A Study on the Measurement of Contact Force of Pantograph on High Speed Train

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Appropriate contact force is required for the pantograph on the high speed train to collect current from the catenery system without separation. However, at high speed, large aerodynamic lifting force is generated by the contact plate and the body of pantograph, which may cause wear of the contact wire. In this study, to confirm the interface performance of the pantograph on Korea High Speed Train, a method to measure the contact force of the pantograph was proposed and the related measuring system was developed. The forces acting on the pantograph were clarified and a practical procedure to estimate the forces was proposed. A special device was invented and applied to measure the aerodynamic lifting force. Measured contact forces were displayed by the developed system and evaluated based on the criteria.

Key Words: Aerodynamic Lifting Force, Catenary System, Contact Force, High Speed Train, Pantograph

Nomenclature

a : Acceleration of contact plate
F_{ac} : Aerodynamic lifting force of contact plate
$\overline{F_{ad}}$: Average aerodynamic lifting force of contact plate in N
$(\overline{F_{ac}})_{run}$: Average aerodynamic lifting force of contact plate in running test
$(\overline{F_{ac}})_{wind}$: Average aerodynamic lifting force of contact plate in wind tunnel test
F_{ah} : Aerodynamic lifting force of horn frame
F_c : Contact force of contact plate
$\overline{F_c}$: Average contact force of contact plate in N
F_{sp} : Spring force below contact plate
$\overline{F_{sp}}$: Average spring force below contact plate
k : Coefficient of aerodynamic lifting force
k_{wind} : Coefficient of aerodynamic lifting force from wind tunnel test
m_{cp} : Mass of contact plate
V : Train velocity in km/h

1. Introduction

KTX (Korea Train eXpress) begins commercial service on April 1, 2004. Korea becomes the fifth country to operate the high speed railway system in the world. At the same time, KHST (Korea High Speed Train) succeeded in trial running on the test track at the speed of 350 km/h. KHST shown in Fig. 1 has been constructed by home grown technologies for 7 years. All of the core systems of KHST have been developed by

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domestic research institutes and related companies. A pantograph is the one of the core systems developed by domestic technologies. The pantograph of electric power car collects current from the catenary system and supplies electric power to the transformer and the main traction system. The pantograph should follow the catenary without separation for continuous current collection. Sufficient contact force is necessary for the contact plate of pantograph not to separate from the catenary system. Separation of the contact plate causes arc generation and gives damages to the catenary system. Separation also deteriorates the quality of the collected current. On the contrary, excessive contact force causes rapid erosion of the contact wire of catenary. Since the pantograph of high speed train is in high speed air flow field, significant lifting force is added to the contact force. So, an upper limit of contact force is regulated by the standard or the guidelines. Control of the contact force is important for current collection and maintenance of the catenary system. However, unless the contact force is known correctly, control can't be done appropriately. In the high speed train, lifting force is the major factor contributing to the contact force (Seo et al., 2002). So, to know the characteristics of the contact force and the lifting force, they should be measured in test running and analyzed correctly.

Domestic researchers studied the dynamic behavior of the pantograph and analyzed theoretically the contact force with the catenary. Measurement of the contact force on the actual track hasn't been tried because the high voltage of the catenary was dangerous and the method and related devices were not prepared. During development of the domestic pantograph on KHST, upward force of the pantograph was measured by a special device in the wind tunnel facility, where the contact plate was fastened by a wire to the load cell on the ground (Bae et al., 2001). In this test, the flexibility of the catenary system was not taken into account and dynamic behavior of the contact plate could not be measured. So, the measured upward force can not be considered as the true contact force.

