Numerical Analysis of Pressure Variation under Train Passage Using the Boundary Element Method*

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A train moving at high speed in an open area induces the formation of pressure distribution around itself. This pressure distribution moves with the speeding train, bringing about environmental problems. Furthermore, pressure variation increases in magnitude as train speed increases. It is therefore necessary to predict the increase in magnitude and the characteristic of pressure variation in order to successfully carry out high speed railway projects. Using the boundary element method, we investigated pressure variation brought forth by train passage. Numerical results are compared with measured results from a field test, and qualitative agreement between them is determined. We are in the process of seeking countermeasures to reduce pressure variation during train passage.

Key Words: Pressure Variation at Train Passage, Low-Frequency Oscillation, Environment, Boundary Element Method, Shinkansen

1. Introduction

In railway speedup projects, the demand for maintenance of the environment along railways has steadily increased. In such cases, harmonization of the projects with the environment is one of the most important problems. In Japan, where densely populated residential areas are found beside railway tracks, a major concern is to minimize the effect of high-speed trains on the environment.

Due to the steady increase in train speed, attention has been shifted to aerodynamic phenomena in railway technology. As one such phenomenon, the pressure variation produced by a train moving

through open sections is investigated. When a train is moving at high speed, positive pressure is produced at the head of the train, while negative pressure is produced at the shoulder of the train, as shown in Fig. 1. Despite the fact that the pressure fields do not vary at all, the pressure field is viewed as a pressure variation beside railway tracks because it moves with the train (Fig. 1). Pressure variation, unlike sound waves, is a phenomenon called pseudo-sound from the point of view of physics⁽¹⁾. Sound propagates by itself at the speed of sound, but the pressure field around a train never propagates by itself. As the train moves, the field moves at the train's running speed.

We consider here a simple fluid dynamic model that is conceived to understand the characteristics of pressure variation. Then a numerical calculation is performed using the boundary element method to examine the effect of a real train configuration on pressure variation during train passage. Numerical results are compared with the results of field tests to confirm the validity of the numerical simulation. Countermeasures for reducing pressure variation are also studied.

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Fig. 1 Pressure distribution around a train and pressure variation with train passage

Fig. 2 Flow patterns around a train

2. Fluid Dynamic Model of Pressure Variation at Train Passage

The air flow around a moving train on the ground is roughly divided into three parts as shown in Fig. 2, i.e., a flow in the vicinity of the head, a boundary layer flow in the middle portion and a wake in the tail. Pressure variation from the passage of a train is observed mainly at the passages of the head and the tail. Pressure variation at the tail becomes smaller than that at the head due to the influence of flow separation at the tail. Accordingly, the maximum pressure variation occurs when the head of the train passes.

A fluid dynamic model is assumed in order to grasp the characteristics of pressure variation at the passage of the train head, although the shape of the head is not simulated correctly. A source moving at speed U , which is equivalent to the source in uniform flow, as shown in Fig. 3, can be regarded as a simple fluid dynamic model of pressure variation at train passage. In addition, the use of an imaging method is recommended to determine the effect of the ground (Fig. 4). If two sources with strength m are placed in a uniform flow of velocity U at positions with heights $b+h$ and $-(b+h)$, then the velocity potential at point P where a flow field is obtained is given by

Fig. 3 Fluid dynamic model with a source existing in a uniform flow

Fig. 4 Expression of the ground effect by an imaging method

$$\Phi = Ux - \frac{m}{r_1} - \frac{m}{r_2} \quad (1)$$

The first term represents uniform flow, whereas the second and third terms represent the source and its image, respectively. Here, m is strength of the source; and r_1 and r_2 are distances between source point and point P and between image and point P , respectively. Flow velocity $\mathbf{u}=(u, v, w)$ is obtained by differentiating the velocity potential with respect to each direction. Pressure coefficient C_p can be obtained from Bernoulli's theorem.

