Distortion of Compression Wave Propagating through Slab Track Tunnel with Side Branches

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When a high-speed train enters a tunnel, a compression wave is generated and propagates to the tunnel exit. At this moment, an impulsive pressure wave (micro-pressure wave) is emitted out of the exit. If its magnitude is large, it poses environmental problems. The magnitude of the micro-pressure wave is closely related to the pressure gradient of the compression wave arriving at the tunnel exit. Hence, to estimate the magnitude of the micro-pressure wave, it is required to investigate distortion of the compression wave propagating through tunnels. In this study, we investigate the distortion of the compression wave propagating through a slab track tunnel with short side branches by field measurement, numerical analysis and model experiment.

Keywords: infrasound, micro-pressure wave, side branch, slab track

1. Introduction

Infrasound problems by pressure waves emitted from tunnel portals could be one of the environmental problems of high-speed railways. A micro-pressure wave is a typical phenomenon of such problems. Figure 1 shows a schematic of the micro-pressure wave phenomenon. When a high-speed train enters a tunnel, a compression wave is generated in front of the train. This compression wave propagates to the tunnel exit and an impulsive pressure wave (micro-pressure wave) is emitted out of the tunnel exit. According to the acoustic theory, the magnitude of the micro-pressure wave is nearly proportional to the maximum rate of the pressure change (pressure gradient) of the compression wavefront. The micro-pressure wave is large in a long tunnel with slab tracks because the compression wavefront steepens due to non-linear effect during its propagation, whereas in a long tunnel with ballasted tracks, the compression wavefront smoothes out. Therefore, it is required to investigate distortion of the compression wave during its propagation through the slab track tunnel to estimate the magnitude of the micro-pressure wave. The distortion of the compression wave propagating through the slab track tunnel is affected by (1) nonlinear effect of the compression wave, (2) friction on the tunnel wall, (3) heat transfer to the tunnel wall and (4) side branches constructed in the tunnel. The side branches in the tunnel have a considerable effect on reducing the micro-pressure wave because the pressure gradient of the compression wavefront is changed when it passes by side branches.

In this study, we investigate the distortion of the compression wave propagating through a slab track tunnel with side branches by a field measurement and a numerical analysis. Furthermore, we investigate the effect of the side branch on reducing the micro-pressure wave by model experiment.

2. Field measurement

We performed field measurement in an actual tunnel (cross-sectional area \( A_{in} = 63.4 \text{ m}^2 \), overall length: 3,064 m). Figure 2 shows the cross-section of the tunnel. To install electrical equipments for train operation, two types of short side branches (cross-sectional area \( A_b \), length \( l_b \)) are constructed in the tunnel, one being a Type 1 short side branch (\( A_b = 7.1 \text{ m}^2, l_b = 3 \text{ m} \)) and the other a Type 2 short side branch (\( A_b = 7.1 \text{ m}^2, l_b = 5 \text{ m} \)). Figure 3 shows the arrangement of the short side branches and the setup of the field measurement. Pressure waves propagating...
through the tunnel are measured by pressure transducers mounted on the tunnel wall at four points: near the entrance \((x = 0 \text{ m})\), before and behind the short side branch at the middle of tunnel \((x = 1,279 \text{ m} \text{ and } 1,379 \text{ m})\) and near the exit \((x = 2,864 \text{ m})\).

3. Numerical analysis

We performed a numerical analysis under conditions similar to those of the field measurement. In the numerical analysis, the tunnel is divided into several duct sections of a constant cross-section and branched sections. The distortion of the compression wave propagating through the duct sections is calculated by one-dimensional compressible flow analysis which takes into account of the non-linear effect, the friction on the tunnel wall and the heat transfer to the tunnel wall. In the analysis, governing equations are described in a coordinate system fixed to the compression wave propagating at the speed of sound in stationary air\(^9\) and calculated numerically by combining the second order upwind TVD scheme\(^10\) and the operator splitting method\(^11\).