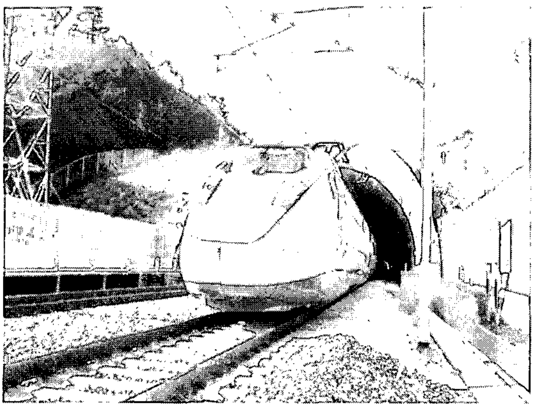

Fig. 1 Korea high speed train

Numerical simulation of the dynamic characteristics of the pantograph has been carried out by the researchers (Park et al., 2002). However, to simulate the dynamic system of the pantograph, input data for the external forces is required. To prepare the external force data, test for the aerodynamic lifting force should be done before simulation. Therefore, numerical simulation is restricted by the test result.

In this study, to measure correctly the contact force of the pantograph on the high speed train, a practically safe and reliable testing method combined with the result from the wind tunnel test is proposed. The forces acting on the pantograph are classified into components and investigated. The components of forces are measured based on the testing method proposed in this study. A data acquisition and analysis system for measurement of forces is also developed. The proposed testing method is proved to be valid and safe by the trial running test on the high speed line.

2. Forces on Pantograph

The pantograph on KHST is of single-armed type. To reduce aerodynamic noise and weight, the structure is designed simple and the outer diameter and thickness of members are designed optimum. Fig. 2 shows the details of the pantograph on KHST. The contact plate of the pantograph is on the secondary suspension in the horn frame to follow the catenary smoothly and to prevent separation. Initial static upward force is supplied by the primary springs on the roof of the power car and transferred to the secondary suspension. It is controlled by the supplied air from the auxiliary compressor. The pantograph in high speed flow field is subjected to aerodynamic lifting force. Contact plate, lifting control plate, horn frame and arms generate aerodynamic lifting force. Inertia force is induced by the accelerating motion of the contact plate. The acting forces on the pantograph are shown in Fig. 3. The spring forces from the primary suspension and the secondary suspension are transferred to the catenary system. In addition, the aerodynamic lifting force of the contact plate is transferred to the catenary system. For the free body diagram of the contact plate, the force equilibrium condition is expressed by Eq. (1).

$$-F_c+F_{sp}+F_{ac}=m_{cp}a \tag{1}$$

The inertia force of the contact plate contributes to the instantaneous contact force, but it doesn't contribute to the average contact force because the fluctuating component of the contact force disappears in average. The average contact plate is directly related with the wear of the contact wire. The fluctuating component can cause arc strike, but it will be discussed later.

In most cases, to measure the contact force, the load cell is installed below the secondary suspension as shown in Fig. 2. The force sensed by the load cell is considered as the contact force (Ikeda and Usuda, 2002). Strictly speaking, this force is not the true contact force but the approximate contact force subtracted by the aerodynamic lifting force of the contact plate. In other words, it is F_c-F_{ac} referring to Fig. 3. In low speed region, the aerodynamic lifting force of the contact plate F_{ac} is negligible, but in high speed region it is not negligible because it is proportional to velocity square. To get the information on the true contact force, another correct measuring method should be invented. If we know the coefficient of aerodynamic lifting force, we can find the true average contact force as the following aerodynamic equation.

