Influence of discontinuous-type hood parameters on high-speed railway tunnel aerodynamic effects

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Abstract. Based on the one-dimensional unsteady compressible non-isentropic flow theory and round-piston radiation theory with infinite baffle plate, the aerodynamic effects generated by a high-speed train through a tunnel with the discontinuous-type hood were numerically investigated, which shows the discontinuous-type hood can attenuate the pressure transition in tunnel and micro-pressure wave intensity around the tunnel exit. That analysis of the hood parameters show the larger cross-section area and the short length of hood with the short binding site length attenuate the aerodynamic effects effectively.

Introduction

The aerodynamic effects, including compression wave and micro-pressure wave, generated by a high-speed train through a tunnel have perniciousness to some extent [1]. It is one of effective measures to install different-type hood at tunnel ends, which can retard the aerodynamic effects [2]. Since the discontinuous-type hood is a common hood type, the aerodynamic effects generated by a high-speed train through a tunnel with the discontinuous-type hood were numerically analyzed. The results demonstrate the influence of the hood parameters on the aerodynamic phenomenon.

Computational model and equations

Figure 1 shows a high-speed train pass through a tunnel with the discontinuous-type hood, where F_H, F_{TU} is the hood end and tunnel cross-sectional area respectively. L_{T0} is train length, L is tunnel length, L_H is hood length and L_C is hood binding site length.

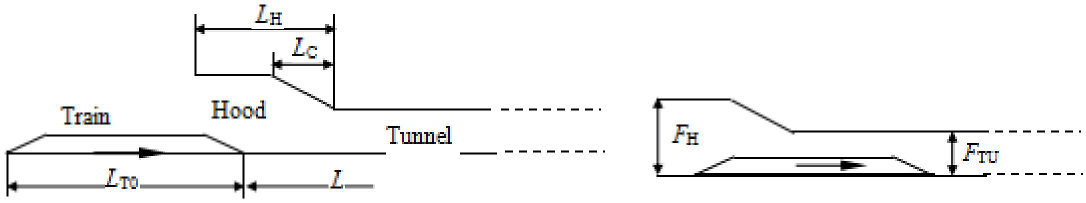

Figure 1. Diagram of the train through the tunnel with high-speed

When a high-speed train passes through a long tunnel, the air flow in tunnel is known as one-dimensional unsteady compressible non-isentropic flow. Then the computational equations including continuity equation, momentum equation,energy equation are as follows.

$$\frac{\partial \rho}{\partial t}+\rho\frac{\partial u}{\partial x}+u\frac{\partial \rho}{\partial x}+\rho\frac{u}{F}\frac{\partial F}{\partial x}+\frac{\rho}{F}\frac{\partial F}{\partial t}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+\frac{1}{\rho}\frac{\partial p}{\partial x}+G=0 \tag{2}$$

$$\frac{\partial p}{\partial t}+u\frac{\partial p}{\partial x}-a^2\left(\frac{\partial \rho}{\partial t}+u\frac{\partial \rho}{\partial x}\right)-\frac{(\kappa-1)p}{F}\frac{\partial F}{\partial t}=(k-1)\rho(q-\xi+uG) \tag{3}$$

Among equations, u is the air flow velocity, p is the air pressure, ρ is the air density, a is the sound velocity, κ is the air specific heat ratio, F is the air flow cross-sectional area, t is the time coordinate, x is the distance coordinate. In addition, G is the friction term, q is the heat transfer term, ξ is the friction work term between air and the train surface. Their representations can consult document [3]. The equation can be numerically solved by means of characteristics method when the proper boundary conditions are put forward at the tunnel ends. Since the tunnel ends are open and have the existence of air inflow and outflow, air inflow can be known as one-dimensional quasi-steady compressible isentropic flow and the accordance with permanent Bernoulli equation, besides, air outflow pressure can be known as atmospheric pressure.

