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Numerical simulation of two trains intersecting in a tunnel

Chia-Ren Chu[a,*], Ssu-Ying Chien[a], Chung-Yue Wang[a], Tso-Ren Wu[b]

[a] Department of Civil Engineering, National Central University, Taiwan, ROC
[b] Institute of Hydrological and Oceanic Sciences, National Central University, Taiwan, ROC

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ABSTRACT

This study uses a three-dimensional, compressible, turbulence model to investigate the pressure waves generated by two trains passing each other in a tunnel. The turbulent flow around the train bodies is computed by the RNG k–ε turbulence model; a sliding mesh method is utilized to treat the moving boundary problem. The numerical results are verified through the results of laboratory experiment and field observation. Then, a series of numerical simulations are carried out to examine the influences of the tunnel length, the blockage ratio, the train speed and the intersecting location on the interactions of aerodynamic waves generated by the trains. The simulation results reveal that the pressure and drag coefficients of the trains reach a maximum when the two trains intersect at the mid-point of the tunnel and the values of pressure and drag coefficients increase as the train speed and the blockage ratio increase due to the train/tunnel interaction. However, the side force coefficient is dominated by the train/train interaction and its maximum value occurs when the two trains are aligned side by side.

1. Introduction

The aerodynamic pressure generated by high-speed trains travelling through a long tunnel is an important factor with regard to the design of tunnel facilities and to the comfort of passengers (Gawthorpe, 2000). Notably, the interaction of pressure waves generated by two high-speed trains intersecting in tunnels is able to cause fatigue load and significant damage to the train bodies (Raghunathan et al., 2002). The pressure variation and flow phenomenon are much more complicated than those of a single train in a tunnel and the rapidly fluctuating aerodynamic loading on the train bodies may result in instability and lead to an undesirable snake-like motion (Hwang et al., 2001). With the advancement of high speed trains in many countries, such an aerodynamic problem becomes an important issue for the designers of the railway technology (Howe, 1998; Uystepruyst et al., 2011).

There are several studies on the aerodynamics of two trains moving in opposite directions and which pass each other inside a tunnel. Fujii and Ogawa (1995) solved the three-dimensional, compressible Euler equations by using the domain decomposition method and the Fortified Solution Algorithm to handle the moving boundary problem. Their results showed that when two trains meet, the high pressure region around the train noses first pushes the trains laterally away from each other, but the lateral force changes direction and pushes the trains toward each other when they are aligned side by side. In addition, they found that the lift force was small compared to the drag and side forces; therefore, it could be neglected in this problem.

Hwang et al. (2001) applied a three-dimensional inviscid numerical model and the domain decomposition method to investigate the influences of several parameters, such as the shape of the train nose, the location of the trains (inside or outside the tunnel), the length of the trains and the gap between two trains on the intersecting problem. Their results showed that the side force is proportional to the square of the train speed and the variation of the side force is primarily dependent on the nose shape. Also, the maximum side force increased as the gap between two trains decreased and the drag force was mainly affected by the intersecting location (inside/outside a tunnel) but insensitive to the train nose shape.

Zhao and Sun (2010) used a two-dimensional incompressible model and a rotational symmetric boundary system to simulate the train-passing problems in open space. Their numerical results show that the peak positive pressure generated by the train-passing event is larger than that of by a single train, while the peak negative pressure is nearly the same as that in the single train case. However, the variation of their simulated pressures is too small to be true.

* Corresponding author. Address: Department of Civil Engineering, National Central University, 300 Jhong-Da Road, Jhong-Li, Taoyuan 32001, Taiwan, ROC. Tel.: +886 3 4227151x34138; fax: +886 3 4252960.

E-mail addresses: crchu@cc.ncu.edu.tw (C.-R. Chu), armani.chien@gmail.com (S.-Y. Chien), cywang@cc.ncu.edu.tw (C.-Y. Wang), tsoren@cc.ncu.edu.tw (T.-R. Wu).

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Nomenclature

A_{tunnel} cross-sectional area of tunnel
A_{train} frontal area of train
$\text{Br} = A_{\text{train}}/A_{\text{tunnel}}$ blockage ratio of the train to tunnel
c speed of sound
C_S side coefficient
C_D drag coefficient
$C_p = \Delta P/0.5\rho V_{\text{train}}^2$ pressure coefficient
E total energy
k turbulent kinetic energy
k_{eff} effective thermal conductivity
k_p turbulent kinetic energy at point P
$\text{Lr} = L_{\text{tunnel}}/L_{\text{train}}$ ratio of the length of tunnel to train
$m = M^2\text{Lr}$ a parameter used to evaluate the compressible effect
$M = V_{\text{train}}/c$ Mach number
M_t turbulent Mach number
Pr_t turbulent Prandtl number
s lateral distance between the two trains
U_p mean velocity at point P
V_t train speed
$X_{sc} = x/L_{\text{tunnel}}$ intersecting location of two trains
Y_M dissipation rate due to of the fluctuating dilatation
y_p the distance from point P to the wall
y^* dimensionless distance
y_T^* dimensionless thickness of thermal sublayer
ρ air density
ε dissipation rate
δ Kronecker delta
μ dynamic viscosity of the air
μ_t turbulent dynamic viscosity
μ_{eff} effective dynamic viscosity
κ von Karman constant

