車輪/レール接触特性の測定とモニタリング

－アタック角、輪重、横圧、脱線係数の観測－

松本　陽*　　佐藤　安弘*　　大野　寛之*　　陸　康思*
留岡　正男**　　谷本　益久***　　佐藤　與志****

Measurement and Monitoring of Wheel/Rail Contact Characteristics

- Observation of contact angles, contact forces and derailment coefficients -

by

Akira Matsumoto*, Yasuhiro Sato*, Hiroyuki Ohno*, Yasushi Oka*
Masao Tomeoka**, Masuhisa Tanimoto***, Yoshi Sato****

Abstract

Various characteristic data on wheel/rail contact interaction, such as "contact forces" interacting between wheel and rail, "attack angle" of wheelset, position of wheel/rail contact point, are very important, because they should provide the dynamics of vehicle and track, and finally affect the safety and maintainability of wheels and rails.

The authors have studied new measuring methods on wheel/rail contact characteristics in order to realize more economical, more efficient, and more accurate measuring and monitoring. In this paper we describe the mechanisms of various new methods for measuring wheel/rail contact characteristics, such as "attack angle", lateral/normal/tangential forces, derailment coefficients, etc, from on-board side and track side, and show examples of the characteristics measured by such methods on real commercial lines.

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＊交通システム研究領域　Traffic System Department
＊＊東京地下鉄　Tokyo Metro Co. Ltd.
＊＊＊住友金属テクノロジー　Sumitomo Metal Technology Inc.
＊＊＊＊住友金属工業　Sumitomo Metal Industries Ltd.

1 INTRODUCTION

In railway system, the contact characteristic values between rail and wheel, such as wheel load, tangential contact force, wheel attack angle, wheel/rail geometrical contact shape and position and so on, have great influences on the railway vehicle's performances such as running stability, safety, curving ability, maintenance facilities, riding quality. It is needed and very important to understand the practical attitude of those values. In most of the cases, the vehicle is in moving at high speed and the phenomena of contact between rail and wheel happened in the very complicated space. It is very difficulty to obtain those values accurately in practice.

Although lot of measurement methods were developed in the past around the world to obtain those values concerning with wheel/rail contact from practical vehicles, most of the methods companied with high cost of financial and human labor, and some of the methods have limitations in practical application [1) 2) 3) 4)].

In order to obtain those characteristic values effectively and more precisely, researches and innovations are carried out by us as a leading measurement and operation group in Japan. In this paper, the research and innovation results are classified and some of the technologies are explained in detail.

2 NECESSITY OF WHEEL/RAIL CONTACT MEASUREMENT

2.1 Wheel/rail contact parameters

The characteristic values concerning with wheel/rail contact include the relative displacements, contact forces acting in the contact patch, location of the contact point on wheel and rail profile, and so on.

Relative lateral displacement and wheel set yawing angle are the major subjects of relative displacement measurement. In the case of wheel and rail profiles are known, wheel rolling radius difference between low rail side and high rail side in the same wheel set, and then the longitudinal creepage can be calculated by applying the relative lateral displacement measurement result to the geometrical contact analyzing process. Lateral creepage and creep force can be calculated from the measured wheel set yawing angle.

Both longitudinal creep force and lateral creep force are very important parameters to evaluate the curving performance of bogie truck. Fig.1 shows one of the estimated states of bogie truck in curving by using measured relative lateral displacement and yawing angle results.

