Sensitivity Analysis of Piston Wind in Hoistway of Super High-Speed Elevator

Shuai Qiao¹, Ruijun Zhang¹* and Luzhong Zhang²

¹School of Mechanical and Electrical Engineering, Shandong Jianzhu University, Jinan, Shandong, 250101, P.R. China
²Shandong Electronic Information Products Inspection Institute, Jinan, Shandong, 250014, P.R. China

*Corresponding author: zhangruijun@sdjzu.edu.cn

Abstract. The piston wind will be produced when the car runs at high speed in the narrow and long hoistway, which will produce aerodynamic noise with the car enclosure and the hoistway walls, thus affecting ride comfort. In order to put forward better noise reduction measures, a piston wind model of super high-speed elevator with ventilation holes during the whole operation process was established firstly in this paper. Then, based on this theoretical model, the influence of the variation of ventilation-hole area, hoistway blockage ratio and car length on the piston wind was analysed separately. The analysis proved that the larger the area of ventilation holes, the more obvious the weakening of piston wind was when the building code permits. With the increase of blockage ratio, the intensity of piston wind increases obviously, but the duration of maximum piston wind does not change obviously. As the length of the car increases, there is no significant change in the movement of the piston wind, and this small change can be ignored in engineering applications.

1. Introduction

Because of the great aspect ratio of elevator hoistway, the airflow in the hoistway can be approximately regarded as one-dimensional flow. When the elevator goes up and down, the air in the windward zone of the car is squeezed forward by the car due to the limitation of the hoistway wall, which is called the piston effect, and this forward flow is called the piston wind. When the elevator is running, the forced gas in the hoistway can’t be discharged in time, and part of the airflow flows to the end of the car through the annular space between the car enclosures and the hoistway walls. During this process, the piston wind rubs violently against the car enclosures and the hoistway walls, which produces aerodynamic noise.

Shi et al. considered that when the elevator reaches a certain speed, the aerodynamic noise generated by the hoistway airflow will become the main part of the interior environmental noise of the elevator car [1]. Based on the theoretical analysis of piston effect, Zhu et al. established a typical physical model of vertical evacuation passage in high-rise buildings, and used large eddy simulation (LES) method to simulate the airflow characteristics in hoistway [2]. Cross et al. studied the effect of changing the blockage rate of metro tunnels on the ventilation airflow under the piston effect [3]. Strege et al. based on field data measurement of high-rise buildings in different cities, explored the size of chimney effect in stairwell and elevator hoistway and vertical movement of airflow in well [4].
Therefore, through the study of the airflow characteristics in tunnel (hoistway), the idea of putting forward effective noise reduction measures has been fully affirmed and valued by academia and engineering circles [5]-[8].

Aiming at the influence of piston wind generated by car running in narrow hoistway on ride comfort of super high-speed elevator, this paper first establishes a piston wind model of super high-speed elevator with ventilation holes in the whole process of car running. Then, based on this theoretical model, the influence of the change of ventilation-hole area, blockage ratio and car length on piston wind in the hoistway is analyzed separately.

2. The Theoretical Model of Piston Wind for Super High-Speed Elevator

2.1. Model Simplification

In order to reduce the influence of aerodynamic noise on elevator ride comfort, the design of ventilation holes should be taken into account in the civil construction of buildings with elevators above 3 m/s. Here, the ventilation holes of super high-speed elevator hoistway in a project are simplified as the ventilation holes on both sides of the hoistway (equal horizontal height and equal area). The running speed of the car is a 6 m/s curve as shown in Fig. 1, the acceleration of the elevator at this speed is 1.5 m/s² and the jerk of the elevator is 1.2 m/s³.

![Figure 1. The operation speed curve of the elevator car](image)

In order to better study the effect of ventilation holes on reducing the piston wind, it is assumed that there is no natural wind outside the hoistway.

2.2. Establishment of Theoretical Model

For the model shown in Fig. 2, the continuity equation is used to obtain:

\[ v_p A_{hoist} = v_f A_f + v_T A_{hoist} \]  \hspace{1cm} (1)

where, \( A_f \) is the sum of the cross-sectional area of two ventilation holes.

