Distortion of Compression Wave Propagating through Very Long Tunnel with Slab Tracks

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Field measurement and numerical simulation were performed on the distortion of the compression wave generated by train entry and propagating through a slab track Shinkansen tunnel, which is the longest mountain tunnel in the world as of 2004. The compression wave was measured at twelve different locations. In the numerical simulation, the distortion of the compression waveform were calculated by one-dimensional compressible flow analysis, which takes account of steady and unsteady friction, combined with acoustic analysis on the effect of side branches in the tunnel. The results of numerical simulation are consistent with those of the field measurement. Furthermore, the results indicate that the compression wavefront steepens in the early stage and smoothes down in the later stage of propagation, and the maximum value of the pressure gradient of the compression wavefront reaches a peak under certain conditions of the initial compression wave and a tunnel length.

Key Words: Compressible Flow, Pressure Wave, Compression Wave, Railway, Tunnel, Field Measurement, Numerical Analysis, Acoustic Analysis

1. Introduction

When a compression wave generated by a train entering a tunnel arrives at the tunnel exit, an impulsive pressure wave termed as “micro-pressure wave” is emitted out of the tunnel exit(1). For high-speed railways, e.g., Shinkansen, the micro-pressure wave causes an infrasound problem. A strong micro-pressure wave even accompanies an audible explosive sound as well as the infrasound. The micro-pressure wave depends on the compression waveform arriving at the exit. Its magnitude is approximately proportional to the pressure gradient of the wavefront of the compression wave arrived at the tunnel exit.

The compression wave distorts during its propagation through the tunnel. Consequently, the clarification of the distortion of the compression wave is necessary to elucidate the phenomenon of the micro-pressure wave and for the development of the countermeasures against it. The distortion of the compression wave depends on the train speed, the type of tracks (slab track or ballasted track), the tunnel length, and other pertinent factors. In a long tunnel with ballasted tracks, the wavefront smoothes out and results in a decrease of the micro-pressure wave. On the other hand, the micro-pressure wave is large in a long tunnel with concrete slab tracks because the wavefront of the compression wave steepens due to a nonlinear effect during its propagation in the tunnel.

A number of researches have been made on the distortion of the compression wave propagating through tunnels by model experiments(2) – (4), field measurements(1), (3), (5) – (7), theoretical analysis(8) and numerical simulations(1), (5) – (7), (9). We conducted a field measurement and a numerical simulation for a slab-tracked tunnel of approximately 3 km in length, and found that the result of the numerical simulation conformed to that of the field measurement(7). On the other hand, for the tunnels longer than 10 km, it is reported in Ref. (1) that the magnitude of the micro-pressure wave seems to be decrease with lengthener of the tunnels and the existence of side branches with
large cross-section is considered as the cause of the decrease of the micro-pressure wave. However, the factors of the decrease of the micro-pressure wave is uncertain since there are not enough data of field measurements.

In this study, we investigate the distortion of the compression wave in a very long tunnel with slab tracks. A field measurement is performed in a Shinkansen slab-tracked tunnel of approximately 26 km in length, which is the longest mountain tunnel in the world as of 2004. The pressure of the compression wave is measured at 12 locations near the both portals and before and after the five inclined shafts along the tunnel. The numerical simulation is also conducted, in which the effects of the non-linearity of the compression wave, the steady and unsteady friction, the heat transfer to the tunnel wall and short side branches. Furthermore, the effect of longer side branches with an orifice-shaped junction is also considered in this numerical simulation. We verify the results of the numerical simulation with that of the field measurement, and investigate the distortion of the compression wave using the numerical simulation in detail.

