Optimization of Overhead Contact Lines for Shinkansen Speed Increases

In order to increase Shinkansen operational speeds, we need to conduct development on the overhead contact line equipment that supplies power to rolling stock in addition to development for rolling stock. At the start of the tests using FASTECH360, we introduced a new overhead contact line system that replaces conventional compound overhead contact line equipment (hereafter “improved compound catenary equipment”). But, as speeds in tests increased, we found many problems due to the change of the height of the overhead contact lines and the arrangement of pantographs that were not major concerns at present operational speeds. We addressed those problems through simulations and tests using an actual train and finally gained a good perspective on supplying power in the speed range of 360 km/h.

In this paper, I will introduce the development of the new system.

1 Introduction

Use of the heavy compound catenary equipment—the standard overhead contact line system for the Shinkansen—is limited to speeds of up to around 240 km/h. So, in order to carry out running tests at around 360 km/h, considerable improvement and development was required. Since the period from planning to start of the tests using FASTECH360 was only a year, we went to work on the development of the overhead contact line system taking into account shortening of the work period.

As is widely known, improving the wave propagation velocity of the overhead contact line c shown in formula (1) is effective for increasing the running speed. For that reason, we have increased the tension of and decreased the weight of the contact wire.

\[ c = \left( \frac{T}{\rho} \right)^{1/2} \times 3.6 \text{ [km/h]} \]  

(1)

\( T \): Tension of the overhead contact line [N],  
\( \rho \): Weight per unit length of the overhead contact line [kg/m]

Table 1 and Fig. 1 shows the compound catenary equipment deployed for JR East Shinkansen.

The “Higher tension heavy compound catenary equipment” in Table 1 is the overhead contact line system that was improved when we increased the speed of the Tohoku Shinkansen to 275 km/h, and the “CS heavy compound catenary equipment” is the system that was improved in tests 15 years before where we successfully increased the speed to 425 km/h using the STAR21 test train on the Joetsu Shinkansen.

In the high speed running tests this time, performance equivalent to that of the CS heavy compound catenary equipment was required. We were concerned, however, that development and construction could not be done in time, because the section that needed improvement was as long as approx. 60 km (60 drums) between Sendai and Kitakami.

3 Issues in Improvement of the Overhead Contact Line System

3.1 Issues in Current Collection Performance

In running tests in 2003 using an operating train to get basic data for tests with FASTECH360, we measured remarkable strain (stress) on the contact wire over 1,000 μst at 360 km/h.

We presumed the cause to be the compound effect of short intervals of 50 m for pantographs of the test train, single-arm contact strips and heavy pull-off arms. Also, we thought that another cause was that wave propagation was prevented because sufficient wave...
propagation velocity was not secured due to loose tension of the auxiliary messenger wire.

3.2 Issues in Construction
When we conducted improvement work of the CS heavy compound catenary equipment for the running tests of STAR21, for example, it took three days to improve one drum length (see Table 4). It was clear that if applying the same work method to the improvement this time, work would take more than half a year. Considering that and a balanced schedule with other maintenance work, we had to drastically shorten the work period.

In improvements to enable a higher tension heavy compound catenary equipment to handle 360 km/h running, we set the following targets as requirements to improve the current collection performance and, at the same time, to allow effective work.

1) Approx. 500 km/h wave propagation velocity for the contact wire
2) No change of the total tension of the overhead contact line system to avoid modification of support components
3) Shortening the work period to 2/3 that of past work

*1) Train speed × wave propagation velocity multiplied by approx. 0.7 or 0.8 is desirable.

In order to achieve 1), we made the diameter of the contact wire thinner (lighter in weight), from 170 mm$^2$ to 110 mm$^2$, and increased the tension from 17.6 kN to 19.6 kN.

Regarding 2), to maintain 53.9 kN total tension of the overhead contact line system, the total tension of the messenger wire and the auxiliary messenger wire needed to be decreased. As for the CS system, we decided to decrease the tension of the auxiliary messenger wire while keeping the tension of the messenger wire the same; but that could result in insufficient wave propagation velocity of the auxiliary messenger wire.

