Analysis of flow velocity fluctuation around a train model running in a tunnel using restored waveforms

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Abstract
A pantograph receives aerodynamic force while a train is traveling. As the aerodynamic force increases in proportion to the square of the flow velocity relative to the pantograph, its influence on the pantograph becomes apparent, especially for high-speed trains. When a high-speed train runs in a tunnel, the flow velocity relative to the pantograph is faster than that in an open section. In this study, we measured the flow velocity around a train model running in a tunnel using a rake of total-pressure tubes mounted on the train model. The measured waveforms were distorted owing to the influence of the frequency characteristics of the measurement system. Therefore, we developed a restoration method and applied it to the measured waveforms to obtain the restored waveforms of the flow velocity. With the restored waveforms, we obtained several statistical values, such as the average flow velocity and standard deviation of the fluctuating flow velocity around the train model. Furthermore, we proposed a method for predicting the flow velocity around the train model, including fluctuating components in a frequency range of a pantograph contact performance. The proposed method can predict the flow velocity at the panhead of a pantograph by considering the average flow velocity profile and turbulence component profile in the tunnel cross section, which could not be taken into account so far.

Keywords: Flow velocity measurement, Train, Tunnel, Restoration filter, Fluctuating flow velocity

1. Introduction

To increase the speed of a train, the aerodynamic phenomena caused by the increase in speed should be clarified. The aerodynamic force increases in proportion to the square of the airflow velocity relative to the pantograph (Baker et al., 2019). A pantograph is a train vehicle equipment installed on the train roof. The lift force that pushes the pantograph to a contact wire is the most important component of the aerodynamic force generated on the pantograph. The panhead is a component that is attached to the top of the pantograph and slides directly on the contact wire. The panhead is also called a collector head. The lift force on the panhead significantly contributes to the total lift force of the pantograph. The contact performance is one of the most important performances of a pantograph. The contact performance is examined by where or not the contact force does not become zero in the frequency range below approximately 20 Hz. The contact performance is greatly affected by the lift force. Thus, it is necessary to properly estimate the flow velocity, including the fluctuating component around the panhead, up to approximately 20 Hz. When a high-speed train travels in a tunnel, the flow velocity relative to the pantograph is faster than that in the open section owing to the influence of the tunnel wall and the pressure waves generated when the train enters the tunnel.

The flow velocity around a train is preferably measured in an on-track vehicle test. Crespi et al. measured the train-side flow velocity in an open section with a laser Doppler anemometer and showed that the average flow velocity distribution followed the 1/10 to 1/11 power laws with a boundary layer thickness of 2.0–2.5 m regardless of the distance from the head of the train (Crispi et al., 1994). Owing to the large influence of natural wind, the average flow velocity distribution deviated from the 1/7 power law, and the development process of the boundary layer thickness in the flow direction could not be captured. Sakuma et al. measured the train-side flow velocity in the open section and tunnel section
using hot-wire anemometers and a rake of pitot tubes and showed that the average flow velocity distribution followed the 1/8 to 1/10 power laws (Sakuma et al., 1998). They used the train velocity instead of the flow velocity outside the boundary layer as the representative velocity when determining the flow velocity distribution in the tunnel section. Morikawa et al. measured the roof flow velocity in a tunnel section with a rake of pitot tubes and showed that the boundary layer thickness was 0.33 m or less at approximately 25 and 175 m from the head of the train. (Morikawa and Iwainaka, 2001). Uster et al. measured the roof flow velocity in the tunnel section with a rake of pitot tubes and showed that the boundary layer thickness was 0.40 and 0.79 m at approximately 100 and 300 m from the head of the train, respectively (Uster et al., 2017). Ikeda et al. installed a three-hole probe on the panhead and measured the flow velocity and flow angle of attack at the panhead position (Ikeda et al., 2011). The actual phenomena can be understood from the results of an on-track vehicle test, which cannot be easily conducted owing to economic and time constraints. In addition, the measured flow velocity is always influenced by natural disturbances, such as wind. All of the on-track vehicle test results mentioned above show only the results of the average flow velocity, not those of the fluctuating flow velocity. In addition, because the results were obtained in on-track vehicle tests, the train shape and tunnel shape were different, and the phenomena were difficult to interpret.