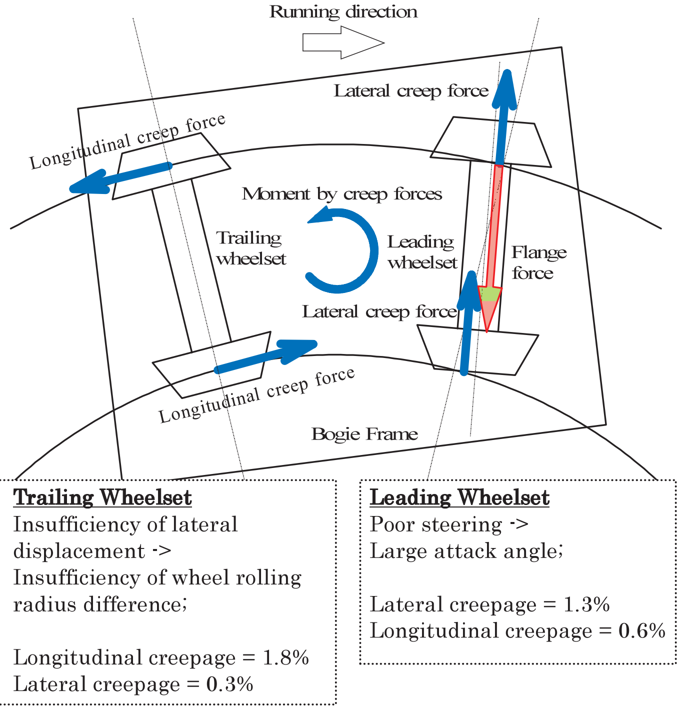


Fig. 1 Characteristic values of bogie in curving [8)]

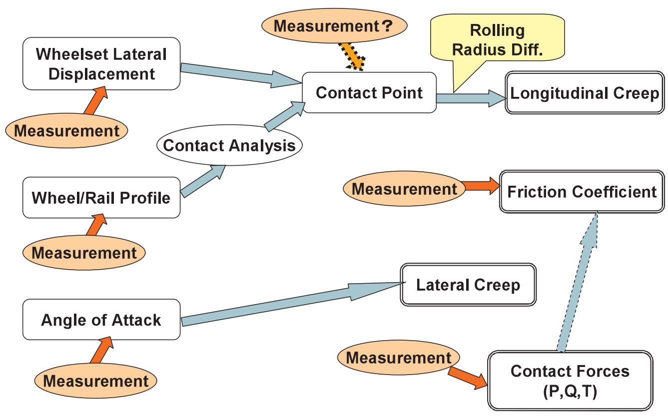


Fig. 2 Relationship between contact parameters [11)]

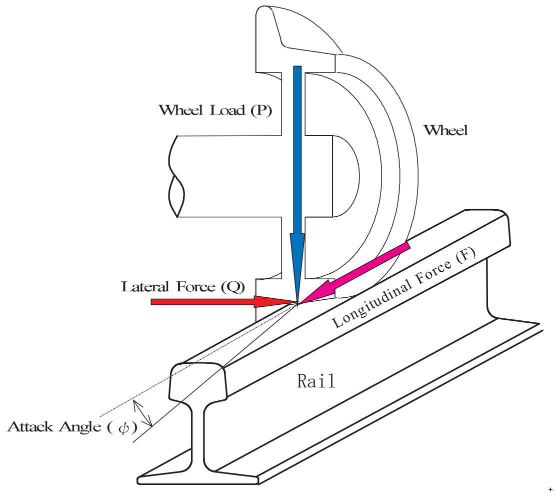


Fig.3 Attack angle and contact forces

Contact forces acting in the wheel/rail contact patch include wheel load, lateral force, longitudinal force (force around wheel) and spin creep force. Those forces concern with supporting, steering, driving and braking functions. Lateral force is a parameter to judge the anti-derailment performance of bogie truck, and longitudinal force is a parameter to determine the racing and slipping risk. For high rail side in curving section, the ratio of lateral force (Q) against wheel load (P) is called "derailment coefficient" and determined as Q/P. This coefficient is the most important factor to identify the wheel climbing through curving section. For this reason, the necessity to derailment possibility of vehicle in measure those values are extremely high.

High derailment coefficient may occur not only in the case of high lateral force, but will happen in the case of wheel load fall off. The fall off of wheel load may occur at certain location or occasional, the monitoring of wheel load is important too.

The location of contact patch on rail and wheel, and the shape and size of the contact patch have great influence on the contact force, but it is very difficult to measure those values from practical railway systems directly. In most of the practical cases, those values are estimated from the relative displacement between wheel and rail, or from the deformation state of wheel and rail.

Fig.2 and Fig.3 shows the relations between the wheel/rail contact parameters and those measurements.

2.2 Measurement Position

The value of most of the contact characteristic parameters can be measured on-board or on track side, or from both sides. Every measurement location has its advantages and disadvantages.