We consider the pressure distribution in the x direction at position y ($y \gg b$ far away from the body) in the transverse direction. The pressure distribution that is formed around the train in a uniform flow is regarded as pressure variation that is generated by a moving train in static fluid. This pressure variation on the ground ($z=0$) is given by the expression below.

$$C_p = -\frac{4m}{U} \frac{x}{r_1^3} - \frac{4m^2}{U^2} \frac{x^2}{r_1^6} \quad (2)$$

Fig. 5 Position where the pressure variation peaks in positive and negative values

The position where the maximum amplitude of pressure variation occurs is calculated by

$$\tan \theta = \frac{\sqrt{y^2 + (b+h)^2}}{x} = \pm \sqrt{2}. \quad (3)$$

From this expression, it follows that peaks of positive and negative pressures are formed along the lines of $\theta = 144.7^\circ$ and $\theta = 54.7^\circ$ in Fig. 5, respectively. That is to say, the interval in the x direction between the positive peak pressure and the negative peak pressure of pressure variation is increased as the distance in the y direction from the train increases. The maximum value of pressure variation is obtained as shown below by substituting the coordinate of maximum amplitude position into Eq. (2).

$$(C_p)_{\max} = \mp \frac{2}{3\sqrt{3}} \frac{b^2}{y^2 + (b+h)^2} - \frac{1}{27} \frac{b^4}{\{y^2 + (b+h)^2\}^2} \quad (4)$$

The maximum value of pressure variation decreases in inverse proportion to the square of the distance from the body in the range $y \gg b+h$.

Pressure is obtained by multiplying pressure coefficient by dynamic pressure.

$$p = \frac{1}{2} \rho U^2 C_p \\ = -\frac{\rho A U^2}{2\pi} \left(\frac{\cos \theta}{r_1^2} + \frac{A \cos^2 \theta}{4\pi r_1^4} \right). \quad (5)$$

where we use the following relations: $b = \sqrt{\frac{A}{\pi}}$, $m = \frac{b^2 U}{4}$, and $\cos \theta = \frac{x}{r_1}$. Distance b is equivalent radius to represent a train. Distance b is determined from the maximum cross section A on the assumption that the cross section of the train body is a circle when only the source is placed in the uniform flow, with h being the distance from the ground to the bottom of the body. From Eq. (5), it is seen that pressure generated by the moving train is proportional to the maximum cross section of the train, and proportional to the square of train speed.

3. Numerical Calculation Method

The flow around the train head is approximated

with the source existing in a uniform flow in section 2. However, it is difficult to consider the effect of the configuration of an actual body with the source in a uniform flow. Accordingly, we make use of the three-dimensional boundary element method while keeping in mind that the flow around the head can be dealt with as a potential flow and that we can express the actual configuration of the train by three-dimensional boundary element method.

Assuming that the flow field is incompressible, inviscid, and irrotational, namely a potential flow, the velocity potential Φ and the disturbance velocity potential ϕ are determined as shown below.

$$\Phi = U(x + \phi) \quad (6)$$

Here, the x -axis is taken in the direction that conforms to the uniform flow U . Furthermore, the governing equation in the flow field is expressed with Laplace's equation with respect to the disturbance velocity potential as follows:

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \phi = 0. \quad (7)$$

Apply the Green function shown below to Eq. (7),

$$\Delta G = -\delta(x-x_1, y-y_1, z-z_1), \quad (8)$$

where δ is Dirac's δ function. Combining Eq. (7) with Eq. (8), using Green's formula, and substituting $G = 1/4\pi r$, as a solution of equation (8), into Green's formula give an integral equation for the disturbance potential ϕ as shown below.

$$\frac{1}{2} \phi(P) = \frac{1}{4\pi} \iint_{S_B} \phi(Q) \frac{\partial}{\partial n(Q)} \frac{1}{r(P, Q)} dS \\ - \frac{1}{4\pi} \iint_{S_B} \frac{\partial \phi(Q)}{\partial n(Q)} \frac{1}{r(P, Q)} dS \quad (9)$$

$$r(P, Q) = \sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2},$$

where r represents the distance between the collocation point $P(x_1, y_1, z_1)$ and the integral point $Q(x, y, z)$ and S_B represents the body surface. Assuming that $\iint$ indicates Cauchy's principal value of the integral, the above expression is a Fredholm integral equation of the second kind.

As the boundary conditions, the expressions shown below are applied.

B.C. 1: The flow moves along the body surface S_B .

$$\frac{\partial \phi}{\partial n} = -\frac{\mathbf{U} \cdot \mathbf{n}}{U} \quad (10)$$

B.C. 2: The flow becomes uniform flow at infinity.

$$\phi = 0, \quad (11)$$

where $\mathbf{U}$ is the velocity vector of the uniform flow, and $\mathbf{n}$ is an outward normal vector perpendicular to the body surface.

