# Application of Jet Ejection to Control Contact Force of Pantograph for High-speed Trains

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**Abstract** Aeroacoustic and aerodynamic characteristics are very important for the pantographs of high speed train to ensure environmental compatibility and steady current collecting performance. In general, these characteristics depend on a number of parameters, such as the attack angle of a panhead, dynamic behavior of the pantograph, track conditions, and the wear of contact strips. Therefore, it is very complicated work to improve these two characteristics simultaneously only by improving the shape of the pantograph. In this study, we developed two kinds of devices to control aerodynamic characteristics of pantograph by using jet ejection technique. One is an external air supply type jet ejection device and the other is a self air supply type jet ejection device. To estimate the effect of these methods, the authors conducted wind tunnel tests using pantograph models. These experimental results and numerical simulation show that the lift force acting on the panhead can be controlled by adjusting the velocity of ejected jets. In particular, the self air supply type jet ejection device can change the lift force of the panhead to the amount of 100N at 300km/h without any external energy. This method has great potential for practical applications.

## 1 INTRODUNTION

As the maximum speed of high-speed trains has risen to 300km/h (83.3m/s) in Japan, the performance of trains has been affected strongly by its aerodynamic properties as explained below.

(1) The ratio of the aerodynamic drag to the running resistance of train sets becomes large, and the aerodynamic drag governs the traction power of train sets[1]. Therefore, the drag has to be reduced to save operational costs.
(2) Passing of a train nose and tail generates pressure variation along the wayside[2]. This causes rattling of window frames or shutters of houses near the railway line.
(3) Lateral vibration of the train increases extremely in tunnel. This vibration is due to the difference in pressure fluctuation between the two sides of the car body passing in the tunnel[3]. This vibration makes passengers feel uncomfortable, hence a semi-active or active control device is installed on the latest train sets.
(4) When a train enters a tunnel, a compression wave is generated in front of the train. This wave

Figure 1 *Examples of high-speed trains in Japan (from left, Series 100, Series 500, Series 700 and Series 300)*

propagates to the tunnel exit to emit an impulsive pressure wave (micro-pressure wave) out of the exit[4]. This impulsive wave causes environmental problems near the tunnel portal. Therefore, tunnel hoods have been installed at the portals of long tunnels for countermeasures.

(5) Aerodynamic noise dominates the railway wayside noise in the high-speed domain[5]. This is because the energy of aerodynamic noise is proportional to the 6-8th power of the velocity, while other noises such as rail and wheel rolling noise are proportional to lower power.

In particular, environmental problems are very severe on railway transporters, since these are controlled by some governmental regulations. In the case of wayside noise, the environment standard for Shinkansen noise that set the maximum wayside noise level ($L_{Amax}$) at 75dB(A) was established in 1975 [5]. This regulation is very strict compared with that in other countries. Continuous efforts to reduce wayside noise make it possible for Shinkansen trains to run at 300km/h in compliance with this standard. However, further noise reduction is demanded to increase the speed of Shinkansen trains.

Pantographs mounted on the roof of car body as in Fig. 2 are one of the typical aerodynamic noise sources of Shinkansen trains[6]. To reduce their aerodynamic noise, the latest train sets are equipped with low-noise pantographs[7)-9)] composed of members of aerodynamically-smoothed shapes. See Fig. 2. This type of pantograph significantly contributes to the reduction of wayside noise. The current collection performance of the pantograph is also influenced considerably by its aerodynamic properties. The contact force between pantograph and contact wire has to be maintained within a suitable range for steady current collection. The aerodynamic force acting on the pantograph directly affects the contact force. Therefore, the aerodynamic force ought to be controlled adequately.

The panhead, which is set on the top of an articulated frame to contact with the contact wire, generates a larger aerodynamic noise than the articulated frame and other members of the pantograph[10]. Furthermore, large lift force tends to act on the panhead due to its large characteristic area. In general, objects of aerodynamically smoothed-shape generate lower aeroaoustic noise than bluff objects, but the aerodynamic force acting thereon is very sensitive to flow conditions such as flow velocity, attack angle and changes in the shape. Therefore, panhead design is very important to realize a pantograph that has sufficient current collection performance without emitting large aerodynamic noise.