For measurement on-board, sensors or transducers are installed to the target vehicle. By running the vehicle, characteristic values can be obtained throughout the operation section. One point need to be reminded is, the measured values just represent the values of the wheel that sensor and transducer are installed but not the values of all fleets that may operate in the section.

Fig.4-1 On-board measurement

Fig.4-2 Track-side measurement

For measurement of track side, sensors or transducers are installed to rail or track of one cross section or a certain length of track section. When the train passes the instrumented section, characteristic values of all wheels could be obtained. Measurement from track side has advantage to measure the wheels that measurement equipments are not easy to install on-board, for example, for the case of passenger train in commercial operation that may has not space to install and operate the measurement equipments. The major disadvantage of measurement track side is, the obtained results just represent the characteristic values of the certain location but not all through the line.

As every measurement location has advantage and disadvantage, the ideal way is to combine the measurements. By this way, measurement on-board throughout the line should be carried out at first in order to detect the severest location. Then, track side measurement is carried out at the detected location. This measurement method is not only expensive but also need long period of time. In the worst case, the contact condition may change in the period. In practice, the decision of measurement method to choose depends on the purpose and the project budget.

3 MEASUREMENTS OF RELATIVE DISPLACEMENT BETWEEN WHEEL AND RAIL [6)]

3.1 Measurement On-board

For the measurement of relative lateral displacement and attack angle of wheel against rail on-board, non-contact displacement sensors are used. Two sensors with certain distance are installed to the end of wheelset perpendicularly pointed to the rail in horizontal at initial state as shown in Fig. 5.

In the measurement, the outputs from the two sensors are recorded at the same time. By averaging the outputs of the sensors, lateral displacement of wheel respecting to rail can be

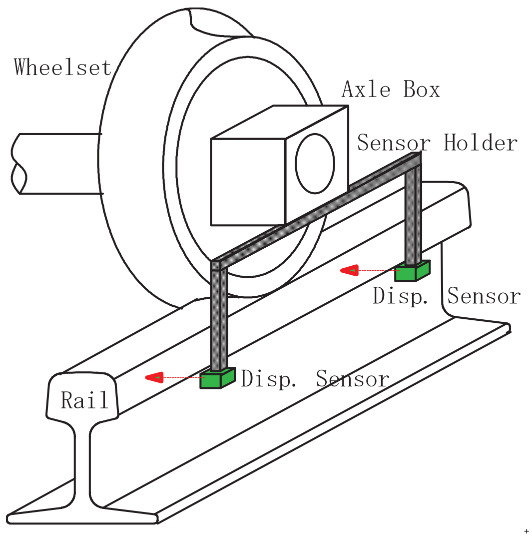


Fig. 5 Measurement of relative displacement on-board

obtained, and dividing the difference of the outputs by the sensor distance, attack angle can be obtained.

By applying this method to the measurement in curving (tangent -> transit -> constant -> transit -> tangent), the behaviors of wheelset in the section can be observed at real time.

Just one point should pay attention is, the sensors are installed out of the limit of vehicle dimension. They may interfere with track structure, especially in switching section. Sensors need to be installed and removed from point to point. For this reason, this method can be applied in test run but not in commercial operation time.

3.2 Measurement from Track Side

By using the same theory of measurement on-board, two non-contact sensors are installed on track side. In this case, sensors are installed perpendicularly to rail and parallel to the plane of rail level. In order to detect the distance between sensors and wheel rim, sensors are installed a little bit higher than rail level but within the limit of track construction dimension. Relative lateral displacement and attack angle are obtained from the same calculation as those of on-board measurement. Fig.6 shows the layout of