And, since we kept the tension of the messenger wire as-is in spite of the lighter contact wire, we had to replace all droppers to maintain the height of the contact wire. That work took a lot of time and manpower.

Accordingly, we tested a method of reducing the tension of the messenger wire according to the reduced tension of the messenger wire, to eliminate the replacement work of droppers. Also, we added that reduced weight of the contact wire to the auxiliary messenger wire to improve the wave propagation velocity up to the test speed (360 km/h) with an aim of improving the current collection performance.

Formula (2) shows the calculation of the dip in the catenary curve D (see Fig. 2).

\[ D = \frac{x}{S \cdot \tan(\alpha)} \cdot \frac{r}{2T} \]  

S: Span length, T and \( \alpha \): As in Formula (1)

Since the unit weight of the overhead contact line system is changed from 4.35 kg to 3.83 kg due to the introduction of 110 mm$^2$ diameter contact wire, approx. 21.6 kN tension of the messenger wire is desirable based on Formula (2).

\[ D = \frac{x}{S \cdot \tan(\alpha)} \cdot \frac{r}{2T} \]  

Formula (2) shows the calculation of the dip in the catenary curve D (see Fig. 2).

\[ D = \frac{x}{S \cdot \tan(\alpha)} \cdot \frac{r}{2T} \]  

Table 2 shows the specs of the improved compound catenary equipment for the tests this time.

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Improved} & \text{Messenger wire} & \text{Auxiliary messenger wire} & \text{Contact wire} & \text{Running speed} \\
\text{compound} & \text{area} & \text{area} & \text{area} & \text{km/h} \\
\text{catenary} & \text{mm}^2 & \text{mm}^2 & \text{mm}^2 & \\
\text{equipment} & 110 & 110 & 19.6 & 360 \\
\hline
\end{array}
\]

5.1 Workability
First, we verified the dropper length of the higher tension heavy compound catenary equipment (before improvement) and the improved compound catenary equipment. Table 3 indicates the comparison results at the 50 m span length.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{No.} & \text{Before} & \text{After} & \text{No.} & \text{After} \\
\text{improvement} & \text{improvement} & \text{improvement} & \text{No.} & \text{improvement} \\
\text{1} & 1,118 & 1,119 & 5 & 1,119 \\
\text{2} & 896 & 896 & 6 & 856 \\
\text{3} & 796 & 856 & 7 & 1,119 \\
\hline
\end{array}
\]

The difference of the dropper length is within a few millimeters at other span lengths also. Therefore, replacement of droppers is not required. In this way, we could drastically simplify the improvement work compared to the CS heavy compound catenary equipment, as shown in Table 4.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{No.} & \text{CS heavy compound catenary equipment} & \text{Improved compound catenary equipment} \\
\hline
1 & \text{Replacement of first and second yokes} & \text{Replacement of first and second yokes} \\
2 & \text{Pre-stretching} & \text{Pre-stretching} \\
3 & \text{Replacement of pull-off arms} & \text{Replacement of pull-off arms} \\
4 & \text{Replacement of hanger, pull-off arms, etc.} & \text{Replacement of hanger, pull-off arms, etc.} \\
5 & \text{Winding up of old contact wire} & \text{Winding up of old contact wire} \\
6 & \text{Adjustment of overlapping} & \text{Adjustment of overlapping} \\
7 & \text{Installation of new droppers} & \text{Installation of new droppers} \\
8 & \text{Replacement of first yoke} & \text{Replacement of first yoke} \\
9 & \text{Pre-stretching} & \text{Pre-stretching} \\
10 & \text{Replacement of hanger, pull-off arms, etc.} & \text{Replacement of hanger, pull-off arms, etc.} \\
11 & \text{Winding up of old contact wire} & \text{Winding up of old contact wire} \\
12 & \text{Adjustment of overlapping} & \text{Adjustment of overlapping} \\
13 & \text{Replacement of movable brackets} & \text{Replacement of movable brackets} \\
14 & \text{Replacement of droppers} & \text{Replacement of droppers} \\
15 & \text{Adjustment to overhead contact line} & \text{Adjustment to overhead contact line} \\
\hline
\end{array}
\]

Table 4 Comparison of Overhead Contact Line Improvement Process
As shown in the above table, we could shorten the improvement work time of almost three days to two days. For the change of the tension of the messenger wire (replacement of anchor yokes), one of our partner companies developed a special jig to shorten the work time.

