Prediction of the Micro-pressure Waves Using an Unsteady Acoustic Analysis

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Micro-pressure waves (MPWs) radiated from a tunnel portal were numerically analyzed using unsteady acoustic analysis. First, the compression waveforms at the tunnel entrance were decided by linear acoustic analysis. Next, the nonlinear distortion of the compression waveform accompanying tunnel propagation was calculated using 1D theoretical propagation equation. Finally, the radiated MPWs were calculated by point source approximation. This research demonstrates that even if the difference in the waveform of the compression waves is slight at the tunnel entrance, it appears as considerable difference in MPW when the effects of the nonlinear distortion of the compression wave are taken into account.

Keywords: micro-pressure wave, compression wave, nonlinear effect, unsteady acoustic analysis

1. Introduction

High-speed trains, such as Shinkansen, generate a compression wave when entering a tunnel. The generated compression wave propagates through the tunnel, and when it reaches the exit portal, part of its energy is radiated as an impulsive wave called a micro-pressure wave (MPW) outward from the portal [1, 2]. The MPW may cause some environmental problems such as noise and/or structure vibration around the exit portal. Thus, one of the essential issues that needs to be addressed with a view to increasing Shinkansen running speeds, is to mitigate MPWs.

The peak value of the MPW is proportional to the maximum value of the wavefront pressure gradient of the compression wave at the tunnel exit [1, 2]. For this reason, typical countermeasures for the MPWs focus on the reduction of the pressure gradient of the compression wavefront. In Japan, the most common countermeasures aim to reduce this value at the generation stage: for example, optimization of the train nose shape [3] or installing a tunnel hood [2]. However, when a compression wave propagates through a slab-track tunnel, the wavefront steepens due to a nonlinear effect. Furthermore, if Shinkansen train running speeds increase, the nonlinear effect is likely to become more significant, because pressure and the pressure gradient at the tunnel entrance will rise. Therefore, in order to evaluate the value of the MPW more accurately, it is necessary to consider the distortion of the compression wave at the propagation stage in the tunnel. Since it is assumed that MPW phenomena are more complex under high-speed train conditions, the approach based on numerical analysis is effective to research these in detail. As shown in Fig. 1, MPW phenomena could be divided into three stages: (i) generation of the compression wave, (ii) propagation of the compression wave and (iii) radiation of the MPW. Most of the previous studies have focused on only specific stages. For example, rapid calculation on the basis of linear acoustic analysis is used to research stage (i) [4, 5]. For stage (ii), the simultaneous equation of the conservation law for 1D compressible flow is used: conservation of mass, momentum and energy [6] or the propagation analysis on the basis of the acoustic theory [7, 8]. For stage (iii), methods which model radiation from the exit portal as monopole sound source [1] or analyses which take into account the geometry around the exit portal [9] are representative. Although numerical methods for every stage of the MPW have been established by these studies, few analyze the phenomena from a comprehensive perspective, i.e. an analysis which considers the effect of all the stages of the MPW, rather just a specific stage. It is assumed that a series of comprehensive results could be compiled as a database, however, today, it appears that the only studies able to conduct a comprehensive analysis of MPW are [2] and [10].

It is useful to increase the setting parameters and number of trials for understanding MPW phenomena systematically.

In this paper, we performed numerical analyses on the basis of the acoustic method for every stage of the MPW under different hood configurations and train speeds. In the propagation stage of the compression wave, the results in the analysis of the generation stage were used as the initial pressure waveforms. Furthermore, in the radiation stage of MPW, the maximum value of the pressure gradient, obtained from propagation stage analyses of the compression wave, were used as evaluation values. By going through these procedures, MPW could be analyzed as a series of unsteady phenomena.

![Fig. 1 Micro-pressure wave stages](image)

2. Numerical method

2.1 Generation of the compression wave

The linear acoustic theory was used for the analysis of the generation stage of the compression wave. The analytical conditions for this stage are shown in Table 1. Assuming that the cross-sectional shapes of the train, the tunnel and the hood are circular, the ground effect is taken into account by the method of images. The hood lengths $L$ were 20 m and 40 m, and several openings (width: 2.5 m x height: 2.6 m; mirror image is considered) were inserted at

