequency of the structure is multiplied by the coefficient 1.50.

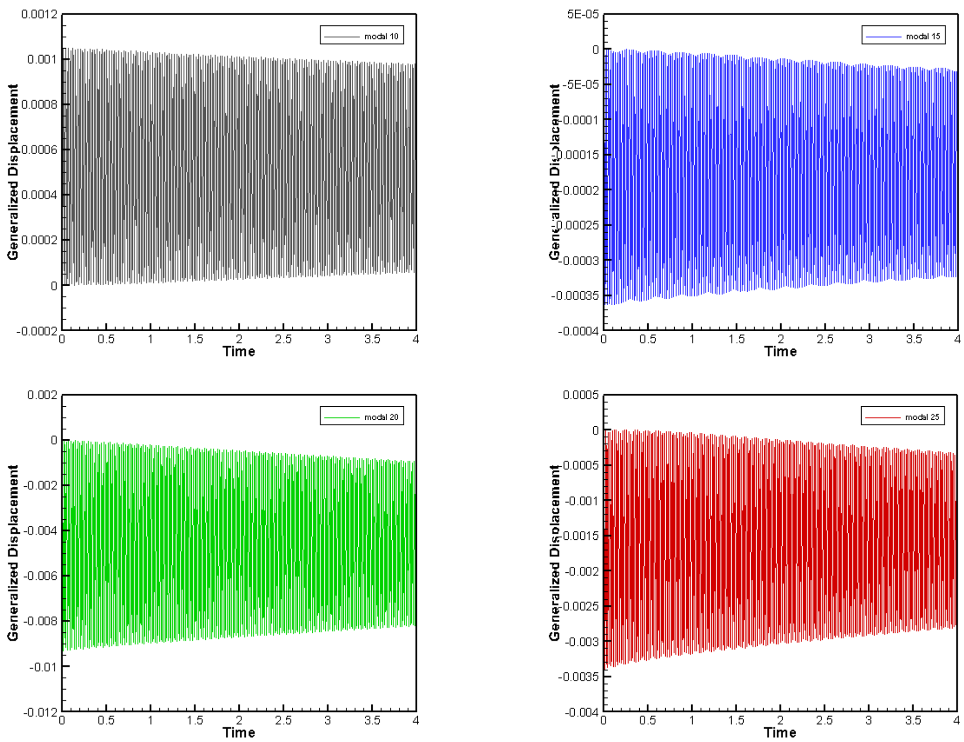


Figure 8: The generalized displacement curve of individual order modes when the intrinsic vibration frequency of the structure is multiplied by the coefficient 1.50.

Compared with numerical simulation results above, it can be seen that the outer windshield of the high-speed train presents the vibration divergence phenomenon under the original condition of structural stiffness. With the increase of structural stiffness, each order frequency of the structure is increasing, and this can make the vibration converge and make the originally unstable structural system become stable.

3.2 The influence of the operating velocity

In order to study the relationship between the flutter characteristic of the windshield and the operating velocity, the windshield flutter characteristic of several train operating velocities is calculated. The increasing multiple of the intrinsic frequency about the structure and the operating velocity data under critical state of flutter for all conditions are listed in Table 1.

Operating velocity (km h^{-1})	A multiple of the increase in the intrinsic frequency of the structure
250.0	0.80
300.0	0.95
350.0	1.10
400.0	1.25
450.0	1.40
500.0	1.60
550.0	1.85
600.0	2.15

Table 1: The relationship between the operating velocity and structural stiffness in the critical state of flutter.

According to the data in the above table, the result is obtained as shown in Figure 9. From the figure, we can know that in order to make the vibration for the outer windshield of the high-speed train reach the flutter boundary at different operating velocities, it is only necessary to multiply the vibration frequency of the windshield by a certain coefficient, and the coefficient basically maintains an approximate linear correlation with the operating velocity of the train. This means that under a given train operating velocity, in order to make the coupling vibration for the outer windshield of the high-speed train converge, it is only necessary to change the section shape, material characteristics to achieve the purpose of changing the intrinsic vibration frequency of the windshield, so that the vibration frequency about each order of the windshield can reach a certain value, finally ensure the coupling vibration of the windshield converge and flutter safety.

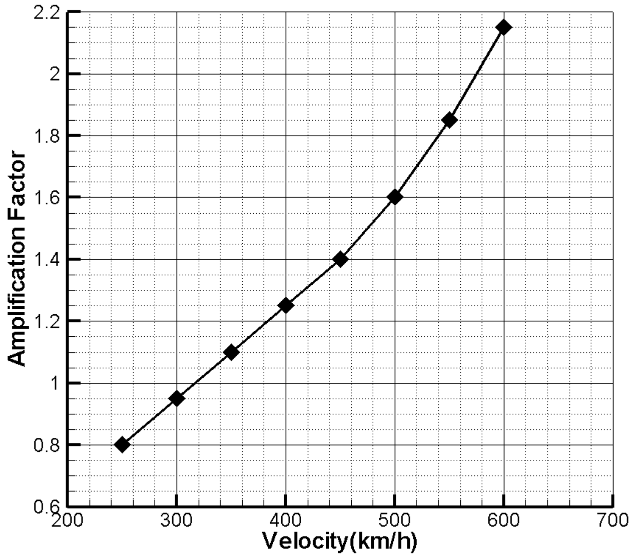


Figure 9: The relationship graph about the operating velocity and the multiplier of increasing frequency.

4 Conclusions and Contributions

The vibration of the outer windshield of the high-speed train contains complex fluid-structure coupling problems. In this paper, the calculation method of bidirectional fluid-structure tight coupling is used to simulate the outer windshield of the high-speed train. Results show that the vibration of the outer windshield can be convergent by changing the intrinsic vibration frequency of the structure. At the same time, the relationship between different operating velocities of the high-speed train and the intrinsic frequency of the structure is studied, and the optimal outer windshield scheme under different operating velocities is proposed: in order to keep the vibration of the windshield from diverging during operation, it is necessary to improve the intrinsic vibration frequency of the structure according to the relationship between the structure stiffness and the flutter boundary of the windshield by changing the section shape and structural material properties, etc., finally ensure the flutter safety of the windshield vibration system.

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