Pressure Waves Generated When a Train Passes Through a Structure*

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Abstract

When a high-speed train passes through a hood-shaped short structure (the length along the railway is typically several times as long as the diameter of its cross section), such as an overpass or a snow shelter, “structure-passing waves (*SPW*),” which are a type of low-frequency noise, radiate from both openings of the structure toward the outside area. The *SPW* could create an environmental problem of a low-frequency noise along the tracks as train speeds increase, for it steeply grows in proportion to the third or fourth power of the train speed. In this study, model experiments and acoustic analyses were conducted to investigate the generation mechanism of *SPW*. The run-time required for the present method of analyses is a few seconds, as opposed to the several hours typically required for an entirely numerical approach. The results of the acoustic analyses, based on a method for predicting a compression wave within a hood-shaped structure generated by a passing train, generally agree well with the experimental results of *SPW* with some exceptions. This implies that *SPW* can be modeled as a superposition of the pressure waves radiating from both openings of the structure. In addition, our model experiment and acoustic analysis show that the magnitude of *SPW* tends to depend on train nose/tail profile.

Key words: Pressure Wave, Low-Frequency Noise, High-Speed Railway, Sound and Acoustics

1. Introduction

Low-frequency noise (LFN), now a recognized problem in many countries. The Japanese guidelines by the Ministry of the Environment state that LFN should be assessed by third octave band measurements in the range 1 – 80 Hz.⁽¹⁾ This method is intended to determine whether suspected LFN is audible or not, rather than whether it should be classed as a nuisance. It is possible that LFN can rattle fittings, such as doors and windows, or exert psychological influences, such as oppressive feelings and tinnitus, even if most people find it hard to perceive LFN as sound.

A high-speed train entering a tunnel generates a compression wave that propagates ahead of the train; when the compression wave is reflected from the distant tunnel exit, a pressure pulse, called a micro-pressure wave, is radiated out of the tunnel.⁽²⁾ This phenomenon is regarded as a major LFN environmental problem that occurs along the Shinkansen line. The micro-pressure wave is a positive and impulsive pressure wave radiated from the tunnel portal. Provided that the tunnel is long, the influence of multiple

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reflections can be negligible, because reflections of the compression/expansion wave propagating in the tunnel occur at sufficiently long time intervals, and it attenuates during its propagation in the tunnel. However, in a short tunnel, multiple reflections of the compression/expansion wave occurring at both portals are important. When the compression wave reflects at the tunnel portals many times within a short time, the impulsive pressure waves are repeatedly radiated from both portals.⁽³⁾ In addition, other types of impulsive pressure waves also radiate from the portals. When a train enters or leaves the tunnel, it generates not only the pressure wave inside the tunnel but also outside pressure waves that are radiated directly from the portal. These direct pressure waves are called entry and exit waves, and can be categorized also as a type of LFN.⁽⁴⁾

A phenomenon of the same kind occurs when a train passes through a hood-shaped short structure such as an overpass or a snow shelter. We call this a “structure-passing wave (hereafter *SPW*).” The length of the structure along the railway is generally several times as long as the diameter of the structure cross-section—much shorter than a tunnel. The *SPW* could create an environmental problem of a low-frequency noise along the tracks as train speeds increase, for it steeply grows in proportion to the third or fourth power of the train speed.⁽⁵⁾

On *SPW*, the axisymmetric flow field, where a simple model train passes through a model structure, was studied with numerical simulation of the compressible Euler equations by Ogawa and Nishida.⁽⁶⁾ Their results showed that pressure waves were generated by the interaction between the flow field around the train and the structure when the train passes it. Moreover, oscillating pressure waves were observed in the calculation, since the pressure waves resonate inside the structure. On the other hand, field measurements conducted at an actual overpass over the Shinkansen railway by Kikuchi et al.⁽⁷⁾ showed that the pressure waves were impulsive waves, not oscillating pressure waves. Then model experiments and simple analyses were performed for a wide range of train speeds, measurement distances, and structure lengths.⁽⁵⁾ The results of analyses were found to be in good agreement with model experiments, assuming that the train is infinitely long to neglect a tail effect. In this paper, an analytical representation of *SPW* generation including the tail effect is given as an extension of the preceding acoustic analysis. Furthermore, we investigate the reducing effect of train nose profile on the waveforms of the pressure waves by the analysis.