$$\overline{F_c}=\overline{F_{sp}}+kV^2 \tag{2}$$

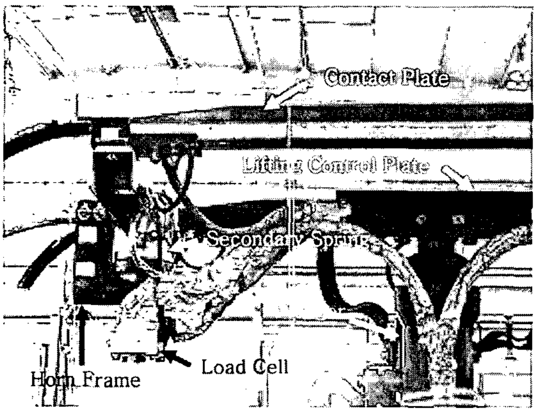

Fig. 2 Details of pantograph

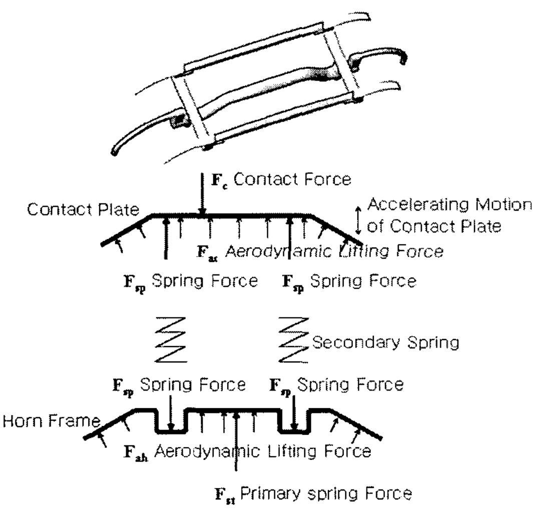

Fig. 3 Forces acting on pantograph

3. Wind Tunnel Test

3.1 Purpose of wind tunnel test

During the development period for the new pantograph on KHST, wind tunnel test was conducted to verify the aerodynamic characteristics of the pantograph (Bae et al., 2001). The upward force of the contact plate was measured for the various cases as shown in Fig. 4 and the effects of design change of the contact plate on the aerodynamic characteristics were investigated. Wind direction and height of current collection were changed in each test. Also, aerodynamic noise induced by the high speed air flow was measured.

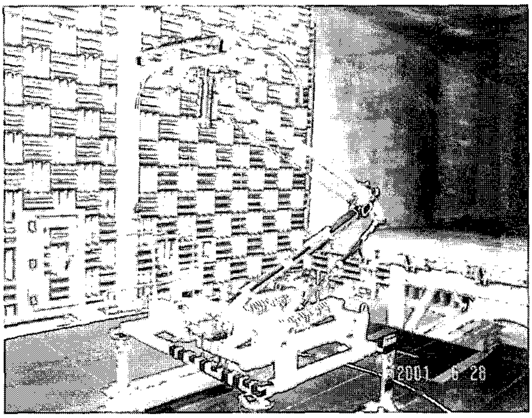

Fig. 4 Pantograph of KHST under wind tunnel test

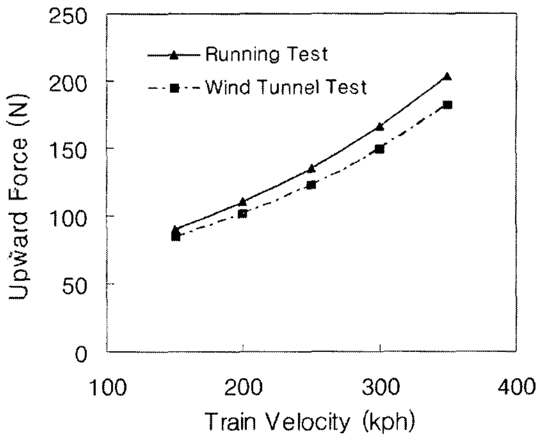

Fig. 5 Measured upward forces of contact plate

3.2 Measurement of upward force and aerodynamic lifting force

To measure the upward force of the contact plate around the high speed flow field, a wire rope was used. The wire rope around the contact plate was connected to the load cell on the bottom which senses the upward force of the contact plate. The signal from the load cell was converted into the force by the measurement system. The results are shown in Fig. 5. The upward force is expressed by the polynomial equation. The upward force isn't the same with the contact force because the wire rope gives the fixed boundary condition to the contact plate. In the actual system, the fixed boundary condition is not given because of the flexibility of the catenary system. In the wind tunnel, the aerodynamic characteristics of each component can be tested. First, the upward force of the whole pantograph was measured. Next, the contact plate was removed and the upward force without the contact plate was measured. The difference of two upward forces could be considered as the lifting force of the contact plate. The test result for the aerodynamic lifting force of the contact plate is shown in Fig. 6 and given by the following equation.