The comparison of before and after the improvement work using the data of an electric and track inspection car proved that the status before the improvement such as the height and deviation of the overhead contact lines could be duplicated well; and almost no adjustment after the work was needed.

5.2 Current Collection Performance
In addition to shortening the work period, we aimed at reducing the stress of the contact wire by increasing the tension of the auxiliary catenary wire, and examined that effect by simulation. Fig. 3 and 4 show part of the simulation results.

The simulations showed that the maximum uplift of the contact wire considerably decreased from 70 mm to 35 mm just as the contact force decreased as shown in Fig. 3. That suggests that the fatigue (stress) of the contact wire could be eased.

The contact loss ratio, which increased as shown in Fig. 4, could be kept within the allowable range of 30%. Since it has been confirmed that multi-fractioned contact strips with less weight of movable parts significantly reduces contact loss, we expect that the actual contact loss ratio can be reduced to only a few percent.

6.1 Change of the Height of the Overhead Contact Lines
After starting the tests, we could observe favorable current collection including better contact loss ratio than expected; but as the running speed increased, we suddenly faced an event where many contact loss cases occurred in a certain section (drum). Fig. 6 shows the event. As we tried running with only one pantograph that was considered difficult, reduction of contact loss was an issue to be overcome.

We found a large contact loss that occurred in every supporting point as a characteristic of the section with many contact losses. So, assuming that the contact loss occurred due to the change of the height of the overhead contact lines between the supporting points, we compared the change of that height and the contact loss ratio between drums** (see Fig. 7).

*2: The unit length between anchors of the line is called a drum.

6. Obstructions to Stable Current Collection

6.1 Change of the Height of the Overhead Contact Lines

Since the simulation also confirmed that approximate 30 mm pre-sagging caused significant increase of contact losses in the 360 km/h speed range, we immediately added work to eliminate pre-sagging***.

*3) Pre-sagging: Giving sag to overhead contact lines taking in account uplifting by pantographs.
In the test with those train sets, we observed interesting results regarding contact loss. Fig. 11 shows that while the contact loss ratio in the 360 km/h speed range on the outbound line was in some sections in excess of the 10% that is considered good due to bad overlap configuration etc., that was mostly by just a few percent; and the duration of contact loss was shorter than a few tens of milliseconds, the standard of the good contact loss ratio. On the other hand, on the inbound line, the duration of contact loss was less than 100 ms, but the contact loss ratio reached nearly 30%, the worst acceptable standard.

We considered that the cause of the difference between the outbound and inbound lines was the difference of the interval of pantographs; so, we carried out a study for improvement.

As shown in Fig. 12, the simulation clarified that rear pantographs only contacted the contact wire weakly at a 138 m interval; so, those easily lost contact at speeds over 275 km/h.

Accordingly, we changed the intervals of current collecting pantographs as shown in Fig. 13 to test the effect of the intervals.

In the test with those train sets, we observed interesting results regarding contact loss.

Replacing pantographs** significantly improved contact losses too and almost no contact losses occurred after the pre-sagging elimination work as shown in Fig. 9. We could thus confirm the effect of those countermeasures.

*4) We replaced pantographs with the low-noise ones that have single arms and higher compliance characteristics from multi-fractioned contact strips.

Pre-sagging had been originally taken to improve current collection performance; but we found that it is better to keep the height of the overhead contact lines the same as much as possible in the high speed range over 300 km/h.

