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Nondimensional maximum pressure gradient of tunnel compression waves generated by offset running axisymmetric trains

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ABSTRACT

A high-speed train entering a tunnel generates a compression wave in the tunnel and a micro-pressure wave. The magnitude of the micro-pressure wave is approximately proportional to the maximum pressure gradient of the compression wave $(\partial p/\partial t)_{max}$. High-speed railway operations require the consideration of the nose shape of the train in order to reduce $(\partial p/\partial t)_{max}$ generated by a train entering a tunnel. In this study, the compression waves generated by axisymmetric trains running at the offset position in double-track tunnels were investigated using a train launcher facility. Paraboloids of revolution, ellipsoids of revolution, and cones were used as the simplest nose shapes. The cone-nose train generated the largest value of $(\partial p/\partial t)_{max}$, and the paraboloid-nose train generated the smallest value of $(\partial p/\partial t)_{max}$ among the three nose shapes. Although this tendency is the same as that for center running, the ratio of $(\partial p/\partial t)_{max}$ for the cone-nose train to that for the paraboloid-nose train became larger for offset running than center running. Moreover, the maximum value for the generation time of the compression wave was derived from acoustic theory, and the nondimensionalization of $(\partial p/\partial t)_{max}$ considering the nose length was proposed using it. Since the inverse of the nondimensionalized $(\partial p/\partial t)_{max}$ denotes the ratio of the generation time of the compression wave to its maximum value, it was defined as the efficiency of a train nose in the range of zero to unity. The values of the efficiency were almost constant with the nose length and 0.7, 0.6, and 0.5 for paraboloid-, ellipsoid-, and cone-nose shapes, respectively.

1. Introduction

A train entering a tunnel generates a compression wave in the tunnel. When this compression wave arrives at the exit portal, a micro-pressure wave radiates outward (Yamamoto, 1977; Ozawa, 1979), possibly causing environmental problems such as explosive noise and vibration.

It is effective to extend the time for the generation of the compression wave by the extension and optimization of train noses (Maeda et al., 1993; Ogawa and Fujii, 1994, 1995; Iida et al., 1996; Ogawa and Fujii, 1996; Matsuo et al., 1997; Maeda, 1998; Howe, 1998; Kwon et al., 2001; Bellenoue et al., 2002; Iida et al., 2003; Kikuchi et al., 2011; Miyachi, 2012; Fukuda et al., 2012; Muñoz-Paniagua et al., 2014) because the main source strength of the micro-pressure wave is approximately proportional to the pressure gradient of the compression wave arriving at the exit portal (Yamamoto, 1977). The characteristics of the compression waves generated by trains running at the center of the tunnel, which have simple nose shapes of ellipsoids of revolution, paraboloids of revolution, and cones, have been investigated (Maeda et al., 1993; Maeda, 1998; Howe, 1998; Iida et al., 1999; Akamatsu and Tsutahara, 2010). This is because the simplest axisymmetric train nose shapes are these three shapes expressed by a quadratic function of the distance from the nose tip. Here, we call the three nose shapes the "three basic nose shapes." Then, optimization of the train nose shape (Iida et al., 1996; Ogawa and Fujii, 1996; Maeda, 1998; Iida et al., 1999; Kwon et al., 2001; Iida et al., 2003; Kikuchi et al., 2011; Muñoz-Paniagua et al., 2014) and acoustic analyses (Sugimoto, 1994; Sugimoto and Ogawa, 1998; Howe, 1998, 1998; Howe et al., 2000, 2006) were carried out. On the other hand, a tunnel entrance hood was developed (Ozawa, 1979; Iida et al., 2002) as an infrastructure countermeasure against micro-pressure waves. In the Japanese high-speed railway, Shinkansen, many tunnel hoods have been installed, and the train nose shapes have been optimized to reduce the micro-pressure waves. These countermeasures enable Japanese railway companies to operate the Shinkansen at 320 km/h every day without serious micro-pressure wave problems.

However, it is necessary to have greater understanding and develop new countermeasures for operation at higher speeds. For instance, the effect of offset running of a train and the nondimensionalization of the pressure gradient of a compression wave are still not completely understood. Trains run at a position offset