To find a suitable shape of the panhead for the new low-noise pantograph, a number of wind tunnel tests have been conducted. Recently, in the field of fluid dynamics, various techniques for active flow control have been studied progressively to improve the aerodynamic properties. These techniques will make it possible to design the panhead not to generate large aeroacoustic noise without severe constraints for lift force adjustment. In other words, high priority will be placed on the reduction of aerodynamic noise in pantograph designing.

Various methods have been proposed as an active flow control technique. However, delicate devices, such as the one using MEMS[11], is difficult to apply to pantographs, which work in severe circumstances. In this study, we tried to achieve lift force control for the panhead by means of jet ejection from the surface of the panhead. We conducted wind tunnel tests to clarify the effect of jet ejection, in order to modify the aerodynamic property of the pantograph.

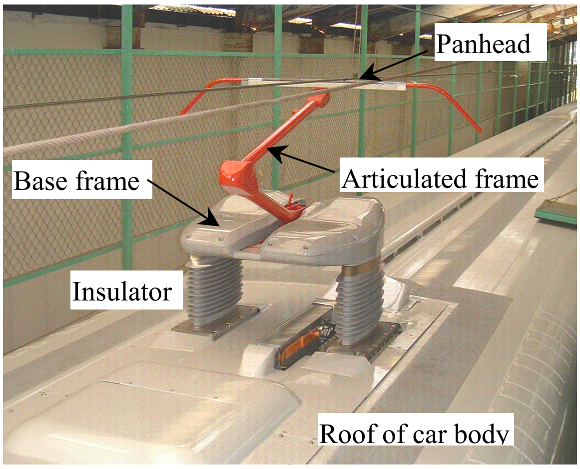

Figure 2 *Example of low noise pantograph for Shinkansen train ( Series E2)*

## 2 FLOW CONTROL TECHNIQUE BY JET EJECTION

To change the lift force by controlling the flow field around an object, time–periodic jet ejection whose frequency is similar to or lager than that corresponding to the shear layer instability is often applied [12)-13)]. It is because the jets have to interact with the quasi-coherent flow structure near the object surface, in order to control the flow pattern with small power. This method requires an ejection device that can be actuated quickly. However, 25kV is applied between pantograph and car body, and large current (400A) flows through the pantograph. Hence, it is very difficult for the pantograph to contain such an advanced device. For this reason, we attempted to control the flow field around the panhead by quasi-steady jets ejected from outlets located near its trailing edge.

## 3 EXTERNAL AIR SUPPLY TYPE JET EJECTION

Figure 3 illustrates the method attempted first to control the lift force of the panhead. This panhead has ejection holes on both sides near the trailing edge. Air is supplied from a high-pressured air tank through a tube. Air can be easily supplied to the pantograph from an air compressor on the train through a pantograph insulator. The lift force is controlled by jet ejection from single side of the panhead.

### 3.1 Validation by two-dimensional model

To validate the basic performance of this jet ejection technique, wind tunnel tests were conducted by using a two-dimensional panhead model[14)] shown in Fig. 3. This model has a 55mm-thick uniform cross-section whose chord length is 120mm. The span length of the model is 600mm to correspond to the dimension of the wind tunnel nozzle. The configuration of this model was designed by numerical optimization based on CFD to minimize lift force fluctuations at various attack angles (±3 degrees), as well as under the conditions of new and worn contact strips[15)]. In this optimization procedure, the chord length and minimum thickness of the panhead, as well as the symmetrical sides (top and bottom sides) were defined as constraints.

This model has 56 ejection outlets with a diameter of 6mm; its interval in the span-wise direction is 20mm. These outlets are located near its trailing edge as in Fig. 3. Every Four consecutive ejection outlets on the each side of this model are connected to a high-pressured air through a 5m-long air tube. To measure the surface pressure distribution of the model, this model has 45 pressure taps in the middle of the span-wise direction. The brass pipe having an internal diameter of 0.5mm is used for each pressure tap.