That the compression wave propagates through the tunnel and radiates out of the tunnel exit causes the appearance of micro-pressure wave. The radiation can be known as radiation of a vibration disk in an infinite baffle, so the pressure P of micro-pressure wave at tunnel center site can be as follows.

$$P(t)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\frac{4A(\omega)}{R(2Kb)+1+jX(2Kb)}\exp(j\omega t)\sin[\frac{Kb}{2}(\sqrt{(\frac{r}{b})^2+1}+\frac{r}{b})]\cdot\exp\{j[\frac{\pi}{2}-\frac{Kb}{2}(\sqrt{(\frac{r}{b})^2+1}-\frac{r}{b})]\}d\omega \quad (4)$$

Among equations, b is the tunnel radius, K is the ratio of vibration frequency to sound velocity a and r is distance apart from the tunnel exit. The representations on function A ( ), R ( ) and X ( ) can consult document [4].

Computational results

Computational data are as follows. The train is 203m in length, 3.38m in width and 3.7m in height. The train streamline length is 12m. The train velocity is 350km/h. The tunnel is 1000m in length. The tunnel cross-sectional area is 100m^2. The discontinuous-type hood length equal to the tunnel hydraulic diameter and its binding site length is 8m.The hood end cross-sectional area is 1.6 times as large as that of the tunnel.

When the train passes through with the tunnel with the discontinuous-type hood, or not, figure 2 and figure 3 shows the air pressure transition and flow velocity at tunnel center respectively, Figure 4 shows relation between the air pressure gradient and time of the compression wave at tunnel exit, and, Figure 5 shows relation between time and the pressure of the micro-pressure wave, which is 20m distant from the tunnel exit in tunnel axis.

