Development of Aerodynamic Brake Device for High-speed Railway

Hajime TAKAMI
Vehicle Aerodynamics Laboratory, Environmental Engineering Division

To shorten stopping distances of high-speed trains in case of emergency braking, the author of this paper developed a small, light-weight aerodynamic braking device. To examine its aerodynamic characteristics, a full-scale prototype was tested in a wind tunnel facility at a maximum flow speed of 400 km/h. Tests confirmed that the response time for deployment of the device was only 0.39 s, and that the prototype was able to produce an aerodynamic drag force of 2.3 kN per unit. In addition, performance was calculated using computational fluid dynamics (CFD). The result of the CFD analysis around a train roof with a large number of devices showed that the staggered arrangement of the devices could increase the total drag force by 10 percent compared to the standard parallel arrangement.

Keywords: high-speed train, aerodynamic brake, air resistance, drag force

1. Introduction

There is a strong demand to improve the braking performance of high-speed trains in Japan to shorten stopping distances, in emergencies such as earthquakes [1]. Emergency braking on conventional trains is achieved with a wheel disk brake system. However, the performance of this type of braking is affected by rail surface conditions (dry, wet, or freezing) because of its dependency on the adhesion between the wheel and the rail, especially at high speed. Therefore, an additional braking system which is unaffected by rail conditions will be required to meet future operating needs.

As a braking device capable of satisfying this objective, a small-sized aerodynamic braking device was developed [2]. This device uses air drag force directly for braking with a resistance panel set on the train roof. Aircraft are generally equipped with similar devices, but the concept has never, to date, been applied to commercial trains.

This paper reports on the bench test results of the developed prototype device that was examined in a wind tunnel, a vibration test machine, and a bird striking test machine. In addition, the flow field around the multiple devices on the train roof was calculated using computational fluid dynamics (CFD).

2. Outline of aerodynamic brakes

2.1 Distributed arrangement with downsized devices

Past research experimented the use of large panels actuated by powerful pneumatic cylinders, as an aerodynamic brake system for magnetic levitated trains (MAGLEV) [3] and on Shinkansen test cars [4]. Running tests using these devices showed that aerodynamic brakes can be used without affecting running stability. However, to apply this system to Shinkansen trains in commercial operation, it is necessary to downsize the device to enlarge the cabin volume, while maintaining brake performance.

Deceleration $\beta$ $(m/s^2)$ by aerodynamic braking can be expressed by the following air resistance equation:

$$\beta = \frac{1}{M} \frac{1}{2} \rho U^2 A \sum_{i} C_d(i) \cdot K_t(i)$$

where, $M$ (kg) is the mass of the train, $\rho$ (kg/m$^3$) is air density, $U$ (m/s) is airspeed, i.e. relative velocity of the train to the atmosphere, $A$ (m$^2$) is the frontal projected area of the resistance panel, $n$ is the number of devices per train, $C_d(i)$ is the drag coefficient at the i-th resistance panel from the head of the train, and $K_t(i)$ is the tunnel coefficient which is the percentage of drag change in the tunnel section.

In order to obtain the required drag force from the aerodynamic brake device, a proper balance between the projected area $A$, the drag coefficient $C_d$, and the number $n$ is achieved by design. The projected area $A$ of the resistance panel is constrained by the loading gauge of the car, which is the maximum space rolling stock can occupy without interfering with trackside structures. A larger number of devices installed on the car generally reduces the interior volume.

One of the originalities of the developed device is that it is thin and compact enough to be mounted on the roof of a car body. Therefore, a large number of devices can be distributed throughout the train without reducing the cabin volume, shown in Fig. 1. In addition, multiple devices installed in a distributed manner throughout the train provides high redundancy against device failure. Finally, the cost of ground infrastructure can be reduced because the small frontal projection area of resistance panel makes the loading gauge smaller, when there is no other equipment on the roof, as with MAG-LEV trains.

2.2 Operating Mechanism

The resistance panels are stored inside the car body during normal operation. When they are activated, the resistance panels open out. While the panel is kept open, the drag force acting on the train increases and a deceleration effect is obtained. Once the train has stopped, the resistance panels are retracted inside the car body. The aerodynamic brake device would only be used in emergencies,
such as earthquakes. Consequently, the actuator of the resistance panels must be failsafe, compact, lightweight and easy to maintain.