A small-scale anechoic wind tunnel of Railway Technical Research Institute (RTRI) was used for this

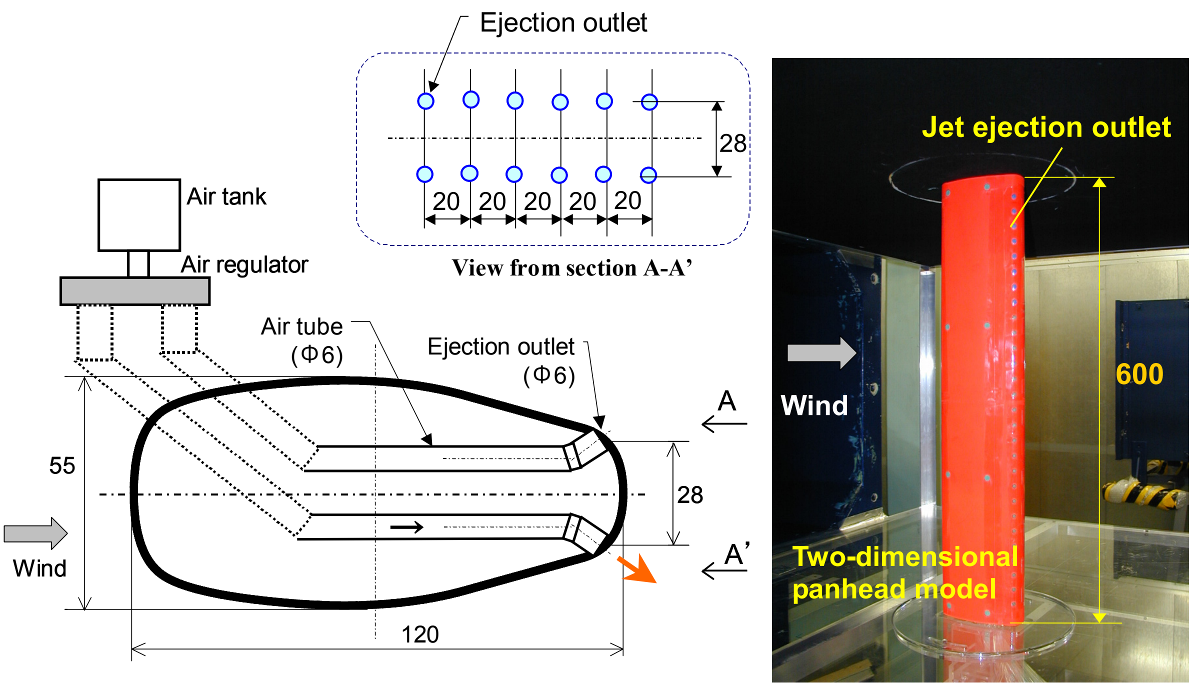


Figure 3 *Two-dimensional pahead model with external air supply type jet ejection device*

test. The maximum flow speed of this wind tunnel is 42m/s, and the dimension of the nozzle is 720mm in width by 600mm in height. Figure 4 shows an experimental apparatus in this wind tunnel test. The model was mounted with force transducers on both sides. In order to maintain a two-dimensional flow in the test section, two end-walls were installed on both sides of the test section. The end-wall measures 1,200mm wide by 2,000mm long. The scaling length and scaling area were 0.12m (chord length of the model) and 0.072m$^2$ (chord length × span length), respectively. The free stream velocity was set at 42m/s (Re=3.3×10$^5$).

Air for jet ejection was supplied from the air tank with a volume of 34*l* located out of the model through the seven air tubes with an inner diameter of 6mm. The air pressure was set at 0.05MPa by a air regulator. Figure 5 indicates the ejected jet velocity measured with a hot-wire anemometer at 1.5mm apart from the ejection outlet on the condition that the free stream velocity was zero. In this measurement, jets were ejected only from one side of the panhead. The jet velocity averaged 5.7m/s, and the ratio of the averaged jet velocity to the free stream velocity of 42m/s was 0.14. As mentioned above, adjacent four ejection outlets on each side was connected with one air tube, hence the total distance from the air tank to each outlet changed periodically every four outlets on each side. This is the reason why the velocity of the jets fluctuated periodically every four ejection outlets.

