Small Model Experiment on the Pressure Wave Formation by Entering the Tunnel of Conventional Limited Express with Diaphragmless Driver Acceleration Apparatus

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Abstract
When a high-speed train enters a long tunnel, compression wave is generated in front of the train. This compression wave propagates in the tunnel at the speed of sound. In recent years, the running speed of train is increasing, and this problem of the tunnel pressure wave may occur by the conventional limited express. This paper deals with the pressure wave formation by the experiment using an apparatus with diaphragmless driver acceleration, and small train nose models of limited express in combination with a short tunnel and some station models. We have obtained pressure waveform data and discussed.

Key words
Tunnel Pressure Wave, Wave Formation & Propagation, Limited Express, Diaphragmless Driver, Small Model Experiment

1. Introduction
When a high-speed train enters a long tunnel, air compression wave is formed in 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, and simultaneously a pulsed pressure wave, called "tunnel micro-pressure wave", is generated from the exit toward the surrounding area. This micro-pressure wave generates strong noise and vibration, which cause environmental problems specially in today's high speed Shinkansen. Several studies on the wave propagation in tunnels caused by the Shinkansen have been performed in recent years[1],[2]. The micro-pressure wave is closely related to the pressure gradient of the compression wave arriving at the tunnel exit. Therefore, the problems of formation and propagation of the pressure wave have been studied, and it is clarified that improvement in the train nose geometry[3] and installation of the tunnel entrance-hood[4],[5] are the effective means to reduce the micro-pressure wave. However, it is still necessary to have the data of the pressure wave behavior for Shinkansen lines with further increase of train velocity up to 102m/s.

Besides the Shinkansen's micro-pressure wave problems, the problem of tunnel pressure wave has also occurred in conventional limited express, as the vehicle performance is recently improving rapidly and the train speed is also increasing. In some conventional lines and subways newly established, the ratio of the train cross-sectional area to the tunnel is much larger than that of the Shinkansen as shown in Table1 in the case of single track tunnels. Consequently, in conventional lines as well as Shinkansen, the pressure wave formation and propagation in tunnel often produce the problems[6]. Especially, in the case of high-speed train which runs into the long slab track tunnel, the aerodynamic and pressure wave problems with appear significantly.

Until now, however, for the existing railways we have not obtained clear solution. In the study of tunnel pressure wave propagation, there are a few research reports[6],[7] on the conventional lines, where the train speed is ranged from 27.8 to 44.4m/s. Therefore, in this study we are focusing on the running speed of limited express as 36.1m/s, and we have performed small-scale experiments with two-types of axi-symmetric train models based on the conventional train data. This paper deals with the pressure wave formation and propagation phenomena near tunnel entrance. In these experiments we have used an apparatus with diaphragmless gas driver acceleration system, small train nose models of limited express in combination with a short tunnel, a station model and signal crossing station model. We have obtained pressure waveform data and compared them with nose geometry difference. In this study we have also performed experiments as both using and without using station in the tunnel.

<table>
<thead>
<tr>
<th>Table 1 Train and tunnel cross-sectional area</th>
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<tr>
<td>$A_{in}$</td>
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<td>---------</td>
</tr>
<tr>
<td>$A_{in}$</td>
</tr>
<tr>
<td>$R_1(A_d/A_{in})$</td>
</tr>
<tr>
<td>$U_{max}$ [m/s]</td>
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</table>

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

2. Background

2.1 Mechanism of the formation of “tunnel micro-pressure wave”
A schematic diagram of the generating mechanism of the tunnel micro-pressure wave is shown in Fig.1. First, compression wave is formed in front of a high speed train when the train enters a tunnel. Secondly, this compression wave propagates in the tunnel at speed of sound. If the compression wave propagates in a long tunnel, the wave is deformed by several factors. In the propagation process the amplitude itself of the compression wave is attenuated by dissipating effects of track in tunnel. Furthermore, slab track tunnel increases rapidly the pressure wavefront steepness on nonlinear effect of the wave, while ballast
track tunnel attenuates the pressure wave on energy dissipation[1]. Therefore, the tunnel pressure wavefront called “pressure gradient”, is steepened due to the nonlinear effect. Especially, it appears prominently in a long slab track tunnel. This compression wave is reflected when it arrives at the tunnel exit. The reflected wave is an expansion wave which returns into the tunnel towards the entrance. At the same time an impulsive wave is emitted to the surrounding area. This impulsive wave is called “micro-pressure wave” or “tunnel sonic boom”.