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equal intervals along the side wall of the hood, as shown in Fig. 2. Up to 4 openings were inserted for when \( L = 20 \) m; and 9 for when \( L = 40 \) m. The analysis was performed using all combinations of open or close windows. The train offset in the horizontal direction was 2.16 m (same as Shinkansen driving conditions), and the openings were on the wall on far-side from the train. With regards to other conditions, the cross-sectional area ratio of the hood to the tunnel was 1.4, the train speeds 260, 320 and 360 km/h, the shape of the train nose was a half spheroid and the cross-sectional area ratio of the train to the tunnel \( \sigma \) was 0.19. Here, the value of \( \sigma \) was a little larger than that of real Shinkansen since the net increment of the cross-sectional area of the train by the flow separation from the snow plow was taken into account [11].

| Table 1 Analytical condition for the generation of the compression wave |
|--------------------------|-----------------|-----------------|
| Train speed \( U (\text{km/h}) \) | 260, 320, 360 | |
| Cross-sectional area of the train (m²) | 12 | |
| Shape of the Train nose | Spheroid | |
| Length of the train nose \( l \) (m) | 15 | |
| Cross-sectional area ratio of the train to the tunnel \( \sigma \) | 0.19 | |
| Train offset (m) | 2.16 | |
| Hood length \( L \) (m) | 20, 40 | |
| Cross-sectional area ratio of the hood to the tunnel | 1.4 | |

Fig. 2 Configuration of the hood considering method of images

2.2 Propagation of the compression wave

In the propagation stage of the compression wave, the 1D theoretical wave equation (1) [7, 8] is used.

\[
\frac{\partial p^*}{\partial x^*} = \frac{\gamma + 1}{2} \frac{\partial p^*}{\partial t} - \alpha p^* - \beta \frac{2}{\pi} \sqrt{r} \varepsilon p^* \frac{1}{c_\infty^*} ds,
\]

where \( p^* \): nondimensional pressure, \( x^* \): nondimensional coordinate, \( \gamma \): specific heat ratio and \( t^* \): nondimensional time. The nondimensionalization process is performed as the following equation (2).

\[
t^* = \frac{t}{d_x/c_\infty}, \quad x^* = \frac{x}{d_x}, \quad p^* = \frac{p}{\gamma p_0^*},
\]

where \( d_x \): hydraulic diameter of the tunnel (the diameter if the cross-section of the tunnel is regarded as a circular pipe), \( c_\infty \): the speed of sound in stationary air \((340 \text{ m/s})\), \( p_0 \): the atmospheric pressure \((101.3 \text{ kPa})\) and the superscript * represents the nondimensional value. The coefficients \( \alpha \) and \( \beta \) existing at the second term and third term of the right-hand sides of (1) are defined as the following equations (3) and (4).

\[
\alpha = \left(1 + \frac{\gamma - 1}{Pr^{\frac{1}{2}}} \right) \frac{16}{\varepsilon_\sigma},
\]

(3)

\[
\beta = \left(1 + \frac{\gamma - 1}{Pr^{\frac{1}{2}}} \right) \frac{1}{\sqrt{Re}} \varepsilon_{\sigma},
\]

(4)

where \( Pr \): Prandtl number, \( Re \): Reynolds number \((Re = c_\infty \rho_0 \sqrt{r} / \nu)\), \( \nu \): the kinematic viscosity of the air, \( \varepsilon_\sigma \): the coefficient of the steady frictional force, \( \varepsilon_{\sigma} \): the coefficient of the unsteady frictional force. Here, the terms related \( \alpha \) and \( \beta \) in the right-hand side (1) represent the frictional effect acting on the compression wave from the tunnel wall, and the values of \( \varepsilon_\sigma \) and \( \varepsilon_{\sigma} \) are referenced [7, 8].

The analytical conditions in the propagation stage of the compression wave are shown in Table 2. As the initial waveform of the compression wave, the numerical result of the generation stage described in the previous section was used. As shown in Fig. 3, type 1 side branches (cross-sectional area: 7.1 m², length: 3 m) and type 2 side branches (cross-sectional area: 7.1 m², length: 5 m) were installed at equal intervals of 1000 m and 500 m, respectively, in the tunnel. The distortion of the compression wave when it passes through the junction of the tunnel and the side branch is calculated by using the acoustic method on the basis of the propagation of the plane wave [6, 7, 8].

