Development of Simple Catenary System for Operation over 300 km/h

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Compound catenary systems on Shinkansen lines will soon enter a period where they will have to be replaced on a large-scale. In order to facilitate replacement and reduce maintenance costs, compound catenary systems can be replaced with simple catenary systems. This study explores new types of simple catenary systems developed for running speeds of about 320 km/h, which is the maximum Shinkansen commercial operating speed. In addition, a simple catenary system for operation up to 360 km/h is also being developed.

Keywords: electric railways, current collection, contact loss, current capacity, connector

1. Introduction

Since 1964 when Tokaido Shinkansen line started operation, compound catenary systems have been mainly used in overhead contact line structures on high-speed lines in Japan. Simple catenary systems for Shinkansen high-speed lines however, were first installed on the Hokuriku Shinkansen line which entered into operation in 1994 [1]. This simple catenary system was designed for lines with low traffic density in contrast with lines where heavy compound catenary systems were installed. The current capacity of the simple catenary system is approximately 70 % of that of the heavy compound catenary system [1].

Soon however, it will be necessary to replace the compound catenary systems on Shinkansen lines on a large-scale. To facilitate renewal and reduce maintenance costs, it is efficient to replace compound catenary systems with simple catenary systems when renewing compound catenary systems. New type of simple catenary system was developed and is being installed on Tokaido Shinkansen line where the maximum operating speed was less than 300 km/h [2]. Moreover, the Shinkansen lines over 300 km/h are in the direction of renewing to install simple catenary systems. However, simple catenary systems tend to cause large vertical oscillations of the pantograph in the intervals between support points compared with compound catenary systems. When thick wires are used to ensure current capacity, fluctuations in the contact force between the contact wire and the pantograph due to the hanger intervals tend to be large: the resulting increase in contact force fluctuations due to this, is a problem for high-speed operations.

This study describes the development of a new type of simple catenary system for operating speeds of 320 km/h, which is the current maximum speed on commercial Shinkansen lines, and of a simple catenary system for operating speeds up to 360 km/h. One of the performance targets of the developed simple catenary system is to achieve a contact loss ratio within 10 %, which is the criterion value for good current collection performance.

2. Structure of simple catenary system for the operation over 300 km/h

2.1 Wave propagation velocity of contact wire

The mass and tension of a contact wire affect the current collection performance between the contact wire and the pantograph. It has been shown that contact loss between the contact wire and the pantograph increases sharply when the train speed is higher than approximately 70 % of the wave propagation velocity of the contact wire, in particular [3].

The wave propagation velocity of the contact wire $c_t$ is expressed by the following equation.

$$c_t = \frac{T_t}{\sqrt{\rho_t}}$$  \hspace{1cm} (1)

where $\rho_t$: Line density of contact wire

$T_t$: Tension of contact wire

Figure 1 shows the relationship between the tension of the contact wire and 70 % of the wave propagation velocity for each contact wire (GT-PHC110, GT-PHC130, GT-Sn150, GT-Sn170). The wave propagation velocity of the contact wire used for the high-tension heavy compound cat-
inary system (cross-sectional area of contact wire: 170 mm\(^2\), nominal tension of contact wire: 19.60 kN) is 411 km/h. The train speed 320 km/h corresponds to 78 % of the wave propagation velocity.

![Wave propagation velocity](image)

**Fig. 1** Relationship between tension and 70 % of contact wire wave propagation velocity

### 2.2 Fluctuation of contact force between contact wire and pantograph

An excessive contact force between the contact wire and the pantograph may generate significant stress in the contact wire, which may lead to fatigue failure of the contact wire. On the other hand, when the contact force is too small, contact loss occurs and the electric power supply to a vehicle will be interrupted. In general, contact force fluctuations increase due to a range of factors as train speed increases. Therefore, it is necessary to keep contact force fluctuations within an appropriate range. The factors that cause contact force fluctuation are due to overhead contact line structures such as the interval of support points and hangers, and irregular unevenness of contact wire height. Contact force fluctuations stemming from intervals between support points and hangers were examined.