The distortion of the compression wave when it passes by the branched section is calculated by acoustic analysis. When a plane harmonic wave passes by a side branch as shown in Fig. 4 (a), the relation between the pressure \(\Delta p_2\) of the transmitted wave and the pressure \(\Delta p_1\) of the incident wave is expressed as follows\(^3\)\(^7\):

\[
\Delta p_2(t) = \frac{2}{2 + R_b} \Delta p_1(t) + \frac{2}{(2 + R_b)^2} \Delta p_1(t - 2t_b) - 2 \frac{2 - R_b}{(2 + R_b)^2} \Delta p_1(t - 4t_b) + \frac{2}{(2 + R_b)^2} \frac{2 - R_b}{2 + R_b} \Delta p_1(t - 6t_b) \]

where \(R_b = (A_b/A_{\text{tun}})\) is the cross-sectional area ratio of side branch to main tunnel; \(t_b = l_b/c_0\); and \(l_b\) is the side branch length corrected for the open end \((= l_b + 0.425d_b\) where \(d_b\) is the diameter of the side branch). Further-

more, when a plane harmonic wave passes by two facing side branches as shown in Fig. 4 (b), the relation between the pressure \(\Delta p_2\) of the transmitted wave and the pressure \(\Delta p_1\) of the incident wave is expressed as follows\(^8\):

\[
\Delta p_2(t) = \frac{2}{2 + R_{b1} + R_{b2}} \sum C_{ij} \Delta p_1(t - 2t_{b1} - 2t_{b2}) \]

where \(C_{ij}\) is the coefficient decided from the cross-sectional area ratio of the side branch to the main tunnel \(R_{b1} = (A_{b1}/A_{\text{tun}})\) and \(R_{b2} = (A_{b2}/A_{\text{tun}})\).

In the numerical analysis, we decide the initial waveform of the compression wave from the data measured in the field (section 2) near the tunnel entrance \((x = 0 \text{ m})\). First, we perform the one-dimensional compressible flow analysis to calculate the distortion of the compression waveform propagating through the duct section from the entrance \((x = 0 \text{ m})\) to the first short side branch. Next, at the branched section, the transmitted waveform \(\Delta p_2(t)\) is calculated by equation (1) or (2) according to the arrangement of the side branch using the result of the one-dimensional analysis as the incident waveform \(\Delta p_1(t)\). Again, \(\Delta p_2(t)\) is considered as the initial waveform for the one-dimensional analysis to calculate the distortion of the compression waveform propagating through the duct section between the first and the second branched sections. We repeat the above-mentioned procedures until the compression wave arrives the exit.

Fig. 3 Schematic diagram of field measurement

Fig. 4 Plane harmonic wave passing by side branches in tunnel

72

QR of RTRI, Vol. 42, No. 2, May. 2001
4. Model experiment

We also performed a model experiment to investigate the distortion of the compression wave when it passes by a side branch. The experimental apparatus is illustrated schematically in Fig. 5. The model of main tunnel consists of a 12.3 m long horizontal circular cylindrical pipe made of vinyl chloride with the inner diameter $d_m = 146$ mm. The axisymmetric model train (length: 500 mm, diameter of uniform section: 58.8 mm, nose and tail shape: ellipsoid of revolution, nose and tail length: 88 mm) is launched at high speed into the tunnel, guided by a 5 mm diameter taut steel wire extending along the tunnel axis. A side branch model (inner diameter $d_b = 40, 51, 67$ and $77$ mm, length $l_b = 1,310$ mm) is set at the main tunnel model. In order to make the influence of the reflected pressure waves at the end of the side branch on the main tunnel smaller and simulate an endless branch, we set an orifice (diameter: $0.2d_b$) at the branch end. The steel wire to guide the train model is offset from the axis of the main tunnel model near the branch side to simulate a train running in a double-track tunnel. The offset distance from the main tunnel center $y$ is set at 28 mm according to the comparison results of model experiments and field measurements. The pressure within the tunnel is measured by two pressure transducers mounted on the tunnel wall before and behind the branched section (measuring points A and B), and the pressure waves emitted from the tunnel exit are measured by a microphone at $2d_m = 292$ mm from the center of the exit portal (measuring point C).