Figure 6 shows the pressure distribution on the panhead model with and without jet ejection. The transverse axis of this Figure indicates the location of pressure taps by means of the angles between the free stream and a line that connects the pressure tap with the center of the model. The symbols θ=0 and θ=180° correspond to the leading edge and the trailing edge, respectively. In this test, jets were ejected only from the outlets located at θ=193° degrees on the bottom side of the panhead. This Figure indicates that the pressure distribution can be controlled by jet ejection. The changes of the lift coefficient of this model by the jet ejection are displayed in Table 1. These were measured by force transducers supporting the model and by integration of the surface pressure measured by pressure taps. As in Table 1, the change of the lift coefficient by jet ejection is about 0.035.

From this result, we can conclude that jets ejected from single side of the model can control the lift force of panheads. The jets ejected from the bottom side of the panhead increase the lift force of the panhead, while the jets ejected from the top side of the panhead decrease its lift force. When the span length of the panhead is assumed to be 900mm, the lift force of this panhead can be changed by about ± 16N at 300km/h with jet ejection. The static up-lift force of Shinkansen pantograph is generally set at 54N, therefore this technique is available to control the uplift force of pantograph. In this experiment, pressure of feeding air was able to be adjusted only within 0.05MPa. If air at higher pressure were used, this technique could be more effective.

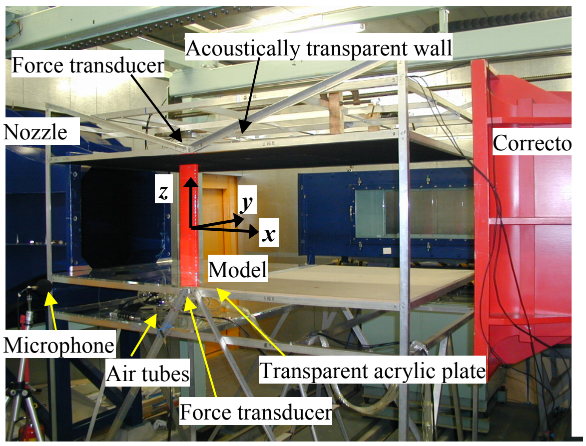


Figure 4 *Experimental apparatus for two-dimensional model*

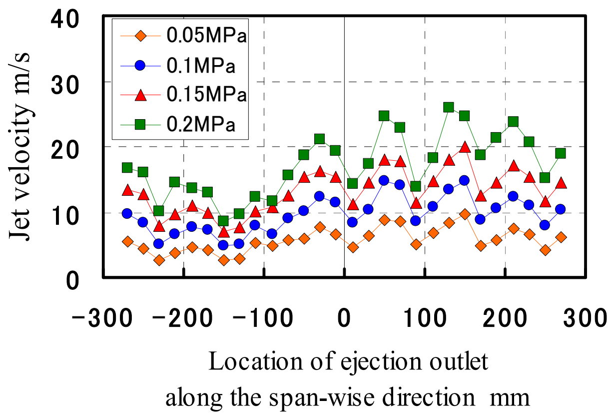


Figure 5 *Velocity of ejected jets on the two-dimensioanl panhead model with external air supply type jet ejection device*

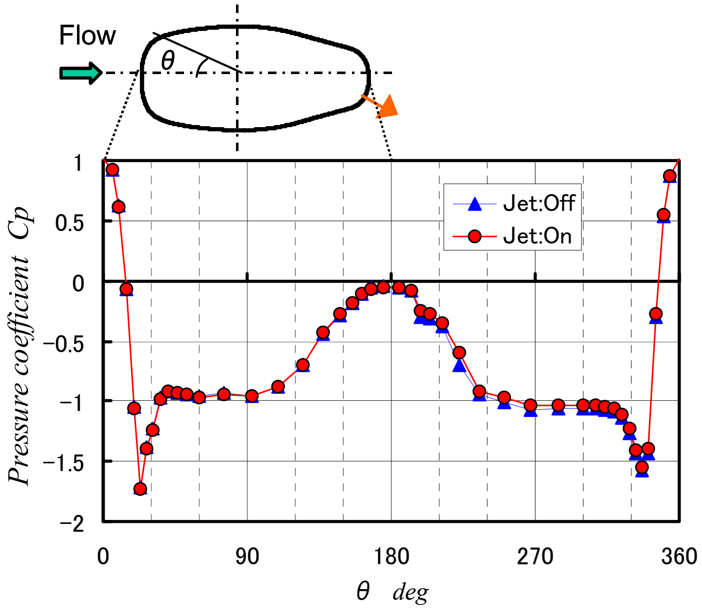


Figure 6 *Surface pressure distribution (Two-dimensional model with external air supply type jet ejection device)*