$$(\overline{F_{ac}})_{wind}=k_{wind}V^2=8.14\times10^{-4}V^2 \qquad (3)$$

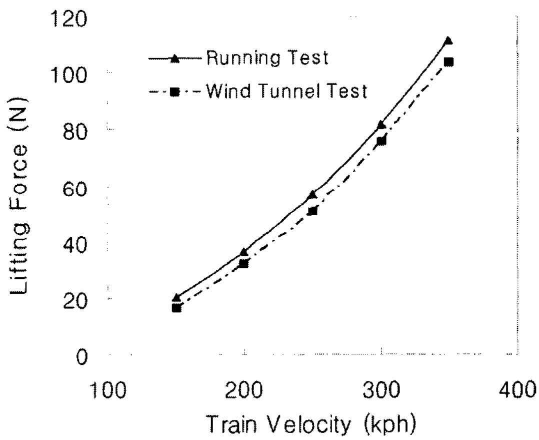

Fig. 6 Measured aerodynamic lifting forces of contact plate

4. Running Test on High Speed Line

4.1 Measuring system

As mentioned above, direct measurement of the contact force is not easy because of the danger of high voltage environment. Under the high voltage environment, safety must be considered first. To prevent inflow of the high voltage current into the measuring system in the cabin, a wireless telemetry system was installed. Transmission by wireless is for safeguard of the test persons and the equipments on the cabin. The configuration of the measuring system is shown in Fig. 7. The system is divided into sensors, sending telemetry, receiving telemetry and data processing part. Sensors such as load cell and accelerometer detect variation of physical quantity and generate signals, which are transmitted to the sending telemetry by wire. The sending telemetry collects the

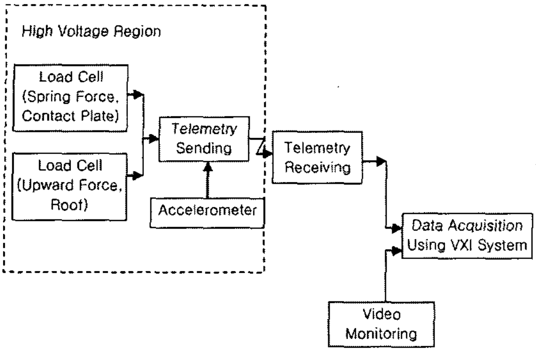

Fig. 7 Configuration of contact force measuring system

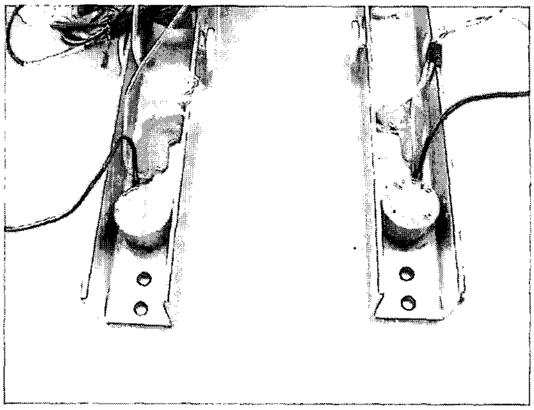

Fig. 9 Accelerometers under cross beam

Fig. 8 Data processing system

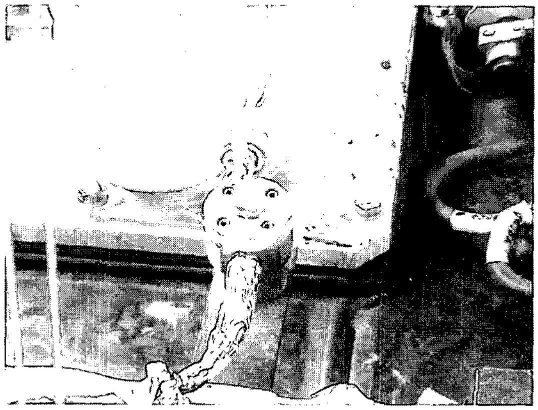

Fig. 10 Load cell on the roof to measure upward force

signal through each channel and transmits it by wireless to the receiving telemetry on the cabin of the trailer. The received signals are processed by the main computer connected with the receiving telemetry. VXI system is used for data processing. Fig. 8 shows the data processing system.