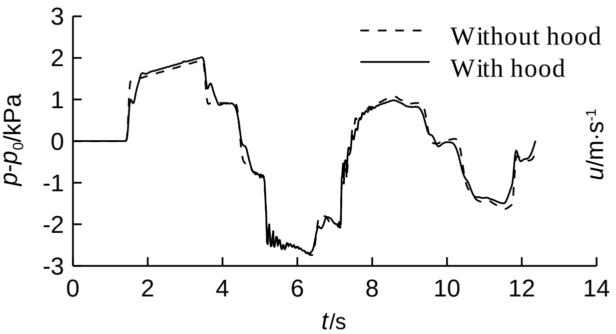

Figure 2. Transient pressure s at tunnel center

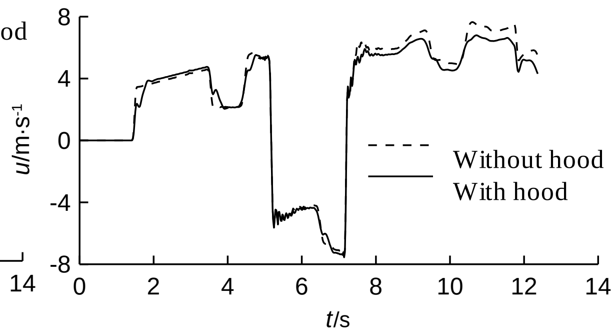

Figure 3. Airflow velocity at tunnel center

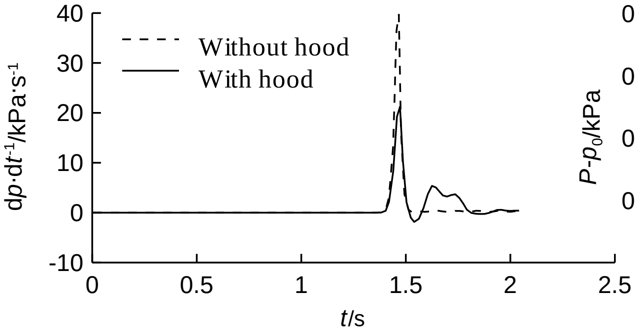

Figure 4. Pressure gradient at tunnel exit

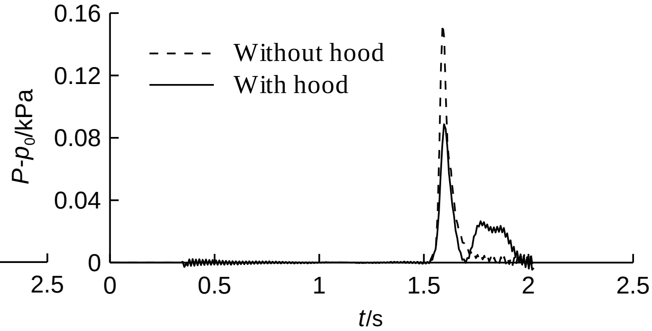

Figure 5. Pressure of micro-pressure wave at tunnel exit

It is obvious from figure 2 and figure 3 that the aerodynamic effects at tunnel with hood are different from ones of tunnel with hood, although both of them have the same change trend. Particularly during 0-4s, because of the reflection action of the hood surface, the compression wave takes place diffusion, which leads to the air pressure and flow velocity at tunnel with hood ascend slower than ones of tunnel without hood. It is obvious from figure 4 and figure 5 that there is the direct proportion relation between the pressure gradient of compression wave and pressure of micro-pressure wave at tunnel exit. Moreover, the wave patterns of pressure gradient of compression wave and pressure of micro-pressure wave generated by the train through the tunnel with hood are different from those of tunnel without hood because the compression wave continuously reflects between train and hood surface. Then the pressure gradient of compression wave and micro-pressure wave generated by the train through the tunnel with hood have two wave peaks, but there is a wave peak not only the pressure gradient of compression but also pressure of micro-pressure when the train passes through the tunnel without hood. Besides, the maximum peak of the pressure gradient of compression wave and pressure of micro-pressure wave at tunnel exit without hood are larger than those of tunnel with hood, because the latter end cross-sectional area is larger than that of the former. Another reason is the reflection action of hood results in the decline of the pressure gradient of compression wave.

Influence of hood parameters on aerodynamic effects

Table 1 show the main characteristic value of the compression wave and micro-pressure wave when the train passes through the tunnel with hood having different end cross-sectional area and same length and binding site length at 350km/h velocity. It is known that along with the hood end cross-sectional area increasing, the compression wave pressure maximum value p_{max} and pressure transition p_{max}-p_{min} gradually increase, and, the air flow velocity maximum absolute value and minimum absolute value gradually increase too, but the pressure gradient maximum value $(dp \cdot dt^{-1})_{max}$ and pressure maximum value P_{max} of micro-pressure wave decrease by a wide margin. The p_{max} and p_{max}- p_{min} of tunnel with larger end cross-sectional area hood（F_H/F_{TU}=2.0）increase 8.13% and1.88%, u_{max} and u_{min} increase 8.02% and 7.54%, but $(dp \cdot dt^{-1})_{max}$ and P_{max} 48.26% and 44.69% decrease than those of tunnel with less end cross-sectional area（F_H/F_{TU}=1.2）respectively. So in condition of constant hood length and binding site length, the hood should be having larger end cross-sectional area, which does well to the aerodynamic effects.

Table 2 show the main characteristic value of the compression wave and micro-pressure wave when the train passes through the tunnel with hood having different length and same end cross-sectional area and binding site length at 350km/h velocity. It is known that along with the hood length increasing, the compression wave pressure maximum value p_{max} appears surge,and pressure transition p_{max}-p_{min} gradually decrease, and, the air flow velocity minimum u_{min} absolute value ascends the peak, then gradually descend, but, air flow velocity maximum u_{max} absolute value gradually descend to trough, then slightly ascend, but the pressure gradient maximum value $(dp \cdot dt^{-1})_{max}$ and pressure maximum value P_{max} of micro-pressure wave increase by a wide margin. The p_{max}-p_{min} of tunnel with long hood（L_H/D=2.0）decrease 2.31%, but $(dp \cdot dt^{-1})_{max}$ and P_{max} 15.04% and12.42% increase than those of tunnel with short hood（L_H/D=0.5）respectively. So in condition of constant hood end cross-sectional area and binding site length, the hood should be having less length, which does well to the aerodynamic effects.