### Symbols

- $A_b$: Cross-sectional area of side branch
- $A_o$: Aperture area of orifice-shaped junction of side branch
- $A_{tun}$: Cross-sectional area of main tunnel
- $C_p$: Specific heat at constant pressure
- $c_0$: Speed of sound in stationary air
- $d_{Ht}$: Hydraulic diameter of main tunnel ($= 4A_{tun}/$periphery length)
- $e$: Total energy per unit volume
- $f$: Friction term
- $f_s$: Steady friction term
- $f_{us}$: Unsteady friction term
- $H(t)$: Unit step function
- $h(t)$: Impulse response
- $i$: Imaginary unit
- $K$: Coefficient of resistance of air passing an orifice
- $k$: Wave number ($= \omega/c_0$)
- $l_b$: Length of side branch
- $l_c$: Characteristic length of flow passing an orifice, Eq. (13)
- $n$: Cross-sectional area ratio of side branch to main tunnel ($= A_b/A_{tun}$)
- $n_o$: Area ratio of opening of orifice-shaped junction of side branch to cross-section of side branch ($= A_o/A_b$)
- $P_r$: Prandtl number
- $p$: Pressure
- $q$: Heat transfer term
- $R$: Gas constant of air
- $T$: Temperature
- $T_w$: Temperature of tunnel wall
- $t$: Time
- $t_b$: Characteristic time of side branch
- $t_c$: Characteristic time of effective mass of air passing an orifice
- $U$: Flow rate
- $u$: Flow velocity
- $V$: Train speed
- $W(t)$: Weighting function of unsteady friction term
- $x$: Coordinate along tunnel axis
- $Z_o$: Impedance of side branch ($= Pressure/Flow rate$)
- $\varepsilon$: Parameter of unsteady friction term
- $\Delta p_t$: Pressure (Gage pressure)
- $\Delta p_i$: Pressure of incident wave
- $\Delta p_t$: Pressure of transmitted wave
- $\delta(t)$: Delta function
- $\gamma$: Ratio of specific heats
- $\lambda$: Wall friction coefficient of steady turbulent flow
- $\nu$: Kinematic viscosity
- $\rho$: Air density
- $\rho_0$: Air density of stationary air
- $\omega$: Angular frequency
- $\tau$: Shear stress on wall ($= f d_{H}/4$)

### 2. Field Measurement

#### 2.1 Method of field measurement

We conducted a field measurement in an actual Shinkansen tunnel of approximately 26 km in length with slab tracks, which is the longest mountain tunnel in the world as of 2004.
world as of 2004(10). Table 1 shows the specifications of the test tunnel, and Fig. 1 shows the arrangement of side branches and the setup of the measurement. In usual long Shinkansen tunnels, two types of short side branches provided at regular intervals of 0.5 km in the tunnel for provision of electric equipment, one being a type-1 short side branch and another a type-2 short side branch. In addition, large type short side branches, small type short side branches and inclined shafts have also been constructed in the tunnel as shown in Fig. 1. Each inclined shaft provides a wall with orifice-shaped apertures at the junction of the main tunnel and the inclined shaft (see Fig. 2). The northern portal does not have an entrance hood for reducing the micro-pressure wave and the southern portal is joined to an adjacent tunnel by a snow-shelter. Frame-shaped slab tracks are laid in the test tunnel(10), which are different from the flat-shaped slab tracks laid in the tunnel previously measured by the authors(1),(6),(7). The frame-shaped slab track is consists of parts to support a load of trains which laid in rail direction and ones to keep the gage which laid in left and right direction (see Fig. 3).

In this field measurement, the pressure of the compression wave propagating through the tunnel was measured by pressure transducers (ST Laboratory Co., PD-80HA) mounted on the tunnel wall at twelve locations near the portals, and before and after the five inclined shafts (see Fig. 3). The pressure transducers were mounted into semi-streamline-shaped covers as shown in Fig. 4 to smoothly fit the pressure transducers to the tunnel wall surface. Signals from the pressure transducers were recorded with PCM DAT data recorders (NF Corporation, 5 881 for the measuring points before and after the inclined shaft A and D, and SONY 200 Ax series for other measuring points).

