Measurement of Air Velocity and Pressure Distributions around High-Speed Trains on Board and on the Ground*

Yutaka SAKUMA**, Masahiro SUZUKI**, Atsushi IDO** and Hiroshi KAJIYAMA**

** Railway Technical Research Institute
2-8-38 Hikari-cho, Kokubunji-shi, Tokyo, 185-8540, Japan
E-mail: sakuma@rtri.or.jp

Abstract

Air velocity and pressure distributions on the sides of 16-car high-speed trains both in open and tunnel sections are measured to investigate the flow structure around the trains, especially in tunnels. For on-board measurement, hot-film probes, pitot tube rakes and pressure gauges are fixed on both sides of the 3rd car from the head end of the outbound train (and the 14th of the inbound). Two glass windows of the 3rd car are replaced with iron plates equipped with the apparatus. For on-the-ground measurement, ultrasonic anemometers and a pressure gauge are installed inside a tunnel at a point 800 m from a tunnel portal. The cruising speeds of the trains are set at between 250 and 290 km/h. It was found that the air velocity in the narrower space between the train side and the tunnel wall in the train coordinate system gradually decreases from the head toward the tail of the train while that in the other wider space increases, and that the features of the velocity and pressure fields observed on board in tunnel sections can be also detected on the ground.

Key words: Railway, High-Speed Train, Shinkansen, Tunnel, Air Flow Measurement, Velocity Distribution, Pressure Distribution, Boundary Layer

1. Introduction

Shinkansen bullet trains in Japan went into operation between Tokyo and Shin-Osaka in 1964. The maximum speed, which was 210 km/h in those days, has been now raised to 300 km/h. Aerodynamic phenomena, such as flow-induced vibration of high-speed trains traveling in tunnels, air velocity and pressure variations generated by the passage of trains, aerodynamic drag and so on, become more pronounced as the maximum speeds of high-speed trains are raised (1). Many of these aerodynamic phenomena are related to high-speed trains passing through tunnels. In order to speed up trains, these aerodynamic phenomena should be reduced. Hence, it is essential for developing effective countermeasures to understand flow fields around high-speed trains, especially in tunnels.

Since 1986, fluid-structure interactions of high-speed trains have been studied in Japan as one of the issues affecting ride quality (2). As trains travel at higher speeds, the vibration amplitude becomes greater, especially in tunnel sections. It has been noted that the yawing and lateral vibrations of trains in tunnels are more pronounced than those generated when the same trains are traveling in the open environment (non-tunnel), and that the vibration amplitude gradually increases from the heads towards the tails of trains. Initially, track irregularity was supposed to be a major cause of the vibrations, but little correlation between track irregularity and the vibrations was found for trains traveling in tunnels; this indicated that track irregularity was not the major cause of the vibrations in
tunnels. Later, the effect of aerodynamic forces acting on the sides of trains was investigated (3)-(5). Air velocity and pressure fluctuations on the sides of a high-speed train were simultaneously measured both in the open and in tunnel sections and aerodynamic forces on the car were estimated from the pressure data. It was found that the velocity profiles of the boundary layer on the sides of the train agree with the 1/8 - 1/10th power law profile, that a strong correlation between velocity and pressure fluctuations indicates the existence of large-scale coherent structures moving downstream at a speed equivalent to about 80% of the train speed, that the aerodynamic force in tunnel sections is much greater than that in the open environment, and that the aerodynamic force and the vibration in tunnel sections gradually increase from the head towards the tail of the train. In addition, it was also shown that these results are independent of the types of Shinkansen trains.

Numerical simulations and wind tunnel experiments for the flow around a high-speed train traveling in a tunnel have been conducted (5)(6). In addition, a theoretical approach for the study of the dynamics of trains and train-like articulated systems subjected to fluid dynamic forces has been conducted recently (7)-(9).

Most previous measurement regarding the fluid-structure interactions of high-speed trains has been done on board, but little measurement on the ground. In this study, we have measured air velocity and pressure distributions on the sides of 16-car high-speed trains not only on board but also on the ground to investigate the flow structure around the trains, especially in tunnels. (The measurement itself was carried out about ten years ago. To our knowledge, very few works (10)(11) have been conducted on this kind of running experiment. Hence, we have decided to present this study now.)