The measurement of the flow velocity using a scale model is excellent in terms of cost and ease of implementation. In scale model experiments, we can control the measurement conditions and obtain data under simplified circumstances. The relative motion between the tunnel and train must be reproduced to measure the flow velocity around the train running inside the tunnel. This experiment must be performed using a moving model propelled by a model launcher instead of a static model in a wind tunnel. Several studies have reported the measurement of the flow velocity around a train using a moving model. Baker et al. measured the roof and side flow velocity in an open section using a rake of hot-film anemometers and particle image velocimetry and showed that the slipstream can be divided into four different regions (Baker et al., 2001). Soper et al. measured the slipstream of a freight train in an open section with cobra probes installed on the ground side and showed that the phenomena of the slipstream of the freight train were different from those of a high-speed train (Soper et al., 2014). Bell et al. measured the slipstream of a high-speed train in an open section with hot-wire anemometers and a rake of pitot tubes installed on the ground side and clarified the wake structure of the train (Bell et al., 2015). The model experiments described above show the results of the flow velocity around the train in the open section measured from the ground side, not those in the tunnel section measured from the train vehicle side.

Various methods have been devised to measure the flow velocity: pressure-type anemometers (e.g., pitot tubes), cup-type anemometers, windmill-type anemometers, hot-wire/hot-film anemometers, ultrasonic anemometers, and laser anemometers. Among these methods, the pressure-type anemometers can only be mounted on the train model with a diameter of several centimeters moving at a speed above 100 km/h to measure the flow velocity around a train model. Because a measurement system using a pressure guide tube has frequency characteristics, distortion of the measured pressure waveform is inevitable. The original waveforms without distortion can be restored by applying a restoration filter to the measurement waveforms.

Until now, the characteristic curve method has been used to predict aerodynamic phenomena around a train running in a tunnel. Yamamoto formulated a system of equations to obtain the variations in the pressure and the flow velocity due to the waves reciprocating in the tunnel and a train running in the tunnel and applied the characteristic curve method to numerical calculations (Yamamoto, 1968). Yamamoto’s method laid the foundations of studies on the unsteady aerodynamic phenomena of the train-tunnel system; this method was improved and extended to deal with various complicated cases (Kajiyama et al., 1994; Vardy, 1976). The characteristic curve method assumes a one-dimensional flow and cannot predict a fluctuating flow velocity due to turbulence.

The purpose of the present study is to clarify the phenomenon of flow velocity around a train model running in a tunnel section. To understand this phenomenon, we simplified the measurement conditions. We used data when a train model with a circular cross-section ran in the center of a tunnel with a circular cross section. We obtained the flow velocity, including the fluctuating component from the pressure waveform measured by the rake of the total pressure tubes. The Bergh–Tijdeman model (Bergh and Tijdeman, 1965) was adopted as the frequency characteristic of the measurement system. A digital restoration filter was used to restore the waveform. The parameters required to determine the frequency characteristics of the measurement system were obtained from the experiments. By analyzing the flow velocity around the train model using the restored waveform, we obtained various characteristics, i.e., the average flow velocity, standard deviation of the fluctuating flow velocity, turbulence intensity, displacement thickness, momentum thickness, shape factor, and frequency distribution of the fluctuating flow velocity. Furthermore, we proposed a method for predicting the
flow velocity, including the fluctuating flow velocity in the frequency range of the pantograph contact performance.

2. Outline of the model experiment

We developed a simple train model equipped with a rake of total-pressure tubes to measure the flow velocity around the train model (Kikuchi et al., 2018). Figure 1(a), (b) and (c) show a schematic of the train model, a photograph of the entire experimental setup, and a magnified photograph of the rake of the total-pressure tubes, respectively. The rake of the total pressure tubes consisted of seven bulge pipes with an outer diameter of 1.1 mm. The length of the train model was 1.300 m, with an outer diameter of 0.060 m. The scale of the train model was 1/62, without considering the mirror image. The nose and tail parts were paraboloids of revolution (aspect ratio = 4). The distance from the tip of the rake of the total pressure tubes to that of the train model was 0.800 m. The heights of the total-pressure tubes from the surface of the train model were \( h = 2.0, 7.0, 12.0 \) and 17.0 mm in Rake A and \( h = 4.5, 9.5 \) and 14.5 mm in Rake B. The distance from the pressure hole to the pressure sensor (including the bulge pipe and pressure guide tube length) was 105 mm. The pressure guide tube was a Scanivalve URTH-063. The pressure sensor was All Sensors 20-INCH-D2-4V-MINI P2NS. The static pressure tap, which was located 0.8 m away from the tip of the train model, was installed on the surface opposite to the rake of total pressure tubes. The data logger mounted on the train model was Tess Ultra-Small data logger (sampling frequency: 5 kHz). The length and inner diameter of the tunnel were 12.240 m and 0.130 m (the ratio of the train/tunnel cross-sectional area was \( R_b = 0.213 \)). The speeds of the train model were 110, 130, and 150 km/h. The measurements were performed three times for each train speed and labeled as No. 1, No. 2, and No. 3. The train model was launched using the model launcher. The train model speed was measured by detecting the magnetic field generated when the train nose passed through two wire coils placed 2 m apart at the tunnel entrance. For details of the experiment, please refer to Kikuchi et al. (2018).

