Study on Transverse Vibration Characteristics of High-Speed Elevator under Gas-Solid Coupling

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Abstract. The purpose of this paper is to study the transverse vibration characteristics of high-speed elevator under the action of gas-solid coupling. A three-dimensional physical model of the high-speed elevator is established, the aerodynamic loads on the car under different transverse vibration states (translation and rotation) are numerically solved, and then the relationship between the different transverse vibration states of the car and the aerodynamic loads is obtained. The transverse vibration model of the high-speed elevator based on gas-solid coupling is established by transferring the attitude parameters and aerodynamic parameters of the car in real time combined with the guide excitation. Finally, the transverse vibration characteristics of high-speed elevators with or without gas-solid coupling are compared and analysed by solving the model with an example. The results show that the effect of gas-solid coupling on the transverse vibration acceleration peak value of high-speed elevator is greater when the running speed is greater than 4m/s, and the greater the speed, the more obvious the effect is, which provide some theoretical guidance for the analysis and control of the transverse vibration of high-speed elevator.

1. Introduction

With the increasing number of high-rise buildings and the rapid development of science and technology, the elevator is developing in the direction of high-efficiency, safety, comfort and high-speed. Compared with the low-speed and medium-speed elevator, the drastic fluctuation of ambient airflow caused by high-speed elevator in the process of high-speed operation in narrow and long shaft has become the main factor affecting its vibration, especially the transverse vibration, which is also an aspect that needs to be improved urgently to meet the high-speed elevator's superior performance [1]. Good system dynamics and aerodynamics performance are the preconditions to ensure the safe operation and ride comfort of high-speed elevator, and a large number of scholars have carried out relevant research. Considering the deviations of the guide rail and guide shoe, Mei [2] fitted the mathematical model of their irregular excitation, and analysed the horizontal vibration response of high-speed elevator with the numerical method; Zhang [3] studied the transverse compound random vibration of the high-speed elevator by considering the nonlinearity of guide shoe and the random unevenness excitation of the guide rail; Santo[4] studied the transverse non-linear response of high-speed elevator under the deformation of guide rail, and proposed a control strategy for it. In the research on aerodynamics, Li [5] studied the aerodynamic characteristics of high-speed elevator by using CFD numerical calculation method, and put forward the specific optimization schemes accordingly; Aiming at different hoistway models, Chen [6] studied the aerodynamic characteristics of
the flow field of super high-speed elevator by using finite element analysis method. It can be seen from the above literatures that the current studies of the dynamics (transverse vibration characteristics) and aerodynamic characteristics of high-speed elevator system are mostly carried out in isolation. With the continuous improvement of elevator speed, the factors neglected in the analysis of transverse vibration characteristics of low-speed and medium-speed elevator need to be reconsidered again. The high-speed elevator runs in a relatively closed hoistway depending on its unique wheel-rail restraint relationship, its motion state (including vibration) changes the airflow field around the car at all times, and at the same time, the airflow affects the response of the car system. That is, the car system and the airflow in the hoistway are an organic coupling system with mutual connection, interaction and energy transfer, and the faster the elevator runs, the more prominent the coupling effect between them will be. Nowadays, with the increasing speed of the elevator, the safety and comfortable operation of existing high-speed elevator and the development of new high-speed elevator need to fully understand their vibration characteristics in real service environment. Therefore, it becomes more and more important to study the transverse vibration characteristics of high-speed elevator under the action of gas-solid coupling.

In this paper, a three-dimensional physical model of the high-speed elevator is established, the aerodynamic loads on the car under different transverse vibration states (translation and rotation) are numerically solved, and the relationship between the aerodynamic loads and the vibration states is analysed. Combined with the guidance system excitation, the transverse vibration model of high-speed elevator is established by real-time transmission of the attitude parameters and aerodynamic parameters of the car, and the coupling effect between the car system and the airflow in the hoistway is realized. Finally, the model is solved by an example, and the transverse vibration characteristics of the high-speed elevator with or without the consideration of gas-solid coupling are compared and analysed.

2. Aerodynamic Loads Analysis

2.1. Analysis of Airflow Field in Hoistway

During the operation of the high-speed elevator, the airflow in the hoistway presents a state of low Mach number and high Reynolds number, which can be regarded as the turbulent motion of incompressible gas. Regardless of energy exchange, the finite volume method of computational fluid dynamics (CFD) is used for analysis. According to the continuity equation, momentum equation and standard $k-\varepsilon$ turbulence model, the integral control equation for each control volume of the gas flow in the hoistway is established as follows:

$$\frac{d}{dt} \int_{CV} \rho \phi dV + \int_{A} (\rho \phi \mathbf{u} - \nabla \phi \nabla \mathbf{u}) dA = \int_{CV} S_{\phi} dV$$

where, $t$ is time, $\rho$ is air density, $\phi$ is generic variable, $\mathbf{u}$ is airflow velocity, $\nabla \phi$ is generalized diffusion coefficient, $S_{\phi}$ is generalized source term, $\nabla \phi$ is gradient, $CV$ is control volume, and $A$ is area surrounding the control volume.