2. Simple scale-model experiment

2.1 Experimental apparatus

The experiments reported here were conducted using a simple scale-model train, projected by model launching apparatus at the Railway Technical Research Institute, as shown in Fig. 1. It is similar to that used to investigate compression wave formation in a tunnel.⁽⁸⁾ Considering the geometrical analogies between the hood-shaped structure and a tunnel, this experimental apparatus is appropriate for simulating *SPW* phenomenon.

The experimental dimensions are given in Table 1; the experiments reported here were conducted with a 1/127 scale model. The model train is projected by a three-stage friction drive involving three pairs of vertically aligned wheels, and it is guided along a 5 mm diameter taut steel wire. The maximum possible launching speed is approximately 400 km/h. The mach numbers of the full- and model-scale flows are identical; the Reynolds number of the model-scale flow is about one-hundredth of the full-scale flow but still sufficiently large for them to be regarded as inviscid during the initial interaction between train and structure.

The dynamics of the formation of *SPW* are basically equivalent to those of the simple problem, in which the structure replaced by a rectangular duct of uniform cross-sectional

Fig. 1 Experimental setup.

Table 1 Specifications of train and structure model.

Train-1	Nose length $l_n = 47$ mm, Overall length $l_T = 922$ mm Diameter $d = 42$ mm, Blockage 0.144	
Train-2	Nose length $l_n = 118$ mm, Overall length $l_T = 922$ mm Diameter $d = 40$ mm, Blockage 0.130	
Structure-A	$L=100$ mm, $L/D=1.0$	Circular cross section, diameter $D=100.0$ mm
Structure-B	$L=200$ mm, $L/D=2.0$	Cross-sectional area $A = 7,853$ mm ²
Structure-C	$L=47.2$ mm, $L/D=0.4$	Rectangular cross section $92.9\text{mm} \times 103.9\text{mm}$
Structure-D	$L=189$ mm, $L/D=1.7$	Cross sectional area $A = 9,652$ mm ² Equivalent circle diameter $D = 110.9$ mm

area A on a ground plane. When the actions of frictional forces on the actual ground and the lower surface of the train are ignored, the problem is dynamically equivalent to calculating the pressure waves generated by the train and a duct in a free space with their images in the ground plane. In this experiment, there are three types of structures having different cross-sectional shapes and axial lengths: Structures A, B, and C. For exact comparison with our acoustical analysis, Structure-A and B have a circular section. In addition, Structure-C has a rectangular section similar to that of an actual overpass.

Let the model train be traveling at constant speed U in the negative x_1 -direction of the rectangular coordinates (x_1, x_2, x_3) , where the origin O is set in the center plane of the model structure, with the x_1 -axis lying in the vertical plane of symmetry (see Fig. 3). The model train travels along the centerline of the structure. The model train has an axisymmetric body, and it has symmetric leading and trailing shapes with a similar distribution of the actual nose cross-sectional area of a train. In Fig. 2, the distributions of cross-sectional area of the nose are shown by black line with left side axis, and the change rates of cross-sectional area are shown by blue line with right side axis. There are two types of nose shapes: Train-1 (basic model) and Train-2 (long nose model). Train-2 has a nose 2.5 times longer than that of Train-1.

2.2 Measurement procedures

The pressure variations were measured by four sound level meters (RION NL-20, frequency response 20–8,000 Hz), at various positions outside the model structure. Small permanent magnets were inserted in the model train, and two wire loops were placed along the guide wire, to measure the train speed by detecting the magnetic field of the passing train. The data were digitized by a 12-bit A/D converter with a sampling rate of 25 kHz per channel, and stored in a personal computer.