Table 1 *Effect of jet ejection (Two-dimensional model with external air supply type jet ejection device)*

| | Estimated by force transducers | Estimated by pressure taps |
|---|---|---|
| $\Delta C_L$ | 0.036 | 0.035 |
| $\Delta C_D$ | -0.001 | -0.002 |

## 3.2 Full-scale pantograph model

To verify the ability of this technique in practical conditions, we conducted a wind tunnel test by using a full-scale pantograph model as in Fig. 7. A full-scale panhead model with the flow ejection device was set on a single arm pantograph TPS301 used for Shinkansen trains. The span length of this panhead is 900mm long, and its cross section is the same shape as that of the two-dimensional panhead model described in the former section. The shape of the ejection outlet is also the same as the two-dimensional model. To reduce the pressure loss in the tubes connecting ejection outlets and air tank, however, these positions are changed to θ=148° and 212° while that of the two-dimensional model locate at θ=167° and 193°. In addition, the interval of the outlets in the span-wise direction is twice that of the two-dimensional model because of the limitation of the inner space of the model; there are 20 ejection outlets on each side.

The test was carried out at the large-scale anechoic wind tunnel of RTRI, which have an open-type test section of 2,500mm, by 3,000mm. The maximum wind velocity is 400km/h. The center of the pantograph was set at 1660mm from the nozzle. The lift force of the pantograph was evaluated by measuring the tension of a wire connecting the panhead and a base frame of the pantograph with a loadcell.

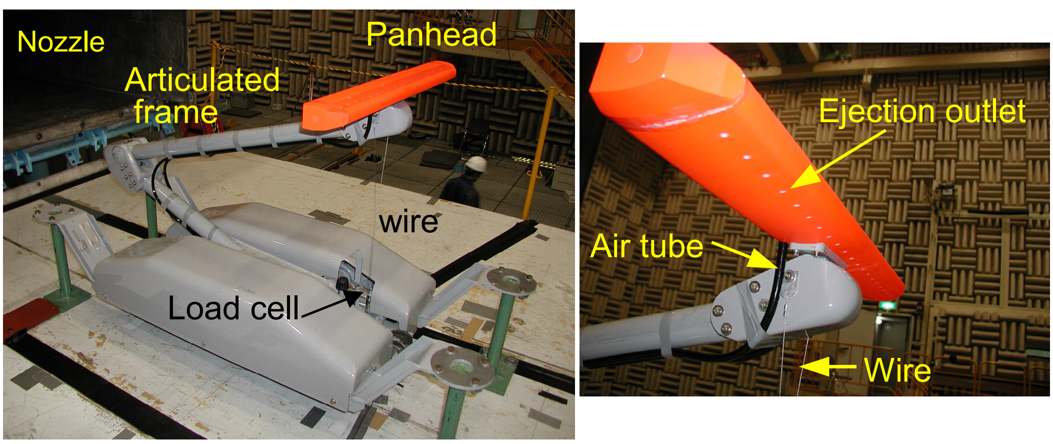


Figure 7 *Full-scale panhead model with external air supply type jet ejection device installed on a TPS301 pantograph*

This method is commonly used to evaluate pantograph lift force characteristics. Air for jets was supplied to the panhead through two air tubes with a diameter of 6mm, which was laid along both sides of the articulated arm. These tubes were connected with an air tank of a volume of 34*l* through an air regulator, which controlled the velocity of ejected jets. The jet velocities of each outlet averaged 36.2 m/s in case of the fed air regulated at 0.2MPa. These were measured with a hot-wire anemometer at 1.5 mm apart from the ejection outlets on the condition that the free stream was zero.