2.2. Solution and analysis of aerodynamic loads

The transverse vibration state of the high-speed elevator includes translation and rotation around the car centroid, and different vibration state produces different aerodynamic loads in the hoistway [7]. Aiming at the kind of high-speed elevator whose car size is $1.7\times1.7\times2.4m$ and cross section is $2.1\times2.1m$, this paper establishes its three-dimensional physical model, ignoring the influence of the weight and the overall flow of airflow in the hoistway, defines the hoistway and the lower surface as the boundary of pressure inlet and outlet respectively, and uses tetrahedral mesh to mesh the calculation area.

Because the influence of the car translation on the aerodynamic load is smaller than that of the rotation [7], this paper only considers the influence of the car rotation on the aerodynamic load considering the
calculation efficiency. In order to ensure the accuracy of the simulation results, the car rotation angles are taken as $0.5\pi/180$ rad, $\pi/180$ rad, $1.5\pi/180$ rad, $2\pi/180$ rad and $2.5\pi/180$ rad, which are combined with the running speed of 4m/s, 6m/s, 8m/s and 10m/s respectively. The transverse forces and torques acting on the car centroid under different rotation angles and running speeds are calculated, and the transverse force and torques of the car in a state of uniform speed are certain values. The calculation results are shown in Figures 1 and 2.

Figure 1. Transverse force generated by car rotation.

Figure 2. Torque generated by car rotation.

Figure 3. Influence factor of car rotation on transverse force.
From Figures 1 and 2, it can be seen that with the increase of elevator speed, the transverse force and torque of the car increase gradually at the same vibration deflection angle. In addition, at the same speed, the bigger the deflection angle, the greater the transverse force and torque of the car, and they all show a near linear relationship (straight line). The linear ratios of each line in Figures 1 and 2 are used to obtain the influence factors of car deflection angle on transverse force and torque at different running speeds, as shown in Figure 3 and Figure 4, respectively. Based on aerodynamic theory, the curves in Figures 3 and 4 are fitted quadratically, and the approximate values of transverse force and torque generated by car rotation of high-speed elevator at different running speeds are obtained respectively as follows:

\[ F_\theta = -1804v^2 \theta \]  \hspace{1cm} (2)  
\[ M_\theta = 886.9v^2 \theta \]  \hspace{1cm} (3)

3. Establishment of Transverse Vibration Model of High-Speed Elevator Under Gas-Solid Coupling

3.1. System Dynamic Model

In the process of coupling action between high-speed elevator and airflow in the hoistway, the car is the main spoiler, and the elastic deformation of the car is very small relative to its own geometric size. Therefore, the elastic deformation of the car can be neglected in the analysis process, and the car system can be regarded as a rigid body. In this paper, the guide wheel-guide shoe system is simplified to a parallel spring-damper system [8]. Under the influence of guide rail excitation, the transverse vibration dynamic model of high-speed elevator system is established as shown in Figure 5, where the car mass is \( m \), the moment of inertia is \( J \), the equivalent stiffness and damping of the guide wheel-guide shoe system are \( k_1 \) and \( c_1 \), the displacement excitation of the guide rail at the contact point between the guide wheel and the guide rail is \( y_{di} \) (\( i = 1,2,3,4 \)), the vertical distances between the upper and lower guide shoes to the car centroid is \( l_1 \) and \( l_2 \). According to Lagrange principle, the dynamic equation of transverse vibration of high-speed elevator system is established as follows:

\[ M\ddot{Y} + C\dot{Y} + KY = F_r \]  \hspace{1cm} (4)

where, \( Y = [y \quad \theta]^T \), \( M = \text{diag}(m,J) \), \( C = \begin{bmatrix} 4c_1 & 2c_1(l_2 - l_1) \\ 2c_1(l_2 - l_1) & 2c_1(l_2^2 + l_1^2) \end{bmatrix} \), \( K = \begin{bmatrix} 4k_1 & 2k_1(l_2 - l_1) \\ 2k_1(l_2 - l_1) & 2k_1(l_2^2 + l_1^2) \end{bmatrix} \), \( F_r = \begin{bmatrix} F_f \\ M_f \end{bmatrix}^T \), \( F_f = k_1(y_{d1} + y_{d2} + y_{d3} + y_{d4}) + c(\dot{y}_{d1} + \dot{y}_{d2} + \dot{y}_{d3} + \dot{y}_{d4}) \).
\[ M_f = -l_1 k_1(y_{d1} + y_{d2}) - l_1 c_1(\dot{y}_{d1} + \dot{y}_{d2}) + l_2 k_1(y_{d3} + y_{d4}) + l_2 c_1(\dot{y}_{d3} + \dot{y}_{d4}). \]

