Small Model Experiment on the Gradient of Pressure Wave by Entering the Tunnel of a Conventional Limited Express

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Abstract
When a high-speed train enters a long tunnel, an air compression wave is generated. This wave propagates in the tunnel at the speed of sound and a pulsed pressure wave is emitted from the tunnel exit. The emitted wave is closely related to the rate of change of pressure as the compression wave arrives at the tunnel exit. Recently, because the running speed of trains has increased, even conventional limited express trains encounter the problem of tunnel pressure wave propagation. In this study we obtained data on the rate of change of pressure and compared the influence of various nose geometries and train speed.

Key words
Tunnel Pressure Wave, Limited Express, Diaphragmless Driver, Small Model Experiment, Rate of Change of Pressure

1. Introduction
When a high-speed train enters a long tunnel, an air compression wave is generated at the front of the train. This compression wave propagates in the tunnel at the speed of sound. When the pressure wave arrives at the tunnel exit, it is reflected back into the tunnel as an expansion wave. Simultaneously, a pulsed pressure wave, called a “tunnel micro-pressure wave”, is generated at the exit and propagates into the surrounding area. This micro-pressure wave generates a loud noise and strong vibrations that cause environmental problems, especially in the case of the present Superexpress Shinkansen. Several studies on the wave propagation in tunnels caused by the Shinkansen have been conducted [1, 2]. The micro-pressure wave is closely related to the rate of change of pressure as the compression wave arrives at the tunnel exit. Therefore, the problems of formation and propagation of the pressure wave have been studied, and it was clarified that improvement of the train nose geometry [3] and installation of a tunnel entrance hood [4, 5] are effective means to reduce the micro-pressure wave. However, it is still necessary to obtain data on the pressure wave behavior for Shinkansen lines with trains traveling at increased velocities of up to 350 km/h.

In addition to the Shinkansen, conventional limited express trains are now also encountering this micro-pressure wave problem, because they too now travel at increased speeds. In some conventional lines and subways, the ratio of the train’s cross-sectional area to the tunnel is much larger than that of the Shinkansen lines, as shown in Table 1 for single-track tunnels. Consequently, in both conventional lines and Shinkansen lines, pressure wave formation and propagation in the tunnels have become problematic [6]. In the case of high-speed trains that run through long slab track tunnels, the aerodynamic and pressure wave phenomena are particularly troublesome.

However, in the study of tunnel pressure wave propagation, few works [6, 7] have reported on conventional lines. Therefore, in this study we focused on limited express trains running at 130–160 km/h and performed small-scale experiments with two types of axisymmetric train models based on conventional train data. This paper deals with the pressure wave formation and propagation phenomena near the tunnel entrance. In these experiments, we used an apparatus with a diaphragmless gas driver acceleration system, small train nose models for the limited express in combination with a short tunnel, a station model and a signal crossing station (SCS) model. We obtained data on the rate of change of pressure \( \frac{\partial p}{\partial t} \) and compared them for different nose geometries and train speeds. In addition, the relation between pressure increase \( \Delta p \) and \( \frac{\partial p}{\partial t} \) was clarified.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Train and tunnel cross-sectional area</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_r (m^2) )</td>
<td>( A_{tu} (m^2) )</td>
</tr>
<tr>
<td>Shinkansen*</td>
<td>12.1</td>
</tr>
<tr>
<td>Streamline**</td>
<td>11.3</td>
</tr>
<tr>
<td>Gangway***</td>
<td>11.9</td>
</tr>
</tbody>
</table>

*: Full-scale N700 Series Tokaido Shinkansen
**: Full-scale 683 Series Hakutaka, Hokuhoku Line

