



Numerical analysis of airflow around a passenger train entering the tunnel



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ARTICLE INFO

Article history:

Received 27 July 2014

Received in revised form 5 September 2014

Accepted 13 October 2014

Keywords:

Numerical simulation

Remeshing method

Passenger train

Pressure wave

Drag coefficient

Side force coefficient

ABSTRACT

In this paper, the characteristics of train-tunnel interaction at a tunnel entrance has been investigated numerically. A three-dimensional numerical model using the remeshing method for the moving boundary of a passenger train in Iran railway was applied. The turbulent flows generated by the moving train in a tunnel were simulated by the $RNG \kappa-\varepsilon$ turbulence model. The simulations have been carried out to understand the effect of the train speed as well as the influences of the hoods and air vents on the pressure waves, drag, and side force coefficients. The results show that the maximum drag coefficient occurs when the train enters the tunnel and is equal to 2.2. The air vents and enlarged hood at the portal are demonstrated to attenuate the pressure gradient and drag coefficient about 28% and 36%, respectively. Furthermore when train is entering the tunnel asymmetrically, a side force is created that pushes the train toward the tunnel wall, which the maximum side force is 900 N.

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1. Introduction

In the last decade, the stability of railway vehicles is recognized to be a safety issue, has matured considerably in the railway community. The optimization of pressure distribution around the train body which influences its performance and stability needs the profound knowledge of train's aerodynamic behavior entering the tunnel. Furthermore, it can affect the construction expenses of tunnel. Unlike the traveling in the open air, the train entering into tunnel plays a role of a piston moving against the air inside tunnel, therefore a compression wave is formed (Auvity et al., 2001).

According to the aerodynamic theory, the resulting compression wave propagates along the tunnel at nearly a sonic speed. Some part of the compression wave is reflected back from the tunnel exit as an expansion wave and a part of it emerges as a pressure pulse, called microwave. In certain circumstances, this micro-wave may be strong enough to generate annoying sonic disturbances. Indeed, it can generate a booming noise up to 140–150 db or more (Maeda et al., 1993). Therefore, the accurate analysis of pressure waves generated by moving train entering the tunnel is necessary to increase transportation efficiency.

Baron et al. (2001) studied the high-speed underground trains. The aim of their study was to investigate the effect of pressure

relief ducts and tunnel configuration on the pressure waves. The simulations have been analyzed by means of the quasi one-dimensional air flow. Mok and Yoo (2001) carried out a numerical simulation of train-tunnel interaction at the tunnel entrance by finite element method using the three-dimensional compressible Euler equation. The results show that the pressure gradients of compression waves front induced by train nose travelling through the tunnel can be reduced by means of a hood with holes about 21.5% and by means of the tunnel with inclined entry about 29.8%. Bellenoue et al. (2001) studied the effect of a hood at a tunnel entrance on the compression waves experimentally by means of an axisymmetric scaled model. Their results indicate that the use of hood at the portal reduces pressure gradient, which is independent of hood cross section and blockage ratio. Raghunathan et al. (2002) have been investigated the effect of aerodynamic shape of high speed trains on the improvement of electric motor power. They believed that the simplifications and the characteristics which are negligible at the low speed trains, can affect high speed trains adversely. Bellenoue et al. (2002) modify the experimental relations regarding pressure gradients of compression waves that are previously obtained by assumption of axisymmetric model, to use for unsymmetrical models. Howe et al. (2003) have made an experimental study into the effect of unvented entrance hood on the reduction of the maximum gradient of the compression wave front. Also, the optimal distribution of 'windows' in the wall of a long tunnel entrance hood was determined to suppress the micro-pressure wave produced when the compression wave generated by an

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entering high-speed train reaches the far end of the tunnel (Howe, 2004). The results show that for having a compression wavefront pressure profile with minimal ‘rippling’ and uniformly small pressure gradient, the axial velocity must decrease linearly to zero. Their results resembled Bellenoue et al. (2002). Shin and Park (2003) simulated the variation of aerodynamic forces and the generation of compression waves, induced by the train entering into a tunnel, by applying three-dimensional unsteady compressible Navier–Stokes equation solver. To account for the relative motion of stationary tunnel and moving train, they implemented sliding multi-block method.