2.2 Result of field measurement

The plotted data in Fig. 5 show an example of the measured compression waveforms. These waveforms are the results obtained when the train speed $V$ is the high-
When the train speed is higher \(V = 256\) and \(248\, \text{km/h}\), the compression wavefront steepens and the value of \((\partial p/\partial t)_{\text{max}}\) increases between the entrance and the inclined shaft-A, and between the inclined shaft-B and -C, whereas the pressure value \(\Delta p\) of the compression wave decreases. Subsequently, the value of \((\partial p/\partial t)_{\text{max}}\) decreases between the inclined shafts-B and -C, because the pressure of the compression wave decreases with its steep wavefront kept. Finally, the steep wavefront attenuates and disappears between the inclined shaft-D and the exit. On the other hand, when the train speed is lower \(V = 163\) and \(128\, \text{km/h}\), the value of \((\partial p/\partial t)_{\text{max}}\) decreases monotonically with the propagation distance as shown in Fig. 6.

### 3. Numerical Simulation

We performed a numerical simulation to investigate the distortion of the compression wave in detail. The distortion of the compression wave is affected by (1) the non-linear effect of the compression wave, (2) the friction on the tunnel wall, (3) the heat transfer on the tunnel wall and (4) the side branches in the tunnel. In the numerical simulation, we consider that the tunnel consists of several sections of a constant cross-sectional area divided by the branches. We calculate the compression wave propagating through the constant cross-sectional area sections of the main tunnel from one-dimensional compressible flow analysis, which takes into account the non-linear effect, the friction and the heat transfer on the tunnel wall. We calculate the distortion of the compression wave when it passes a junction of the main tunnel and the side branch from acoustic analysis.

#### 3.1 Calculation of compression wave propagating through constant cross-sectional area sections

In the numerical simulation of the compression wave propagating through the main tunnel, we assume that the air is a perfect gas and the flow is one-dimensional and compressible. We use three conservation equations (mass, momentum and energy) described in the coordinate system fixed to the compression wave propagating at the speed of sound in stationary air as\(^{6}\),

\[
\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + G = 0, \tag{1}
\]

\[
U = \begin{bmatrix} \rho \\ \rho u \\ e \end{bmatrix}, \quad F = \begin{bmatrix} \rho u \\ p + \rho u^2 \\ (e + p)u \end{bmatrix}, \quad G = \begin{bmatrix} 0 \\ f - c_0 f \end{bmatrix}, \tag{2}
\]

\[
e = \frac{p}{\gamma - 1} + \frac{1}{2} \rho u^2, \tag{3}
\]

\[
f = f_s + \varepsilon f_{\text{us}}, \tag{4}
\]

\[
f_s = \lambda p (u + c_0)^2 \frac{c_0}{2d_h}, \tag{5}
\]

\[
f_{\text{us}} = \frac{16 \rho u}{d_h^2} \int_0^T W(\tau) \left( \frac{\partial u}{\partial t} \right)_{x=c_0(t-\tau)} - c_0 \left( \frac{\partial u}{\partial x} \right)_{x=c_0(t-\tau)} \, d\tau
\]

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\[ \frac{16 \rho V}{d_1} \int_0^t W(\tau) \left\{ -c_0 \left( \frac{du}{dx} \right)_{x=c_0(t-\tau)} \right\} d\tau, \quad (6) \]

\[ q = 4C p(T - T_w) \frac{(u + c_0)d_1^2}{2 \rho V} \tau_w, \quad (7) \]

\[ p = \rho RT. \quad (8) \]

The friction term \( f \) is expressed as \( f = f_s + \varepsilon f_{us} \) in the numerical simulation as Ref. (11). The wall friction coefficient \( \lambda \) of the turbulent flow in the steady friction term \( f_s \) and the parameter \( \varepsilon \) in the unsteady friction term \( f_{us} \) are estimated from the measured data, since they depend on the roughness of the tunnel wall and on the shape of the laid tracks (11). In the numerical simulation, we set \( \lambda = 0.04 \) and \( \varepsilon = 11 \) from the comparison between the compression waveform before passing the inclined shaft-B obtained by the field measurement shown in Fig. 5 (the train speed \( V = 256 \text{ km/h} \)) and that obtained by the numerical simulation when the initial waveform is the compression waveform after passing the inclined shaft-A (the propagation distance of the compression wave is approximately \( 2.3 \text{ km} \)).