![Fig. 1 Experimental equipment and rake of the total-pressure tubes](image-url)
3. Waveform-restoration method  
3.1 Outline of the frequency characteristics of the measurement system

As shown in Fig. 2(a), a measurement system comprising a pressure gauge with volume \( V_p \) at the end of a single pressure guide tube with radius \( R \) and length \( L \) was considered. According to Bergh and Tijdeman (1965), who investigated the frequency characteristics of a measurement system using a pressure guide tube and pressure gauge, the following theoretical equation holds for the relationship between the fluctuating pressures on the input side \( p_i \) and the output side \( p_o \) according to the fluid dynamics model:

\[
\frac{p_o}{p_i} = \left[ \cosh \left( \frac{a_0 \Gamma}{\nu} \right) + \frac{v \pi n}{\nu} \left( \frac{a_0 \Gamma}{\nu} \right) \sinh \left( \frac{a_0 \Gamma}{\nu} \right) \right]^{-1},
\]

where \( \Gamma = \left[ \frac{J_0(\frac{3\pi S}{\nu})}{J_2(\frac{3\pi S}{\nu})} \right]^{\frac{1}{n}} \), \( S = R \left( \frac{p_o \omega}{\mu} \right)^{\frac{1}{2}}, \sigma = \left( \frac{\mu C_p}{\lambda} \right)^{\frac{1}{2}}, \) and \( a_0 = \sqrt{\frac{\rho_a}{\nu}} \).

Here, \( a_0 \) is the speed of sound, \( C_p \) is the specific heat at a constant pressure, \( f \) is the frequency, \( i \) is the imaginary unit, and \( J_0 \) and \( J_2 \) are the first-kind Bessel functions of the 0th and 2nd orders, respectively. Furthermore, \( n \) is the polytropic constant of the air in the pressure guide tube, \( n_p \) is the polytropic constant of the air in the pressure gauge volume, \( p_o \) is the average pressure, \( S \) is the shear wave number, \( V_p \) is the volume of the pressure guide tube (= \( \pi R^2 L \)), \( \Gamma \) is the propagation constant of the pressure wave passing through a circular tube, \( \gamma \) is the specific heat ratio, \( \mu \) is the viscosity coefficient of air, \( \rho_a \) is the density of air, \( \sigma \) is the square root of the Prandtl number, and \( \lambda \) is the thermal conductivity of the air, and \( \omega \) is the angular frequency (= \( 2\pi f \)).

3.2 Parameter estimation using an acoustic calibration device

As described in Section 3.1, the main parameters for determining the frequency characteristics of the measurement system are the radius \( R \) and length \( L \) of the pressure guide tube and the volume \( V_p \) of the pressure gauge. We conducted experiments on pressure guide tubes with two different inner diameters and five different lengths and a pressure gauge to obtain the standard parameter values. The following target pressure guide tubes were used in our experiments: Scanivalve URTH-040 (inner diameter \( \phi = 0.86 \) mm; length \( L = 100 \) mm) and URTH-063 (inner diameter \( \phi = 1.37 \) mm; length \( L = 70, 100, 200, 1000, \) and \( 2000 \) mm). The target pressure gauge was the All Sensors 20-INCH-D2-4V-MINI P2NS (full scale = 4980 Pa; resonance frequency = 2000 Hz). The reference pressure gauge was Kulite XCS-190-5G (full scale = 35000 Pa; resonance frequency = 150000 Hz).

Figure 2(b) shows the schematic of the acoustic calibration device. The device was equipped with small speakers above and below the cylindrical pressure chamber. Fluctuating pressures were generated by inputting signals with opposite phases to the upper and lower small speakers. The oscillator was RS PRO AFG21005, with the NF Corporation NF 4005 DC amplifier and NF Corporation EZ7510 data recorder. The sampling frequency of the data was changed between 5 and 20 kHz depending on the length of the pressure guide tube.