2.2 Tunnel micro-pressure wave problem and solutions in Shinkansen
With an increase in the running speed of the Shinkansen, many aerodynamic problems, for example, vibrations of window, noise from pantograph, and pulsed noise from the tunnel exit called “tunnel micro-pressure wave”, have been observed. It is found that the tunnel micro-pressure wave causes significant environmental problems. Hence, the clarification of its mechanism and the solution of the problems have been mainly conducted. According to the survey results[8], the amplitude of micro-pressure wave is proportional to the third power of the train speed, and it is inversely proportional to the radius of the tunnel. Furthermore, the micro-pressure wave is closely related to the pressure gradient (\( \frac{\partial p}{\partial t} \)) of the compression wave arriving at the tunnel exit. Therefore, the gradual change of train nose geometry is one of the effective means to reduce the micro-pressure wave. The other effecting way is installation of a tunnel entrance hood. These solutions have enabled us to obtain Shinkansen speed up to 97m/s with the minimized environmental influence.

2.3 Tunnel pressure wave problem in conventional lines
The problems of the tunnel micro-pressure wave in Shinkansen have been studied by Railway Technical Research Institute[9], several Japanese universities[10],[11] and also European researchers[12]. Meanwhile, the problem of “tunnel pressure wave” is also to be observed by the limited express in the conventional lines, because the running speed has been improved with railway technological advancement in recent years. For instance, the limited express “Hakutaka” in the Hokuhoku Line (in Niigata Prefecture) is one of the fastest train in Japan which can travel at 44.4m/s. This line has a single-track railway, and also has long length and small tunnel cross-sectional area. Hence, the pressure wave in the tunnel becomes a problem when a limited express train enters in or runs through the tunnel. The data of these trains and tunnel cross-sectional areas are shown in Table1. In this table, \( A_{tr} \) is maximum value of train cross-sectional area. The running speed of the limited express is slower than the Shinkansen, however if we take a look on the \( R_t \), the Hokuhoku Line’s \( R_t \) is twice larger than that of the Shinkansen, because the \( A_{max} \) of the Hokuhoku Line is smaller than half of the Shinkansen. This is because the Shinkansen line has double tracks, while the Hokuhoku Line has a single track tunnels.

In addition, there is a relation between pressure increase and \( U \), \( R_t \) (and \( M_c \)) as shown by the following Eq.(1). Pressure increase \( \Delta p_c \) in the tunnel entrance[8] is expressed as

\[
\Delta p_{c,\text{cm}} = \frac{1}{2} \rho U^2 \left( \frac{1}{1-\sqrt{M_c}} \right) \left( \frac{(1-R_t)^3}{(1-R_t)} \right)
\]

With the parameter of train speed, this relation is presented as the curves of \( \Delta p_c \) and \( R_t \) as shown in Fig.2. From this figure \( \Delta p_c \) is susceptible to \( R_t \) variation for high-speed train.

3. Experimental Setup
3.1 Experimental train models
In this study we focus on the limited express “Hakutaka” of Hokuhoku Line from conventional lines. The currently-modeled train is the Series 683 express which has been developed by West Japan Railway Company. This train has two kinds of nose geometry. One is a streamline-shaped nose which is called “Streamline-type”. The other is a train nose with gangway door which is called “Gangway-type”. In the experiments we made the train models of both geometries based on the shapes of these train’s noses.