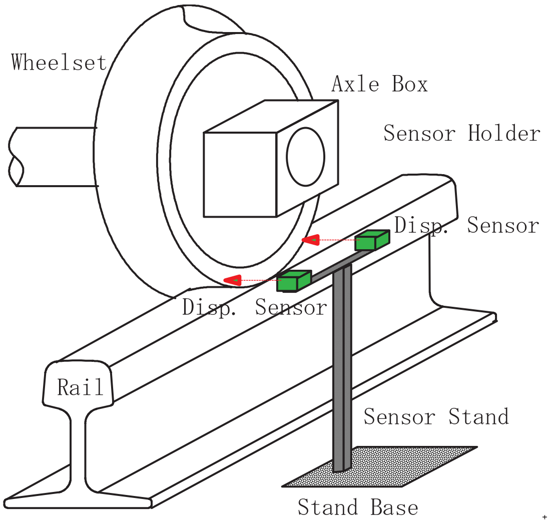


Fig.6 Measurement of relative displacement from track side

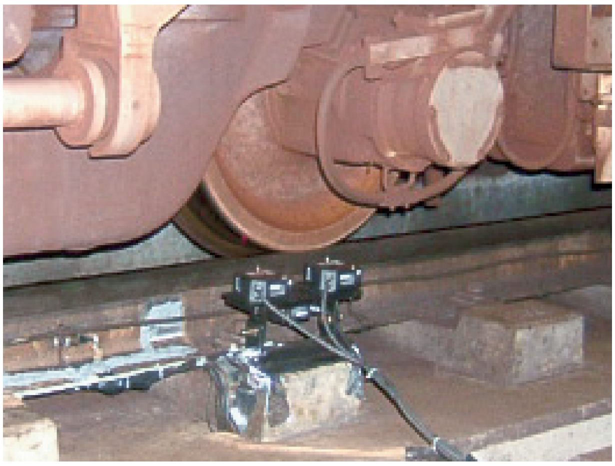


Fig.7 Sensors for relative displacement measurement from track side

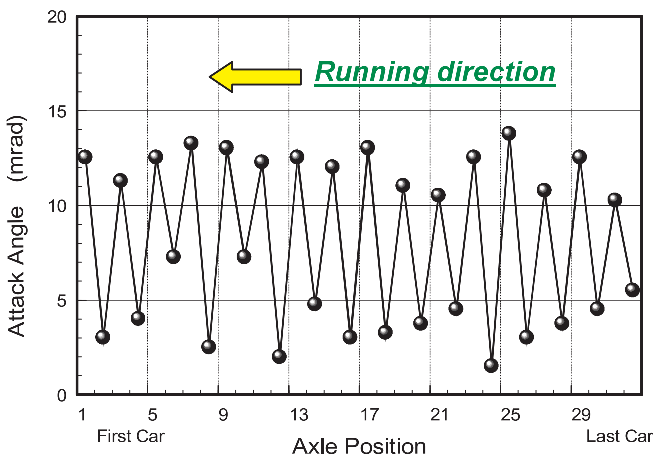


Fig.8 A result of attack angle measurement [7]
- Variation in a train-set -

the measurement system and Fig.7 the application in practice.

As all of the sensors can be installed without interfering with vehicle structure limit, this method can be used to measure the characteristic values of passenger ridden commercial operation train.

This method is applied to the investigation process of the tragic derailment happened in the year 2000 at a subway in order to understand the behaviors of wheelset at the derailed point. Fig. 8 shows one of the results of attack angles measured at the same place after the accident.

From the result it can be found, the axle with odd number, which is the leading axle in the bogie, has large attack angle. Some of them may be larger than 13 mrad. At another hand, the axle with even number, which is the trailing axle in the bogie, has small attack angle. Some of them may be smaller then 2 mrad. Due to the large attack angle of leading axle, large lateral contact force is generated at the high rail side. As mentioned before, large lateral contact force leads to the large derailment coefficient, which is considered as the major reason of derailment.

It is very popular that leading axle has larger attack angle to compare with trailing axle. It is much more evident if the bogie or vehicle has poor curving performance. The curving performance of the bogie or vehicle, furthermore to say the derailment safety in curve can be judged from the wheel/rail relative displacement measurement results.

4 MEASUREMENTS OF CONTACT FORCES OF WHEEL/RAIL INTERFACE

4.1 Measurement from On-board

4.1.1 PQ wheelset measurement

Traditionally in Japan, the measurement of contact forces on-board is carried out by using what is called “PQ wheelset”.

PQ wheelset is a specially designed wheelset with strain gauges attached on the wheel web. The theory of PQ wheelset measurement is to detect the strain changes on the web. Contact forces are transduced from the measured changes of strain. By detecting the compressed strain of the web, vertical contact force can be measured and by detecting the bending strain, lateral contact force can be measured.