For this purpose, the author developed a torque balancing mechanism that simultaneously operates a pair of resistance panels. To obtain the torque for actuating the panels, this mechanism utilizes the difference in drag force between the two resistance panels caused by the headwind from running. The other forces required, namely locking and folding are obtained by a combination of small pneumatic cylinders. An outline of the configuration is shown in Fig. 2.

A double rod air cylinder (hereafter, cylinder 1) unlocks the resistance panel. This makes the resistance panel with the rotation axis open in the horizontal direction to about 4 degrees or more. The locking device is a mechanical lock that prevents the resistance panel from opening unexpectedly due to pressure loads when the train passes through a tunnel, or from vibrations while running. A small air cylinder with a short stroke (hereafter, cylinder 2) is also installed to assist the initial motion of cylinder 1. The purpose is to prevent the resistance panel from sticking due to freezing, and to ensure failsafe operation.

Each pair of resistance panels is connected by a spur gear to make each of them rotate in the opposite direction. When a pair of resistance panels is opened slightly, they generate a rotating torque around the axis due to the headwind from running. Each direction of torque acts on panel 1 to assist in opening and on panel 2 to resist opening. Each torque strength is different according to its angle of attack against the headwind. When the angle of attack is small, the drag coefficient of the panel 1 is about twice as large as that of the panel 2. Thereby, both panels connected by the gear can be actuated by the headwind without external power.

If the angle of attack is vertical, both panels achieve almost the same drag force and swing unsteadily due to the disturbance. Therefore, the angle of attack at full opening is set to 75 degrees so that the drag force of panel 1 is always larger than that of panel 2. Since the device is placed point-symmetrically from the top view, the operation is performed following the same principle in case the train operates in reverse.

After the train stops and in the unloaded condition to the resistance panels, the reverse operation of the cylinder 1 folds the resistance panels, which are mechanically locked at the same time.

With the torque balancing mechanism using the headwind from running, a large drive unit is not required and the size and weight of the device are reduced. This operating mechanism is another originality of the developed device. By comparison with the former device [4], while the area of the resistance panel is 1/3, the device volume per unit is about 1/25.

2.3 Outline of the prototype device

A prototype of the aerodynamic brake is shown in Fig. 3 and its specifications are shown in Table 1. This is the sixth prototype since development commenced. It was designed for practical operation on a train with improved durability and lower cost.

The maximum drag force acting on the device is achieved when a train is running at 400 km/h in a tunnel section. In addition, both the impact forces of initial inertia and vibration force from disturbances act on the device. In the folded position, consideration was also given to the pressure load generated in a tunnel section or the...
concentrated weight load of a worker stepping on the resistance panel. Here, the pressure load is a distributed load while the weight load is a concentrated load like a worker stepping on the upper surface of the device during inspection.

Particular environmental conditions such as sub-zero temperatures of $-30^\circ$C were taken into account since the Shinkansen lines will be extended to colder regions in the future. Therefore, robust air cylinders with enhanced cold and dust resistance based on general-purpose products were developed. In addition, the bearings for the resistance panels and the enclosure of locking device were made to be watertight to prevent sticking from freezing.

The air cylinder is driven by compressed air within the pressure range commonly used in train. The cylinder output is designed to enable the initial motion of the resistance panel even when there is a pressure load acting on the device in tunnel sections or when the resistance panel is stuck due to ice.

The device is released and folded by switching the air supply port from the outside; thus, there are no control valves or electrical components in the device.

### Table 1 Specification of prototype

|                         | Width 500 × Height 250 (mm) |
|-------------------------|------------------------------|
| Resistance panel        | Width 1024 × Length 566 × Thickness 65 (mm) |
| Device size at folding  |                              |
| Weight                  | 36.3 (kg)                    |
| Design load             | Maximum drag force 3.3 (kN) |
|                         | Impact force 4.0 (kN)        |
| Process time            | < 0.5 (s)                    |
| Compressed air range    | 580 – 950 (kPa)              |
| Atmospheric temperature | $-30 \sim +40$ (°C)          |

3. Wind tunnel tests

3.1 Test method

Figure 4 shows an experimental apparatus set up at RTRI’s large-scale low-noise wind tunnel facilities. Two prototypes were tested at a maximum flow speed of 400 km/h (111 m/s, Mach number 0.32). The prototypes were mounted on a linear slider to measure the drag force with force sensors.