Contact force fluctuations due to the intervals between support points are mainly caused by the change in elasticity of overhead contact lines, within the span. The contact force fluctuation amplitude \( |F_{csp}| \) is modeled by the following equation [4].

\[
|F_{csp}| = \frac{\rho_i}{K} \left( \frac{1}{1 + \beta_i^2} + \frac{1}{(1 - \beta_i^2 - \gamma_s^2)} \right)
\]

where \( \rho_i \): Line density of contact wire

\( g \): Acceleration of gravity

\( L_s \): Distance of hanger position

\( \gamma_s \): Reflection coefficient of hanger position

\( Z_i \): Mechanical impedance of contact wire

\( \beta_i \): Dimensionless velocity of contact wire

\( \nu/c_i \)

The reflection coefficient \( \gamma_s \) at the hanger point is expressed by the following equation.

\[
\gamma_s = \frac{Z_m}{Z_t}
\]

where, \( Z_i \) is the mechanical impedance of the wire and is expressed by (5). The subscript \( i \) indicates a wire where \( i \) is the contact wire and \( m \) is the suspension wire of the contact wire.

\[
Z_i = 2\rho_i\gamma_i T
\]

### 2.3 Cross-sectional area and tension of wires

#### 2.3.1 Simple catenary system for operating speeds of 320 km/h

(1) Contact force fluctuation

Considering maintenance, first, contact wire having a cross-sectional area of 170 mm\(^2\) and tension of 19.60 kN were investigated, which are the same as those used in high-tension heavy compound catenary systems for 320 km/h operations in Japan. A hard-drawn copper stranded conductor was selected for the messenger wire to ensure current capacity, while a cross-sectional area of 200 mm\(^2\) (PH200) was selected in consideration of allowable load. The higher the tension of the messenger wire, the higher the static mean stiffness of the overhead contact lines \( K \) and the lower the contact force fluctuation due to the support point intervals from (2). On the other hand, from (3) to (5), since the mechanical impedance of the messenger wire \( Z_m \) and the reflection coefficient in the hanger position \( \gamma_s \) increase, contact force fluctuation due to the hanger intervals increases. Therefore, contact force fluctuation due to hanger intervals was examined and compared with that in the case of the high-tension heavy compound catenary system for 320 km/h operations. The calculation model for the pantograph is a simple one-mass model, and the mass was set to 12.4 kg (sum of \( m_1 \) and \( m_2 \)) with reference to pantograph A [5] for train speeds over 300 km/h, as shown in Table 1.

As a result of estimating contact force fluctuation due to hanger intervals at a speeds of 320 km/h using (3), the contact force fluctuation of the simple catenary system with total tension of 39.20 kN is 150 N, and that with total tension of 55.90 kN is 170 N. This indicates that the contact force fluctuation of the simple catenary system is 35 to 55 N larger than that of the high-tension heavy compound catenary system. To reduce the contact force fluctuation due to hanger intervals, the increase in wave propagation velocity of the contact wire was investigated. Considering the wear allowance, the increase in the contact wire ten-
sion was examined up to 22.54 kN (2.3 tf) to increase the wave propagation velocity without changing its cross-sectional area (mass). When the contact wire tension is 22.54 kN, the contact force fluctuation due to hanger intervals is 101 to 122 N (total tension is 39.20 to 58.80 kN), which is approximately the same as in the high-tension heavy compound catenary system. Therefore, the contact wire tension was set to 22.54 kN. The wave propagation velocity of the contact wire is 440 km/h, and the train speed of 320 km/h corresponded to 73% of 440 km/h.

(2) Evaluation of dynamic characteristics

The contact force fluctuation modeled by (2) and (3) is useful for qualitative evaluation, but is not reliable enough for quantitative evaluation. Furthermore, in a train set with more than one pantograph, the rear pantograph is affected by overhead-contact-line oscillation caused by the front pantograph which depends on train speed, the distance between the pantographs and the span length. Therefore, to quantitatively evaluate the effect of the pantograph interval on the current collection performance of the rear pantograph, dynamic characteristic evaluation [6] was performed using the dynamic simulation of overhead contact lines and pantographs.