| Table 2 Analytical condition for the propagation of the compression wave |
|--------------------------|-----------------|-----------------|
| Cross-sectional area of the tunnel \( A \) (m²) | 63.4 | |
| Hydraulic diameter of the tunnel \( d_x \) (m) | 8.1 | |
| Prandtl number \( Pr \) | 0.72 | |
| Reynolds number \( Re \) | \( 1.8 \times 10^8 \) | |
| Coefficient of the steady frictional force \( \varepsilon_\sigma \) | 1500 | |
| Coefficient of the unsteady frictional force \( \varepsilon_{\sigma} \) | 5 | |
| Space step increment \( \Delta x \) (m) | 5, 10 | |
| Time step increment \( \Delta t \) (s) | 0.001 | |
| Type 1 side branch | 1000m pitch | |
| Type 2 side branch | 500m pitch | |

Fig. 3 The standard allocation of the side branch

2.3 Radiation of the micro-pressure wave

When a compression wave propagated through the tunnel reaches the tunnel exit, the relation of the peak value of the MPW \( P_{\text{max}} \) and the pressure gradient of the
compression wave \((\partial \tilde{p} / \partial t)_{\text{max,Exit}}\) at the tunnel exit is given as the following equation (5) if the radiation of the pressure wave from the tunnel is assumed as the monopole source.

\[
P_{\text{max}} = \frac{2A}{\Omega c' r'} \left( \frac{\partial \tilde{p}}{\partial t} \right)_{\text{max,Exit}},
\]

where \(A\): the cross-sectional area of the tunnel (\(\approx 63.4\ \text{m}^2\)), \(\Omega\): the radiation solid angle, \(r\): the distance from the tunnel exit to the measuring point (\(\approx 20\ \text{m}\)). Here, it was assumed that the hood was not installed at the tunnel exit portal. Although the value of \(\Omega\) depends on the geometry around the tunnel exit, in this study, the geometry around the tunnel exit portal is assumed to be infinite plane, and its value is set to \(2\pi\).

3. Results of the numerical analysis

3.1 Numerical results related to the generation of the compression wave

The combinations of open/closed windows that proved to be most effective in terms of reducing the maximum value of the compression wave pressure gradient during the generation stage of the compression wave, (No. 1, No. 2 and No. 3) are shown in Table 3. In Table 3, the open or closed state of the windows is represented in binary form: 1 means open, and 0 means closed, as shown in Fig. 4 (the most effective pattern for reducing the maximum value of the pressure gradient of the compression wave in the case \(L=40\ \text{m}\) and \(U=360\ \text{km/h}\) is shown in Fig. 4). First, focusing on the open/closed patterns of windows under each set of conditions, the best three window patterns were the same even with different train speeds in the case of the \(L=20\ \text{m}\). On the other hand, the best three window patterns changed with different train speeds in the case of the \(L=40\ \text{m}\) hood. This suggests that the optimal open/closed pattern of windows may change with different parameter conditions (in this study, train speed) even if the hood length is the same.

The pressure gradient waveforms of the compression wave corresponding to window patterns No. 1-No. 3 in Table 3 are shown in Fig. 5. These waveforms were multiplied by the modified coefficient \(c_r\) calculated using the following equations (6)-(8) in order to consider the nonlinear effect at the generation stage of the compression wave.

\[
c_r = \frac{\Delta p_{i}}{\Delta p_{s}},
\]

\[
\Delta p_{i} = \frac{1}{2} \rho U^2 \frac{2R(1 + R)}{1 - M^2},
\]

\[
\Delta p_{s} = \frac{1}{2} \rho U^2 \frac{1 - (1 - R)^2}{(1 - M)(1 + (1 - R)^2)},
\]

where \(\rho\) : density of the air, \(U\): train speed, \(R\): blockage ratio, \(M\): Mach number, (7) represents the pressure increment in the tunnel based on the linear acoustic theory [4, 5], and (8) represents the pressure increment in the tunnel considering the nonlinear effect [12]. From the results shown in Fig. 5, the differences in pressure gradient waveform between situations with the hood and without the hood are apparent: almost forming a trapezoid shape by installing the hood, and with allotted openings in proper locations.

As a result, the maximum value of the pressure gradient was 40% smaller in the case of the \(L=20\ \text{m}\) hood, and 60% smaller in the case of the \(L=40\ \text{m}\) hood, than without the hood. Next, focusing on the difference in maximum value of the pressure gradient between window patterns No. 1-No. 3, the maximum difference was about 6% in the case of the \(L=20\ \text{m}\) hood, and about 1% in the case of the \(L=40\ \text{m}\) hood. It is considered that the reason for the large difference between different window settings for the \(L=20\ \text{m}\) hood, was that the effect of one opening on the compression wave was relatively large when the hood length was short. However, these differences are much smaller than the difference in effect with/without a hood and differences in length of hood. Therefore, it is considered that this degree of difference will not have a critical effect on the MPW in the case of a short tunnel.

