Effect of Expansion Wave Generated by Train Tail Entering into Tunnel on Lateral Vibration of High-Speed Train

Hiroaki AKAI¹, Shun TAKAHASHI², Masanori OTA¹ and Kazuo MAENO¹

¹ Graduate student, Department of Mechanical Engineering, Graduate School of Engineering, Chiba University, Chiba 263-8522, Japan
² Department of Prime Mover Engineering, Tokai University, Kanagawa 259-1292, Japan
³ Department of Mechanical Engineering, Graduate School of Engineering, Chiba University, Chiba 263-8522, Japan
⁴ National Institute of Technology, Kisarazu College, Chiba 292-0041, Japan

(Received 10 January 2016; received in revised form 18 April 2016; accepted 24 April 2016)

Abstract: It is well known that the lateral vibration of the trains running in tunnel becomes larger than that at open section, where we cannot find strong relevance to track irregularity in contrast to the vibration at open section. This vibration has been explained mainly by the aerodynamic flow separation and vortex shedding from the surface of trains. In this paper we focus on lateral vibration of the high-speed train (Shinkansen), and try to investigate not only flow separation but also expansion wave effect from the tail part of the trains on the vibration when they enter the tunnel. We have started to investigate with compressible and two-dimensional numerical analysis of aerodynamic flows around the trains. For the trains entering the tunnel, we performed the CFD with ghost cells and level set functions. As a result of interference of expansion waves and aerodynamic flow separation and shed vortices, for the first stage of our research on aerodynamic pressure waves and forces caused by strong interference of expansion waves and aerodynamic flow separation and shed vortices. For the first stage of our research on aerodynamic pressures and forces caused by strong interference of expansion waves and aerodynamic flow separation and shed vortices. For the first stage of our research on aerodynamic pressures and forces caused by strong interference of expansion waves and aerodynamic flow separation and shed vortices. For the first stage of our research on aerodynamic pressures and forces caused by strong interference of expansion waves and aerodynamic flow separation and shed vortices. For the first stage of our research on aerodynamic pressures and forces caused by strong interference of expansion waves and aerodynamic flow separation and shed vortices. For the first stage of our research on aerodynamic pressures and forces caused by strong interference of expansion waves and aerodynamic flow separation and shed vortices. For the first stage of our research on aerodynamic pressures and forces caused by strong interference of expansion waves and aerodynamic flow separation and shed vortices. For the first stage of our research on aerodynamic pressures and forces caused by strong interference of expansion waves and aerodynamic flow separation and shed vortices. For the first stage of our research on aerodynamic pressures and forces caused by strong interference of expansion waves and aerodynamic flow separation and shed vortices.

Keywords: High-speed Train, Lateral Vibration, Expansion Wave, Train Tail Entering, Tunnel Pressure-effect

1. Introduction

When a high-speed train runs through the relatively long tunnel, vibration phenomena by aerodynamic effects may sometimes be observed. Especially in the case of high-speed operation over 250 km/h, the vibration of trains running in the tunnel becomes larger than that at open section. In previous studies, lateral vibration phenomena of the trains running through the tunnels have been investigated, but there was no explicit relevance to track irregularity in contrast to the vibration at open section [1], and the phenomena have been explained mainly by the aerodynamic flow separation and vortex shedding from the surface of trains [2]. We, however, consider it is not enough to explain lateral vibration of the trains running in tunnel only by flow separation, and further investigation should be necessary of the effects besides the vortex shedding and aerodynamic force on lateral vibration.

In general, when trains enter the tunnel, compression and expansion waves are generated from the train. Figure 1 shows schematic of generation and propagation of pressure and expansion wave when train entering into tunnel. The compression wave moves forward from the train nose, whose behavior has been widely investigated as ‘tunnel micro-pressure wave’ to decide the nose shapes of high-speed train (Shinkansen) [3], while the latter part of expansion waves proceed forward from the tail around the train when the tail part enters the tunnel entrance. Furthermore, at the end of tunnel exit these waves reflect out of phase by 180 degrees. These waves interact with each other. As almost tunnels of high-speed train lines (Shinkansen etc.) are double track, so trains must run at one side, not center. This running pattern in the tunnel produces a kind of wave lag and pressure difference along the train body surfaces, which may also produce the lateral vibration from the tails. Thus we have to try to investigate both of the aerodynamic and pressure effects on lateral vibration.