The observed pressure fluctuations consist of both SPW and hydrodynamic pressure variations⁽⁹⁾, produced by the passage of the train nose and tail. On the condition that the

Fig. 2 Distribution of model cross-sectional area.

two phenomena differ in frequency, *SPW* can be separated using an appropriate band-pass filter. Each dominant frequency is estimated from the frequency analysis of experimental data, and band-pass filter cut-off frequencies are set to 500 Hz and 5000 Hz. Filtered data corresponding to *SPW*'s waveforms have multiple peaks of positive and negative pulses. In consideration of environmental impact, a representative value of *SPW* is defined as the pressure amplitude between the maximum positive and the minimum negative pulse peaks observed when the train passes through the structure.

3. Acoustical analysis

Recently, an acoustic analytical method was developed by Howe⁽¹⁰⁾, which predicts a compression wave generated by a train entering a tunnel, without the need for large-scale numerical simulation. Here, we apply the same analytical method for calculating the compression wave in short-length structures. The micro-pressure wave and the entry/exit waves are calculated from the pressure gradient of the compression or expansion wave, with the exception of long structures like tunnels within which significant nonlinear steepening and dissipation due to wall friction occur.⁽¹¹⁾⁽¹²⁾ By superimposing the calculated results of pressure waves obtained using the pressure gradient of the compression or expansion wave, we can predict *SPW*.

Figure 3 shows a schematic diagram of the analytical model. We use a simple geometric model of a circular cylinder in an infinite free space. As in the experiment mentioned above, we consider the effect of the ground plane by employing the mirror image method, assuming that the ground plane is flat and infinitely extended.⁽¹³⁾ The train is projected along the negative x_1 -direction into the structure at uniform speed U . The train has a circular cross-section of area A_0 except for the nose and tail, where the area $A_T(y_1)$ and $A_T'(y_1)$ varies in a prescribed manner, with distance y_1 measured from the nose tip. However, because the actual train usually has symmetric nose and tail shapes, the area $A_T'(y_1)$ is obtained by the symmetric transformation of $A_T(y_1)$ with the distance l_n of varying area at the nose and tail equal.

3.1 Compression wave inside the structure

The speed of the train is less than half the speed of sound; therefore, the dominating wavelength of the compression wave (D/M , D is the diameter of the structure cross-section and M is the Mach number of the train) generated by the train nose entering the structure is several times larger than the radius of the structure cross-section.⁽¹⁴⁾ In other words, the structure cross-section is acoustically compact. Hence, the compression

Fig. 3 Analytical model.

wave in the structure propagates as a plane wave.⁽¹¹⁾⁽¹²⁾⁽¹⁵⁾

If the structure is too short, the compression wave in the structure should be calculated taking into consideration a reflection wave at the opposite opening; however, this is a difficult calculation. Therefore, we assume that the structure is not too short and that the compression wave has been formulated before the wave front of the wave returns to the entry opening after reflection at the exit opening. Hence, the structure length should meet the requirements of

$$\frac{2L}{c_0} > \Delta t, \quad \text{namely} \quad \frac{L}{D} > \frac{c_0 \Delta t}{2D}, \quad (1)$$

where c_0 is the speed of sound and Δt is the time span of the compression wave. When the train nose is streamlined, as it is in most high-speed trains, the compression wave at position $\mathbf{x}'$ (within the structure) is given⁽¹³⁾ as a function of the time t as

$$p_{en}(\mathbf{x}', t) = \frac{\rho_0 U^2}{A(1-M^2)} \left(1 + \frac{A_0}{A} \right) \int_{-\infty}^{\infty} \frac{\partial A_T}{\partial y_1}(y_1 + U[t]) \frac{\partial \varphi_{en}}{\partial y_1}(y_1, 0, z_T) dy_1, \quad (2)$$