Table 3 show the main characteristic value of the compression wave and micro-pressure wave when the train passes through the tunnel with hood having different binding site length and same end cross-sectional area and length at 350km/h velocity. It is known that along with the hood binding site length increasing, the compression wave pressure maximum value p_{max} and pressure transition p_{max}-p_{min} gradually decrease, and, the air flow velocity maximum absolute value and minimum absolute value gradually decrease too, but the pressure gradient maximum value $(dp \cdot dt^{-1})_{max}$ and pressure maximum value P_{max} of micro-pressure wave gradually increase to peak value then decrease by a wide margin. The p_{max} and p_{max}-p_{min} of tunnel with larger binding site length hood（L_C =14）decrease 6.89% and1.63%, u_{max} and u_{min} decrease 6.36% and 5.58%, but $(dp \cdot dt^{-1})_{max}$ （L_C =10） and P_{max} （L_C =12） decrease 4.07% and 6.32% than those of tunnel with less binding site （L_C =4） respectively. So in condition of constant hood length and binding site length, the hood should be having less binding site length, which does well to the aerodynamic effects.

Table1. The main characteristic value of aerodynamic effects（V=350km/h,L_H/D=1,L_C=8m）

F_H/F_{TU}	$(p_{max}-p_0)$[kPa]	$(p_{max}-p_{min})$[kPa]	u_{max}[m·s^{-1}]	u_{min}[m·s^{-1}]	$(dp \cdot dt^{-1})$ [kPa·s^{-1}]	$(P_{max}-p_0)$[kPa]
1.2	1.94643	4.67437	4.59670	-4.22774	30.8915	0.12336
1.4	1.97552	4.68991	4.66378	-4.29074	25.2038	0.10473
1.6	2.01547	4.71311	4.75716	-4.35569	21.2154	0.08874
1.8	2.05954	4.73908	4.86009	-4.44545	18.2620	0.07660
2.0	2.10465	4.76240	4.96538	-4.54654	15.9817	0.06823

Table 2. The main characteristic value of aerodynamic effects（V=350km/h,F_H/F_{TU}=1.6,L_C=8m）

L_H/D	$(p_{max}-p_0)$[kPa]	$(p_{max}-p_{min})$[kPa]	u_{max}[m·s^{-1}]	u_{min}[m·s^{-1}]	$(dp \cdot dt^{-1})$ [kPa·s^{-1}]	$(P_{max}-p_0)$[kPa]
0.5	2.00990	4.74007	4.74393	-4.28185	18.4317	0.07968
1.0	2.01547	4.71311	4.75716	-4.35569	21.2154	0.08874
1.5	1.99107	4.66561	4.70041	-4.33759	21.3262	0.0891
2.0	1.99621	4.63037	4.71266	-4.42169	21.2047	0.08958

Table3. The main characteristic value of aerodynamic effects（V=350km/h,F_H/F_{TU}=1.6,L_H/D=1）

L_C	$(p_{max}-p_0)$[kPa]	$(p_{max}-p_{min})$[kPa]	u_{max}[m·s^{-1}]	u_{min}[m·s^{-1}]	$(dp \cdot dt^{-1})$ [kPa·s^{-1}]	$(P_{max}-p_0)$[kPa]
4	2.10990	4.76899	4.97758	-4.53972	20.4983	0.08471
6	2.04761	4.73297	4.83222	-4.41572	20.9600	0.0870
10	1.99601	4.70206	4.7117	-4.33305	21.3322	0.08971
12	1.98308	4.69535	4.68148	-4.30618	21.3037	0.09006
14	1.97394	4.69108	4.66103	-4.28642	21.1304	0.08982

Summary

In comparison with tunnel without hood, the maximum pressure, air flow velocity, pressure gradient of compression wave and pressure of micro-pressure wave at tunnel with hood at all decrease to a certain degree, which give the fact that installing hood at tunnel end can attenuate generated by a high-speed train through the tunnel. In condition of the discontinuous-type hood with larger end cross-sectional area, less length and binding site length, the effect of retarding the aerodynamic effects achieves a good result.

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