3.2 Change in peak value of the micro-pressure waves following propagation of compression wave

Using the pressure waveform from the previous section, (1) is solved numerically to obtain the maximum value of the pressure gradient of the compression wave. Then, by substituting it into (5), quantitative evaluation of the MPW considering the nonlinear distortion during the propagation stage of the compression wave becomes possible. The relationship between the tunnel length and the

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Table 3 The best three window patterns at the generation stage of the compression wave

| Windows condition | No. 1 | No. 2 | No. 3 |
|-------------------|-------|-------|-------|
| \(L=20\ \text{m}\) | \(U=260\ \text{km/h}\) | \(U=320\ \text{km/h}\) | \(U=360\ \text{km/h}\) |
| (a) | | | |
| --- | --- | --- | --- |
| No. 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| No. 2 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| No. 3 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 |
| (b) | | | |
| --- | --- | --- | --- |
| No. 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| No. 2 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| No. 3 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 |

Fig. 4 An example of a windows pattern (No.1 for \(L=40\ \text{m}, U=360\ \text{km/h}\) in Table 3)
peak of the MPW at the 20 m point from the tunnel portal is shown in Fig. 6. In the case of $U=260$ km/h and installation of a $L=20$ m hood, the peak value of the MPW peaks when the tunnel length is 20 km, and that value decreases as tunnel length is extended. It is considered that the decrease in the peak value is due to the compression wave propagating over a long distance: the damping effect of the compression wave due to friction with the tunnel wall exceeds the effect of its steepness due to the nonlinear effect at a certain propagation distance. Similar characteristics like this have been confirmed in field tests [6]. Focusing on the difference between windows combinations when the tunnel length is around 20 km, the MPW was the smallest with arrangement No. 3 and largest with No. 1: the difference of the MPW between them was over 30% (absolute quantity is 20 Pa). Therefore, it can be seen that the window combination which was considered to be optimal for reducing the MPW at the tunnel entrance was not the optimal combination at the tunnel exit when nonlinear distortion during the propagation stage of the compression wave is taken into account. In addition, these facts suggest that the distortion of the compression wave during its propagation could depend on the waveform shape itself. On the other hand, when the $L=40$ m hood was installed, although the peak of the MPWs peaked when the tunnel length was 20 km-22.5 km, the values were much smaller than those with the $L=20$ m hood. These results demonstrate that even if the MPW is comprehensively analyzed as a series of unsteady phenomena, lengthening the

Fig. 5 The waveforms of the pressure gradient at the generation stage of the compression wave

Fig. 6 The relationship between the tunnel length and the peak value of the MPW

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hood is an effective measure for reducing MPWs. In the case of \(U=320\) km/h and \(U=360\) km/h shown in Fig. 6 (b) and (c), the nonlinear effect is obvious. The peak value of the MPWs exceeds 100 Pa when the tunnel length exceeds a certain length under these conditions. Note that the maximum value of the vertical axis shown in Fig. 6 (b) and (c) are set to 100 Pa since (5) overestimates the value of the pressure gradient of the compression wave when the compression wave steepens excessively. Similar to the case of \(U=260\) km/h, the peak value of the MPW with a \(L=40\) m hood is smaller than with the \(L=20\) m hood; the difference of the tunnel length reaching the peak value of MPW 100 Pa is about 3 km under \(U=320\) km/h and about 2 km under \(U=360\) km/h. Therefore, the extension of the hood may suppress the nonlinear effect during the propagation stage of the compression wave even with such high train speeds. Furthermore, comparing the value of the vertical axis shown in Fig. 6 (b) and (c), the nonlinear effect is obvious. The peak value of the MPW 100 Pa, is newly defined as the MPW itself could depend on the pressure waveforms, even when train speed increases. These results demonstrate that the configuration of the hood openings (windows combinations) should be comprehensively determined in consideration of the influence of the characteristics during the propagation stage of the compression wave, especially in the case of a long tunnel over several kms or more in length.