2. Background

2.1 Generation mechanism of the “tunnel micro-pressure wave”
A schematic diagram of the generation mechanism of the tunnel micro-pressure wave is shown in Fig. 1. First, a compression wave is formed in front of the high-speed train when the train enters the tunnel. Second, this compression wave propagates through the tunnel at the speed of sound. If the compression wave propagates in a long tunnel, the wave is deformed by several factors. For example, in the propagation process, the amplitude of the compression wave is attenuated by the effects of the track in the tunnel. A ballast track tunnel attenuates the pressure wave due to energy dissipation [1], but the maintenance of ballast track tunnels is laborious and the ballast flying problem caused by snow dropping occurs. Thus, ballast is not used in snowy areas. A slab track tunnel rapidly
increases the pressure wavefront steepness due to the nonlinear effect of the wave. Thus, a higher rate of pressure change appears prominently in a long slab track tunnel. Finally, the reflected wave is an expansion wave that propagates back into the tunnel. At the same time, an impulsive wave propagates into the surrounding area. This impulsive wave is called a “micro-pressure wave” or a “tunnel sonic boom”. This micro-pressure wave generates a loud noise and strong vibrations, which cause environmental problems, especially in the case of the current Shinkansens.

European researchers [14]. Meanwhile, the problem of the “tunnel pressure wave” has also been observed in the case of a limited express traveling on conventional lines, because the running speed has been improved following advancements in railway technology in recent years. For example, the limited express “Hakutaka” that runs on the Hokuhoku Line (in Niigata Prefecture) can travel at 160 km/h and is one of the fastest trains in Japan. This line has a single-track railway and long tunnels with small cross-sectional area. Hence, the pressure wave produced when the limited express train enters a tunnel has become problematic. The data for these trains and the tunnel cross-sectional areas are shown in Table 1. In this table, $A_{st}$ is the maximum value of the train cross-sectional area. The running speed of the limited express is slower than that of the Shinkansen; however, $R$ for the Hokuhoku Line is twice as large as that for the Shinkansen lines, because $A_{st}$ of the Hokuhoku Line is less than half of that for the Shinkansen lines. The reason for the different $A_{st}$ values is that the Shinkansen line has double tracks, whereas the Hokuhoku Line has single-track tunnels.

In our previous study, we focused on the limited express “Hakutaka” and performed an experiment on the pressure wave by using an apparatus with diaphragmless driver acceleration and small train nose models for the limited express in combination with a short tunnel and some station models. We obtained and discussed data on the pressure increase $\Delta p$ and found that $\Delta p$ in the case of the conventional express line is in the same range as that for the Shinkansen lines. It was determined that the installation of the station models decreases the pressure increase as the wavefront propagates through the tunnel [15, 16].

3. Experimental Setup

3.1 Experimental train models

In this study we focus on the limited express “Hakutaka” of the Hokuhoku Line. The modeled train is the 683 Series express, which was developed by the West Japan Railway Company. This train has two nose geometries. One is a streamline-shaped nose, which is called the “streamline-type”. The other is a train nose with a gangway door, which is called the “gangway-type”. In the experiments, we made train models of both nose geometries.

First, we calculated $A_{St}$ as a function of the train’s longitudinal axis, along with the ratio of $A_{St}$ to the maximum cross-sectional area of the train, $A_{dp}/A_{dp,max}$, based on the vehicle drawings of the 683 Series [17]. Second, after we converted the areas obtained into circular areas, we calculated $r_d/r_{d,max}$ along the longitudinal axis also. A graph of the calculated results is shown in Fig. 2. The horizontal axis is the distance from the front of the train, and the vertical axis shows $r_d/r_{d,max}$ and $A_{dp}/A_{dp,max}$. Finally, axisymmetric train models were fabricated and made of polyethylene. We used $R$ in Table 1 and $r_d/r_{d,max}$ in Fig. 2. The designed model scale was 1/125. The fabricated train models are shown in Fig. 3.

\[
\frac{\partial p}{\partial x} = \frac{\partial p}{\partial t} \tag{1}
\]
3.2 Considerations in the model experiment

In our study, we used axisymmetric train models in the experiments. We needed only the cross-sectional profile of the limited express “Hakutaka”. We did not have to consider the intricacy of the train shape, for example, the wiper, because the pressure wave is of a low enough frequency that the effect of such features is negligible\[18\].