Ricco et al. (2007) carried out a numerical and experimental study of pressure waves generated by a train entering and running through a tunnel. The results showed that the maximum pressure extensively depends on train speed and the shape of train nose. Furthermore local separation region, which occurs near the train head for high-angled noses, depends on semi-angle of train nose. Kim and Kim (2007) investigate the unsteady three-dimensional flow in the subway tunnel caused by the passage of a train experimentally and numerically. The numerical simulation was implemented using the sharp interface method for the moving boundary of an immersed solid. The predicted numerical model results showed good agreement with the experimental data. Xiang and Xue (2010) studied the effect of tunnel hood on the compression waves numerically by employing sliding mesh technology. The calculation results indicated that inclined entry without tunnel hood or asymmetric distribution of holes is not available for alleviating the impulsive wave. Uystepuyst et al. (2011) introduced a new methodology involving sliding meshes and a conservative treatment of the faces between two domains in order to reduce the computational time, and validated their methodology with different test cases. The results confirm the reliability of the numerical method. Ko et al. (2012) performed a series of field measurements near the portal and the shaft of the tunnel during normal operation in Taiwan. Their measurements indicated that when the cross-sectional area of the tunnel increases, the measured train-induced pressure will generally be less intensive, especially for the positive pressure due to the entering of the nose. Aboutalebi (2013) made an experimental analysis of pressure waves generated by the passenger train of Iran when it is entering the tunnel. The effect of the parameters such as the train speed and blockage ratio on the pressure waves was also investigated. The results demonstrated an interaction between the pressure waves in the tunnel. Choi and Kim (2014) evaluated the effects of the train nose length and the tunnel cross-sectional area on the aerodynamic drag for constructing a new high-speed subway system. Their results showed that when the train speed increases by a factor of two, the aerodynamic drag increases approximately four times. In addition, the aerodynamic drag is reduced up to approximately 50% by changing of the nose from a blunt to a streamlined shape.

The aim of the present study is the investigation of the variation of aerodynamic forces involving side force and drag coefficients acting on the passenger train in Iran using the remeshing method.

In the first step, the numerical method has been validated with the study of Aboutalebi (2013) and in the second step the higher speed of 30 m/s (the common speed of passenger trains in Iran) and the parameters which are not studied in Aboutalebi's work have been investigated numerically. Furthermore, the pressure distribution around the train entering and running the tunnel symmetrically and asymmetrically as well as the effect of different factors such as hood entrance, air vent, blockage ratio (Br), and train speed (V_{train}) on the aerodynamic forces have been investigated.

2. Numerical simulation

2.1. Governing equation

The airflow over the train/tunnel aerodynamic system has unsteady characteristics that originates from the compression waves induced by the train moving through the tunnel. The governing equations are the continuity, the Navier–Stokes and the energy equations, which describe the physical principles of conservation of mass, momentum and energy respectively. They can be written in Cartesian tensor as (Chien, 2012):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j) = & -\frac{\partial p}{\partial x_i} + \rho g \delta_{i2} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] \\ & + \frac{\partial}{\partial x_j} (-\rho \overline{u'_i u'_j}) \end{aligned} \quad (2)$$

$$\frac{\partial (\rho E)}{\partial t} + \frac{\partial}{\partial x_i} [u_i (\rho E + p)] = \frac{\partial}{\partial x_j} \left[k_{eff} \frac{\partial T}{\partial x_j} + u_i (\tau_{ij})_{eff} \right] \quad (3)$$

The terms $-\rho \overline{u'_i u'_j}$ are the time-averaged Reynolds stresses, representing the turbulent momentum fluxes. Based on the Boussinesq hypothesis, the Reynolds stresses are related to the mean velocity gradients:

$$-\rho \overline{u'_i u'_j} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left(\rho k + \mu_t \frac{\partial u_k}{\partial x_k} \right) \delta_{ij} \quad (4)$$

where μ_t is the turbulent viscosity, k is the turbulent kinetic energy, and C_μ is a model constant.

The turbulent airflow around the high speed train is characterized by velocity fields and pressure fluctuations. The computation of fluctuations needs high accuracy at every moment of time because these fluctuations are small in scale and high frequency. Therefore, in the present study in comparison with the analytical standard methods the RNG $k-\epsilon$ model is selected for simulation of turbulence domain due to its high accuracy (Chien, 2012; Huang et al., 2012).

Regarding the compressibility effect, this concept has been investigated by the expression employed by Ricco et al. (2007), where it is shown that one must operate in the framework of compressible flows when $M^2 L_{tunnel}/L_{train} \ll 1$, where M is the Mach

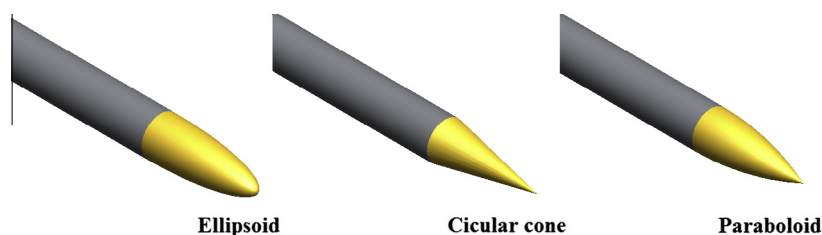


Fig. 1. Three configurations of train nose.

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