$$[t] = t + \frac{L}{2U} - \frac{|\mathbf{x}' - (L'/2, 0, 0)|}{c_0}, \quad (3)$$

where $p_{en}(\mathbf{x}', t)$ is the compression waveform in the structure, generated by the nose entry; $[t]$ is the retarded time; L' is the overall structure length including the end corrections; ρ_0 is the air density; A is the doubled area of the structure cross section; z_T is the offset of the train axis from the structure axis in the horizontal direction; and $\varphi_{en}(x_1, x_2, x_3)$ is the velocity potential determined from geometry of the structure entrance (the right opening in Fig. 4, which is given analytically when the structure is unflanged, thin-walled circular cylinder).

The compression wave $p_{ex}(\mathbf{x}', t)$ generated by the train nose leaving the structure can be given by equation (2) by replacing $\varphi_{en}(x_1, x_2, x_3)$ with $\varphi_{ex}(x_1, x_2, x_3)$, which is the velocity potential determined from the geometry of the structure exit (the left opening in Fig. 4). The function $\varphi_{ex}(x_1, x_2, x_3)$ is obtained by inverting $\varphi_{en}(x_1, x_2, x_3)$ with respect to x_1 , on the condition that the openings have identical geometries. In reality, $p_{ex}(\mathbf{x}', t)$ tends to be small than $p_{en}(\mathbf{x}', t)$ because the flow around the train is in a transition state when the train leaves the structure immediately after the train entering. In this regard, the extent of the transition is difficult to know beforehand, as it depends on the structure length,

Fig. 4 Compression wave and pressure gradient obtained by analysis.

details of the train shape, the Mach numbers, and the Reynolds numbers. Therefore, we introduce a coefficient α representing the extent of the transition, and we set a common value of $\alpha = 0.5$, which has been found to give good agreement with current experiment. Hence, we can write

$$p_{ex}(\mathbf{x}', t) = \alpha \frac{\rho_0 U^2}{A(1-M^2)} \left(1 + \frac{A_0}{A}\right) \int_{-\infty}^{\infty} \frac{\partial A_T}{\partial y_1}(y_1 + U[t']) \frac{\partial \varphi_{ex}}{\partial y_1}(y_1, 0, z_T) dy_1, \quad (4)$$

$$[t'] = t - \frac{L}{2U} - \frac{|\mathbf{x}' - (L/2, 0, 0)|}{c_0}. \quad (5)$$

Figure 4 shows the compression waveforms of normalized pressure p_{en} , p_{ex} and their gradients inside the structure, generated by nose entry and exit, which are calculated from equations (2) and (4). Here, the time origin corresponds to the instant when the front edge of the nose (the cross-sectional area becomes null) cuts the entry/exit opening plane, R is the radius of the structure cross-section, black lines with left side axis indicate the pressure, and blue lines with right side axis indicate the pressure gradient.

Similarly, the expansion waves generated by the train tail entering and leaving the structure can be given by equations (2) and (4), by replacing $A_T(y_1)$ with $A_T'(y_1)$, which is the train tail condition. Even if the train tail shape is streamlined, the flow is separated to some extent around the tail. Here, we introduce an coefficient β representing the extent of the separation at the tail, and the expansion waves are calculated from equation (2) and (4) multiplied by β . For this study, we always set a common value of $\beta = 0.6$, which has been found to give reasonable agreement with current experiment.

3.2 Pressure wave outside the structure

An individual pressure wave, radiated from the opening outside the structure in a free space, is calculated from the wave-front steepness of the compression wave inside the structure, namely the pressure gradients $\partial p_{en}/\partial t$ and $\partial p_{ex}/\partial t$.