This method is popularly used in the measurement of wheel-rail contact forces on commercial line and test stand on board. Fig. 9 shows the position of strain gauges attached on the wheel web. Strain gauges on both surfaces of the web are the gauges to measure lateral contact force, and strain gauges in the center of holes (neutral axle of web) are the gauges to measure normal contact force, i.e. vertical wheel load. Fig. 10 shows the circuit of strain gauge bridges and Fig. 11 shows a practical PQ wheelset.

This "special wheelset" is expensive and has no sufficient resistance against heat generated by tread braking. Tread braking system need to be released in measurement. This may cause limit of measurement in commercial operation train. This method also requires the equipment for data transmissions from the rolling wheelset to the fixed bogie frame, for example slip rings or radio telemeters. As PQ wheelset has so many shortages, it is difficult to execute the measurement so frequently.

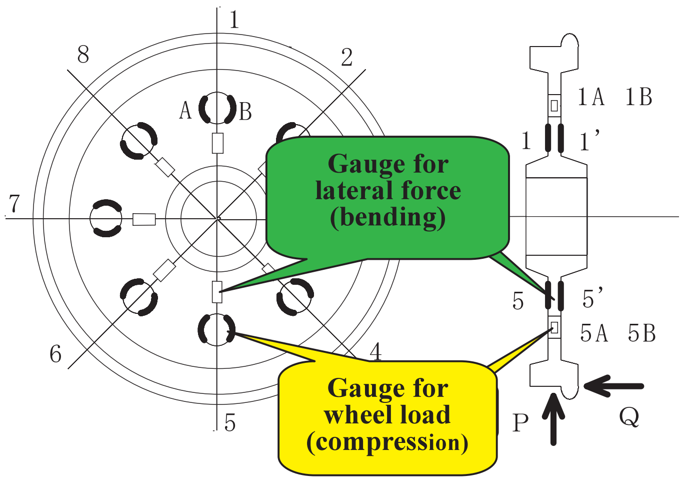
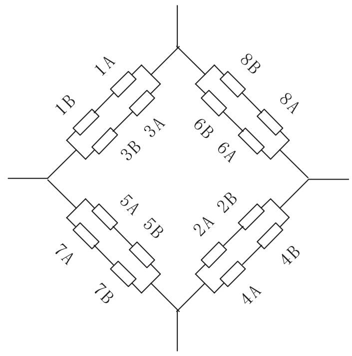
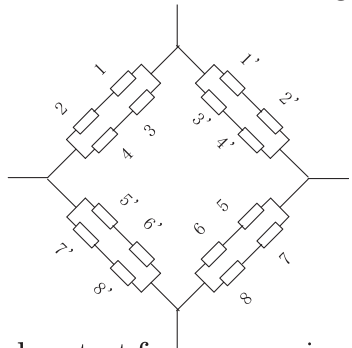