Load cells for measurement of the spring force are installed below the suspension springs as shown in Fig. 2. Accelerometers are attached below the cross beam of the contact plate as shown in Fig. 9 to measure the inertia force. Train velocity and kilometer post are measured by the speed sensor on the wheel.

To compare the wind tunnel test results with the running test ones, the upward force of the contact plate was also measured. The load cells were installed on the roof as shown in Fig. 10. The wire rope is connected to the load cell on the roof which senses the upward force of the contact plate. During running, KHST collects current only through the backward pantograph which provides the electric power to the whole electric systems. The forward pantograph is for emergency mode. The design specification prohibits simultaneous current collection by the two pantographs for safety because short circuit may be created on the high voltage line. So, one pantograph is raised only for measurement and the other pantograph is raised for current collection (Kim et al., 2002). For this purpose, the forward pantograph is constrained temporarily by a wire rope as shown in Figs. 10 and 11. The wire rope is used not only to transfer the upward force of the contact plate but also to prevent the contact plate from touching the catenary. At the same time, the spring force of the secondary suspension is also measured. The difference between the upward force and the spring force is the aerodynamic lifting force of the contact plate as shown in Eq. (2). The proportional coefficient of aerodynamic lifting force is calculated by the following Eq. (4). Once the upward force is measured, the wire rope is removed and emergency mode to raise the forward pantograph is cancelled.

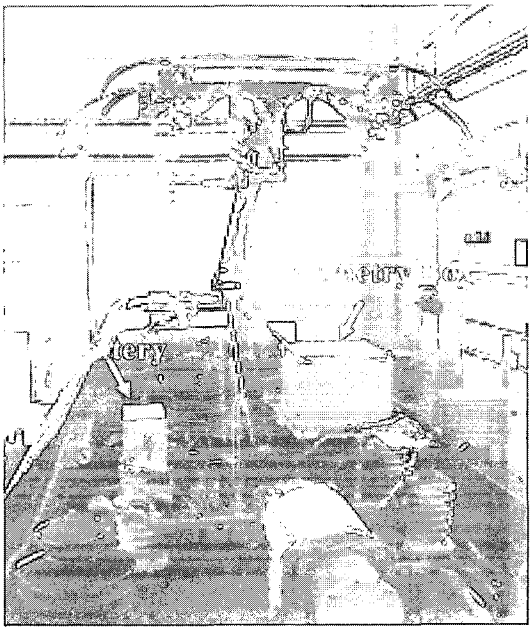

Fig. 11 Measuring equipments on the roof

$$k=\frac{\overline{F_c}-\overline{F_{sp}}}{V^2} \tag{4}$$

4.2 Comparison of upward forces

During the test running, the received signals from the telemetry are converted into the text files by the software and are displayed in real time on the monitor. All the data are recorded in the hard disk and useful information is extracted and shown by the analysis software. The measured upward forces of the contact plate are shown in Fig. 12. It reveals that the upward force increases in proportion to velocity square. The average upward forces changing with the velocity are shown in Fig. 5 and compared with the wind tunnel test results. Figs. 5 and 6 indicate that two results are in good agreement and the wind tunnel test results give the reliable data for prediction of aerodynamic characteristics of the pantograph.