6.2 Pantograph Interval and Dynamic Characteristics

Since our actual trains with the highest speed are coupled Shinkansen-exclusive cars and cars for through service on conventional and Shinkansen lines, we carried out the tests using a coupled train of two train sets.

Fig. 10 briefly illustrates the tested train sets. Pantographs are the above-mentioned low-noise type.

*Car No. 7 pantograph – Car No. 15 pantograph: 138 m (usual interval on inbound line)
*Car No. 7 pantograph – Car No. 12 pantograph: 91 m (the shortest interval)
*Car No. 2 pantograph – Car No. 12 pantograph: 198 m (usual interval on outbound line)
*Car No. 2 pantograph – Car No. 15 pantograph: 246 m (the longest interval)

The contact loss ratio per interval is as shown in Fig. 14. In the tests, the running speed was 275 km/h and the results shown are the

![Fig. 9 Measurement Results of Contact Loss Ratio Before and After Elimination of Pre-Sagging](image)

![Fig. 10 Test Train Set](image)

![Fig. 11 Measurement Results of Contact Loss Ratio (Upper: Outbound line, Bottom: Inbound line)](image)

![Fig. 12 Simulation Results of Contact Loss Ratio at 138 m Interval](image)

![Fig. 13 Difference in Intervals According to Change of Current Collecting Pantographs](image)
results of the rear pantographs.
The order of better results is
\[ 91 \, \text{m} \geq 198 \, \text{m} > 246 \, \text{m} > 138 \, \text{m}. \]

Fig. 14 Change of Contact Loss Ratio According to Difference in Pantograph Interval

The order clarifies that the contact loss ratio is affected by wave propagation and reflection too; so, longer pantograph intervals are not always better.

Looking at the characteristics of pantographs in each pattern, rear pantographs are positioned in the running direction at 246 m and 138 m intervals, while those are positioned on the opposite direction** at 91 m and 198 m intervals. In this context, we can estimate that contact loss is affected not only by pantograph intervals, but also by the characteristics of pantographs including differences in aerodynamic characteristics based on the direction.

**5: The > direction to the ← running direction.

Since pantographs in the running direction cannot generate sufficient lifting force and the insufficient contact to the contact wire could cause much contact loss, we carried out the test while increasing stationary uplifting force of rear pantographs.

As the simulation results in Fig. 15 show, we expect that contact loss ratio can be improved to approx. 10%—the standard good ratio—with 138 m pantograph intervals by increasing the stationary uplifting force from 54 N to 74 N.

Fig. 15 Simulation Results with Increased Stationary Uplifting Force

Since contact loss is affected by wave propagation and reflection too, longer pantograph intervals are not always better.

We thus introduced damper hangers to a section between the Iwate Ichinohe tunnel and the Ninohe station to check the effect.
speed. That might lead to smaller allowable wear, and we are thus concerned about a shorter lifespan.

On the other hand, the number of pantographs that slide on the contact wire will be reduced (for example, the number of pantographs of Hayate-Komachi type Shinkansen will be reduced from four to two because single train set will use only one pantograph); so, we can expect longer lifespan.

For the time being, we will be watching the results of those conflicting effects.

8.2 New Equipment Diagnosis Method

Recent advances in optical sensing technology have enabled easier measurement at points where high voltage is applied, and a measurement method of the contact force of pantographs to the contact wire is even allowing for multi-fractioned contact strips to be established.

If we can identify the contact force of pantographs, we can expect the following new equipment diagnosis methods to be established.

- Continuous measurement of the stress on the contact wire that we can now measure only at fixed points
- Daytime measurement of contact loss that we can now measure only at night or in tunnels
- Detection of improper equipment structure such as bad overlap configuration
- Estimation of progress of wear of contact wire

We have repeated running tests for almost three years since 2005. The test results are being applied to the coming increase of operation speed to 320 km/h, and the equipment and facilities are being improved right now.

Based on the tests, we gained a perspective on stably supplying power in the 360 km/h speed range. I hope this paper will pass down valuable data to future railways in the process of increasing speeds.