2. Test equipment and procedure

Two different series of trains, namely, the A and B-Series, were employed for on-board and on-the-ground measurements, respectively. Note that, from the previous results obtained in running experiments of several series of Shinkansen trains (5), flow fields focused on here around the A and B-Series trains can be considered almost the same. The lengths of the trains are about 405 m and that of the tunnel about 3 km. The cruising speeds of the trains were set at between 250 and 290 km/h.

2.1 On-board measurement

A hot-film probe (TYPE55R71, Dantec Dynamics Inc.), a pitot tube rake and a pressure gauge (P325-01, Sankei Engineering Inc.) were fixed on each side of the 3rd car (68.2 m) from the head end of the outbound train (and the 14th car (336.5 m) of the inbound one).
Two glass windows on both sides of the 3rd car were replaced with iron plates equipped with the apparatus as shown in Fig. 1. The positions of the hot-film probes were adjustable from $y = 5$ to 100 mm perpendicular to the iron plates. The positions of two pitot tube rakes were set at $y = 5, 15, 50, 100$ mm perpendicular to the iron plates and their measurement data can be collected simultaneously. In the open section, data were collected for 10 seconds when the train ran on a straight track. In the tunnel section, data were collected for 10 seconds just after the entry of the tail of the train into the tunnel.

### 2.2 On-the-ground measurement

The positions of the trains are deviated from the tunnel center, as they run on one of double tracks. The cross sections of the train (approx. 11 m$^2$) and tunnel (approx. 62 m$^2$) and their geometric relations are illustrated in Fig. 2. The side of the train facing the tunnel wall here is named “Tunnel wall side,” and that facing the tunnel center “Tunnel center side.” Three ultrasonic anemometers (WA-200, Toho Electric Inc.) and an absolute pressure gauge (PD80HA, ST Lab., Inc.) were installed inside a tunnel at a point about 800 m from a tunnel portal. The angle of the flow direction is defined as shown in Fig. 2. Note that the section where the data is acquired on board covers the measurement points on the ground.
3. Results and discussions

3.1 Air velocity and pressure measurements on board

Figure 3 illustrates the typical time histories of velocity and pressure fluctuations on the tunnel wall side of the 14th car from the head end of the A-Series train. Pressure coefficient $C_p$ is defined by $C_p = (p - p_0) / (0.5 \rho U^2)$, where $p - p_0$ (Pa) is the measured pressure; $p_0$ (Pa), the atmospheric pressure; $\rho$ (kg/m$^3$), the air density; $U$ (m/s), the cruising speeds of the train. Note that the air velocity was measured relative to the train (in the train coordinate system). The velocity and pressure waves have periodic variations with a period of 0.4 to 0.5 seconds, which are the typical time histories of pressure fluctuations observed on the tunnel wall sides of the trains running at about 270 km/h (5). As shown in Fig. 3, both the maximum spectra of the pressure and velocity in the tunnel section are seen at the frequency of a little less than $f = 2$ Hz (or dimensionless frequency $St = fW/U = 2 \times 3.4/75 = 0.09$, based on the width of the car $W$).

Figure 4 shows mean streamwise velocity profiles on the sides of the 3rd and 14th cars from the head end of the A-Series train measured by using pitot tube rakes. It is possible to approximate velocity profiles in the turbulent boundary layer by the $1/n$th power law,

$$\frac{u}{U} = \left(\frac{y}{\delta}\right)^{1/n},$$

where $u$ is the mean relative streamwise velocity; $y$, the distance from the side of the train; $\delta$, the boundary layer thickness; and $n$, the parameter which varies slightly with the Reynolds number. It is known that the value of $n$ increases as a function of the Reynolds number (12). In Fig. 4, the curves of mean streamwise velocity are drawn by the least squares method based on the $1/n$th power law by using measured data, giving $n = 8$ to 10 in Equation (1). The present results agree well with the previous ones (4).