The entry wave $P_{en}(\mathbf{x}, t)$ caused by the train nose entering the structure and radiating directly from the opening is given⁽¹²⁾ as a function of time t at the measurement point $\mathbf{x}(x_1, x_2, x_3)$ by

$$P_{en}(\mathbf{x}, t) = -\frac{A}{4\pi c_0} \frac{1}{r_1} (1 - \cos \theta_1) \times \frac{\partial p_{en}}{\partial t} \left(t - \frac{r_1}{c_0} \right), \quad (6)$$

where θ_1 is the angle between the direction from the train nose to tail, and the direction from the entrance opening (the right opening in Fig. 3) to measurement point $\mathbf{x}$. Equation (6) indicates that the component of the entry wave ahead of the train motion (negative x_1 -axis) is stronger than that behind of the train motion (positive x_1 -axis). Furthermore, the experimental results of tunnel entry wave suggested that the spreading of the entry wave transverse to train motion (x_3 -axis) is asymmetric when the train axis is offset from the structure axis, i.e., z_T is nonzero.⁽¹⁶⁾ To calculate the transverse directionality in analysis, we should take into consideration the three-dimensional arrangement of the train and the structure. However, under center running conditions ($z_T = 0$), that is, when the train runs along the structure axis, we can ignore this transverse directionality.

Similarly, the exit wave $P_{ex}(\mathbf{x}, t)$, caused by the train nose leaving the structure, and radiating directly from the opening is given as

$$P_{ex}(\mathbf{x}, t) = -\frac{A}{4\pi c_0} \frac{1}{r_2} (1 + \cos \theta_2) \times \frac{\partial p_{ex}}{\partial t} \left(t - \frac{r_2}{c_0} \right), \quad (7)$$

where θ_2 is the angle between the direction from the train nose to tail and the direction from the exit opening (the left opening in Fig. 4) to the measurement point $\mathbf{x}$.

The pressure waves inside the structure propagate away from the openings at the speed of sound. When the compression wave is reflected backward as an expansion wave, which is inverting a sign at the reflected opening, part of the energy radiates out of the structure as pressure pulses, corresponding to the tunnel micro-pressure wave. The micro-pressure waves are radiated repeatedly at each reflection from both openings. The strength of these micro-pressure waves is proportional to the wave-front steepness of the compression/expansion waves at the reflected opening. The initial waveform of the pressure waves in the structure given by equations (2) and (4) changes during propagation inside the structure. Considering the retarded time for propagation in the structure and attenuation of the waves, we can express the micro-pressure wave $P_{mp}(\mathbf{x}, t)$ attributable to the i -th reflection as

$$P_{mp}(\mathbf{x}, t) = \sum_{i=1}^{\infty} \left\{ (-\gamma)^{i-1} \frac{A}{2\pi c_0} \left[\frac{1}{r_{i+1}^*} \frac{\partial p_{en}}{\partial t} \left(t - \frac{r_i^* - iL'}{c_0} \right) + \frac{1}{r_i^*} \frac{\partial p_{ex}}{\partial t} \left(t - \frac{r_i^* - iL'}{c_0} \right) \right] \right\},$$

$$r_i^* = \begin{cases} r_1, & i = \text{odd} \\ r_2, & i = \text{even} \end{cases} \quad (8)$$

where i is the number of reflections and γ is an experimental parameter for attenuation of the pressure waves in the structure. The attenuation is mostly attributable to the reflection/radiation at the structure openings, and the effect of friction forces on the smooth inner wall during propagation along the short length of the structure should be small. In general the attenuation of a plane wave due to reflection depends on its frequency and the shape of the opening.⁽¹⁷⁾ Therefore, we measured the approximate attenuation parameter γ of the compression wave at various frequencies for the experimental model.⁽¹⁸⁾ As a result, we obtained the range of γ from 0.6 to 0.9 relative to the train speed in the present analysis.