The dynamic model and parameters of the pantographs are given in Table 1. The parameters for pantograph A correspond to a train speed over 300 km/h [5], and pantograph B for a train speed up to 300 km/h. The intervals between front and rear pantograph were set at 50 to 300 m (in 25 m increments). The contact wire tension was 22.54 kN and with total tension between 39.20 and 58.80 kN (4.90 kN increments).

Table 1 Dynamic model of pantographs

| Pantograph | A     | B     |
|------------|-------|-------|
| $m_0$ [kg] | 0.6   | 9.2   |
| $w_0$ [kg] | 11.8  | 8.5   |
| $k_1$ [N/m]| 10750 | 10600 |
| $c_1$ [Ns/m]| 0.0   | 80.0  |
| $c_2$ [Ns/m]| (Bi-direction) | 81.0 | (Uni-direction) |
| $P_a$ [N]  | 54    | 54    |

| Aerodynamic force [N] (300 km/h) | Front: 35.0 | Rear: 35.0 |
|----------------------------------|-------------|------------|
|                                  | Front: 36.9 | Rear: 62.1 |

Figure 2 shows an example of the speed characteristics of the contact loss ratio calculated through simulation. According to Fig. 2, contact loss did not occur under some conditions at any speed in the case of pantograph A, while contact loss occurred under all conditions in the case of pantograph B. Figure 3 shows the relationship between the total tension and the contact loss rate. This figure indicates that as the total tension increased, the maximum contact loss ratio decreased, and the overall contact loss ratio tended to decrease.

The contact wire height in the simulation is treated as no irregular condition, but the actual overhead wire has contact wire irregularities caused by installation errors such as the contact wire height at support points and the variation in the hanger intervals. Since these contact wire irregularities cause contact force fluctuation [7], there is a possibility that contact loss increases from the simulation results. Therefore, in this study, total tension was determined with a view to achieving a contact loss target ratio of approximately 5% or less. This contact loss ratio is half the 10% contact loss ratio which is the development target. Figure 3 shows that when the total tension was 53.90 kN or more, the maximum contact loss ratio of pantographs A and B was approximately 5%. These results therefore suggest that it is appropriate to set the total tension of the simple catenary system for operating speeds of 320 km/h, to 53.90 kN.

2.3.2 Simple catenary system for operating speeds up to 360 km/h

Contact wire tension must be determined considering the work required to replace the contact wire, and the strength of the supports and fittings. Therefore, the contact wire tension is set to 24.5 kN, and the contact wire cross-sectional area is set to 130 mm² in order to satisfy the train speed less than 70% of the wave propagation velocity, based on Fig. 1. Under these conditions, the wave propagation velocity of the contact wire is 528 km/h, and
the train speed of 360 km/h corresponds to 68 % of the wave propagation velocity. A hard-drawn copper stranded conductor with a cross-sectional area of 200 mm² (PH200) was selected for the messenger wire, in consideration of current capacity and allowable load.

(1) Contact force fluctuation

Contact force fluctuation due to hanger intervals at a train speed of 360 km/h estimated from (3) is 66 to 75 N for a total tension of 39.20 to 58.80 kN. These values are approximately 40 to 50 N smaller than the values found with the high-tension heavy compound catenary system at a train speed of 320 km/h (115 N), and expected to have good current collection performance.

(2) Evaluation of dynamic characteristics

Figure 4 shows the relationship between total tension and the contact loss ratio calculated by dynamic simulation. It shows that as total tension increases, the maximum contact loss ratio decreases reducing the overall contact loss ratio tends. This tendency resembles the results of the simple catenary system for operating speed of 320 km/h. Figure 4 also shows that the contact loss ratios at the total tension with 49.00 kN and above are all within 10 % which is the development target. The maximum contact loss ratio is approximately 5 % when the total tension is 53.90 kN or more. Therefore, the total tension for the simple catenary system for operating speeds up to 360 km/h was set to 53.90 kN.

Based on the results of these investigations, the specifications of the simple catenary system for operating speeds of 320 km/h and up to 360 km/h were determined in the way shown in Table 2. This table also shows the specifications of the high-tension heavy compound catenary system.