A flow field can be obtained by solving the integral equation with the disturbance velocity potential ϕ

as an unknown. Here, let the body surface be divided into square elements in accordance with Morino et al.'s method⁽²⁾; furthermore, let the variations ϕ and $\mathbf{n}$ on the individual elements be represented by the values at the center of the elements. Assuming that the distribution in the elements is constant, discretization is made. This method allows the disturbance velocity potential ϕ on the body surface S_B to be divided into the division number N of the elements. Thus, the simultaneous equation shown below is obtained.

$$[\delta_{hk} - C_{hk}]\{\phi_k\} = -[B_{hk}]\left\{-\frac{\mathbf{U} \cdot \mathbf{n}_k}{U}\right\}, \quad (12)$$

where δ_{hk} indicates Kronecker's delta, and aerodynamic influence coefficients C_{hk} and B_{hk} are expressed as shown below, respectively.

$$C_{hk} = \left[\frac{1}{2\pi} \iint_{S_h} \frac{\partial}{\partial n} \left(\frac{1}{r} \right) dS \right]_{P=P_h}$$

$$B_{hk} = \left[\frac{1}{2\pi} \iint_{S_h} \frac{1}{r} dS \right]_{P=P_h}$$

The aerodynamic influence coefficients were analytically obtained by Morino et al.⁽²⁾ Therefore, no numerical integrals are used in obtaining C_{hk} and B_{hk} .

The velocity can be obtained by differentiating the velocity potential. For the differential along the surface of the body, Yanagizawa and Kikuchi's method⁽³⁾ is employed. In order to obtain velocity and pressure distribution, we approximate the velocity potential Φ using the parabolic distribution for steady flow:

$$\Phi = U(x + \phi) = as^2 + bs + c, \quad (13)$$

where s is the length along a circular arc through three consecutive collocation points, to be measured from the center collocation point. Constants a , b and c are calculated from the values of velocity potential at the three collocation points. We need derivatives of Φ with respect to s in two directions determined by a pair of three collocation points as

$$\frac{d\Phi}{ds_1} = \Phi_{s_1} = 2a_1s_1 + b_1, \quad (14)$$

$$\frac{d\Phi}{ds_2} = \Phi_{s_2} = 2a_2s_2 + b_2,$$

where s_1 measured from $P_{i,j}$ is the length along the circular arc through points $P_{i-1,j}$, $P_{i,j}$, $P_{i+1,j}$ and s_2 measured from $P_{i,j}$ is that along the circular arc through $P_{i,j-1}$, $P_{i,j}$, and $P_{i,j+1}$, as shown in Fig. 6.

We want to determine the unit tangential vectors $\mathbf{l}_1$ and $\mathbf{l}_2$ at the central collocation point $P_{i,j}$ along s_1 and s_2 , respectively. In a special case of the three consecutive collocation points lying on a straight line, the unit tangential vector $\mathbf{l}$ is simply given by

$$\mathbf{l} = \frac{\mathbf{b}}{|\mathbf{b}|}. \quad (15)$$

If this is not the case, $\mathbf{l}$ is determined according to the following scheme. We denote here by $\mathbf{r}_0$ the

position vector of the center of the circle through points $P_{i-1,j}$, $P_{i,j}$, $P_{i+1,j}$ and define vectors $\mathbf{a}$, $\mathbf{b}$ and $\mathbf{c}$ as shown in Fig. 6. With these preliminaries, vector $\mathbf{r}_0$ is calculated as follows:

$$\mathbf{r}_0 = \mathbf{a} + s_c \mathbf{b} + t_c \mathbf{c} \quad (16)$$

with

$$s_c = \frac{(\mathbf{b}^2 - \mathbf{b} \cdot \mathbf{c}) \mathbf{c}^2}{2(\mathbf{b}^2 \mathbf{c}^2 - (\mathbf{b} \cdot \mathbf{c})^2)} \quad (17)$$

$$t_c = \frac{(\mathbf{b} \cdot \mathbf{c} - \mathbf{c}^2) \mathbf{b}^2}{2((\mathbf{b} \cdot \mathbf{c})^2 - \mathbf{b}^2 \mathbf{c}^2)}.$$