Similarly, the pressure waves outside the structure generated by the train tail entering and leaving the structure can be given by equations (6)–(8), by replacing $\partial p_{en}/\partial t$ and $\partial p_{ex}/\partial t$ with train tail conditions. By adding the entry wave of equation (6), the exit wave of equation (7), and the micro-pressure waves of equation (8), the overall waveform of SPW caused by the train passing through the structure are given as

$$P(\mathbf{x}, t) = P_{en}(\mathbf{x}, t) + P_{ex}(\mathbf{x}, t) + P_{mp}(\mathbf{x}, t). \quad (9)$$

3.3 Comparison of analytical and experimental results

First, we examine the differences between analytical and experimental results for the identical shape of the structure cross-section. Here, we regard the train as infinitely long for evaluating the pressure waves generated by the nose only. Figure 5 compares pressure waveforms between analyses and experiments for the same circular cross-section measured at the point $x(0,0,400\text{ mm})$ that corresponds to a field measurement of a point 50 m from the structure center, for Train-1 running at 350 km/h. Time zero is the time when the tip of the train nose cuts the plane of the structure opening.

When the nose of the train passes through Structure-A (Fig. 5a), about three or four impulsive pressure waves are radiated. By contrast, when the train passes through Structure-B (Fig. 5b), which are longer than Structure-A, oscillatory pressure waves are radiated. These waveform characteristics are similar to the results of field measurements⁽³⁾⁽⁷⁾ and the numerical simulation⁽⁶⁾ with the compressible Euler equations.

The results of the analysis and experiment are in good agreement for Structure-B. For Structure-A, however, which is relatively short, the results differ after the third positive pulse, probably because the length is too short compared to the wavelength of the compression wave. The compression wave has not been formed completely before their wave front returns to the entry opening by reflection at the exit opening. Consequently, the model length of the analysis need to meet the requirement of equation (1)—namely, the requirement of $L/D > 1.5$, derived by an estimation of the time span of the compression wave in Fig. 4.

Fig. 5 Comparison of pressure waves between experiment and analysis for a circular cross-section structure. [Train-1, $U=350\text{ km/h}$, $x(0,0,400)$]

Therefore, we conduct detailed calculations under the condition $L/D = 1.7 > 1.5$, equivalent to the experimental model of Structure-D. Figure 6(a) shows individual waveforms for equations (6), (7), and (8). Figure 6(b) shows a comparison of SPW 's waveforms between the analysis, where the final waveform is obtained by adding these pressure waves together, and the experiment of structure-C with rectangular cross-section. The waveforms of the analysis and the experiment are in reasonable agreement. Indeed, a slight difference in shape of the structure cross-section would be unimportant, provided that the cross-sectional area of the structure is unchanged. The analytical pressure waveform due to the tail slightly disagrees with the experimental one, because our manner of treating the separation of flow around the tail may be inaccurate. As described in 3.1, the

Fig. 6 Comparison of pressure waves between experiment and analysis for a rectangular cross-section structure. [Structure-D, Train-1, $U=350$ km/h, $x(0, 0, 400)$]

expansion waves generated by the tail entering and leaving the structure are calculated from equation (2) and (4) multiplied by the constant β . However, in principle, the degree of the flow separation may differ depending on whether the train tail is positioned inside or outside the structure. In that case, it would be better to make β a variable coefficient varying with respect to the running conditions of the train.

Even though some waveform details do not agree in a structure that is too short or that in case of the tail conditions, it is thought that the fundamental generation mechanism of pressure waves remain unchanged and our analysis can reproduce the *SPW*'s overall tendency satisfactorily. Hence, the waveform of *SPW* can be modeled as a superposition of all impulsive pressure waves, which consist of entry wave, exit wave, and micro-pressure waves with multiple reflections.

Figure 7 shows the time history of the instantaneous acoustic pressure distribution outside the structure at a cross-section of $x_1 - x_3$ obtained by the analysis, excluding the near field unsteady flow around the train. The train runs from right to left and passes through the structure, with its center located at $(x_1, x_3) = (0, 0)$. Figure 7 clearly indicates that several pressure waves radiate from both sides of the structure, and then overlap each other. Accordingly, *SPW* exhibits a complex pattern at measurement points around the structure.