First, we calculated the \( A_{tr} \) at each point of longitudinal axis, and the cross-sectional ratio of the train to the maximum area, \( A_{tr}/A_{tr,max} \) based on the vehicle drawing of Series 683[13]. Secondly, after we converted the project areas into circular areas, we calculated \( r_{tr}/r_{tr,max} \) from areas of circle at each point. A graph of calculated results is shown in Fig.4. The horizontal axis is the distance from the top of the train, and the vertical axis is \( r_{tr}/r_{tr,max} \) and \( A_{tr}/A_{tr,max} \). Finally, the axi-symmetric train models were fabricated and made of polyethylene with \( R_t \) in the Table1 and \( r_{tr}/r_{tr,max} \) in Fig.4. The designed model scale is 1/125. The circular tunnel model was made based on the designed
train models. We needed only cross-sectional change of the limited express “Hakutaka”, however we did not have to make train shape in detail, for example, wiper. Because the pressure wave can be considered plane wave of low-frequency component[14].

We obtained pressure waveform data and compared them with nose geometry difference. The speed conditions of the experiment for Series 683 express are around 130km/h. The condition of the dynamic similarity is satisfied by the conformity of the Mach number between the model experiment and the full-scale. In this case, Reynolds number is possible to disregard, because we cover only pressure wave transformation in these experiments[2].

In addition to the model experiment into the straight tunnel, we investigate the influence of the cross-sectional area change, by inserting an station model as shown in Fig.7(a) and a signal crossing station model, as shown in (b). The (a) modeled Misashima station in Hokuhoku line and the (b) modeled Akakura signal crossing station model in Hokuhoku line. The pressure transducers are installed at 400, 1540 and 2160mm from the tunnel entrance in this case. The pressure gauge at these station models is installed in the 1540mm from the tunnel entrance, the cross-sectional area of the station model is 1.39 times larger than the tunnel model, the signal crossing station model is 2.61 times larger than the tunnel model. In this experiment the total length of tunnel-station model is also kept 2420mm. In this study we performed experiments on both using and without using station in the tunnel.

3.2 Experimental train models
In this experiment we focused on the initial stage of pressure wave formation and propagation when the train model entering into a tunnel model. The experimental apparatus is shown in Fig.6. The length of model tunnel is 2460mm. A tunnel model diameter ratio is 1/125 of the size of real scale tunnel diameter. We have developed an original gas acceleration device with diaphragmless high pressure driver section. The train model is accelerated by high pressure gas from the driver, and it is stopped at the stopper. At the same time, the frontal part of the train nose enters the tunnel model, and the compression wave is generated. Our past study has also shown that the Young's modulus of pipe affected our pressure wave propagation[15]. Therefore, the tunnel model is made of a steel pipe covered with concrete. The pressure transducers are installed at 400, 1540 and 2160mm from the tunnel entrance, where the formed pressure wave propagating in the tunnel model is measured by these pressure gauges. The train speed is calculated from the time duration by the model passing through the two laser beams installed at -2mm and -102mm from the tunnel entrance as shown in Fig.6. The aluminum film is also installed in the 90mm before the tunnel entrance. It presents driven air to enter into tunnel caused by train model acceleration.
Table 2 Tunnel and station models cross-sectional area

<table>
<thead>
<tr>
<th></th>
<th>Tunnel</th>
<th>Station*</th>
<th>Signal station**</th>
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<tbody>
<tr>
<td>$d$</td>
<td>44.0</td>
<td>52.0</td>
<td>70.0</td>
</tr>
<tr>
<td>$A \times 10^{-3}$</td>
<td>1.52</td>
<td>2.12</td>
<td>3.85</td>
</tr>
<tr>
<td>$l$</td>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A/A_{\text{min}}$</td>
<td>1.00</td>
<td>1.39</td>
<td>2.61</td>
</tr>
</tbody>
</table>

*: Model scale Misahima station, Hokuhoku Line
**: Model scale Akakura signal crossing station, Hokuhoku Line