This paper deals with the aerodynamic vibrational pressures and forces caused by strong interference of expansion waves and aerodynamic flow separation and shed vortices. For the first stage of our research on aerodynamic problems by CFD, we investigate with two-dimensional numerical analysis of viscous and compressible flow equation system with ghost cells and level set functions for moving train boundaries. We also have performed field measurement of acceleration inside of real Shinkansen by using a small mobile data acquisition system for directional acceleration. Both two-dimensional CFD pressure data and field data have been compared, which can be utilized to our future research of comparison of lateral vibration data of trains.

- Generation of compression wave
- Generation of expansion wave

Fig.1 Schematic of generation of pressure and expansion wave (U: train speed, a: sound speed)
2. Field Measurement

2.1 Method of field measurement

Figure 2 shows a schematic diagram of field measurement of Shinkansen. Train length is 251.4 m of 10 cars, where an accelerometer was put on floor of center side (opposite tunnel wall side) of 29.45 m from the train tail, which is on the rear bogie of 9th car. The accelerometer for the measurement is G-MEN DR01, whose sampling time is 5 ms and data resolution of acceleration is 0.098 m/s² (0.01 G). The train speed was measured by GPS speedometer. The outside scenery image and sounds were also taken for the verification of the time series data. \( X, Y \) are used for moving coordinate system fixed train and \( x, y \) are used for absolute coordinate system fixed tunnel.

![Fig.2 Schematic of field measurement](image)

2.2 Results of field measurement

When the Shinkansen train with the length of 251.4 m enters a tunnel of 2965 m length at the speed of 265 km/h (73.6 m/s), compression wave from the nose portion and expansion wave from the tail of the train are produced and they propagate through the tunnel, and reflect at the exit. Figure 3 shows their x-t diagram in the tunnel, and also indicates acceleration PSD (power spectral density) for 5 s before tunnel entrance in open section, and PSD at the measuring point of train after tail entering.

From acceleration data in Fig. 3, a certain wave passed train side, and near \( t = 0 \), we measured strong acceleration onset as compared to the data in open section, which keeps strong vibrating acceleration until \( t = 15-20 \text{ s} \). Generally speaking, when nose of the train enters the tunnel, compression wave is generated, and when the tail enters, expansion wave is also generated. Then the expansion wave passes through the measurement point at sound velocity, and later reflection wave (expansion wave) of compression wave reaches in accordance with x-t diagram.

Figure 4 represents the PSD of the field data of acceleration. When the train tail runs at open section (5 s before entering of the train tail), peak of PSD is around 1.2 Hz, but when the train tail runs in tunnel (5 s after the train tail entering), peak of PSD shift 2.2 Hz. This drastic shift in PSD may be caused by aerodynamic force and its interaction of the lateral body vibration.

3. Numerical Analysis

We have also tried fluid-dynamic analysis by two-dimensional numerical simulation program for viscous and compressible flow, and compared with preliminary field experiment by measuring acceleration of the real Shinkansen for understanding aerodynamic and pressure effects on lateral vibration in a qualitative way. Of course the simulated results are quantitative ones, but our simulation is two-dimensional, so it is hard to compare the simulated results to the field measurement data.

3.1 Numerical method

3.1.1 Governing equation

In this study, the governing equation is two-dimensional compressible Navier–Stokes equation expressed as Eq. (1). No averaging or filtering process is involved, and the flows are solved without any turbulence models. In this section, \( x, y \) are used for normal CFD theory.

\[
\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} = \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y}
\]
contains the conservative variables. The pressure

Ghost cells take the role of imposing boundary condition.

cell.

where

differentiation between the fluid and object regions, and are assigned in two

Fig. 5. Level set functions and cell classification

Fig. 6 Schematic of ghost cell and image point

layers under the present definition in Eq. (3).