Next, this section describes the basic factors considered in the model experiment. First is the influence of viscosity. In the transformation of a compression wave by wave propagation, an experiment using a long tunnel is just not realistic. The viscosity has a significant influence on wave propagation. Hence, field measurements and numerical calculations are available. Meanwhile, in the formation of a compression wave, the viscosity has a relatively small effect on the wave. As a result, a model experiment can be conducted. The next factor is the time scale. The time scale is shortened in proportion to the diminishing scale. Therefore, the time of the experimental data is converted into actual time.

Finally, we explain the scaling law. In these experiments, we simulate air compressibility. Therefore, the present experiment can reproduce the real phenomena for each train speed $U$ [1].

3.3 Experimental apparatus

In this experiment, we focused on the initial change in pressure when the train model enters the tunnel. The experimental apparatus is shown in Fig. 4. The length of the model tunnel is 2460 mm. The ratio of the tunnel model diameter is 1/125 of the size of a real tunnel diameter. We developed an original gas acceleration device with a diaphragmless high pressure driver. The train model is accelerated by high-pressure gas from the driver and is stopped by the stopper. At the same time, the front part of the train nose enters the tunnel model and the compression wave is generated. Our past study showed that the Young's modulus of a pipe affects pressure wave propagation [15]. Therefore, the tunnel model is made of a steel pipe covered with concrete. Pressure transducers are installed at 400, 1540 and 2160 mm from the tunnel entrance to measure the formed pressure wave propagating in the tunnel model. The train speed is calculated from the time taken to pass through two laser beams installed 2 mm and 102 mm before the tunnel entrance, as shown in Fig. 4.

We obtained data on the rate of change of pressure and compared them for different train running conditions. The speed conditions of the experiment for the 683 Series express were approximately 130 km/h ($M_{tr}=0.105$) and 160 km/h ($M_{tr}=0.129$). The condition of dynamic similarity is satisfied by conformity of the Mach number between the model experiment and the full-scale data. In this case, the Reynolds number can be disregarded, because we cover only the pressure wave transformation in these experiments [2, 9].

In addition, we investigated the influence of the cross-sectional area by inserting a station model and a SCS model. The station modeled is an underground station in the Hokuhoku line and the SCS tunnel model is also from the Hokuhoku line. The cross-sectional area of the station model was 1.39 times larger than the tunnel model, and the signal crossing station model was 2.61 times larger than the tunnel model. In this study, we performed experiments with and without the station in the tunnel.

4. Experimental Results and Discussion

The average rate of change of pressure ($\partial p/\partial t$)$_{ave}$ was calculated using the following equations based on measurements of the pressure waveform.

$$\left( \frac{\partial p}{\partial t} \right)_{ave} = \frac{p_{n+1} - p_{n-1}}{t_{n+1} - t_{n-1}}$$

Table 2 Tunnel and station model cross-sectional areas

<table>
<thead>
<tr>
<th></th>
<th>$d$ (mm)</th>
<th>$A$ [$10^{-3}$ (m$^2$)]</th>
<th>$l_{max}$ (mm)</th>
<th>$A/A_{tun}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel*</td>
<td>44.0</td>
<td>61.4</td>
<td>600</td>
<td>1.00</td>
</tr>
<tr>
<td>Station**</td>
<td>52.0</td>
<td>23.7</td>
<td>600</td>
<td>1.39</td>
</tr>
<tr>
<td>SCS**</td>
<td>70.0</td>
<td>23.7</td>
<td>600</td>
<td>2.61</td>
</tr>
</tbody>
</table>

*: Model of Misashima station, Hokuhoku Line
**: Model of Akakura signal crossing station, Hokuhoku Line
The values of \((\partial p/\partial t)_{ave}\) for various driving conditions are shown in Fig. 5. The measurement position was 400 mm from the tunnel entrance for these data. The symbols are the average values of eight or more experiments, and the error bars show the standard deviation. Changing the train nose geometry and train speed has significant effects on the wave formation. The gangway-type nose produces a higher rate of change of pressure at 130 km/h. However, \((\partial p/\partial t)_{ave}\) is nearly the same at all measuring positions for both nose types. These results agree with our past study, which was a model experiment on the pressure increase \(\Delta p\) [7].