3.2 Calculation methods of distortion of compression wave when it passes a junction of main tunnel and side branch

The distortion of the compression wave passing a junction of a main tunnel and a side branch is calculated using acoustic analysis. The calculation methods for the distortion of a compression wave passing a junction without orifice-shaped apertures of the type-1, type-2, large type and small type short side branches are the same as Refs. (1) and (7).

As mentioned in the chapter 2, there are five inclined shafts-A to -E in the test tunnel. Each inclined shaft provides a wall with orifice-shaped apertures at the junction of the main tunnel and the inclined shaft (see Fig. 2). Below, we describe relation between the pressure \( \Delta p_b \) of the incident wave and the pressure \( \Delta p_t \) of the transmitted wave when the compression wave passes the orifice-shaped junction of the main tunnel and the side branch.

Here, we consider the distortion of a compression wave passing a junction of a main tunnel and a side branch with an orifice-shaped aperture as shown in Fig. 7 (the cross-sectional area of the main tunnel \( A_{h_{sn}} \), the cross-sectional area of the side branch \( A_b \), and the area of the orifice-shaped aperture \( A_0 \)). For a plane harmonic wave of angular frequency \( \omega \) propagating in a tunnel with a side branch, the relation between the pressure \( \Delta p_i \exp(i\omega t) \) of the incident wave and the pressure \( \Delta p_t \exp(i\omega t) \) of the transmitted wave is expressed as\(^{(12)}\),

\[ \frac{\Delta p_t}{\Delta p_i} = \frac{\frac{Z_b}{Z_0} + \frac{\rho_0 c_0}{2A_b}}{1 + \frac{\rho_0 c_0}{2A_b} \frac{1}{Z_0}}. \quad (9) \]

The pressure difference \( \Delta p_b \) when a plane harmonic wave passes an orifice in a tube is expressed as follows.

\[ \Delta p = \left[ \begin{array}{c} \Delta p_1 \\ \Delta p_2 \end{array} \right] = \left[ \begin{array}{cc} G(Kl_c + i\omega l_c) & \frac{Z_0}{1} \\ 0 & 1 \end{array} \right] \left[ \begin{array}{c} \Delta p_1 \\ U_1 \end{array} \right], \quad (14) \]

where the flow rate \( U = A_0u \), the characteristic time for the flow passing an orifice \( l_c = l_c/c_0 \) and \( G = \rho_0 c_0 / A_b \). Furthermore, from the relation

\[ \left[ \begin{array}{c} \Delta p_1 \\ U_1 \end{array} \right] = \left[ \begin{array}{cc} \frac{\cos kl_b}{G} & \frac{i G \sin kl_b}{\sin kl_b} \\ \cos kl_b & \cos kl_b \end{array} \right] \left[ \begin{array}{c} \Delta p_2 \\ U_2 \end{array} \right], \quad (15) \]

Eq. (14) becomes
\[ \begin{bmatrix} \Delta p \\ U \end{bmatrix} = \begin{bmatrix} 1 & G(K_L + i\omega \ell) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos k_h \ell & iG \sin k_h \ell \\ i \sin k_h \ell & \cos k_h \ell \end{bmatrix} \begin{bmatrix} \Delta p_2 \\ U_2 \end{bmatrix}. \]  

(16)