4.3 Practical measuring method

In the high speed zone, the effect of the aerodynamic lifting force of the contact plate on the contact force can't be neglected as shown in Fig. 6. The wire rope test to measure the upward force of the contact plate is not practical because the operating mode to raise the pantograph must be changed whenever it is carried out. Also, the upward force is not the exact contact force because

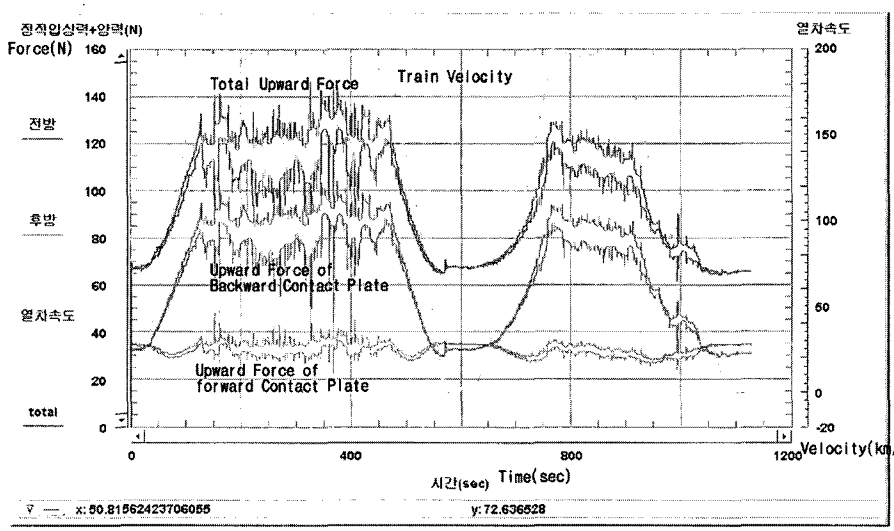

Fig. 12 Measured results of upward forces of contact plate

the flexible boundary condition is not provided. The measurable spring force doesn't include the aerodynamic lifting force of the contact plate. Therefore, a reasonable and practical method to measure the contact force is necessary. As shown in the test results of Fig. 6, the wind tunnel test gives accurate data for the aerodynamic lifting force of the contact plate. The new practical measuring method substitutes the wind tunnel test results for the unreasonable running test results. During the running test, only the spring force under the contact plate is measured for safety and the aerodynamic lifting force resulting from the wind tunnel test is added for correction. In other words, the contact force is given by the following equation.

$$\overline{F_c}=\overline{F_{sp}}+(\overline{F_{ac}})_{run}\cong\overline{F_{sp}}+k_{wind}V^2 \qquad (5)$$

The actual aerodynamic lifting force of the contact plate is replaced by the wind tunnel test result. Since the aerodynamic lifting force of the contact plate measured in the wind tunnel test was proved to be in good agreement with the force measured in the running test, Eq. (5) gives a reasonably accurate result for the contact force.

5. Numerical Simulation of Dynamic Characteristics

The dynamic characteristics of the pantograh can be simulated by numerical analysis. The pantograph is modelled as a lumped mass and spring system with multi-degrees of freedom (Park et al., 2002). The catenary system is divided into beam elements and the finite element analysis method is used to find the solution. The external forces applied to the pantograph such as aerodynamic lifting force are given by the previous test data. The simulation results of the dynamic characteristics of the pantograph on KHST were presented by several researchers (Kim et al., 2003). The typical results for the contact force are shown in Fig. 13 and compared with the measured results. The difference of the average contact forces seems to be caused mainly by the difference of the external forces, because the fluctuating component

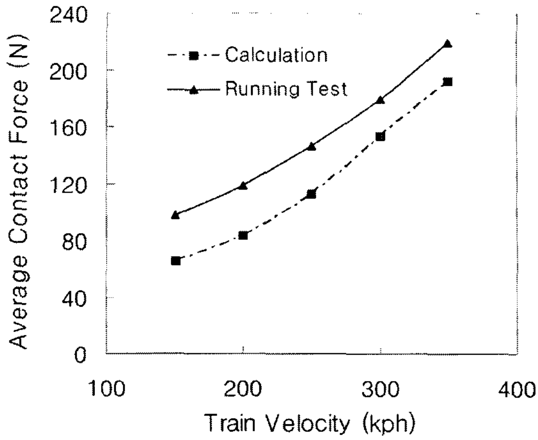

Fig. 13 Comparison of average contact forces

of the contact force disappears in the time average value. Correct estimation of the aerodynamic lifting forces composing the external forces is important for good prediction of the contact force.