### 3.3 Evaluation of micro-pressure waves with limited tunnel length

The previous section found that as tunnel length becomes longer, the peak values of the MPW radiated from the tunnel portal grow to values over 100 Pa, due to a nonlinear effect during the propagation stage of the compression wave when the train speed is fast (for example over 300 km/h). Currently in Japan, the reference value for preventing sonic booms around tunnel portals is below 50 Pa of the peak value of the MPW at 20 m from the portal [13]. Therefore, with peak MPW values of 100 Pa, there are concerns that this could generate serious sonic booms around tunnel portals. As such, in this study, the maximum tunnel length at which the peak value of the MPW 20 m from the portal is less than 50 Pa, is newly defined as the ‘limited tunnel length’. From now on, this value is used as an evaluation index for MPW radiation. The relationship between the train and the limited tunnel length is shown in Fig. 7. In Fig. 7, the numerical results are shown as dashed lines, while results of the prediction formula by solving following (9)-(11) as a function of \(U\), are simultaneously shown with lines.

\[
\frac{\partial p}{\partial t}_{\text{max},0} = \frac{D}{D+L} \left( \frac{\partial p}{\partial t} \right)_{\text{max},0,\text{no hood}}, \quad (9)
\]

\[
\frac{\partial p}{\partial t}_{\text{max},0,\text{no hood}} = \frac{U \partial p}{\partial t} \left( \frac{8.9}{l} \right)^{1/\eta}, \quad (10)
\]

\[
\frac{\partial p}{\partial t}_{\text{max},r} = \left( \frac{\partial p}{\partial t} \right)_{\text{max},0} \exp \left( \left( \frac{\partial p}{\partial t} \right)_{\text{max},0} - \left( \frac{\partial p}{\partial t} \right)_{\text{max},r} \right) \exp \left( \frac{\partial p}{\partial t} \right)_{\text{max},r} \right) \cdot (11)
\]

where \(\left( \frac{\partial p}{\partial t} \right)_{\text{max},r}\): maximum value of the pressure gradient when the propagation distance equals \(x\), \(\left( \frac{\partial p}{\partial t} \right)_{\text{max},0}\): maximum value of the pressure gradient at the tunnel entrance; \(\left( \frac{\partial p}{\partial t} \right)_{\text{max},0,\text{no hood}}\): maximum value of the pressure gradient at the tunnel entrance without the hood; \(\left( \frac{\partial p}{\partial t} \right)_{\text{cr}}\): critical maximum value of the pressure gradient (the minimum value at which the compression wave steepen); \(\eta\): constant which represents the degree of the nonlinear effect; and, \(D\): characteristic length of the hood (determined by least-squares approximation). Equation (9) is often used to evaluate the pressure gradient reduction effect when a hood is installed, and \(\eta\) in (10) represents the efficiency of the nose of the train [14]. Equation (11) represents the empirical formula of the change in maximum value of the pressure gradient during the propagation stage of the compression wave. Here, \(a=0.027\) (km kPa/s), \(\left( \frac{\partial p}{\partial t} \right)_{\text{max},cr}=2.7\) kPa [13, 15] are used, in order to ensure correspondence of the propagation through the slab track tunnel. From (11), this empirical formula depends on the maximum value of the pressure gradient at the tunnel entrance, and waveform dependence is not considered. Here, the values of \(D\) and under window combination No. 1, \(D=33.2\) and \(\eta=0.568\) in the case of \(U=260\) km/h, \(D=36.2\) and \(\eta=0.566\) in the case of \(U=320\) km/h and \(D=38.5\) and \(\eta=0.565\) in the case of \(U=360\) km/h. The prediction formula shown in Fig. 7 adopts the average value of these three train speed conditions. From the results shown in Fig. 7, it can be confirmed that the limited tunnel length becomes shorter depending on the increase in train speed and the decrease in the hood length, and is different depending on the windows conditions. However, these results are plotted on the curve of the prediction formula for the case where the length of the train nose is \(l=15\) m (the figure also shows the limited tunnel length in the case of \(l=12\) m with the dashed lines and the limited tunnel length in the case of \(l=18\) m with the chain line). Therefore, if the values of \(D\) and \(\eta\) are obtained from the data of the compression wave at the tunnel entrance, the approximate value of the limited tunnel length can be estimated by (9)-(11).

### 4. Conclusions

In this study, we comprehensively numerically analyzed micro-pressure waves (MPWs) as a series of unsteady phenomena by analyzing each stage of MPW respectively;
the generation of the compression wave, the propagation of the compression wave and the radiation of the MPW. The obtained results are as follows:

(i) In the generation stage of the compression wave, installation of the hood with an optimal window arrangement can greatly reduce the maximum of the pressure gradient. When the nose of the train is spheroid, the mitigation effect is 40% with a L=20 m hood, and 60% in the case of a L=40 m hood, compared to when no hood is installed.