3. Examination of current capacity

In this chapter, current capacity and temperature increases in the simple catenary systems are calculated. For comparison, the same calculations were performed for the high-tension heavy compound catenary system. Train speeds were set to 300 km/h, 320 km/h, and 360 km/h, with headways of 6 minutes (10 trains/h), 10 minutes (6 trains/h), and 4 minutes (15 trains/h). The following assumptions were made with reference to conventional studies:

- Even when one substation SS1 is stopped, the extended feeding system shown in Fig. 5 enables trains to run on time without any restrictions on train speed or run curve. The inbound and outbound lines of the feeding system were connected only at the 30 km point (sectioning post: SP) and the terminal (extended substation: SS2). The overhead contact lines layout was a standard open air section layout with a power frequency of 50 Hz.
- There were no stations, no gradients and no curves. In terms of Shinkansen running resistance, resistance in open air sections is significantly different from that in tunnels. As shown in Fig. 5, it was assumed that 40 km from SS1 to SSP3 was a tunnel section, and 20 km from SSP3 to SS2 was open air section. Running resistances were calculated with calculation formulae for the 700 series Shinkansen (16-car train set) and the E2 series Shinkansen (10-car train set) [8].
- From the given train speed and the running resistance, the mechanical power that achieves balanced power running was obtained. The collected current of each train set was determined assuming a gross train efficiency of 90 %, a power factor 1.0, and a pantograph position voltage of 25 kV.
- Train operation followed the pattern diagram shown in Fig. 6 with constant intervals and constant speed balance.
- The location where the current was maximized was in the immediate vicinity of SS1, and was treated as an open air section. This location was used for calculating the rise in temperature using general assumptions (ambient temperature 40°C, wind speed 0.5 m/s, radiation...
coefficient 0.9, solar radiation 0.1 W/cm²).

- Calculations were made to obtain the current of the T phase with respect to the train position and the division current ratio of each wire of the overhead contact lines as a numerical table beforehand. After that, when each train was arranged, the current was added according to the train interval and the train speed. Calculations were conducted to obtain the contact wire current and the rise in temperature in the immediate vicinity of SS1 (Fig. 7).

Table 3 shows the calculation results of the contact wire temperature. The most severe condition for all overhead contact lines is provided when the cross-sectional area of the contact wire is worn down to the minimum cross-sectional area (contact wire remaining rate: 79.6 %). When the calculated contact wire temperature is below the allowable temperature of 90°C, it is considered acceptable for use in operation. The simple catenary system used with operating speeds of 320 km/h and up to 360 km/h had a maximum temperature of 90°C or less for all trains running at 320 km/h with a headway of six minutes. However, at 360 km/h, the maximum temperature of the contact wire exceeded 90°C, and it was difficult to operate all train sets with 16 cars in terms of temperature rise. When train sets were mixed, such as sets with 10 cars, the maximum temperature of the contact wire is 90°C or less, suggesting that the simple catenary system could withstand used at operating speeds up to 360 km/h. For the reference 4-minute headway, the maximum temperature of the contact wire exceeded 90°C under all conditions.

When the substation no-load voltage was 57.4 kV, which is a voltage between the T phase and F phase and was also 28.7 kV between the pantograph and the rail, the feeding transformer single side capacity was 60 MVA, and percentage impedance %Z was 11.7 %, for 16-car trains running with a 6-minute headway at 320 km/h, the estimated minimum voltage of the simple catenary system for operating at 320 km/h was 25.7 kV and for 360 km/h was 25.6 kV. These values satisfy the criterion minimum voltage of the Shinkansen (22.5 kV). However, this voltage drop also includes voltage drops caused by substation feeding transformers. On the other hand, when the train ratio of 16-car trains to 10-car trains was 2:1, running at 360 km/h, the estimated minimum voltage of the simple catenary system for operating speeds of 360 km/h was 22.9 kV, which satisfied the minimum criterion Shinkansen voltage (22.5 kV).