6. Test Results and Investigation

Once the aerodynamic lifting force coefficient shown in Eq. (4) is found, the aerodynamic lifting force of the contact plate can be calculated and automatically added to the spring force during data processing. The corrected contact force is recorded and displayed on the monitor. Fig. 14 shows the measured results for the contact force and acceleration of the contact plate. The train velocity is also measured and shown simultaneously.

Because large contact force accelerates wear of the contact wire, it should be controlled in a limit. The normal limit of average contact force for high speed train is 200 N (Kim et al., 2002) (Alstom, 2001). Fig. 14 shows that the maximum average contact force is below 200 N. In fact, the measured contact forces during first trial running was above 200 N, when the train speed exceeded the speed of 270 km/h. To prevent excessive wear of the contact wire, the contact force should be reduced to 200 N in the velocity range above 270 km/h. A plate is attached on the horn frame to control the lifting force as shown in Fig. 15. To reduce the lifting force, the plate was changed into a smaller one. The length of the plate couldn't be

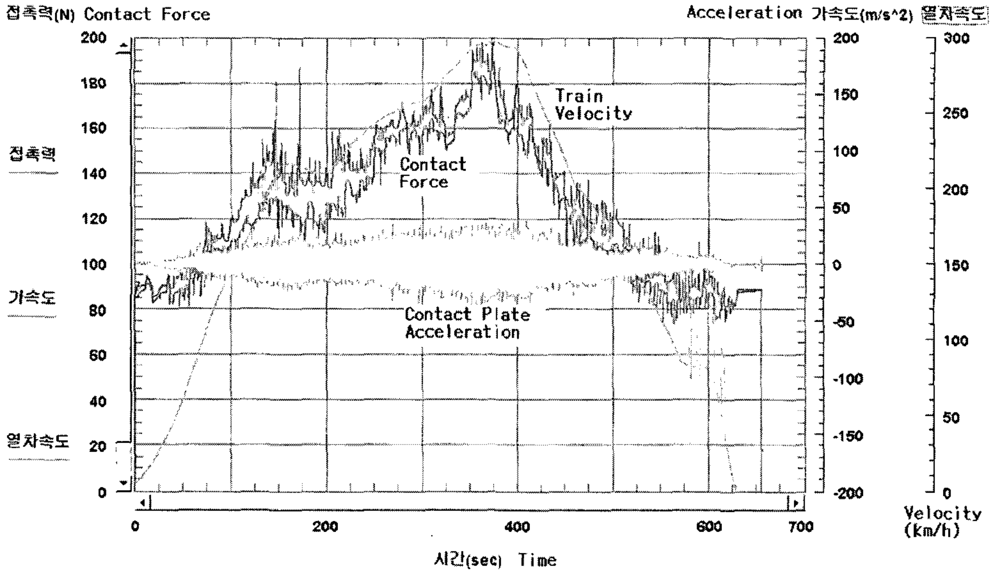

Fig. 14 Measured contact force and acceleration

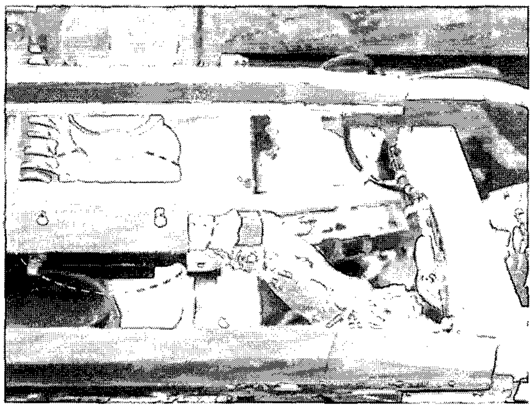

Fig. 15 Lifting control plate and contact plate

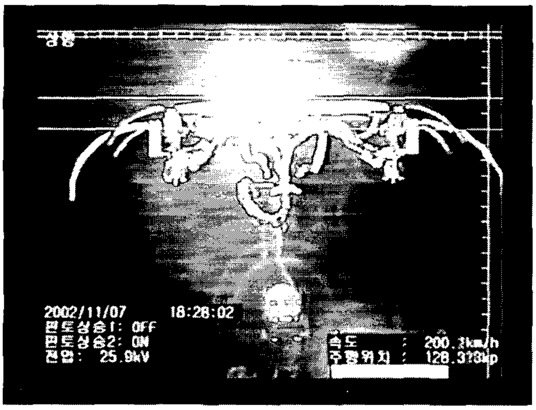

Fig. 16 Video monitoring of arc generation

reduced because of the fitting location. Instead, the breadth and thickness of the plate was reduced. After the lifting force control plate was changed, the contact plate was reduced below 200 N as shown in Fig. 14.

Separation of the contact plate from the catenary causes arc generation as shown in Fig. 16 and damages the contact wire of the catenary. It has been known that the accelerating motion of the contact plate causes separation from the catenary instantaneously. Several criteria have been proposed to judge the arc generation (UIC, 1996). Negative contact force or standard deviation of the instantaneous contact force was proposed as the arc generation parameter. However, the analysis result for the video monitoring of arc generation showed that surface roughness or mismatch of the contact wire was closely