In the open section, the mean streamwise velocity decreases with distance along the train side from the 3rd to the 14th car (see the {1} arrow in Fig. 4). This is because the boundary-layer thickness increases along the train sides. The flow velocities increase when the train enters the tunnel; that is, the flow velocities in the tunnel section (solid lines in Fig. 4) are higher than those in the open section (dashed lines). The increment in
velocity on the tunnel center side (\( \{3\} \)) is larger than that on the tunnel wall side (\( \{2\} \)); in other words, the velocity on the tunnel center side is higher than that on the tunnel wall side.

In the tunnel section, with distance from the 3rd to the 14th car, the velocity on the tunnel wall side decreases (\( \{4\} \)), while that on the tunnel center side increases (\( \{5\} \)). Hence, the mean streamwise velocity distributions in the cross-sectional areas between the train and the tunnel are different between at the 3rd and at the 14th car. Note that the volume flow rate in these cross-sectional areas along the train can be regarded as constant. This is because the flow around the train in the tunnel can be considered as incompressible since the train speed is about 20 percent of the speed of sound. For this reason, these results indicate existence of three-dimensional flows around the high-speed train in the tunnel.

3.2 Air velocity and pressure measurements on the ground

Figure 5 illustrates a schematic drawing of mean streamwise velocity profiles around a train traveling through a tunnel in the train and ground coordinate systems. The solid lines represent velocity profiles without reverse flow regions in the ground coordinate system. The dashed and dotted lines represent velocity profiles with reverse flow regions.

3.2.1 Outbound train

Figure 6 shows the time histories of air velocity and pressure fluctuations by the passage of the outbound B-Series train in the tunnel in the ground coordinate system. The
origin (0 sec.) of the horizontal axis is a time point chosen arbitrarily just before the passing of the front end of the train. The pressure drops by about 2 kPa during the passage of the train in the time period from 0.7 to 6.2 seconds as seen in Fig. 6.

The overall behavior of air velocities at the measurement points B (1.29 m above the rail head) and that at C (1.66 m) are similar to each other even though the amplitude of the velocity at the point C is a little smaller than that at the B. Accordingly, the amplitude of the velocity at the point of measurement on board (2.23 m) may be a little smaller than that at the C. The directions of the flow at the points B and C are almost the same as that of train travel except during the passage of the train nose. From this result, no reverse flow occurs at the points B and C located in the narrow space between the train side and the tunnel wall, with their velocity distribution corresponding to the solid line in Fig. 5. If the reverse flow occurs in the narrow space between the train side and the tunnel wall, the reverse flow region should be in the space located closer to the tunnel wall than the points B and C. In addition, by considering the reduction of the flow velocity on the train wall side

Fig. 6 Time histories of air velocity and pressure fluctuations by the passage of the *outbound* B-Series train in the tunnel in the ground coordinate system

Fig. 7 Time histories of air velocity and pressure fluctuations by the passage of the *inbound* B-Series train in the tunnel in the ground coordinate system
from the 3rd to the 14th car (\{4\} in Fig. 4) as shown in Section 3.1, the size of the reverse flow region should decrease with distance along the tunnel wall side from the head toward the tail of a train. Hence, the velocity profiles in the narrow space between the train side and the tunnel wall can be estimated to be those of the solid line or the dashed as given in Fig. 5.

At the measurement point C in the narrow space, the flow velocity increases from about 5 to 35 m/s during the passage of the first four cars of the train in the period from 1.0 to 2.2 seconds. This velocity increment can be attributed to the development of the boundary-layer on the side of the train. And then, the flow velocity decrease to about 5 m/s during the passage of the 6th and 7th cars. During the passage of the 8th to 16th cars, the similar periodic fluctuations can be observed. The frequency of the peak in the power spectral densities (PSD) of the velocity fluctuations at the point C can be estimated about 0.5 Hz (see Fig. 8(a)).

At the measurement point A in the wider space, the flow velocity oscillates between about 0 and 10 m/s while the flow direction fluctuates between the same and opposite directions of train travel during the passage of the train. Thus, in the space around the measurement point A, the air flows in the same and opposite directions of train travel, which may correspond to the dashed and dotted lines in Fig. 5 representing velocity profiles with reverse flow regions.

From the above results, it is shown that the behavior of the airflow in the narrow space between the train side and the tunnel wall is different from that in the other wider space. This difference can be attributed to the eccentricity of the position of the train in the tunnel. It should be noted that the results obtained about the velocity profiles on the ground are consistent with those on board as given in Fig. 4.