The reference pressure gauge was directly attached to the pressure chamber, and the target pressure gauge was attached via a target pressure guide tube. The frequency characteristics of the measurement system were evaluated by comparing the pressure waveforms measured by the reference and target pressure gauges. The amplitude ratio and phase difference of the measurement system were obtained using a fast Fourier transform analyzer (Ono Sokki CF-7200A).

In the target frequency range of these experiments, one or two points of the resonant frequency of the measurement system were observed. The phase characteristics were observed to be nonlinear. Figure 2(c) shows one of the experimental results. We estimated the standard values of the parameters by trial and error so that the theoretical values described in Section 3.1 matched the experimental values. The standard value of the radius of the pressure guide tube \( 2R \) was approximately 0.8 times the nominal value \( \phi \), namely \( R = 0.8 \phi / 2 \) (\( R = 0.344 \) mm for URTH-040 and \( R = 0.548 \) mm for URTH-063), the length of the pressure guide tube was the same as that used in the experiment, and the volume of the pressure gauge was approximately 1/4 times the approximate external volume of the pressure gauge (\( V_p = 100 \) mm\(^3 \) for the All Sensors pressure gauge). The standard values of the parameters obtained in this study differed slightly from those reported by He et al. (2019). The target frequency range was 0–100 Hz in their experiment, whereas that in our study was 0–1000 Hz. We estimated the standard values of the parameters by trial and error so that the
theoretical values matched the experimental values. Conversely, He et al. (2019) directly measured the values of the parameters. These conditions could explain the slight difference between the two experimental results.

\[ p_s + p_t e^{j\omega t} \]

Volume of pressure guide tube

\[ V_t = \pi R^2 L \]

Volume of pressure gauge \( V_p \)

3.3 Restoration filter

In this section, we describe the restoration method. Two methods can be used to restore a waveform distorted by the frequency characteristics of a measurement system: The first is the Fourier series expansion method, in which the obtained measurement waveform is regarded as a periodic one. This method is suitable for restoring the measured waveform for offline processing but cannot be used for online processing in an on-track vehicle test. The other method is the restoration filter method, in which a restoration filter is independent of the measured waveform. Unlike the Fourier series expansion method, the restoration filter method does not require an unreasonable assumption that the measured waveform is periodic. In addition, online processing can be performed in an on-track vehicle test. Therefore, we adopted
the restoration filter method in this study.

Let \( H(\omega) \) represent the frequency characteristics of the measurement system and \( H_i(\omega) \) represent those of the restoration filter. The restoration filter must satisfy the following conditions:

\[
H(\omega) \cdot H_i(\omega) = 1 \cdot e^{-i\alpha \omega},
\]

where \( \omega \) is an angular frequency and \( \alpha \) is an arbitrary phase constant.

Several examples of waveform restoration using restoration filters have been reported (Yoshimura, 1995). However, only a few studies have reported on the application of a restoration filter to restore the waveform distorted by the nonlinear phase characteristics, as is the case in this study. In this study, a restoration filter was designed as a finite impulse response type digital filter, which was designed using the frequency sampling method proposed by Rabiner and Schafer (1971). As defined in Eq. (2), the phase constant \( \alpha \) is arbitrary. Although the details are not described here owing to space limitations, a reasonable impulse response could not be obtained by an arbitrary phase constant (e.g., \( \alpha = 0 \)), similar to the findings of Halkyard et al. (2010). In this study, we adopted the following value as the arbitrary phase constant so that the rational impulse response can be obtained through numerical experiments:

\[
\alpha = \frac{N-1}{2} \cdot \Delta t,
\]

where \( N \) is the number of impulse response and \( \Delta t \) is the sampling interval.

### 3.4 Validity of the restoration filter

Figure 3 shows the waveforms before and after the restoration to confirm the validity of the restoration filter. A square waveform was used for comparison, and the All Sensors pressure gauge was used. The inner diameter and the length of the pressure guide tube URTH-063 were \( \phi = 1.37 \) mm and \( L = 100 \) mm, respectively. The fundamental frequency for generating a square wave was 50 Hz. Although the input electrical signal was square, the output pressure waveform obtained was not completely square. As shown in Fig. 3(a), an increase in the amplitude and phase delay was observed in the waveform with the pressure guide tube. In Fig. 3(b), the waveform after restoration showed good agreement with that obtained without the pressure guide tube. This result demonstrates the validity of the restoration filter.

![Figure 3](image_url)

(a) Before restoration  
(b) After restoration

Fig. 3 Confirmation of the validity of the restoration filter for a rectangular wave.