Figure 8 indicates the lift force characteristics of the pantograph with the jet ejection device. The supplied air was regulated at 0.2MPa. In the same way as in the case of the two-dimensional panhead model, it is proven that the lift increases by jet ejection from the bottom side of the panhead, and decreases by that from the top side of the panhead. At 300km/h, the lifts of the pantograph can be changed within ±20N. Figure 9 shows the effect of fed air pressure on the change of the lift force. In the region of 0.05MPa – 0.2MPa, the change of the lift force is proportional to the pressure of fed air. These results prove that the lift force of the pantograph can be controlled by regulating the fed air.

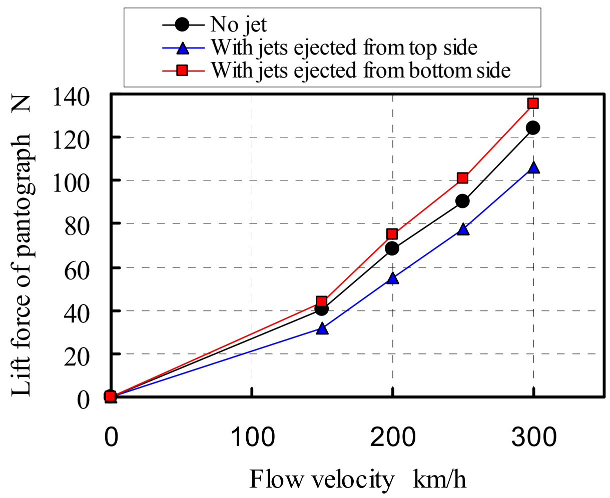


Figure 8 *Effect of jet ejection on lift force of the pantograph with external air supply type jet ejection device*

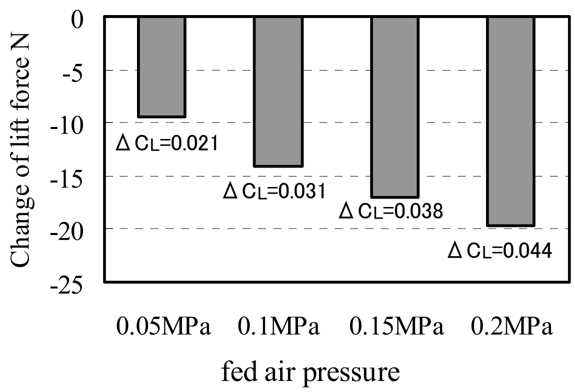


Figure 9 *Change of pantograph lift force due to regulated fed air pressure*

## 4 SELF AIR SUPPLY TYPE JET EJECTION

The lift control technique proposed above has some problems to be solved for practical use. The most serious one is to ensure a sufficient volume of air for jet ejection. Therefore, we contrived a new method for air supply. In this method, the ejection outlet near the trailing edge is connected with the inlet at the stagnation point of the panhead by an air tube as in Fig. 10. The differential pressure between the stagnation point and the trailing edge supplies air to the ejection outlet without any external energy.

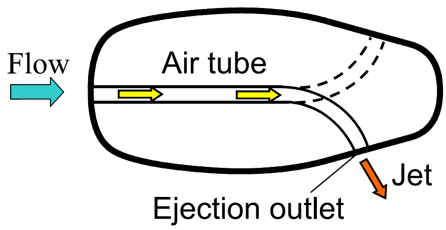


Figure 10 *Self air supply type jet ejection device*

### 4.1 Validation by two-dimensional model

To verify this method, a wind tunnel test was conducted by using a two-dimensional panhead model equipped with a self air supply type jet ejection device. The cross section of the panhead model is the same as that of the panhead model with the external air supply type jet ejection device described in the former chapter. The ejection outlets are located at θ=193° on the bottom side of the model. The ejection outlets, air inlets and air tubes between inlets and outlets have the same circular cross section with a diameter of 6 mm. The intervals of each outlets is 20mm. The test was carried out at the small-scale anechoic wind tunnel of RTRI. The experimental apparatus used in this test was the same as that shown in Fig. 4. The free stream velocity was set at 42m/s.