\[
\begin{align*}
E &= \begin{bmatrix}
\tau_{xx} & \tau_{xy} & \tau_{xv} \\
\tau_{xy} & \tau_{yy} & \tau_{yv} \\
\tau_{xv} & \tau_{yv} & \tau_{vv} + \kappa \mathbf{T}_y
\end{bmatrix} \\
F &= \begin{bmatrix}
0 \\
\tau_{xv} \\
\tau_{yv} + \kappa \mathbf{T}_y
\end{bmatrix}
\end{align*}
\]

where \( E, F, E_c, \) and \( F_c \) are the inviscid and viscous fluxes in the \( x \)- and \( y \)-directions, respectively. \( Q \) contains the conservative variables. The pressure \( p \) is related to the total energy \( e \) per unit mass with density \( \rho \), velocity \( u, v \) in the \( x \)- and \( y \)-directions and specific heat ratio \( \gamma \) by the equation of state:

\[
\rho e = \frac{p}{\gamma - 1} + \frac{1}{2} \rho (u^2 + v^2)
\]

To eliminate the additional numerical dissipation everywhere, except in the vicinities of shock waves and potential flows, the inviscid terms are computed by a hybrid scheme that combines the pseudo skew-symmetric central difference scheme [4] and the monotone upstream-centered scheme for conservation laws (MUSCL)-Roe scheme [5, 6]. The flux in the turbulent region is evaluated by the pseudo skew-symmetric central difference scheme with a minimum dissipation term. In this study, the Ducros-type sensor [7] is used to classify the shock and potential flow regions, although previous studies have combined this sensor with the Jameson sensor [8] in the shock region [7, 9]. The viscous fluxes are treated by a second-order, central difference scheme using the mid-point fluxes. The time marching is conducted by the three-stage total variation diminishing Runge–Kutta scheme [10].

3.1.2 Boundary representation

An object boundary is specified by the level set method. The level set function is a signed distance to the object boundary. A schematic of the method around an object boundary is shown in Fig. 5. On the basis of the level set function, all cells are classified into three categories: fluid, ghost, and object cells. The ghost cells can behave as guard cells between the fluid and object regions, and are assigned in two layers under the present definition in Eq. (3).

\[
\begin{align*}
d_{ec} > 0 \\
d_{ec} \leq 0 \text{ and } d_{ec} \geq -2\sqrt{2}\Delta x \\
d_{ec} \leq -2\sqrt{2}\Delta x
\end{align*}
\]

where \( FC, GC \) and \( OC \) are fluid cell, ghost cell and object cell.

Ghost cells take the role of imposing boundary condition. An image point extended from a ghost cell collects flow information for the ghost cell. A primary advantage of this kind of ghost cell method is its robustness. A schematic of the present immersed boundary method is shown in Fig. 6.

\[
V_{gc} = V_p - \frac{d_{ep} + d_{gc}}{d_{wp}} (V_p - V_{ib})
\]

where \( IP \) and \( IB \) are image point and immersed boundary. The length of the probe which is a line from a ghost cell to a image point denoted as \( dip \) in Fig. 6, is an important parameter that eliminates recursive interpolation. Here we fix the length of \( d_{wp} \) as 1.75 times of the mesh size, considering the extension to the three-dimensional problem. The primitive variables on the image point are obtained by the bilinear interpolation from the surrounding cells. Finally, the ghost values are calculated by the image point. The flow velocity is assumed to be linearly distributed along the probe from the boundary point to the image point with keeping non-slip boundary condition on the object (Eq. (4)). For the pressure and density, a Neumann condition is assumed on the boundary.
3.2 Analysis condition
In this study, numerical region is two-dimensional as shown in Fig. 7. Train length and width is real Shinkansen scale, but tunnel width is calculated for coinciding with cross-sectional ratio in two-dimensional simulation. Shape of the train nose and tail are corresponding to the spatial change of the cross-sectional ratio of real Shinkansen. In the numerical simulation, the tunnel length is 1000m and its exit is assumed to be no-reflection boundary. In this numerical simulation, the wave reflection of tunnel exit is out of consideration and x, y are used for absolute coordinate system fixed tunnel. Grid size is 0.2m x 0.2m, the number of grid is about 5,000,000. Number of iteration was 100,000 in this simulation. Train speed was assumed to be 265 km/h (73.6 m/s), which is decided by field measurement. For the first 10,000 steps, it is assumed that the train accelerates to 265km/h from initial static condition, \( U = 0 \), because that initial pressure and expansion waves by train starting should be reduced. In this numerical calculation CFL number is 0.400, and the time step is 19.1 ms.