### 4. Flow velocity analysis

#### 4.1 Waveforms of the flow velocity

Figure 4 shows the waveforms of the flow velocity when the train model enters the tunnel. The waveforms in Fig. 4 are the raw and restored ones. The used gauge was the All Sensors pressure gauge, and the inner diameter and length of the pressure guide tube were \( \phi = 1.37 \) mm and \( L = 70 \) mm. The raw waveforms of the pressure were passed through a 1000 Hz low-pass filter and converted into a pressure coefficient with a dynamic pressure of \( 0.5\rho_s v^2 \) based...
on the train model speed $v$. The waveforms of the pressure coefficient were then restored. The waveforms of the total-pressure coefficient, $C_{p,\text{total}}(t)$, and those of the static pressure coefficient, $C_{p,\text{static}}(t)$, can be obtained. The flow velocity $u(t)/v$ can be calculated from the following pressure coefficients:

$$\frac{u(t)}{v} = \sqrt{C_{p,\text{total}}(t) - C_{p,\text{static}}(t)}.$$  \hspace{1cm} (4)

In this study, Eq. (4) was used to convert the pressure to the flow velocity, and the unsteady term $\partial \Phi / \partial t$ in the generalized Bernoulli theorem was ignored, where $\Phi$ is the velocity potential. Although details are not given owing to space limitations, we estimated that the error due to the elimination of the unsteady term was approximately 0.5%.

The origin on the horizontal axis in Fig. 4 represents the time when the rake of the total pressure tubes entered the tunnel. The train model speed was 150 km/h, and the distances of the total-pressure tubes from the surface of the train model were 2.0, 4.5, 7.0, and 17.0 mm. As shown in Fig. 4, the fluctuation of the restored waveforms was smaller than that of the raw waveforms. Moreover, the amplitude of the fluctuation increased as the measurement point approached the surface of the train model.

![Fig. 4 Comparison between the flow velocities obtained from the restored and raw waveforms](image)

**4.2 Analysis section**

The flow velocity was analyzed in five sections labeled as sections A, B, C, D and E (Fig. 5). In Fig. 5, the horizontal axis is the distance and the vertical axis is the time, and Fig. 5 shows the trajectory of the train passing through the tunnel. The dotted line, solid line, and broken line are the trajectories of the train head, the rake of the total pressure tubes, and the train tail, respectively. The one-dotted line is the trajectory of the pressure wave generated when the head of the train enters the tunnel, and the two-dotted line is the trajectory of the pressure wave generated when the tail of the train enters the tunnel. In these sections A, B, C, D and E, the train model does not encounter any pressure waves, and the influence of the pressure waves on the flow velocity is small. The speeds of the train model in the experiment were...
110, 130, and 150 km/h. Figure 5 illustrates the $x - t$ diagrams for a train model speed of 150 km/h. At time $t = 0$, the rake of the total pressure tubes entered the tunnel. The time interval for each section was approximately 0.020 s, and the number of data was approximately 100 in each analysis section.

![Diagram](image)

**Fig. 5** $x - t$ diagram (at $t = 0$, the rake of total pressure tubes enters the tunnel)

### 4.3 Analysis results

#### 4.3.1 Average flow velocity, standard deviation, and turbulence intensity

We calculated the average flow velocity $\bar{u}$, standard deviation $\sigma$, and turbulence intensity $I (= \sigma / \bar{u})$. The average flow velocity $\bar{u}$ and standard deviation $\sigma$ were calculated as follows:

$$\bar{u} = \frac{1}{N_d} \sum_{i=1}^{N_d} u_i, \quad (5)$$

$$\sigma^2 = \frac{1}{N_d-1} \sum_{i=1}^{N_d} (u_i - \bar{u})^2, \quad (6)$$

where $u_i$ is the sampled data of the instantaneous flow velocity and $N_d$ is the number of data points in each analysis section.