The upstream device was set near the tip of the wind tunnel nozzle, and the maximum load was applied to the device when the main stream of wind tunnel was acting on the device directly. Since the downstream device received the deviated flow from the upstream device, the drag force downstream was generally lower due to interference depending on the space between the upstream device and the downstream device. The stream-wise space between the two devices was varied from 1 m to 5.8 m.

3.2 Wind operated prototype

Figure 5 shows the time histories of the drag forces when the device was operating. The locking device was released about 0.29 seconds after the release command of operation was input to the solenoid valve of the pneumatic circuit; the resistance panel moved from folded position to open position in about 0.1 seconds; the total time for the whole process was 0.39 seconds. At the moment the resistance panel reached its maximum opening angle, an impact force occurred, but the maximum force was within the design value.

![Fig. 3 Prototype device](image)

![Fig. 4 Experimental setup in wind tunnel](image)

![Fig. 5 Drag force time histories](image)
In the case of past devices with large resistance panels actuated by a large cylinder, it took several seconds for the panel to open.

### 3.3 Prototype drag force

The average drag force at each speed range is shown in Fig. 6. The drag force increases in proportion to the square of the flow speed according to (1), and the maximum drag force at 400 km/h is 2.3 kN for the upstream device.

When two devices were placed in the flow direction, the drag force of the downstream device decreased due to flow interference, and the degree depended on the space r between the two devices. In particular, when two devices were close together and the space between them was narrower than 1 m, the drag force of downstream device was negative due to the reverse flow from the upstream device. Therefore, multiple devices must be arranged suitably to optimize drag.

### 3.4 Vibration tests

Figure 7 shows the vertical acceleration power spectral density (PSD) of the device during wind tunnel testing. The vibration increased as flow velocity rose, especially in the downstream device, because the turbulence from the upstream device caused the downstream device to vibrate. However, the magnitude of the vibration is within the range of Class 1-B in Japanese Industrial Standards JIS E 4031 of vibration and shock tests. The peak frequency of the acceleration was around 40 Hz, which was almost the same as the resonance frequency of the resistance panel obtained through a vibration analysis using the finite-element method.

In order to check the durability of the device when subject to vibration, a vibration test was conducted using an electrodynamic vibration test system shown in Fig. 8. The prototype was set up on the shaking table with a frame that simulates the stiffness of the car body. The vibrations applied corresponded to class 1 vibrations according to JIS E 4031, and endurance tests at 45 Hz and resonance tests up to 80 Hz were carried out.

Results showed that there was no resonance frequency below 45 Hz in the folded position, and the prototype passed the vertical and lateral vibration endurance tests of over 8 hours. In operating position, the resonance frequency of the resistance panel was 43 Hz, which was the same as in the wind tunnel tests.

### 4. Bird striking tests

The device was designed to operate only for emergencies such as earthquakes. In addition, the height of the resistance panel from the roof of the car does not reach the height of other equipment on the roof (e.g. pantographs, electrical insulators). Thus, the possibility of some object such as a bird colliding with the resistance panel at high speed (hereafter, bird striking) is extremely low.

Nevertheless, in the event of a bird strike, in order to prevent the broken parts of a panel from being blown away and damaging other equipment and/or facilities, a crushable structure was adopted to reduce the collision load. In the unlikely event of a bird colliding with the panel, the resistance panel deforms plastically and the collision load is transferred to other parts of the device.
the rotating shaft of the resistance panel, the shaft support with bearing unit, and other joints are strong enough not to break in such a collision.

4.1 Test method

The bird striking tests were carried out using compressed air cannon facilities. A number of resistance panels were tested in the same configuration and material as the actual device.

A bird-like flying object made of clay was packed into a Styrofoam cylinder with a diameter of 100 mm, a length of 200 mm, and a mass of 1.25 kg. The mass was equivalent to a large heron, which is larger than a common wild bird such as a crow or a kite usually found around railways. The maximum ejection speed was set to 400 km/h, with an error of about ±10 km/h in the collision speed due to the performance of the test facilities. The collision target was set to be the center of the resistance panel and the collision angle was set horizontally.

4.2 Bird-strike test results

Figure 9 shows the deformation of the panel after a collision at 394 km/h and the results of the crash analysis. Crash analysis was performed using a finite element method with a strain-rate dependence on a material yield stress.