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Nomenclature

(x', y, z)	coordinates fixed on the train
(X, Y, Z)	$=(x/r_0, y/r_0, z/r_0)$
(x, y, z)	coordinates relative to the origin at the center of the tunnel
$[T]$	$=T - M(X - \ell/r_0)$
α	ratio of $(\partial p/\partial t)_{max}$ defined by Eq. (15)
Δp	pressure increase
Δp_H	pressure increase calculated by Hara's formula Eq. (4)
Δt	characteristic time of a compression wave defined by Eq. (7)
Δt_{max}	characteristic time of a compression wave generated by the optimum train nose
ℓ	end correction of the unflanged pipe ($=0.61r_0$)
ℓ_n	train nose length
η	efficiency of train nose
$(\partial p/\partial t)_{max}$	the maximum pressure gradient of a compression wave
ϕ	velocity potential
ρ	atmospheric density
τ	representative time of the compression wave
τ_0	representative time of the compression wave for a snub-nose train (r_0/UW_{max})
$A(x)$	cross-sectional area distribution of the train nose
$A^*(X)$	A/A_t
A_0	cross-sectional area of the main tunnel
A_t	cross-sectional area of the train
c	speed of sound
d	diameter of the main tunnel without its mirror image
d_0	diameter of the main tunnel considering its mirror image ($=2r_0$)
d_H	hydraulic diameter of the main tunnel without its mirror image
L_0	nondimensional length defined as $L_0 = \tau_0 U/r_0$
L_n	nondimensional train nose length $=\ell_n/r_0$
M	Mach number of the train ($=U/c$)
p	sound pressure
R	blockage ratio between the cross-sectional areas of the train and the tunnel ($=A_t/A_0$)
r_0	radius of the main tunnel considering its mirror image ($=\sqrt{(2A_0/\pi)}$)
T	$=tU/r_0$
t	time
U	train speed
W	weighting function, nondimensional pressure gradient waveform generated by a snub-nosed train (impulsive response)
W_s	simplified weighting function
Z_t	$=z_t/r_0$
z_t	train offset
superscript$*$	nondimensional or normalized value

from the tunnel center, such as the situation in double-track tunnels, whereas previous studies on the optimization of the train nose shape have assumed that a train runs at the center of the tunnel. Every Shinkansen train runs at the offset position because every tunnel in the Shinkansen line is a double-track tunnel. Therefore, the relationship between the train nose shape and the offset running should be clarified. A few reports on the effect of offset running are available, i.e., an experimental method (Tanaka et al., 2003), an acoustic analysis method (Howe, 1998), and the relationship between the offset and the windows on the entrance hood (Howe et al., 2006). The generation time of a compression wave depends on both the train nose length and the diameter of the tunnel. We need to nondimensionalize the results reported in the existing literature in order to compare them using a representative pressure and time because several different specifications are assumed in these studies, i.e., the train speed, the nose length, and the blockage ratio between the cross-sectional areas of the train and the tunnel. However, few studies have theoretically focused on the nondimensionalization considering the nose length.

In this study, the authors investigated the characteristics of compression waves generated by offset running axisymmetric trains to experimentally clarify the effect of offset running. The compression waves were measured by using a train launcher facility. The nondimensionalization of the compression waves considering the nose length was proposed on the basis of acoustic theory.

2. Model experiment for offset running trains with three basic nose shapes

2.1. Experiments to evaluate the micro-pressure waves generated by the three basic train nose shapes

The performance of the train nose shapes for achieving a micro-pressure wave reduction is evaluated on the basis of the maximum pressure gradient $(\partial p/\partial t)_{max}$ using train launcher facilities (Johnson and Dalley, 2002; Bellenoue et al., 2002; Fukuda and Iida, 2007; Fukuda, 2013) because the strength of the main source of the micro-pressure wave is proportional to $(\partial p/\partial t)_{max}$ when using the low-frequency approximation (Yamamoto, 1977).

Maeda (1998) conducted model experiments to evaluate $(\partial p/\partial t)_{max}$ of the three basic nose shapes using a train launcher facility that belonged to the Railway Technical Research Institute (RTRI) and clarified the following: (a) the smallest value of $(\partial p/\partial t)_{max}$ is observed for the paraboloid of revolution, and the largest value of $(\partial p/\partial t)_{max}$ is observed for the cone among the three basic nose shapes and (b) cutting off the front end of a train nose has little effect on $(\partial p/\partial t)_{max}$. Iida et al. (1996) reported the optimum cross-sectional area distribution of train noses using axisymmetric numerical simulations. From these results, they proposed a train nose shape design principle (Maeda et al., 1993; Maeda, 1998; Iida et al., 1996); "an effective nose shape has a small variation in the cross-sectional area along the nose axis, except at the front end." Today, this design principle has been applied to the nose shapes of many Japanese Shinkansen trains.

Maeda et al. (1993) first reported that the largest value of $(\partial p/\partial t)_{max}$ among the three basic nose shapes was obtained for the ellipsoid of revolution in an experiment, although numerical results and other experimental data in the same report showed that the largest value of $(\partial p/\partial t)_{max}$ was obtained for the cone. Later, after reexamination of the previous experimental results in Maeda et al. (1993), they Maeda (1998) corrected the data and showed that the largest value of $(\partial p/\partial t)_{max}$ was also obtained for the cone in experiments (Appendix A). Maeda et al. measured train speeds using optical sensors. Because a train model was guided with a taut steel wire at RTRI's train launcher facility, which Maeda et al. used, the model oscillates as the wire oscillates. In the train-speed measurement using the optical sensors, the optical sensors can fail to detect a train passing because of this oscillation. For a sharper train nose and a larger oscillation of the train model in the vertical plane normal to the horizontal sensor direction, a larger train-speed measurement error is caused. In the first report of Maeda