Fig.9 Strain gauges on PQ wheelset



(a)Vertical contact force measuring circuit



(b)Lateral contact force measuring circuit

Fig.10 Strain gauge circuits in PQ wheelset

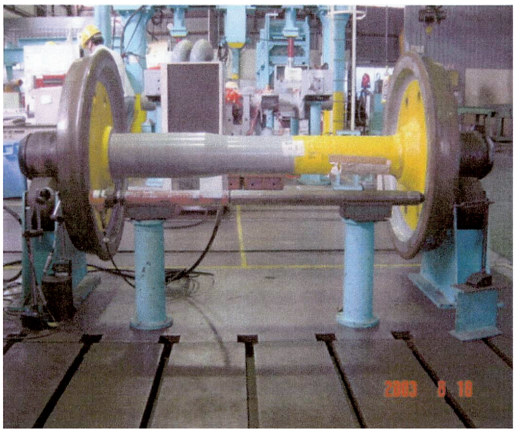


Fig.11 PQ wheelset for conventional measuring method

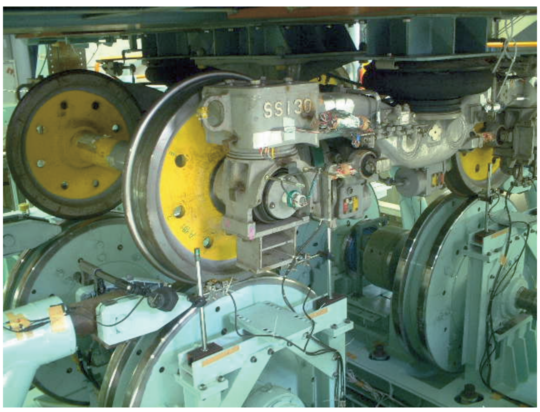


Fig.12 Measurement on test stand by using PQ wheelset

4.1.2 Newly developed method with non-contact gap sensor [10)]

(a) Principle of measuring lateral force

From the subway derailment investigation process we found, the adhesion coefficient between wheel and rail varies from time to time. This means the derailment coefficient is in changing too. It is ideal if the derailment coefficient can be monitored regularly and frequently in order to prevent the derailment caused by abnormally high derailment coefficient. As the conventional PQ wheelset measurement method is not convenient for a regular monitoring, we try to develop a new method for measurement of wheel/rail contact forces, i.e. derailment coefficient, even on a passenger car in commercial service. The new method has no sensors on rolling part, i.e. wheelset, and no transmission equipment, such as slip rings or radio telemeters.

Among the measurement of contact forces without using of PQ wheelset, the most difficulty one is the lateral contact force. In the conventional PQ wheelset method, lateral force is transduced from web strains detected by strain gauges attached on the wheel. In the new method, such distortion of wheel is detected by sensors installed on the bogie frame which is not rotating. As shown in Fig. 13, the wheel distortion is calculated from the displacement of the wheel rim (4a) which is measured by the non- contact gap sensor (3) installed on the bearing box (2) through the sensor base (7).

Because accuracy less than 0.005mm is required, inductive displacement sensors which have resolution higher than 0.002mm are selected. In order to get highest accuracy, the gap sensor is better to be installed pointing at wheel "rim" position. But at this position, the sensor is slightly interfering with the limit of vehicle dimension according to Japanese regulations. Even at this position, the sensor is still out of the limit of track construction dimension. Although it is not so serious problem in practice, we selected other position in order to avoid the interference