4. Experimental Results and Discussion

The waveform data are shown in Fig.8 when the Streamline-type train model entering the tunnel model at 36.1m/s. The horizontal axis is the elapsed time from the trigger signal $\Delta t$, and the vertical axis is pressure increase $\Delta p$. The origin of horizontal line is the trigger signal point, because trigger signal point is about the same as tunnel entrance. Measuring positions $x_1$, $x_2$, $x_3$ are 400, 1540 and 2160mm. We made a mark on characteristic point, where $a$ is point of first maximum pressure increase, $b$ is starting point of pressure dropping, $c$ is minimum pressure point and $d$ is reflected when $c$ arrives at tunnel model exit. Then lines drawn to connect these points can be used to calculate the propagation speed $V$. Propagation speed of the wavefront $V_0$ is 348m/s. This wave is not shock wave but strong pressure wave because the pressure wave propagates nearly at the sound speed. The data of pressure increase $\Delta p$ are shown in Fig.9 when the Streamline-type train model entering the tunnel model at 36.1m/s. In this figure $a$ indicates maximum pressure increase point and solid line corresponds pressure gradient. In the case of $A_{\text{min}}=\text{const.}$, pressure increase was nearly-constant at all measuring positions. In addition, the pressure increase data of the wavefront are shown in Fig.10 when the Gangway-type train model entering the tunnel model at 36.1m/s because we have to compare it with nose geometry difference. Changing the model train nose geometry has the significant effects on the pressure wave formation as shown in this figure. However, pressure increase is nearly-constant at all measuring positions not only Streamline-type but also Gangway-type. These shapes are the same as the reported result when Shinkansen enters the tunnel[1]. On the other hand, the measured maximum pressure increase ranges about 1.0 to 1.5 kPa in our experiments, and these values are almost equal to the reported value when Shinkansen enters the tunnel at 63.0 to 75.0 m/s[16]. These data indicate the significance of the train nose geometry.

Furthermore, we installed a station or a signal crossing station model in the middle of the tunnel model to investigate the influence of the tunnel cross-sectional area change. The pressure gradient change of produced wavefront with the station model is shown in Fig.11 when the train speed is 36.1m/s and the train nose geometry is Streamline-type. The measuring positions are 400mm, 1540mm and 2160mm from the tunnel entrance. The measuring position inside the station model is 1540mm from a tunnel entrance. Pressure is attenuated inside the station model. The decrease of $\Delta p$ from entrance to station model is 21.9%. However, we found pressure restoration at exit side can be found. The change of produced pressure wavefront with the signal crossing station model is also shown in Fig.12 when the train speed is 36.1m/s and the train nose geometry is Streamline-type. As the results of Fig.12, attenuation of pressure is the larger in these experiments. The decrease of $\Delta p$ from the entrance to the station model is 48.2%. In addition, the pressure is significantly attenuated inside the station model, and pressure shape is restored at exit side. As the results of Fig.11 and 12, installation of a station models decreases the pressure increase of the wavefront when propagating in the tunnel.
5. Conclusion

In this paper we have focused on a limited express "Hakutaka" in the Hokuhoku line in connection with tunnel pressure wave problems reported in limited express. Experimental studies using model trains and tunnel, tunnel/station or tunnel/signal crossing station model have been performed, where we have obtained the pressure waveform data and compared them with nose geometry difference. As a result, changing of train nose geometry has significant effects on the pressure wave formation, while that little effects in short length propagation process.

We have found that $\Delta p$ in the conventional express line is the same range as in the Shinkansen. However, installation of a station models decreases the pressure increase of the wavefront propagating in the tunnel. It is found that by increasing the area of tunnel 2.5 time of origin area we can reduce the pressure increase $\Delta p$ to almost half of its original pressure increase.

Nomenclature

- $A$ cross-sectional area, $m^2$
- $d$ tunnel model diameter, mm
- $l$ tunnel model length, mm
- $M$ Mach number
- $R_t$ ratio of the train cross-sectional area to the tunnel cross-sectional area
- $U$ train speed, m/s
- $V$ propagation speed of pressure wave, m/s
- $x$ position from tunnel entrance, mm
- $\Delta p$ pressure increase, kPa
- $\Delta t$ elapsed time, ms
- $\rho_0$ air density, kg/m$^3$

Subscripts

- 0 initial stage
- c characteristic value of pressure wave
- ent tunnel entrance
- ext tunnel exit
- max maximum
- sig signal crossing station
- sta station
- tr train
- tun tunnel

References


Fig.12 Pressure increase of compression wave with signal crossing station model (36.1m/s, Streamline-type)