Then the tangential vector is given by

$$\mathbf{l} = \mathbf{n}_n \times \mathbf{n}_r, \quad (18)$$

where

$$\mathbf{n}_n = \frac{\mathbf{b} \times \mathbf{c}}{|\mathbf{b} \times \mathbf{c}|} \quad (19)$$

$$\mathbf{n}_r = \frac{\mathbf{a} - \mathbf{r}_0}{|\mathbf{a} - \mathbf{r}_0|}.$$

Vector $\mathbf{n}_n$ is the unit normal vector of the plane determined by vectors $\mathbf{b}$ and $\mathbf{c}$, while vector $\mathbf{n}_r$ is the unit vector along the radius of the circle through point $P_{i,j}$. The symbol $(\cdot)$ denotes the inner product of vectors and the symbol $(\times)$ denotes the external product of vectors. In the directions of s_1 and s_2 , we have

$$\mathbf{l}_1 = \frac{\mathbf{b}_1}{|\mathbf{b}_1|}, \mathbf{l}_2 = \frac{\mathbf{b}_2}{|\mathbf{b}_2|} \quad \text{along straight lines,} \quad (20)$$

$$\mathbf{l}_1 = \mathbf{n}_{n_1} \times \mathbf{n}_{r_1}, \mathbf{l}_2 = \mathbf{n}_{n_2} \times \mathbf{n}_{r_2} \quad \text{along curves.} \quad (21)$$

If we take the e_1 axis in the direction of s_1 , and the e_2 axis in the direction perpendicular to e_1 and in the plane spanned by s_1 and s_2 , we have

$$\phi_{e_1} = \frac{d\Phi}{de_1} = \frac{d\Phi}{ds_1} \quad (22)$$

$$\phi_{e_2} = \frac{d\Phi}{de_2} = \frac{1}{\sqrt{1 - (\mathbf{l}_1 \cdot \mathbf{l}_2)^2}} \left\{ \frac{d\Phi}{ds_2} - (\mathbf{l}_1 \cdot \mathbf{l}_2) \frac{d\Phi}{ds_1} \right\}. \quad (23)$$

Fig. 6 Derivative along body surface

Then the pressure coefficient and the velocity vector are expressed as

$$\nabla \Phi \cdot \nabla \Phi = \Phi_{e1}^2 + \Phi_{e2}^2 \quad (24)$$

$$C_p = \frac{p - p_\infty}{\frac{1}{2} \rho U^2} = 1 - \frac{(\Phi_{e1}^2 + \Phi_{e2}^2)}{U^2} \quad (25)$$

$$\mathbf{v} = \Phi_{e1} \cdot \mathbf{l}_1 + \Phi_{e2} \cdot \frac{\mathbf{l}_2 - (\mathbf{l}_1 \cdot \mathbf{l}_2) \mathbf{l}_1}{\sqrt{1 - (\mathbf{l}_1 \cdot \mathbf{l}_2)^2}} \quad (26)$$

On the other hand, the differential in obtaining a velocity field in space is given in accordance with Suciu and Morino's method⁽⁴⁾, and the equation shown below is used for that purpose.

$$\mathbf{v}_h = -\frac{1}{2} \sum_k \left(\frac{\partial \phi}{\partial n} \right)_k \nabla_* B_{hk} + \frac{1}{2} \sum_k \phi_k \nabla_* C_{hk} + \mathbf{U} \quad (27)$$

$$\nabla_* C_{hk} = \left[\frac{1}{2\pi} \iint_{S_h} \nabla_* \frac{\partial}{\partial n} \left(\frac{1}{r} \right) dS \right]_{P=P_h}$$

$$\nabla_* B_{hk} = \left[\frac{-1}{2\pi} \iint_{S_h} \nabla_* \frac{1}{r} dS \right]_{P=P_h}$$

where ∇_* is gradient at point $P(x_1, y_1, z_1)$. The aerodynamic influence coefficients $\nabla_* C_{hk}$ and $\nabla_* B_{hk}$ can be evaluated analytically as coefficients C_{hk} and B_{hk} .