Figure 6 shows the results for $v = 150$ km/h. Figure 6(a) shows the profile of the average flow velocity $\bar{u}$ normalized by the speed $v$ of the train model. As shown in Fig. 6(a), the average flow velocity decelerates as the train model travels through the tunnel. Figure 6(b) shows the profile of the average flow velocity $\bar{u}$ normalized by the average flow velocity $\bar{u}_0$ outside the boundary layer at $h = 17$ mm in each analysis section. As shown in Fig. 6(b), the profile of the average flow velocity $\bar{u} / \bar{u}_0$ can be represented by one curve regardless of the analysis section. The boundary layer thickness was $\delta \approx 11$ mm. Figure 6(c) shows the profile of the standard deviation $\sigma$ normalized by the average flow velocity $\bar{u}_0$ outside the boundary layer in each analysis section, and Fig. 6(d) shows the profile of the turbulence strength $I$. The standard deviation $\sigma / \bar{u}_0$ in Fig. 6(c) and the turbulence intensity $I$ in Fig. 6(d) can also be represented by a single curve, regardless of the analysis section. The results for the other speeds of the train model showed the same tendency; however, these are not shown here owing to space limitations.
4.3.2 Displacement thickness, momentum thickness, and shape factor

By using the average flow velocity \( \bar{u}/\bar{u}_0 \), we calculated the displacement thickness \( \delta^* \), momentum thickness \( \theta \), and shape factor \( H \) as follows:

\[
\delta^* = \int_0^\infty \left(1 - \frac{\bar{u}}{\bar{u}_0}\right) dy,
\]

\[
\theta = \int_0^\infty \frac{\bar{u}}{\bar{u}_0} \left(1 - \frac{\bar{u}}{\bar{u}_0}\right) dy,
\]

\[
H = \frac{\delta^*}{\theta}.
\]

We used the trapezoidal rule for the numerical integration. The integral points correspond to the seven measurement points. The results are shown in Fig. 7, where the horizontal axis represents the average flow velocity at \( h = 17 \) mm, i.e., the average flow velocity outside the boundary layer.

From Fig. 7, the displacement thickness was 1.7-2.1 and the momentum thickness was 0.6-0.8 in our experiment. The shape factor was 2.4-2.8 and it decreased as the average flow velocity outside the boundary layer became higher. In the boundary layer on a flat plate parallel to the uniform flow, the shape factor is \( H \approx 2.6 \) in the laminar flow and \( H \approx 1.4 \) in the fully developed turbulent flow (Pope, 2000). The flow around the train model in this experiment developed from the laminar boundary layer to the turbulent boundary layer.
Fig. 7 Displacement thickness, momentum thickness, and shape factor obtained from the average velocity $\bar{u}/\bar{u}_0$

Fig. 8 Frequency distribution of the fluctuating flow velocity for $v = 150$ km/h
4.3.3 Frequency distribution of the fluctuating flow velocity

The frequency distribution of the fluctuating flow velocity was investigated. The variable \( t_u \) was obtained as \( t_u = \frac{(u-\bar{u})}{\sigma} \). The number of data, \( N_d \), in each section was approximately 150–380 because the datasets obtained from measurement No.s 1–3 were assembled into one dataset. The number of classes \( k \) was determined using the Sturges formula: \( k = \log_2 N_d + 1 \). As the number of classes was \( k = 9 \), the ranges of the two outer classes were \( t_u \leq -3 \) and \( t_u > 3 \), and the remaining range \( (-3 < t_u < 3) \) was divided into seven bins of equal interval \( d_r \). The relative frequency was plotted at the center of each class for \( -3 < t_u < 3 \), at \( t_u = -3 - d_r/2 \) for \( t_u \leq -3 \), and at \( t_u = 3 + d_r/2 \) for \( t_u > 3 \). Figure 8 illustrates the results for \( v = 150 \text{ km / h} \) and the standard normal distribution for comparison. As shown in Fig. 8, the frequency distribution of the fluctuating flow velocity was similar to a standard normal distribution regardless of the analysis section and the height from the surface of the train model, from an engineering point of view. The same tendency was observed for the other model speeds (the corresponding figures are not shown here owing to space limitations).

5. Method for predicting the fluctuating flow velocity

5.1 Procedure of the flow velocity prediction

The results in Section 4 show that the profile of the average flow velocity \( \bar{u}/\bar{u}_0 \) and standard deviation \( \sigma/\bar{u}_0 \) can be represented by the curves, which do not depend on the train model speed or analysis section within the experimental results. The profiles of the average flow velocity and standard deviation were approximated using the data in section A (Fig. 9), as formulated below:

\[
\alpha_u = \frac{\bar{u}}{\bar{u}_0} = \left(\frac{h}{\delta}\right)^{\frac{1}{\alpha}} , \quad 0.18 < \frac{h}{\delta} \leq 1
\]

\[
= 1 , \quad \frac{h}{\delta} > 1 ,
\]

\[
\beta_\sigma = \frac{\sigma}{\bar{u}_0} = -0.047 \frac{h}{\delta} + 0.050 , \quad 0.18 < \frac{h}{\delta} \leq 1
\]

\[
= 0.003 , \quad \frac{h}{\delta} > 1 .
\]

When determining the approximate expressions, we considered that the flow obtained in the experiment as the turbulent boundary layer-like flow for the following reasons: the normalized average flow velocity in Fig. 6 approximately followed the 1/7 power law as shown in Fig. 9; the normalized standard deviation in Fig. 6 had a larger value as the measurement point approached the wall surface; the distribution of the fluctuation flow velocity in Fig. 8 was close to the normal distribution; and the measured waveform in Fig. 10 clearly contained turbulence.