![Numerical region](image)

**Fig.7 Numerical region**

3.3 Results of numerical analysis and comparison
Figure 8 represents the time-depending change of contour figures of pressure distributions for vortex wakes and upstream propagating compression and expansion waves when the train tail enters. These results are written by every 500 step (0.0955 s) interval, where 0s is corresponding to the entry time of the measuring point into the tunnel inlet. As shown in this figure, after train tail entering into the tunnel, the size of trailing vortices in the wake after the train become larger than running at open section. Furthermore, expanding and negative pressures from the tail pass upstream through alternately train sides. This is because of the interaction of expansion waves and vortices at the entrance of the tail and wakes. This interaction causes large pressure difference between both sides of the train. As the trailing vortices are produced periodically and alternately from the tail of the train cars, the interacted expansion waves with these vortices propagate upstream alternately along the both sides of the running train at sound velocity, which is about 340 m/s. Thus the alternately interacting pressure waves yield the vibrating pressure difference on the train surfaces, which results in the complicated excitation of the lateral vibration of the train from the tail side.

![Pressure and pressure difference at train body](image)

**Fig.9 Pressure and pressure difference at train body on the rear bogie of 9th car**

![Measured acceleration data at floor on the rear bogie of 9th car](image)

**Fig.10 Measured acceleration data at floor on the rear bogie of 9th car**

---

Figure 9 shows the two-dimensional simulated pressure variations on both sides of the train car and resulting time-variation of pressure difference at train body on the rear bogie of 9th car where accelerometer was settled, and Fig. 10 presents the measured time-variation of acceleration at same place by field measurement, where \( t = 0 \) s corresponds to the measurement point entering into the tunnel. In Fig. 9, when the measurement point of the train entered the tunnel, pressure decreases by high-speed running of the train tail with slightly expanding waves propagating around the train, and immediately after the entrance the steep decrease of the pressures appears, and large pressure difference is raised because pressure fluctuation of tunnel wall side becomes larger than that of center side.
4. Concluding Remarks

In the results of this paper, we have clarified that there exist the strong effects of the expansion waves from the train tail entrance on the lateral vibration of the train where lateral means $Y$ direction shown in Fig. 2. With two-dimensional numerical analysis, the strong interference of expansion waves in the tunnel with aerodynamic flow separation and shed vortices from the train tail makes the lateral vibration stronger than in open section. Alternately expansion waves pass through the train sides and resulting large pressure difference is raised, which causes lateral vibration of the train just after its entrance.

To clarify these effects and to give the quantitative comparison, we are going to investigate the situation with three-dimensional numerical experiments of aerodynamics, and to combine the results to calculate train dynamic vibration analysis with MATLAB and Simulink, which includes the pressure and acceleration results of CFD together with the simulation of lateral vibration by calculating input of the results of aerodynamic forces of pressure waves to vibration analysis, and compare it to running test data.

References


Fig.8 Simulated pressure distribution around the train tail entering the tunnel
4. Concluding Remarks
In the results of this paper, we have clarified that there exist the strong effects of the expansion waves from the train tail entrance on the lateral vibration of the train where lateral means $Y$ direction shown in Fig.2. With two-dimensional numerical analysis, the strong interference of expansion waves in the tunnel with aerodynamic flow separation and shed vortices from the train tail makes the lateral vibration stronger than in open section. Alternately expansion waves pass through the train sides and resulting large pressure difference is raised, which causes lateral vibration of the train just after its entrance.

To clarify these effects and to give the quantitative comparison, we are going to investigate the situation with three-dimensional numerical experiments of aerodynamics, and to combine the results to calculate train dynamic vibration analysis with MATLAB and Simulink, which includes the pressure and acceleration results of CFD together with the simulation of lateral vibration by calculating input of the results of aerodynamic forces of pressure waves to vibration analysis, and compare it to running test data.

References