4. Analytical Results

Calculations were made with respect to three types of trains as shown in Fig. 7. These are 16-car trains each of which is 400 m long. Equipment on the roof such as pantograph shields, bogies, and equipment underneath the floor are eliminated. The maximum cross sections A of the individual trains are listed below.

Train A: 11.2 m²

Train B: 12.9 m²

Train C: 14.1 m²

To facilitate the development of numerical models, the part ranging from the side of the car to the bottom of the car is reduced to a structure similar to a body mount. For this reason, a slightly wider cross section than the real one is adopted with the car in this case. Regarding the configuration of the ground, simplification is attained by eliminating the roadbed, cross-ties, and rails on the assumption that the ground surface is level with the track formation.

Fig. 7 Numerical models

In Fig. 8, the pattern of pressure variation at a point 10 m from the center of the train is shown (refer to Fig. 11 for the measurement points). The pressure coefficient C_p can be obtained from the calculation, and the equation shown below is used for conversion of C_p to pressure.

$$\Delta p = C_p \cdot \frac{1}{2} \rho U^2, \quad (28)$$

where Δp is the difference of pressure from standard atmospheric pressure (Pa), ρ is the density of air (1.226 kg/m³), and U is the train speed (m/s). The characteristics shown below can be read from the figure. The pressure variation pattern exhibits positive pressure/negative pressure at the head, and negative pressure/positive pressure at the tail (in the potential analysis, pressure variation is symmetric at head and tail). At the head, the negative pressure peak is slightly greater than the positive pressure peak. Since the pressure variations accompany train movement, they are considered to be proportional to the square of train speed, and the widths of the peak values are inversely proportional to train speed.

To confirm the propriety of the calculation, comparison is made between calculated and measured values with respect to Train A and Train B for which measured values are given. At the head, the calculated results of peak values of positive pressure are almost the same as the measured ones, whereas the calculated results of absolute peak values of negative pressure are smaller than the measured ones. This phenomena might be caused by the frequency response of a measuring device used in the field test. At the tail, the measured pressure variation is smaller than the calculated one because separation occurs in the measured values. In the field test result of Train

Fig. 8 Patterns of pressure variation

A, the negative pressure variations caused by pantograph shield are seen in the middle part of pressure variation, on the other hand, in numerical result no pressure variation pattern is found in the middle part of pressure variation since pantograph shields are neglected.

It is difficult to take the effect of viscosity or compressibility in the boundary element method into consideration, but the maximum pressure variation is produced when the head of a train passes. Thus, the calculated value fully reflects the tendency of the measured value for this part. Therefore, when pressure variation at the time of train passage is estimated using the maximum amplitude (p-p value), the method referred to here is found to be suitable. On the other hand, it seems that accurate estimation of pressure variation at a position of tens of meters from the center of the train is difficult by other numerical methods.

Next, power spectra of pressure variation of Train A are shown in Fig. 9. Although there is a difference between calculated value and measured value in the high-frequency region of more than 10 Hz, they are in good agreement in the low-frequency region of less than 10 Hz. The difference in the region

of more than 10 Hz is believed to result from the fact that pressure variation as a sound wave is contained in this part. Since a stationary pressure field of the flow is calculated this time, no phenomenon of pressure variation as a sound wave is reproduced. However, as can be deduced from the figure, almost all the components of the spectrum are less than 10 Hz. Therefore, to grasp pressure variation at the time of train passage, a method by which the components in this range can be determined is believed to be sufficient.

Numerical results are also compared with the measured values with respect to the distance attenuation of the maximum amplitude (Fig. 10). As the measurement point, the distance from the center of the train is taken. Five points of 7, 10, 13, 23, and 30 m are taken depending on the measured values (Fig. 11). In the measured values, there is a tendency for the maximum amplitude to be almost inversely proportional to the square of the distance from the center of the train. It is noted that the result of the numerical calculation becomes smaller than the value inversely proportional to the square of the distance in the vicinity of the train, especially for Train C. This might result from the fact that the head configuration

Fig. 9 Power spectra of pressure variation

Fig. 10 Distance attenuation of the maximum amplitude of pressure variation

of Train C is less reduced in the transverse direction, resulting in a wedge-like configuration. Thus, the flow leaps vertically, decreasing in the transverse direction.