(ii) In the propagation stage of the compression wave, although pressure waveforms steepen due to a nonlinear effect, this effect can be suppressed to some extent by extending the hood.

(iii) Even if the effect of the windows combination in the hood is small in the generation stage of the compression wave, the difference in the MPW could be considerable if the distortion of the waveform of the compression wave during the propagation stage is taken into account.

(iv) The limited tunnel length becomes longer depending on the decrease in train velocity and the extension of the hood length, and could change depending on the windows arrangement in the hood. However, it is possible to estimate the approximate value from the data at the tunnel entrance using an experimental prediction formula.

References

[1] Yamamoto, A., “Micro-pressure wave radiated from tunnel exit,” presented at the Spring Meeting of the Physical Society of Japan, pp. 137, 1977 (in Japanese).
[2] Ozawa, S., “Studies of micro-pressure wave radiated from a tunnel exit,” RTRI Report, No. 1121, 1979 (in Japanese).
[3] Iida, M., Matsumura, T., Fukuda, T., Nakatani, K. and Maeda, T., “Optimization of train nose shape for reducing impulsive pressure wave from tunnel exit,” Transactions of the Japan Society of Mechanical Engineers. B, Vol. 62, No. 596, 1964 (in Japanese).
[4] Howe, M. S., Iida, M., Fukuda, T. and Maeda, T., “Theoretical and experimental investigation of the compression wave generated by a train entering a tunnel with flared portal,” Journal of Fluid Mechanics, Vol. 425, pp. 111-132, 2000.
[5] Howe, M. S., Iida, M., Maeda, T. and Sakuma, Y., “Rapid calculation of the compression wave generated by a train entering a tunnel with a vented hood,” Journal of Sound and Vibration, Vol. 297, pp. 267-292, 2006.
[6] Fukuda, T., Ozawa, S., Iida, M., Takasaki, T. and Wabayashi, Y., “Distortion of the compression wave propagating through a very long tunnel with slab tracks,” Transactions of the Japan Society of Mechanical Engineers. B, Vol. 71, No. 709, 2005 (in Japanese).
[7] Miyachi, T., Ozawa, S., Fukuda, T., Iida, M. and Arai, T., “A new simple equation governing distortion of compression wave propagating through Shinkansen tunnel with slab tracks,” Transactions of the Japan Society of Mechanical Engineers. B, Vol. 75, No. 785, 2012 (in Japanese).
[8] Miyachi, T., Saito, S., Fukuda, T., Sakuma, Y., Ozawa, S., Arai, T., Sakaue, S. and Nakamura, S., “Propagation characteristics of tunnel compression waves with multiple peaks in the waveform of the pressure gradient; Part 1: Field measurements and mathematical mode,” Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Vol. 230, No. 4, pp. 1297-1308, 2016.
[9] Miyachi, T., “Theoretical model for micro-pressure wave emission considering the effect of topography around the tunnel portal,” QR of RTRI, Vol. 52, No. 2, pp. 117-122, 2011.
[10] Miyachi, T., Iida, M. and Ozawa, S., “Optimization of tunnel entrance hood for reducing micro-pressure wave from long slab-track tunnel portal,” The proceedings of the Symposium on Environmental Engineering, 2007 (in Japanese).
[11] Fukuda, T., Miyachi, T., Saito, S., Iida, M., Kurita, T. and Kikuchi, Y., “Experimental on the compression wave generated by a train entering a tunnel using three-dimensional and axisymmetric train models,” Transactions of the Japan Society of Mechanical Engineers. B, Vol. 78, No. 793, 2012 (in Japanese).
[12] Hara, T., “Aerodynamic problems when train is running into tunnel with large velocity,” Railway Technical Research Report, No. 153, 1960 (in Japanese).
[13] Nakamura, S., Fukuda, S., Miyachi, T. and Saito, S., “A method for estimating the length of a tunnel hood,” RTRI Report, Vol. 52, No. 11, 2018 (in Japanese).
[14] Miyachi, T., Iida, M., Fukuda, T. and Arai, T. “Non-dimensional maximum pressure gradient of tunnel compression waves generated by offset running axisymmetric trains,” Journal of Wind Engineering and Industrial Aerodynamics, Vol. 157, pp. 23-35, 2016.
[15] Miyachi, T., Hieke, M., Tielkes, T., Fukuda, T., Iida, M., Saito, S. and Nakamura, S., “Numerical simulation of compression wave propagation in German slab-track tunnels,” presented at the World Congress on Railway Research, 2016.

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