4. Influence of train nose profile

It is clear from equations (2) and (4) that, under constant train velocity and structure geometry conditions, reducing the cross-sectional area of the train is one of the best ways to depress the pressure magnitude within the structure, but it leads to a decrease in passenger capacity. According to equations (6)–(8), the magnitude of *SPW* depends not on the pressure magnitude within the structure but on the pressure gradient within it. Consequently, adapting an appropriate cross-sectional area distribution of the train nose/tail is adequate to reduce the magnitude of *SPW*. For instance, a longer nose/tail of the train

Fig. 7 Instantaneous acoustic pressure distribution obtained by analysis.
[Structure-D, Train-1, $U=350$ km/h]

will be a great advantage. Figure 8 compares the pressure waveforms for Train-1 and Train-2 passing through Structure-C, obtained from experiments. As shown in this figure, the magnitude of *SPW* for Train-2, which has the longer nose, is much smaller than that for Train-1.

In this regard, the ratio of the *SPW*'s magnitude agrees roughly with the maximum change rate of cross-sectional area of the train nose. In fact, this characteristic is the same as the case of the tunnel micro-pressure wave. Therefore, an optimum train nose profile for reducing *SPW* corresponds substantially with that for reducing the micro-pressure wave—a parabolic nose shape with blunt front end is very efficient.⁽¹⁹⁾

Figure 9 compares the pressure waveforms generated by typical nose profiles, obtained from analyses. There are two axisymmetric profiles where the front of the train is Train-1 or of a paraboloid of revolution shown in the left column of Fig. 9 about the horizontal axis through the nose. Let the ratio of nose length with model train be defined by the equation $l'_n = l_n / l_{n0}$, where l_n and l_{n0} respectively denote the nose length of the evaluation models and the nose length of the original Train-1. As shown in the right column of Fig. 9, the magnitude of *SPW* for the long paraboloidal nose is much smaller than that for the original

Fig. 8 Comparison of pressure waves between Train-1 and Train-2, obtained from experiments.
[Structure-C, $U=350$ km/h, $\mathbf{x}(0, 0, 400)$]

Fig. 9 Comparison of pressure waves generated by typical train nose profiles, obtained from analyses. [Structure-D, $U=350$ km/h, $x(0, 0, 400)$]

nose profile of Train-1. In particular, when the nose length is short, the magnitude of *SPW* is little affected by the nose profile, but it is dramatically affected by the proper nose profile when the nose length is long to some extent, say $l'_n \geq 2$.

5. Conclusion

When a high-speed train passes through a hood-shaped short structure (the length along the railway is typically several times as long as the diameter of its cross section), such as an overpass or a snow shelter, structure-passing waves (*SPW*), which are a type of low-frequency noise, radiate from both openings of the structure toward the outside area.

In this paper, model experiments and acoustic analyses were conducted to investigate the generation mechanism of *SPW*. We consider *SPW* is modeled as a superposition of all impulsive pressure waves, which consist of entry wave, exit wave, and micro-pressure waves with multiple reflections. The results of the acoustic analysis, based on a method for predicting compression waves within a hood-shaped structure generated by the entry/exit of the train nose/tail, generally agree well with our experimental results with some exceptions. Very short structures ($L/D < 1.5$, structure length L is shorter than 1.5 times structure diameter D), which are beyond the limitation of the present analysis, require the entirely numerical simulation. In addition, more precise analysis for the train tail conditions requires an appropriate consideration of the separation of flow. Nevertheless, the present analysis can account for the overall tendencies of *SPW* satisfactorily, even though some details in the waveform do not agree. Our model experiment and acoustic analysis demonstrate some typical train profiles to reduce the magnitude of *SPW*.

It would be possible to obtain more precise pressure waveform based on an entirely numerical approach, but the computer run-time for it would be typically several hours, as compared with a few seconds required for the present method. The present method enables us to analyze *SPW* very efficiently, thereby aiding in the prior estimation of trackside LFN conditions that would exist under higher speed operations for the Shinkansen and other high-speed vehicles.

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