4. Examination of connector for high system height

On Shinkansen lines, the system height of the overhead contact lines (distance between the messenger wire and the contact wire at the support point) on the compound catenary system is 1,500 mm in open air sections and 1,100 mm in tunnels. In the simple catenary systems currently used on projected Shinkansen lines, this distance is 950 mm in all sections. When the compound catenary systems are replaced with new simple catenary systems, it would be ideal to be able to have the same separation height to facilitate construction work and keep costs down. However, the larger the connector height, the lower its natural frequency [9], so reducing this distance raises the concern of possible resonance of the connector with the overhead contact lines which could then lead to fatigue failure.

Therefore, as shown in Fig. 8, the connector for the system height of 1,500 mm (the lead wire is an annealed copper stranded conductor with cross-sectional area of 100 mm²) was developed. The fatigue characteristics of the developed connector were compared with that of the projected Shinkansen line (the system height is 950 mm, lead wire is an annealed copper stranded conductor with cross-sectional area of 40 mm²). Figure 9 shows the primary natural frequency of each connector with respect to the connector height, which was calculated using finite element analysis. The frequency range (1.0 to 1.7 Hz) in the residual oscillation of the overhead contact lines calculated with reference to Reference [9] is also shown in the figure. Figure 9 shows that the natural frequency of the developed connector is higher than that of the projected Shinkansen line and is outside the natural frequency range of the residual oscillation of the overhead contact line. This means the developed connector is free from resonance with the residual oscillation of the overhead contact line.
5. Current collection test on commercial line

The developed simple catenary systems for operating speeds of 320 km/h and up to 360 km/h were installed on a commercial Shinkansen line, and the current collection performance was measured at train speeds up to 320 km/h. Both simple catenary systems were installed in an open air section. Using wayside equipment, contact loss (used measurement equipment at wayside [10]), uplift and strain of contact wire were measured. Figure 10 shows the installation of the overhead contact lines.

Figures 11 to 13 show the measurement collected for two types of newly developed simple catenary systems and of the high-tension heavy compound catenary system from before installation of the simple catenary system. These figures also show results calculated through dynamic simulation of overhead contact lines and pantographs. From these figures, it can be seen that the performance of the simple catenary system for operating speeds of 320 km/h was almost the same as the high-tension heavy compound catenary system. Though contact loss did not occur in the simulation, it was observed through measurements on both the simple catenary system for operating speeds of 320 km/h and the high-tension heavy compound catenary system. This is thought to be due to the influence of overhead contact lines installation errors that were mentioned previously in this paper.

The contact loss ratio for the simple catenary system for operating speeds of 320 km/h and up to 360 km/h was 10% or less. In both catenary systems, the measured values and the calculated values of uplift and strain of the

| Train condition | Calculated value | Measured value |
|-----------------|-----------------|----------------|
| 200 km/h        | 10              | 8              |
| 300 km/h        | 15              | 14             |
| 400 km/h        | 20              | 18             |

![Fig. 8 Configuration of connector](image)

![Fig. 9 Relationship between connecter height and natural frequency](image)

![Fig. 10 Installation situation of overhead contact lines](image)

![Fig. 11 Measurement result of current collection performance on commercial line (simple catenary system for operating speeds of 320 km/h)](image)

![Fig. 12 Measurement result of current collection performance on commercial line (simple catenary system for operating speeds up to 360 km/h)](image)

![Fig. 13 Measurement result of current collection performance on commercial line (high-tension heavy compound catenary system)](image)
contact wire were almost the same. These results demonstrate that both newly developed simple catenary systems meet the expected current collection performance. Furthermore, for each of the simple catenary systems, during the installation period (approximately half a year), there was no progress in local wear of the contact wire.

6. Conclusions

A new type of simple catenary system for operating speeds of 320 km/h, the maximum speed of commercial Shinkansen lines, was developed. A simple catenary system for operating speeds up to 360 km/h was also developed. The results of dynamic overhead contact lines and pantograph simulations and actual installation test results with operating speeds up to 320 km/h, confirmed that both simple catenary systems achieved the expected current collection performance. During the installation period (approximately half a year), the contact wire remained in good condition without any local wear.

Plans are in place to install the developed simple catenary system for operating speeds up to 360 km/h to conduct current collection performance tests on a commercial Shikansen line.

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