Figure 11 shows the surface pressure distribution of the panhead model at 42m/s with and without this type of jet ejection device. As compared with Fig. 6, it can be seen that the self air supply type jet ejection can control the surface pressure distribution more effectively than the external air supply type jet ejection. Without any external air supply, the lift coefficient changed by 0.2, which is almost four times that by the external air supply type jet ejection by using 0.05MPa fed air. Therefore, this method is very effective to control the lift of the pantograph in the high-speed domain.

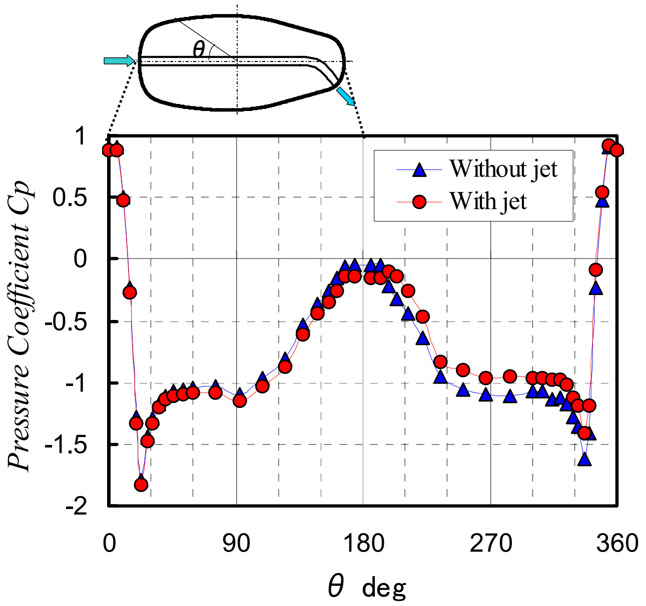


Figure 11 *Surface pressure distribution (Two-dimensional model with self air supply type jet ejection device)*

## 4.2 Numerical simulation

To obtain detailed flow information, the flow around a panhead with the self air supply type jet ejection device was evaluated numerically by FLUENT-6 CFD code. The large eddy simulation (LES) with static Smagorinsky-Lilly model was used for this simulation.

The shape of the panhead is the same as that of the experimental models treated above. The length of the computational domain in the span-wise direction is the half of the chord length of the panhead. Structural grid was used for this computation. There are about 800,000 cells in total and about 300 cells adjoining to the model. A uniform flow of 42m/s without turbulent disturbance is assumed for the inlet boundary condition. At both ends in the span-wise direction, the periodic boundary condition is applied. The no-slip condition for velocity is applied to the model surface. To simplify the grid generation, the cross section of the ejection tubes, air inlets and ejection outlets are set as rectangular with dimensions of 5.3mm x 5.3mm. Its cross sectional area is the same as that of the experimental model.

Figure 12 shows the calculation results of the averaged velocity field around the panhead with and

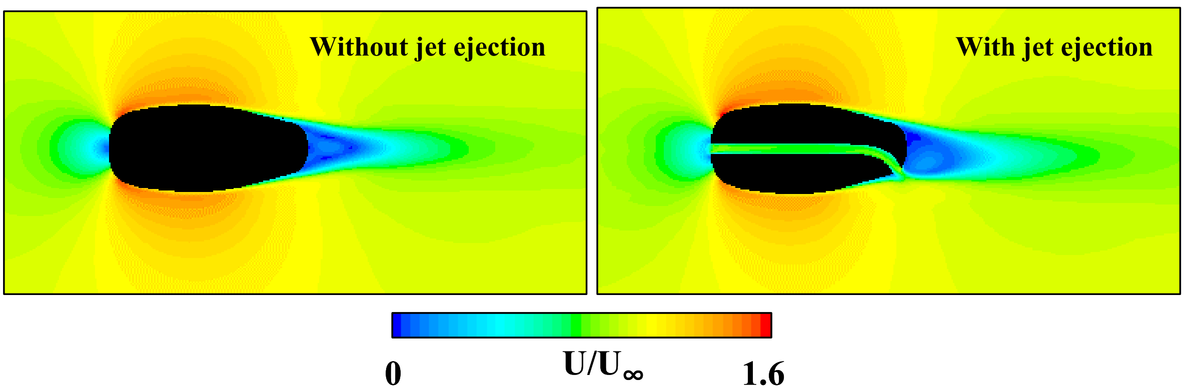


Figure 12 *Averaged velocity field with and without jet ejection* (CFD)