5. Results and discussion

5.1 Field measurement and numerical analysis

Figure 6 shows an example of the pressure and pressure gradient waveform of the compression wave at four points in the tunnel obtained by the field measurement and numerical analysis. These waveforms are the results when the train speed $U$ is the highest ($U = 273$ km/h) and the compression waveform of the initial waveform ($x = 0$ m) is the steepest among all the cases in the field measurement. In Fig. 6, we also show the results of the one-dimensional compressible flow analysis combined with the acoustic analysis of the effect of the side branches ($1D$-Branch) as well as the results of the one-dimensional compressible flow analysis ($1D$) only. By comparing the $1D$ analysis results and field measurement results, we can see that the pressure gradient of the compression wavefront $\partial p/\partial t$ by the $1D$ analysis is larger than that by the field measurement, although the total pressure rise of the compression wave by the $1D$ analysis agrees with that by the field measurement. On the other hand, the results by the $1D$-Branch analysis and those by the field measurement are in good agreement regarding both the total pressure rise and the pressure gradient of the compression wave.

Figure 7 shows the relation between the maximum pressure gradient of the compression wavefront $\partial p/\partial t_{\text{max}}$ and the propagating distance of the compression wave $x$, where the arrangement of its short side branches are also indicated. We can see that the results of the $1D$-Branch analysis and those of the field measurement agree well while there is discrepancy between the $1D$ analysis and the field measurement. Furthermore, from the $1D$-Branch results, we can see that $(\partial p/\partial t)_{\text{max}}$ of the compression wavefront increases during the propagation in the duct sections of constant cross-section in the tunnel and decreases at the branched sections.

5.2 Model experiment

Figure 8 shows an example of $x$-$t$ diagram and pressure histories $p$ at the measuring points obtained by the model experiment. We can see that the compression wave is generated by the train nose entry into the tunnel and propagates through the main tunnel and an impulsive pressure wave (micro-pressure wave) is emitted outside from the exit portal (measuring point C). Figure 9 shows the relation between the reduction ratio of the maximum pressure gradient of the compression wave generated by the train entering the tunnel $\epsilon_b$ by the model experiment and that by equation (1) namely $\epsilon_b = 2/(2 + R_b)$. Since the magnitude of the micro-pressure wave is proportional to the maximum pressure gradient of the compression wavefront arriving at the tunnel exit, $\epsilon_b$ means the effect of the side branch on the reduction of the micro-pressure wave per side branch. We can see that the value of $\epsilon_b$ by the model experiment agrees quantitatively with that by equation (1), and also the micro-pressure wave becomes smaller as the branch cross-sectional area becomes larger.
Furthermore, we can also see from Fig. 8 that other kinds of pressure waves are generated (measuring points A and B) when the train nose and tail pass by the side branch, and impulsive waves are emitted outside from the portal (measuring point C); the former in the tunnel are called *branch wave* and the latter are called *emitted branch wave*. Figure 10 shows the pressure waveform emitted from the portal obtained by the model experiment (measuring point C) with and without the side branch. We can see that when the side branch is installed, the emitted branch wave is generated although the magnitude of the micro-pressure wave is reduced by the side branch when the side branch is installed. Although the magnitude of the emitted branch wave is smaller than that of the micro-pressure wave, it could cause environmental problems with the increase of train speed. Therefore, countermeasures for this branch wave will be necessary.

**Fig. 6** Example of pressure and pressure gradient waveform (Train speed $U = 273$ km/h)

**Fig. 7** Relation between maximum pressure gradient of compression wavefront and propagating distance
6. Conclusions

We have investigated the distortion of the compression wave propagating through a slab track tunnel with side branches in Shinkansen. Furthermore, we have investigated the effect of the side branch on reducing the micro-pressure wave. Conclusions are summarized as follows.

(1) The agreement between the results of 1D+Branch numerical analysis and those of field measurement is very good for the distortion of the compression wave propagating through the slab track tunnel with side branches.
(2) The maximum pressure gradient of the compression wavefront increases during propagation in duct sections of constant cross-section in slab track tunnels and decreases at branched sections.

(3) Although the magnitude of the micro-pressure wave is decreased by the side branches, other kinds of pressure waves are generated by a train passing by the side branches.

References