The average flow velocity, \( \bar{u}_0 \), outside the boundary layer changed with time in the tunnel. We used the analytical solution of Kikuchi et al. (2020) to predict the flow velocity outside the boundary layer. For details on the calculation of \( \bar{u}_0 \), please refer to Kikuchi et al. (2020).

The flow velocity \( u/v \) was predicted by the following procedure:

Step 1. The average flow velocity \( \bar{u}_0/v \) outside the boundary layer was obtained from the analytical solution.

Step 2. The average flow velocity \( \alpha_u \) was calculated by Eq. (10).

Step 3. The average flow velocity at an arbitrary time was calculated as \( \frac{\bar{u}}{v} = \alpha_u \frac{\bar{u}_0}{v} \) with the values obtained at Steps 1 and 2.

Step 4. The standard deviation \( \beta_\sigma \) was calculated by Eq. (11).

Step 5. The standard deviation at an arbitrary time was calculated as \( \frac{\sigma}{v} = \beta_\sigma \frac{\bar{u}_0}{v} \) with the values obtained at Steps 1 and 4.

Step 6. The fluctuating flow velocity was calculated as \( \frac{u_2}{v} = \frac{\bar{u}}{v} + 2 \frac{\sigma}{v} = \alpha_u \frac{\bar{u}_0}{v} + 2 \beta_\sigma \frac{\bar{u}_0}{v} \).
In step 6, the amount of fluctuation is assumed to be twice the standard deviation for the two reasons: first, several experimental values exceeded the predicted value when the amount of fluctuation was assumed to be once the standard deviation. Second, the predicted value of the flow velocity is specified to be twice the standard deviation plus the average flow velocity in CEN (2009).

![Fig. 9 Approximate curves α_α and β_β of the average velocity and standard deviation in section A](image)

**5.2 Evaluation waveform of the instantaneous flow velocity for the pantograph**

When evaluating the contact performance of the pantograph, we need to consider the dynamic characteristics of the pantograph. Vibration sources of the pantograph include ones due to a hanger interval, an unevenness of the contact wire and a vertical vibration of a vehicle body. Vibration source due to the hanger interval has the greatest effect on the contact performance of the pantograph. The hanger is a metal fitting that hangs the contact wire from a messenger wire. The standard distance between hangers (hanger interval) is 5m.

The frequency in the model experiment corresponding to the excitation frequency due to the hanger interval in the on-track vehicle test was explained below. Subscript \( f \) was added to the variables of the on-track vehicle test, and subscript \( m \) was added to those of the model experiment. Let \( v \) be the train speed, \( L \) be the representative length, and \( f \) be the representative frequency. We assumed that the normalized frequency in the on-track vehicle test was the same as that in the model experiment. The representative frequency in the model experiment is expressed as follows:

\[
f_m = \frac{v_m}{\frac{l_f}{l_m}} f_f.
\]

By substituting \( v_f = 300 \text{ km/h} \), \( v_m = 110–150 \text{ km/h} \), \( l_f/l_m = 62 \) (model scale), and \( f_f = 16.7 \text{ Hz} \) (excitation frequency due to the hanger interval; \( v_f = 300 \text{ km/h} \) and the hanger interval of 5 m) into Eq. (12), we obtained \( f_m = 380–518 \text{ Hz} \) as the representative frequency in the model experiment. Therefore, we applied a low-pass filter with a cutoff frequency of \( f_c = 400 \text{ Hz} \) to the waveform of the flow velocity. We used a moving average for the low-pass filter. The time interval in the moving average was \( \tau = 0.00125 \text{ s} \), based on the relationship of \( f_c = 1/2\tau \).