It can be seen that there exists a difference in the maximum amplitude depending on train type. Because of the difference in either the shape of the head or the car's maximum cross section, it cannot be decided what is the cause of such difference. However, taking account of the fact that the size of the train follows the order of Train A, B, and C, the car's maximum cross section is believed to exert a major influence on the matter mentioned above.

5. Reduction Method of Pressure Variation due to Train Passage

In order to reduce pressure variation due to train

Fig. 11 Measurement points of pressure variation

Fig. 12 Numerical model with wall

Fig. 13 Pattern of pressure variation with and without a wall

passage, the magnitude of the peak pressure should be decreased and the gradient of pressure variation should be reduced. As countermeasures for such reduction, different approaches to the car and to the ground can be taken. First, a qualitative treatment of the countermeasure is described.

A moving train always displaces the air mass surrounding itself. It is expected that the smaller the amount of air mass displaced, the smaller will be the resulting pressure variation. To minimize the amount of air mass displaced by the train, the cross section of the cars should be minimized. On the other hand, if the air mass displaced by the train is allowed to disperse not in the transverse direction but in the upward direction of the train, its influence on the wayside is believed to be lessened. To realize such flow, a two-dimensional wedge-like configuration is believed to be adequate for the head of the train. To reduce the gradient of pressure variation, the head of a car should be elongated.

Although the countermeasures mentioned above can be applied to newly designed cars, other countermeasures should be taken from the ground side for cars currently in use. One such countermeasure is to install a wall in order to prevent pressure from acting on the sides of the railway.

The results of calculations made to explain the effect of the wall on reducing pressure variation are summarized as follows.

As shown in Fig. 12, a calculation was made, exclusively for Train A, to clarify the effect of a wall installed on the side of the railway. Measurement points are shown in Fig. 11. A wall with finite length was built to obtain measured values, but it was assumed that a calculated train model is placed in a uniform flow with an infinitely long wall. The wall is located 6 m away from the center of the train, and is 5 m high. The patterns of pressure variation with and without a wall are shown in Fig. 13. It is doubtful whether the effect of the wall on pressure variation at the time of train passage can be determined by potential analysis. However, as can be deduced from the figure, pressure variation is decreased by presence of

Fig. 14 Effect of height on pressure variation

a wall. Thus, the analysis of the wall effect on pressure variation at the time of train passage may also be possible by the present method.

The relationship between the maximum amplitude of pressure variation and the distance from the center of the train is shown in Fig. 14. The maximum amplitude in the presence of the wall is smaller than that in the absence of the wall. The reduction effect in the vicinity of the wall is greater than that at a distance from the wall.

To explain the effect of wall height, calculations were made with 3 wall heights, i.e., 2.5, 3.5, and 5.0 m. The results are shown in Fig. 14. As expected, as the wall height is increased, the maximum amplitude is decreased. For the sake of comparison, measured values are also shown. The calculated values exhibit the same tendency as the measured values. It is revealed that the reduction effect is decreased when the measurement point is far from the wall.

The reduction of pressure variation, of which the maximum amplitude value at a point 13 m from the center of the train is standardized for the value without a wall, is shown in Table 1. It seems that the calculated values slightly underestimate the effect of wall height compared with the measured value; however, the tendency reflects the results of the measured values very well.

6. Conclusions

For the purpose of clarifying the characteristics of pressure variation due to train passage, a simple fluid dynamic model was conceived and numerical simulation was performed using the boundary element method. Numerical results were compared with the results of field tests to confirm the validity of the numerical simulation, and qualitative agreement was found between them. We sought countermeasures to

Table 1 Comparison of the reduction effect by wall height

(Measurement point : 13 m from the center of the train)

Wall height	Without wall	2.5m	3.5m	5.0m
Calculated value	1	0.86	0.76	0.61
Measured value	1	0.75	0.62	0.54

reduce pressure variation during train passage. As a countermeasure, the effect of a wall installed on the side of the railway was analyzed.

Many 270 km/h-class trains, including Nozomi of Tokaido/Sanyo Shinkansen, are in operation, and commercial operation at a maximum speed of 300 km/h is about to be realized. To increase the speed even more, it is imperative to understand aerodynamic phenomena at high speeds such as pressure variation and train wind. To this end, we are determined to continue our research in cooperation with JR companies.

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