In view of the above studies, there is a need to use a true three-dimensional turbulence model to investigate the aerodynamic flow field induced by two trains passing each other inside a tunnel. Most of the previous numerical studies used symmetry effect in their calculation and assume a train intersecting with a virtual train under the same speed at the mid-point of the tunnel. However, the intersecting location x may not be at the mid-point of the tunnel ($x/L_{\text{tunnel}} = 0.5$) and the intersecting location may affect the pressure waves in the tunnel; the aerodynamic forces acting on the trains may vary when two trains are traveling at different speeds.

Therefore, the objective of this study is to utilize a three-dimensional, compressible, turbulence model to investigate the variation of pressure waves and aerodynamic loading on the trains when two trains are passing each other in a tunnel. The simulation results were analyzed to understand the influences of the length ratio, the train speed, the blockage ratio and the intersecting location on the interaction of pressure waves in the tunnel.

2. Numerical model

2.1. Governing equations

The aerodynamics of the train/tunnel systems was solved by a three-dimensional, compressible, RNG k–ε turbulence model. The RNG k–ε model was developed by Yakhot and Orszag (1986) using the *Renormalization Group* (RNG) method. It is similar to the standard k–ε model but includes an additional term in the dissipation rate ε equation for interaction between the mean shear and turbulence dissipation. It also improved the predictions of heat and mass transfers near the wall. The governing equations are the continuity equation and the Reynolds-averaged Navier–Stokes equations:

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

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \rho g \delta_{i3} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j} \times (-\rho\overline{u_i' u_j'}) \tag{2}$$

where u and P are the mean velocity and pressure, ρ is the density of the air, g is the gravitational acceleration, δ is the Kronecker delta, μ is the dynamic (molecular) viscosity of the air and the subscripts i, j = 1, 2, 3 represent the x, y, z directions, respectively. The Reynolds stress tensors $-\rho\overline{u_i' u_j'}$ are related to the mean velocity gradients via the Boussinseq approximation:

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

where μ_t is the turbulent viscosity and k is the turbulent kinetic energy. The turbulent viscosity can be computed from the kinetic energy k and the dissipation rate ε:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{4}$$

where the model coefficient is $C_\mu = 0.0845$. The transport equations of the turbulent kinetic energy and energy dissipation rate are:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\frac{\mu_{eff}}{\alpha_k}\frac{\partial k}{\partial x_j}\right) + G_k - \rho\varepsilon - Y_M \tag{5}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left(\frac{\mu_{eff}}{\alpha_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon}G_k\frac{\varepsilon}{k} - C_{2\varepsilon}^*\rho\frac{\varepsilon^2}{k} \tag{6}$$

where μ_{eff} is the effective dynamic viscosity equal to the sum of the molecular and turbulent viscosities. The model coefficients: $C_{1\varepsilon} = 1.42$ and $C_{2\varepsilon}^*$ is given by:

$$C_{2\varepsilon}^* = C_{2\varepsilon} + \frac{C_\mu \eta^3(1 - \eta/\eta_o)}{1 + \beta\eta^3} \tag{7}$$

where $C_{2\varepsilon} = 1.68$, $\eta_o = 4.38$, $\beta = 0.012$, $\eta = Sk/\varepsilon$, S is the skewness factor of turbulent velocity. The term G_k is the generation of turbulent kinetic energy by the mean velocity gradients, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence and is calculated as follows:

$$Y_M = 2M_t^2 \tag{8}$$

where M_t ($=k^{1/2}/c$) is the turbulent Mach number, c is the speed of sound. The transport equation of the total energy, E, is:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}[u_i(\rho E + p)] = \frac{\partial}{\partial x_j}\left(k_{eff}\frac{\partial T}{\partial x_j} + u_i(\tau_{ij})_{eff}\right) \tag{9}$$

where T is the temperature, k_{eff} is the effective thermal conductivity (sum of the molecular and turbulent conductivities). The two terms on the right-hand side of Eq. (9) represent the energy transfer due