Furthermore, we installed a station or a SCS model in the middle of the tunnel model to investigate the influence of a change in the tunnel cross-sectional area. The change in \((\partial p/\partial t)_{ave}\) relative to the station model is shown in Fig. 6 for a gangway-type nose traveling at 130 km/h. The measuring position inside the station model is 1540 mm from the tunnel entrance. The rate of change of pressure is attenuated inside the station model. The decrease in \((\partial p/\partial t)_{ave}\) from the entrance to the station is 11%; however, we found \((\partial p/\partial t)_{ave}\) is restored at the tunnel exit. The total decrease in \((\partial p/\partial t)_{ave}\) from the entrance to the exit is only 3.6%, indicating that the installation of a station model cannot attenuate the pressure wave exiting the tunnel. This experimental result shows a different tendency from our past study on pressure increase \(\Delta p\) [7], \((\partial p/\partial t)_{ave}\) with the SCS model is also shown in Fig. 7 for a gangway-type nose traveling at 130 km/h. The attenuation of \((\partial p/\partial t)_{ave}\) is larger in these experiments. The decrease in \((\partial p/\partial t)_{ave}\) from the entrance to the SCS model is 35%. In addition, the rate of change of pressure is significantly attenuated inside the SCS model, and the pressure shape is restored at the exit side. We found that increasing the area of the tunnel to 2.5 times the original area can reduce \((\partial p/\partial t)_{ave}\) at the exit to 30%–40% of that at the entrance. In other words, a sufficient cross-sectional area of the tunnel can effectively reduce \((\partial p/\partial t)_{ave}\).

\[
\left( \frac{\partial p}{\partial t} \right)_{ave} = \frac{\sum_{n=1}^{19} \left( \frac{\partial p}{\partial t} \right)_{n}}{19} \tag{3}
\]

Fig. 5 Rate of change of pressure at \(x = 400\) mm
(a) Gangway-type, 130 km/h
\((\partial p/\partial t)_{ave,max} = 9.10\) [kPa/s] \(\Delta t [s]\)
(b) Streamline-type, 130 km/h
\((\partial p/\partial t)_{ave,max} = 14.1\) [kPa/s] \(\Delta t [s]\)
(c) Streamline-type, 160 km/h
\((\partial p/\partial t)_{ave,max} = 13.5\) [kPa/s] \(\Delta t [s]\)

Fig. 6 Rate of change of pressure with station model (130 km/h, gangway-type)
(a) \(x = 400\) mm
\((\partial p/\partial t)_{ave,max} = 13.7\) [kPa/s] \(\Delta t [s]\)
(b) \(x = 1540\) mm
\((\partial p/\partial t)_{ave,max} = 12.1\) [kPa/s] \(\Delta t [s]\)
(c) \(x = 2160\) mm
\((\partial p/\partial t)_{ave,max} = 13.2\) [kPa/s] \(\Delta t [s]\)
5. Conclusion

In this paper we focused on the limited express “Hakutaka” that runs on the Hokuhoku line and investigated the problematic tunnel pressure wave that occurs when a train enters a tunnel. We obtained data on the rate of change of pressure and compared them for different nose geometries and train speeds, both of which were found to have significant effect on the rate of pressure change as the wave propagates. In addition, installations of some station models decreased the rate of change of pressure as the wave propagates through the tunnel. Increasing the area of the tunnel to 2.5 times the original area was found to reduce the rate of pressure change at the exit to 30%–40% of that at the entrance.

Nomenclature

- $A$: cross-sectional area [m$^2$]
- $c$: speed of sound [m/s]
- $d$: tunnel model diameter [mm]
- $l$: tunnel model length [mm]
- $L$: distance from the front tip of the train
- $p$: pressure [kPa]
- $R_t$: ratio of train cross-sectional area to tunnel cross-sectional area
- $U$: train speed [km/h]
- $V$: propagation speed of pressure wave [m/s]
- $x$: position from tunnel entrance [mm]
- $\Delta t$: time [s]
- $(\partial p/\partial t)$: rate of change of pressure

Subscripts

- 0: initial stage
- ent: tunnel entrance
- ext: tunnel exit
- max: maximum
- mid: middle part of tunnel
- n: given value
- SCS: signal crossing station
- sta: station
- tr: train
- tun: tunnel

References