We analyze \( \Delta p \) and \( U \) by setting \( K = 0 \) for applying Eq. (11) to Eq. (16) and \( U_2 = 0 \) since the end of the side branch is closed. By this analysis, the impedance \( Z_b = \Delta p/U \) is expressed as

\[ Z_b = G \left[ \frac{1 + \exp(-2st_b) + t_c[1 - \exp(-2st_h)]}{1 - \exp(-2st_b)} \right], \]  

(17)

where \( s = h_0/c_0 \) and \( s = i\omega \). By substituting Eq. (17), Eq. (9) becomes the following:

\[ \frac{\Delta p_i(s)}{\Delta p_f(s)} = \frac{1}{1 + \frac{n}{2} \left[ 1 + \exp(-2st_b) \right] + t_c[1 - \exp(-2st_h)]}. \]  

(18)

By expansion of Eq. (18) by \( \exp(-2st_b) \), Eq. (18) becomes

\[ \frac{\Delta p_i(s)}{\Delta p_f(s)} = \frac{2 + 2st_c}{2 + n \cdot 2st_c} + \frac{4n\exp(-2st_b)}{(2 + n \cdot 2st_c)^2}. \]  

3.3 Distortion of compression wave passing by orifice-shaped junction of main tunnel and side branch

For the verification of the Eqs. (20) and (21) for the distortion of the compression wave passing the junction of the main tunnel and the side branch, we compare the result of the transmitted waveforms calculated by Eqs. (20) and (21) considering the orifice-shaped aperture (see Fig. 9 (a)), that by the analysis neglecting the orifice-shaped aperture for \( A_b = 47.9\, \text{m}^2 \) (cross-sectional area of the inclined shaft-B, see Fig. 9 (b)), and that by the analysis neglecting the orifice-shaped aperture for \( A_b = 9.0\, \text{m}^2 \) (total area of the orifice-shaped apertures, see Fig. 9 (c)).

Figure 10 shows the incident waveform \( \Delta p_i(t) \) and the transmitted waveform \( \Delta p_f(t) \) given by the field measurement, and also the results of \( \Delta p_f(t) \) given by the numerical simulation. The incident waveform \( \Delta p_i(t) \) in Fig. 10 is the compression wavefront before passage of the inclined shaft-B (see Fig. 5). The pressure of the transmitted waveform by the numerical simulation is smaller than that by the field measurement. Accordingly, prediction of the transmitted waveform without consideration of the orifice-shaped aperture for \( A_b = 47.9\, \text{m}^2 \) overestimates the effect of the side branch. On the other hand, the pressure of the transmitted waveform by the numerical simulation is larger than that by the field measurement, and therefore the prediction of the transmitted waveform without consideration of the orifice-shaped aperture for \( A_b = 9.0\, \text{m}^2 \) underestimates the effect of the side branch. However, the pressure and pressure gradient of the wavefront of the transmitted waveform obtained by the Eqs. (20) and (21) with consideration of the orifice-shaped aperture agree well with those obtained by the field measurement. Hence, we can say that it is possible to estimate the transmitted waveform using Eqs. (20) and (21) when the compression wave passes the junction of the main tunnel and a side branch with an orifice-shaped aperture.

3.4 Comparison of calculated results with results of field measurement

For the verification of the method of the numerical simulation, we compare the results of the numerical simulation with those of the field measurement. The lines in Fig. 5 show the examples of the waveform obtained from the numerical
simulation using the initial waveform (the train speed $V = 256$ km/h) measured at $x = 0.1$ km. Furthermore, the lines in Fig. 6 show the examples of variations of the maximum pressure gradient of the compression wavefront $(\partial p/\partial t)_{\text{max}}$ with propagation obtained from the numerical simulation when $V = 256$ (the waveforms are shown in Fig. 5), 248, 163 and 128 km/h respectively.