### 3.2.2 Inbound train

Figure 7 shows the time histories of air velocity and pressure fluctuations by the passage of the inbound B-Series train in the tunnel in the ground coordinate system. The pressure drops by about 1 kPa during the passage of the train in the period from 0.9 to 6.7 seconds. Note that, for the measurement of the inbound trains, the points B and C are located in the wider space as seen in Fig. 2. The overall behavior of flow velocities and directions at the point A and those at both the points B and C are significantly different to each other even though these three measurement points are positioned in the wider space in the tunnel.

At the points B and C located far from the tunnel center side of the train, the flow directions change to the direction opposite to that of train travel during the passage of the train while the flow velocities first become almost zero and then gradually increase from 0 to 15 m/s.

At the point A, the flow direction remains almost unchanged before and after the passage of the train; that is, it is always the same as the direction of train travel. On the other hand, the flow velocity fluctuates from 0 to 30 m/s during the passage of the train.

These results indicate that, at the points B and C in the wider space, the flow direction changes to the direction opposite to that of train travel while the flow velocity first become almost zero and then gradually increase from 0 to 10 m/s during the passage of the train, which corresponds to the gradual change of velocity profiles from the dashed line to the dotted one as given in Fig. 5 as the train passes by the measurement points.

### 3.2.3 PSD

If we compare the difference between Figs. 6 and 7, it is clear that the amplitude of the velocity and pressure fluctuations of Fig. 6 is much larger than that of Fig. 7. Figure 8 gives the PSD of velocity and pressure fluctuations during the passage of the train. No
Fig. 8 Power spectral densities of velocity and pressure fluctuations of the B-Series train in the tunnel

Clear peaks of the PSD of the velocity at the point A on the tunnel center side are seen in Fig. 8 (a). In addition, the maximum PSD of the pressure for the inbound train is about half that for the outbound as shown in Fig. 8 (b). Hence, it should be noted that these results are consistent with the previous results that the amplitude of velocity and pressure fluctuations on the tunnel center side is much smaller than that on the tunnel wall side (3)-(5).

3.3 Comparison of measurements on board and on the ground

It is known that the frequencies of the maximum power spectra of the pressure fluctuation acting on the tunnel wall sides of trains traveling at \( U = 270 \text{ km/h} \) (75 m/s) are about \( f = 2 \text{ Hz} \), and that the pressure fluctuations observed on board move downstream at a speed equivalent to about 80\% of the train speed (4)(5), as mentioned previously. In other words, the pressure fluctuations move in the direction of the train travel at a speed equivalent to about 20\% of the train speed, which have not been analyzyed on the ground. Here, we will compare both measurements on board and on the ground and then verify the relationship.

The wave length \( \lambda \) of the moving pressure fluctuations must be invariable regardless of the coordinate systems and thus the following expression holds:

\[
\lambda = 0.8 \times \frac{75}{2} = 0.2 \times \frac{75}{f_g},
\]

(on board) (on the ground)

where \( f_g \) is the frequency giving the maximum power spectra of the pressure fluctuation on the ground coordinate system. Equation (2) gives \( f_g = 0.5 \text{ Hz} \), which agrees well with the frequency corresponding to the maximum PSD of the pressure fluctuation for the outbound train as shown in Fig. 8 (b). A similar discussion can be applied to the case of the velocity fluctuation. Hence, it is demonstrated that the air velocity and pressure fluctuations observed on board in tunnel sections can be also detected on the ground.

4. Conclusion

Air velocity and pressure distributions on the sides of 16-car high-speed trains both in
open and tunnel sections have been measured to investigate the flow structure around the trains, especially in tunnels. The following conclusions may be drawn from the results of this study: (a) the air velocity in the narrower space between the train side and the tunnel wall in the train coordinate system gradually decreases from the head toward the tail of the train, while that in the other wider space increases, indicating the existence of three dimensional flow around high-speed trains in tunnels; and (b) the features of the velocity and pressure fields observed on board in tunnel sections can be also detected on the ground.

References

(12) Hoerner, S. F., Fluid-Dynamic Drag, Published by the Author (1958).