Based on Bernoulli's principle for unsteady flows and the law of conservation of energy in stationary fluid, the following conclusions are obtained:

\[ k_p \frac{v_f^2}{2} + \xi_{45} \frac{v^2}{2} + L_f \frac{dv_f}{dt} = \xi_{46} \frac{v_f^2}{2} + k_f \frac{v^2}{2} + L_c \frac{dv}{dt} \]  \hspace{1cm} (2)

In which, \( k_p = \lambda_p \frac{v_f}{v} + \xi_p \), \( k_f = \lambda_f \frac{v}{v_f} + \xi_f \), \( \xi_{45}, \xi_{46} \) is the local drag coefficient of airflow diverting into ventilation holes, \( \lambda_p \) is the drag coefficient along the ventilation hole, \( \xi_p \) is the local drag coefficient at cross-
section 5-5, \(l_p\) is the length of the ventilation hole, \(d_p\) is the hydraulic diameter of the ventilation hole, \(\xi_{in}\) is the local drag coefficient of airflow from cross-section 4-4 to cross-section 6-6.

\[
S = \int_0^t v_{car} \, dt
\]  

Figure 2. Before the car passes through the ventilation holes

Figure 3. After the car passes through the ventilation holes

When the car starts to run, the displacement of the car is as follows,

\[
S = \int_0^t v_{car} \, dt
\]  

It can be obtained from Bernoulli’s principle for unsteady flows and the continuity equation,
\[ A \frac{dv_B}{dt} + L_2 \frac{dv_L}{dt} + k_B \frac{v_B^2}{2} + k_L \frac{v_L^2}{2} = \frac{1}{2} \frac{dv_{car}}{dt} + k_{23} \left( v_{car} - v_B \right)^2 + k_{23} \left( v_{car} - v_L \right)^2 + \lambda_{23} \left( \frac{dv_{car} - v_B}{2(1-\alpha)} \right)^2 + \lambda_{23} \left( \frac{dv_{car} - v_L}{2(1-\alpha)} \right)^2 \]  

(4)

where, \( k_B = \xi_2 + \lambda \frac{v_B}{d_B} \), \( k_L = \xi_2 + \lambda \frac{v_L}{d_L} \), \( \lambda = \frac{k_{23} - d_B - d_L}{\xi_2} \).

Therefore, the variation of piston wind with time during the operation of the car in section L_1 of the hoistway is shown as follows:

\[
\begin{cases}
\frac{v_B}{A_{hoist}} = v_f A_f + v_r A_{hoist} \\
k_f \frac{v_B^2}{2} + \xi_{46} \frac{v_B^2}{2} + l_f \frac{dv_f}{dt} = \xi_{46} \frac{v_B^2}{2} + k_f \frac{v_f^2}{2} + L_2 \frac{dv_f}{dt} \\
A \frac{dv_B}{dt} + L_2 \frac{dv_f}{dt} + k_B \frac{v_B^2}{2} + k_T \frac{v_T^2}{2} = \frac{1}{2} \frac{dv_{car}}{dt} + k_{23} \left( v_{car} - v_B \right)^2 + k_{23} \left( v_{car} - v_T \right)^2 + \lambda_{23} \left( \frac{dv_{car} - v_B}{2(1-\alpha)} \right)^2 + \lambda_{23} \left( \frac{dv_{car} - v_T}{2(1-\alpha)} \right)^2
\end{cases}
\]

(5)

The computational domain of the above mathematical model is \([0,t_f]\) \( S = \xi_{car} dt < L_3 \), and its initial value is \( v_B |_{t=0} = 0 \), \( v_T |_{t=0} = 0 \), \( v_r |_{t=0} = 0 \).

Similarly, the variation of piston wind with time during the operation of the car in section L_2 of the hoistway in the model shown in Fig. 3 is shown as follows:

\[
\begin{cases}
\frac{v_T}{A_{hoist}} = v_f A_f + v_B A_{hoist} \\
k_f \frac{v_T^2}{2} + \xi_{46} \frac{v_T^2}{2} + l_f \frac{dv_f}{dt} = \xi_{46} \frac{v_T^2}{2} + k_f \frac{v_f^2}{2} + L_2 \frac{dv_f}{dt} \\
A \frac{dv_T}{dt} + L_1 \frac{dv_f}{dt} + k_B \frac{v_B^2}{2} + k_T \frac{v_T^2}{2} = \frac{1}{2} \frac{dv_{car}}{dt} + k_{23} \left( v_{car} - v_B \right)^2 + k_{23} \left( v_{car} - v_T \right)^2 + \lambda_{23} \left( \frac{dv_{car} - v_B}{2(1-\alpha)} \right)^2 + \lambda_{23} \left( \frac{dv_{car} - v_T}{2(1-\alpha)} \right)^2
\end{cases}
\]