related with the arc generation. The moment and kilo post of arc generation were displayed on the video monitoring system and the location was traced. The most arc generation points were found to be the spots with surface mismatch of the contact wire. When examination-in -service was carried out after a number of strong arcs were generated, the carbon strip of the plate was found to be damaged as shown in Fig. 17. As to the arc generation, further research is needed.

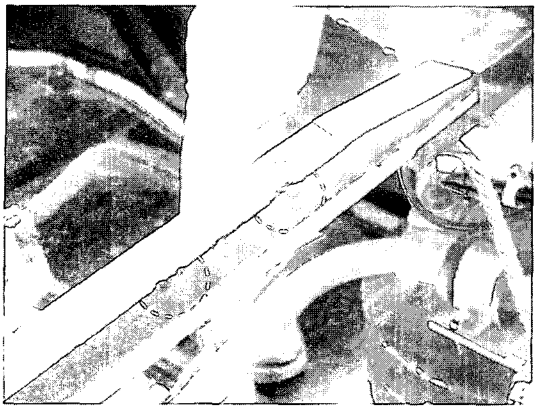

Fig. 17 Damaged carbon strip of contact plate after strong arc generation

7. Conclusions

To confirm the interface performance of the pantograph on the high speed train, correct information on the contact force with the catenary system is necessary. The previous measuring methods couldn't take into account the aerodynamic lifting force of the contact plate which was the dominant component of the contact force in the high speed train. Also, dangerous high voltage environment around the pantograph makes it difficult to directly measure the contact force. In this study, a method to measure the contact force was proposed and the related measurement system was developed. A special device and procedure was invented and applied to measure the contact force. The wind tunnel test data was used to estimate the aerodynamic lifting force of the contact plate. The obtained results can be summarized as follows ;

(1) The wind tunnel test results for the upward force and aerodynamic lifting force of the contact plate show good agreement with the running test results.

(2) The contact force measuring method proposed in this study gives good and reasonable results, where the actual aerodynamic lifting force of the contact plate was replaced by the wind tunnel test result.

(3) For KHST, the measured contact forces were compared with the limit which is regulated to protect the contact wire from excessive wear. During the test running process, the contact force could be lowered by the change of the lifting force control plate.

(4) According to the video monitoring result, arc generation was related not only with the deviation of the contact force, but also with the surface condition of the contact plate and catenary wire.

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