From Fig. 5, it is shown that the waveforms obtained from the numerical simulation are consistent with those from the field measurement with respect to the pressure and the gradient of the wavefront. FromFig. 6, it is also shown that the values of $(\partial p/\partial t)_{\text{max}}$ obtained from the numerical simulation agree well with those from the field measurement at any initial value of $(\partial p/\partial t)_{\text{max}}$ between 2 and 12 kPa/s. Thus, we can conclude that our numerical method is useful to estimate the distortion of the compression wave propagating through the slab-tracked long railway tunnel with side branches.

From the results of the numerical simulation when the train speed is higher ($V = 256$ and 248 km/h) in Fig. 6, the compression wave propagates with the increase of $(\partial p/\partial t)_{\text{max}}$ in the main tunnel and with the decrease of $(\partial p/\partial t)_{\text{max}}$ at the short side branches and the inclined shafts between the northern portal and the inclined shaft-C. From Fig. 6, it is also shown that the values of $(\partial p/\partial t)_{\text{max}}$ when $V = 256$ and 248 km/h become maximum just before passing the large-type short side branch arranged between the northern portal and the inclined shaft-A. Furthermore, it is also shown that the compression wave propagates without the increase of $(\partial p/\partial t)_{\text{max}}$ after passing the inclined shaft-C. On the other hand, from Fig. 6, it is shown that the compression wave propagates without the increase of $(\partial p/\partial t)_{\text{max}}$ in the main tunnel when the train speed is lower ($V = 163$ and 128 km/h).

3.5 Distortion of compression wave propagating through usual Shinkansen tunnels with slab-tracks

There are several large and small type short side branches and inclined shafts in the test tunnel mentioned above. However, usual Shinkansen tunnels have an arrangement of side branches shown in Fig. 11: type-1 and/or type-2 short side branches are provided at regular intervals of about 0.5 km. Here, we investigate the distortion of the compression wave propagating through the usual tunnel with frame-shaped slab tracks by the numerical simulation. The cross-sectional area of the main tunnel, and the cross-sectional area and the length of the short side branches are the same as shown in Table 1. Initial waveforms are extrapolated from the measured initial waveform shown in Fig. 5 according to the relation that the
pressure is in proportion to $V^2$ and the time is in inverse proportion to $V$.

Figure 12 shows the results of the numerical simulation. From Fig. 12, it is shown that there exists the tunnel length at which the value of $(\partial p/\partial t)_{\max}$ becomes its maximum: these lengths are 7, 7, 7, 6, 5 and 4 km at $V = 220$, 240, 260, 280, 300 and 320 km/h respectively, and the value of $(\partial p/\partial t)_{\max}$ becomes small with an increase of the tunnel length when the tunnel is longer than these lengths. These results demonstrate the existence of a tunnel length at which the maximum value of the pressure gradient of the compression wavefront reaches a peak under certain conditions of the initial compression wave and the tunnel.

4. Conclusions

We performed a field measurement to investigate the distortion of a compression wave in a very long tunnel with slab tracks. In the field measurement, we measured the pressure of the compression wave at twelve locations near the both portals and before and after the five inclined shafts along the tunnel. We also performed a numerical simulation to investigate the distortion of the compression wave front in detail. In the numerical simulation, the effect of the side branch with an orifice-shaped aperture is also considered. Conclusions are summarized as follows.

(1) Distortion process of the compression wave propagating through a tunnel with slab tracks becomes clear in detail by the field measurement and numerical simulation: the compression wavefront steepens in the initial stage and smooths out in the later stage of the propagation.

(2) Results of the numerical simulation by setting the wall friction coefficient of the steady friction term $\lambda = 0.04$ and the parameter of the unsteady friction term $\varepsilon = 11$ and by considering the effect of the side branch with an orifice-shaped aperture are consistent with those of the field measurement in regard to the pressure waveform and the maximum value of the pressure gradient of the compression wavefront.

(3) There exists a tunnel length at which the maximum value of the pressure gradient of the compression wavefront reaches a peak, and it becomes shorter as the initial compression wavefront generated by the train entering the tunnel is steeper.

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