(6)

where, \( k_f = \lambda_f \frac{d_f}{d_f} + \xi_{46} \), \( k_B = \xi_{2} + \lambda \frac{d_B}{d_B} \), \( A = \frac{\xi_{23} - d_B - d_L}{\xi_2} \), \( k_{23} = \xi_2 + \lambda \frac{d_3}{d_3} \), \( k_i = \xi_4 + \lambda \frac{d_i}{d_i} \), \( A_f \) is the sum of the cross-sectional area of two ventilation holes, \( \xi_{46} \) is the local drag coefficient when the air enters the ventilation hole, \( \lambda_f \) is the drag coefficient along the ventilation hole, \( \xi_i \) is the local drag coefficient at cross-section 5-5, \( l_f \) is the length of the ventilation hole, \( d_f \) is the hydraulic diameter of the ventilation hole, \( \xi_{46} \) is the local drag coefficient of airflow from cross-section 1-1 to cross-section 4-4. The computational domain of the above mathematical model is \([t_f, t_r]\) \( S = \xi_{car} dt < L_3 \), and its initial value is \( v_B = v_B |_{t=v_{in}}, v_T = v_T |_{t=v_{in}}, v_f = v_f |_{t=v_{in}} \).

3. Parametric Impact Analysis

3.1. The Effect of Ventilation-Hole Area on Piston Wind

In order to better observe the influence of ventilation-hole area on piston wind, the motion of piston wind in the range of ventilation holes area from 1.0 m² to 2.6 m² is observed, and the piston wind operation state without ventilation hole is compared to check the effect of ventilation hole on reducing piston wind intensity.

In Fig. 4, before the car passes through the ventilation holes, the drag of the parallel connection between the ventilation holes and the L_2 section of the hoistway (the car is in the L_1 section) is generally smaller than that of the L_2 section of the hoistway itself, so the piston wind in the hoistway section where the car is located is higher than that in the hoistway without the ventilation holes. When the car passes through the ventilation holes, that is to say, after reaching L_2 section, the drag of the parallel connection between the ventilation holes and L_1 section of the hoistway is smaller than that of
L₁ itself. Therefore, when the car decelerates in L₂ section of the hoistway, the piston wind speed decreases rapidly, which is much faster than that without the ventilation holes.

Fig. 4 shows that the drag of parallel connection between L₂ section and ventilation holes decreases and the piston wind speed increases with the increase of ventilation-hole area before the car passes through the ventilation holes. When the car passes through the ventilation holes, the drag of parallel connection between L₁ section and the ventilation holes decreases with the increase of the ventilation holes area, so the decline speed of the piston wind is obviously higher than that of the piston wind without the ventilation holes.

![Figure 4. The effects of different ventilation holes areas on piston wind](image)

3.2. The Effect of Different Blockage Ratios on Piston Wind

In order to study the influence of blockage ratio on piston wind in elevator hoistway with ventilation holes, the change of blockage ratio from 0.1 to 0.9 is selected.

![Figure 5. The effects of different blockage ratios on piston wind](image)

Fig. 5 shows that with the increase of blockage ratio, the piston effect is strengthened and the maximum velocity of piston wind is increased obviously, but the variation of the maximum velocity duration of piston wind is not obvious. And in the process of elevator acceleration to uniform speed, the piston wind speed increases rapidly until it reaches the maximum speed and tends to be flat; and when the car passes through the ventilation holes, the piston wind speed begins to decline rapidly.
3.3. The Effect of Different Car Lengths on Piston Wind

![Figure 6. The effects of different car lengths on piston wind](image)

In order to better study the effect of car length on the piston wind, the range of car height from 2 m to 3.2 m is analysed here, which covers the height dimensions of most elevators in the current elevator market.

It can be seen from Fig. 6 that as the height of the car increases continuously, the maximum speed of the piston wind increases, but the growth rate is small. After the car passes through the ventilation holes, the piston wind speed drops rapidly, but when the car length changes, the downward trend of the piston wind is almost invisible, that is, the variation range of the piston wind is negligible in engineering applications.

4. Conclusion

The main conclusions of this study follow.

(1) Based on Bernoulli's principle for unsteady flows, a theoretical model of super high-speed elevator with ventilation holes was established.

(2) With the increase of ventilation-hole area, the piston wind speed increased rapidly due to the decrease of drag of the parallel connection until it was higher than the piston wind speed without ventilation holes; after passing through the ventilation holes, the piston wind speed decreased rapidly, and the decreasing trend is significantly higher than that without ventilation holes.

(3) With the increase of blockage ratio, the maximum velocity of piston wind increased obviously, but the duration of maximum piston wind did not change obviously.

(4) As the length of the car increased, the maximum speed and duration of the piston wind changed very little. Considering the running speed and operation environment of the elevator, this small change could be ignored.

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