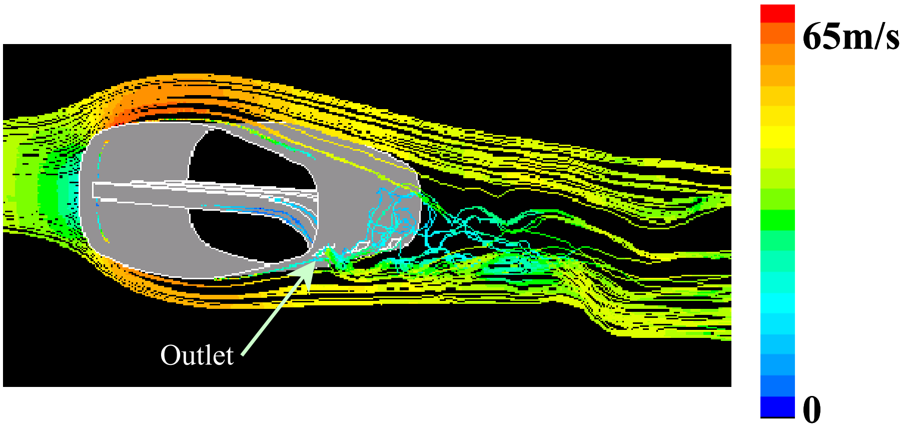


Figure 13 *Particle path line in the section include the center of the ejection outlet (CFD)*

without jet ejection. Figure 13 indicates the particle path around the panhead with jet ejection in the section including the center of the ejection outlet obtained by CFD. We can see that the ejected jet attracts the wake of the panhead to generate circulation of the flow field around the panhead. As a result, the lift force acts on the panhead. This is the mechanism of controlling the lift force by using jet ejection near the trailing edge.

## 5 CONCLUDING REMARKS AND NEAR FUTURE PLAN

We have developed two lift control devices for pantographs of high-speed trains. One is an external air supply type jet ejection device and the other is a self air supply type jet ejection device. Wind tunnel tests and numerical simulations prove that these devices can control the lift force acting on the panhead successfully. In particular, the self air supply type jet ejection device can change the lift force of the panhead sufficiently without any external energy.

Our final purpose is to establish a lift control system to reduce contact force deviation. Figure 14 illustrates a schematic view of the panhead with a contact force control device using the jet ejection technique. The volume of the ejected jets changes due to the stretch of the spring supporting contact strips. In the low-frequency domain, the distance between panhead and contact strips is proportional to the contact force. Therefore, the lift force of the panhead can be controlled by jet ejection according to the contact force. We are going to verify the validity of this method by a wind tunnel test presently.

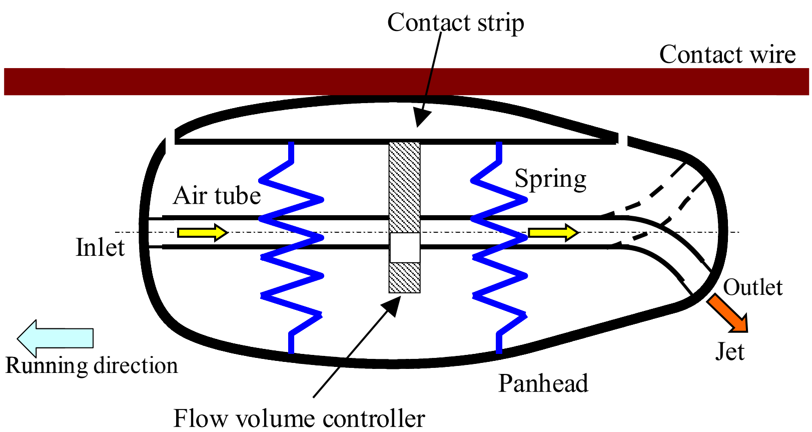


Figure 14 *Schematic view of panhead with contact force control device using jet ejection technique*

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