**Figure 5.** Transverse vibration dynamic model of high-speed elevator.

### 3.2. Transverse Vibration Dynamic Model under Gas-Solid Coupling

Equations (2) and (3) are written in the form of a matrix product and expressed as \( F_a \):

\[
F_a = \begin{bmatrix} F_\theta \\ M_\theta \end{bmatrix} = \begin{bmatrix} 0 & -1804v^2 \\ 0 & 886.9v^2 \end{bmatrix} \begin{bmatrix} y \\ \theta \end{bmatrix}
\]  

(5)

From the above analysis, it can be seen that different vibration states correspond to different aerodynamic loads during the operation of high-speed elevator, and different loads will produce different vibration states. Therefore, this paper adopts the interactive coupling method to iterate within each coupling time step. According to the above method, the real-time transmission between the car attitude parameters and aerodynamic parameters is carried out, and then the transverse vibration states of the high-speed elevator under the gas-solid coupling are solved. Combined Equations (4) and (5), the transverse vibration dynamic model of high-speed elevator under gas-solid coupling can be obtained as follows:

\[
MY'(t+1) + CY'(t+1) + KY'(t+1) = F_x(t) + F_y(t)
\]

(6)

### 4. Case Study

This paper takes a high-speed elevator of Shandong Fuji Elevator Co., Ltd. as the reference, and the parameters as shown in Table 1.

**Table 1.** Parameter values of high-speed elevator.

| Parameter          | Value       | Parameter          | Value       |
|--------------------|-------------|--------------------|-------------|
| m/(kg)             | 1100        | l_1/(m)            | 1.2         |
| J/(kg·m^2)         | 1850        | l_3/(m)            | 1.2         |
| Δm/(kg)            | 800         | Hoistway cross-section /(m) | 2.1×2.1 |
| k_1/(N/m)          | 1.6e5       | Car height /(m)    | 2.4         |
| c_1(N·s/m)         | 700         | Car cross-section /(m) | 1.7×1.7 |
For the displacement excitation of the guide rail, its unevenness is the main expression form, and is close to the sinusoidal excitation mode [9]. Therefore, this paper uses the unevenness of the sinusoidal form with an amplitude of 0.7mm as the displacement excitation of the guide rail. On the premise of high calculation accuracy, the Newmark-β method in numerical integration form is used to solve the dynamic model iteratively in this paper. When the elevator speed is 4m/s, 7m/s, 10m/s and 13m/s, the transverse vibration acceleration of high-speed elevator without air flow and gas-solid coupling under the medium-load condition is obtained by solving the Equations (4) and (6) respectively, the results are shown in Figures 6-9.

Figures 6-9 show that when the elevator speed is less than 4m/s, the effect of gas-solid coupling on the transverse vibration acceleration peak value of high-speed elevator is small, while when the speed is greater than 4m/s, the effect of gas-solid coupling on the transverse vibration acceleration peak value of high-speed elevator is increasing with the increase of speed. And when the running speed reaches 13m/s, the transverse vibration acceleration peak value is much higher than the allowable value of 0.1m/s², which seriously affects the operation safety and ride comfort of the high-speed elevator.

5. Conclusion
For the high-speed elevator with running speed less than 4m/s, the action of gas-solid coupling hardly affects the transverse vibration acceleration peak value, and guide rail excitation is the main influencing factor, so the emphasis should be placed on the guide rail excitation in the analysis and control of transverse vibration. For the high-speed elevator with speed greater than 4m/s, with the speed increases gradually, the effect of gas-solid coupling on the transverse vibration acceleration peak value of high-speed elevator is increasing. When the speed is greater than 13m/s, the transverse vibration acceleration peak value is much high than 0.1m/s², which exceeds the maximum allowed. Therefore, gas-solid coupling is the main factor affecting the transverse vibration of high-speed elevator, and the effect should be fully considered in design, dynamic analysis and vibration control of the high-speed elevator. The above conclusions have some academic guidance and applied merit for the high-speed elevator in its vibration characteristics analysis and vibration damping and noise reduction.
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