**5.3 Comparison of the predicted and experimental values**

Figure 10 illustrates a comparison between the predicted and experimental values of the flow velocity for \( v = 150 \text{ km/h} \). As mentioned above, the experimental values were passed through a low-pass filter. In Fig. 10, the blue squares represent the predicted values \( \bar{u}/v \), orange triangles represent the predicted values \( \bar{u}/v + 2\sigma/v \), and the green line shows the experimental values. As shown in Fig. 10, the predicted values of \( \bar{u}/v + 2\sigma/v \) envelop the experimental values well. When the measurement point was sufficiently immersed in the boundary layer, the turbulence component of the
flow was large, and the predicted value of $\frac{\bar{u}}{v}$ underestimated the flow velocity. If the flow velocity is predicted as $\frac{\bar{u}}{v} + 2 \frac{\sigma}{v}$ by considering the turbulence component of the flow, then the predicted values envelop the experimental values well.

When the measurement point was located outside the boundary layer, the turbulence component of the flow decreased, and the fluctuation of the flow velocity due to the compression wave, which was not considered in this study, became slightly conspicuous. If the panhead is sufficiently immersed in the boundary layer, then the value of $\frac{\bar{u}}{v} + 2 \frac{\sigma}{v}$ can be appropriately used to predict the flow velocity at its position. If the panhead is located outside the boundary layer, then the prediction of the flow velocity using $\frac{\bar{u}}{v} + 2 \frac{\sigma}{v}$ is slightly underestimating but sufficiently accurate from an engineering point of view. The same tendency was observed for the other speeds of the train model, which, however, are not depicted here owing to space limitations. Considering the spatial change in the vertical direction and the temporal change from the entrance to the exit of the tunnel, we can predict that the maximum value of the flow velocity at the panhead position is 1.3 times the train speed. within the range of the experimental results.

When examining the flow velocity around the train running inside the tunnel, three effects must be considered: the time variation of the average flow velocity $\bar{u}$ due to the piston effect, fluctuating flow velocity $u'_p$ due to the pressure wave, and $u'_t$ due to the turbulence. Let the representative frequencies of $\bar{u}$, $u'_p$ and $u'_t$ be $f_\bar{u}$, $f_P$ and $f_t$, respectively, the relationship of $f_\bar{u} < f_P \ll f_t$ can hold. To date, the characteristic curve method has been used to predict the flow velocity around a train running in a tunnel by assuming a uniform profile of the flow velocity in the tunnel cross-section and considering the effect of pressure waves as mentioned in Introduction. The proposed prediction method considers the profiles of the average flow velocity in the tunnel cross-section, the time variation of the average flow velocity outside the boundary layer, and the effect of turbulence. Table 1 summarizes the relationship between the characteristic curve method and the proposed method.

![Graphs showing flow velocity comparison](image)

**Fig. 10** Comparison of the predicted and measured velocities for $v = 150$ km/h
6. Conclusions

In this study, we presented the flow velocity, including the fluctuating components, of a train model running inside a tunnel, which was calculated from the pressure waveform measured by the rake of the total-pressure tubes. We adopted the Bergh–Tijdeman model as the frequency characteristics of the measurement system and a digital filter to conduct the waveform restoration. Using the restored waveforms of the flow velocity, we obtained several statistical values, such as the average flow velocity and standard deviation of the fluctuating flow velocity. Furthermore, we proposed a method for predicting the flow velocity, including fluctuations. The conclusions of this study are summarized as follows:

1) When designing a restoration filter, we can obtain a reasonable impulse response by setting an arbitrary phase constant to $\alpha = (N - 1) \cdot \Delta t / 2$. The restoration filter method is effective for restoring waveforms distorted by a measurement system with nonlinear phase characteristics.

2) The average flow velocity, standard deviation, and turbulence intensity are represented by curves that are independent of the train model speed and analysis section of the tunnel.

3) The shape factor was approximately 2.5, and the flow around the train model developed from the laminar boundary layer to the turbulent boundary layer.

4) The relative frequency of the fluctuating flow velocity is similar to a normal distribution from an engineering point of view, regardless of the train model speed, analysis section, and height from the surface of the train model.

5) The predicted values of $\frac{\bar{u}}{v} = \alpha \cdot \left(\frac{\sigma}{\bar{u}}\right) + 2\beta \cdot \left(\frac{\sigma}{\bar{u}}\right)$ envelop the experimental values well. The waveforms of the experiment were low-pass filtered at the excitation frequency caused by the hanger interval. The flow velocity acting on the panhead is expected to be approximately 1.3 times the train speed in the tunnel.

Regarding the representative frequency, we assumed that the normalized frequencies in the on-track vehicle test were the same as those in the model experiment. In the future, the validity of this assumption will be examined. Also, we would like to apply the restoration method in an on-track vehicle test.

References


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