In the experiment, the resistance panel tilts backward 45 to 90 degrees at the time of impact, then it returns forward, and finally came to rest tilting backward slightly. The resistance panel was plastically deformed and bent horizontally and vertically. The rotating shaft was bent to about 5 mm near the center, and the resistance panel could no longer rotate after the collision. However, neither the resistance panel nor any other parts were blown away, and the shaft, the bearing unit, and bolt joints did not break.

In the analysis, when the resistance panel was rigid, the collided clay collapsed in $2 \times 10^{-3}$ seconds and the collision load was 142.9 kN at 360 km/h. On the other hand, the crushable structure, which allowed the deformation of the resistance panel, reduced the collision load to 14.7 kN within the allowance of the material’s strength.

The collision at the center of the resistance panel shown Fig. 9 is the largest collision load in the collision position. When the collision position was close to the corner or edge of the resistance panel, the collision load was smaller because the resistance panel underwent greater deformation.

5. Computational fluid analysis (CFD) around multi devices

5.1 Analysis model

The analysis method used was the Detached Eddy Simulation (DES) combined with Reynolds Averaged Navier-Stokes (RANS) equations near the wall. The analysis area was the rooftop area of 10 cars, and single-arm pantograph models were placed on the roof of cars No. 3 and No. 7. A uniform inflow of 360 km/h was applied.

Of the wide range of device arrangements investigated, one set the panels in alternating position on the left and right sides of the car (hereafter, staggered arrangement) as shown Fig. 10. The staggered arrangement maintains the flow velocity down the center line of the car, as the separated flow from the resistance panels forms a meandering stream along the center line of the car. The space $r$ between upstream and downstream device was $r / h = 14$, where $h$ is the height of the resistance panel.

5.2 Analysis results

Figure 10(a) represents the horizontal cross-sectional distribution of the mean flow velocity. Figure 10(b) represents the vertical cross-sectional distribution of the flow velocity in the instantaneous field, and the distribution of the pressure coefficient on the resistance panels.

The flow was dammed at the front of the resistance panels to generate a high positive pressure, and the separated flow from the edge of the resistance panels accelerated to form a shear layer from the top and sides of the panel toward the downstream. The separated shear layers from edges of the panel were coupled to form an arch vortex at the rear of the resistance panel. The distance required for reattachment was approximately $r / h = 6$, and there were reverse flow areas upstream from this.

The drag force of analysis can be obtained by integrating the surface pressure of the resistance panel. The drag forces at the most upstream device and the second device obtained by analysis agreed well with the measured drag force from the wind tunnel tests; the error for the most upstream device was within 3.7%, and the error in the second device was within 3.6%. In an analysis with all the devices on the train, the staggered arrangement achieved a 10% higher drag force than the parallel arrangement.

The side force in the lateral direction was less than ±1% of the average drag force, and the lift force in the vertical direction was less than ±5%. Thus, the fluid forces do not affect train running stability.
6. Conclusions

To shorten emergency braking stopping distances of high-speed trains, the author developed an aerodynamic braking device increasing air resistance. One of the originalities of the developed device is that it is sufficiently thin and light weight to be mounted on the roof of a train. Another innovative feature is that the pairs of resistance panels are actuated using the headwind generated by the running train, without the need for a large drive unit. Therefore, a large number of devices can be distributed throughout the train to obtain the required drag force without reducing the interior volume of the train.

To examine its aerodynamic characteristics, the author tested a prototype device in a wind tunnel facility at a maximum flow speed of 400 km/h. It was confirmed that the response time of motion takes only 0.39 seconds, and that the prototype can produce a drag force of 2.3 kN per unit. In addition, the result of CFD analysis around a train roof with a large number of devices, found that a staggered arrangement increases the total drag force by 10 percent compared to the standard parallel arrangement.

Some technical issues remain to be resolved to make the system use ready for in-service use:
1) The flow around an actual train is more complex due to separation flows from multiple devices, and the estimation value of the drag force by analysis is uncertain. Thus, it is necessary to verify the drag force of multiple devices on an actual train and calculate their contribution to the braking performance.
2) The installation method on the car roof requires a simple structure design that achieves both a reduction of an aerodynamic noise in the folded position and is light weight.
3) It is necessary to verify the long-term durability in real operating conditions.

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Author

Hajime TAKAMI, Dr. Eng.
Senior Chief Researcher, Vehicle Aerodynamics Laboratory, Environmental Engineering Division
Research Areas: Aerodynamics