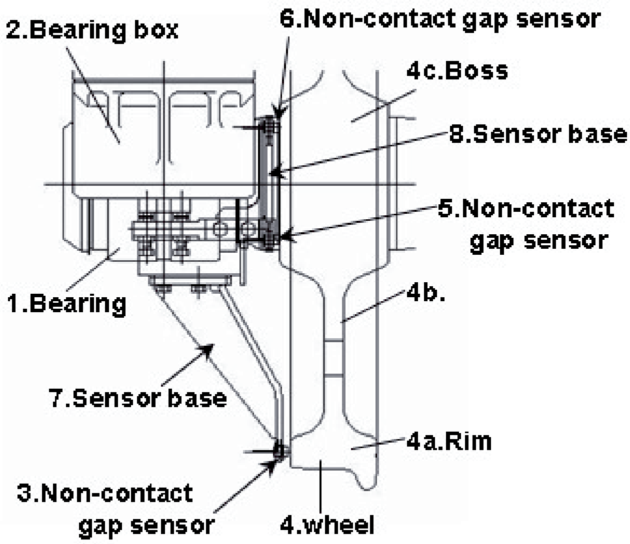


Fig.13 Layout of sensors in new method for measuring lateral force

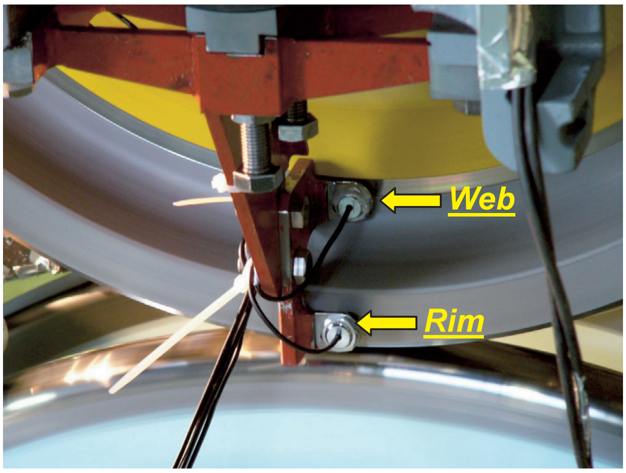


Fig.14 Gap sensors for lateral force measuring

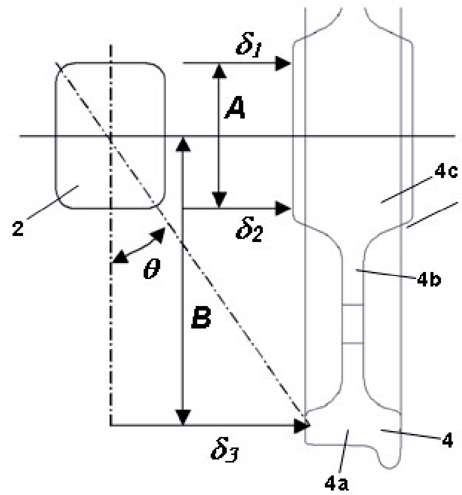


Fig.15 Principle of compensation

with regulation. Fig. 14 shows the positions of gap measuring. Sensor pointed to the rim is the ideal installation position, and the sensor at higher position pointed to the out edge of wheel web is the position in practical usage.

(b) Compensation

As the measured values by gap sensors are small, the movement of the wheelset cannot be neglected. For compensation of the wheelset movement, two more gap sensors (5, 6 in Fig. 13) installed to bearing box are introduced.

Two errors need to be compensated. One is the axial movement δ_4, which is produced by the thrust clearance of bearings, and the other is the inclination δ_5, which is produced by the relative inclination of the wheelset against bearing box. δ_4, δ_5 and the wheel lateral distortion after compensation δ can be obtained using the following equations. $\delta_1, \delta_2, \delta_3$ are the measured gap shown in Fig. 15.

$$\delta_4 = (\delta_1 + \delta_2) / 2 \quad \cdots\cdots(1)$$

$$\delta_5 = B \tan\theta = (B/A)(\delta_2 - \delta_1) \quad \cdots\cdots(2)$$

$$\delta = \delta_3 - (\delta_4 + \delta_5) = \delta_3 - (\delta_1 + \delta_2)/2 - (B/A)(\delta_2 - \delta_1) \quad \cdots\cdots(3)$$

(c) Verification of new measuring method

In order to verify the new measuring methods of contact forces, we carried out truck running tests on the test stand at first stage. For this purpose we use the bogie rolling test stand installed in NTSEL, which can simulate curving conditions.

In stand tests we carried out the measurement by the conventional method and the new method in various curving conditions. In order to evaluate

(1) the correlation between "lateral force" measured by the conventional method and "wheel lateral distortion" measured by the new method,

(2) the sensitivity and the linearity of "wheel lateral distortion" against lateral force,

we carried out curving tests at the curvature of 120m radius to 600m radius.

Fig. 16 shows the relationship between

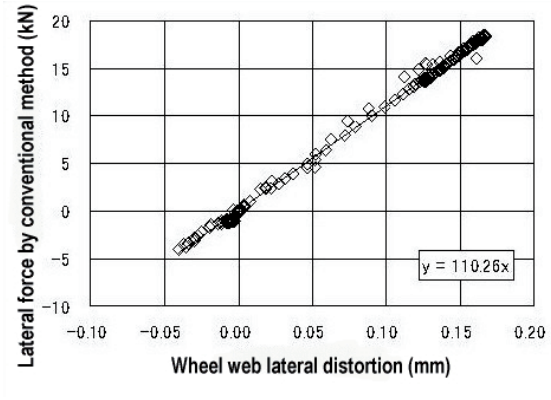


Fig.16 Relationship between wheel distortion and lateral force by conventional method

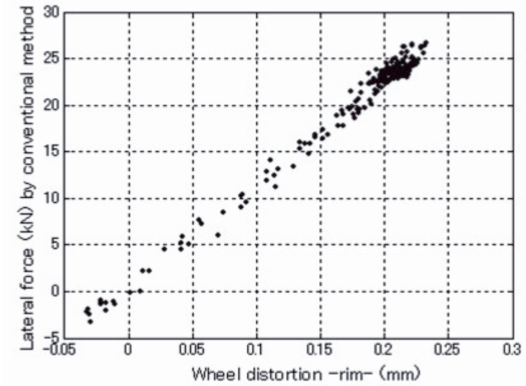
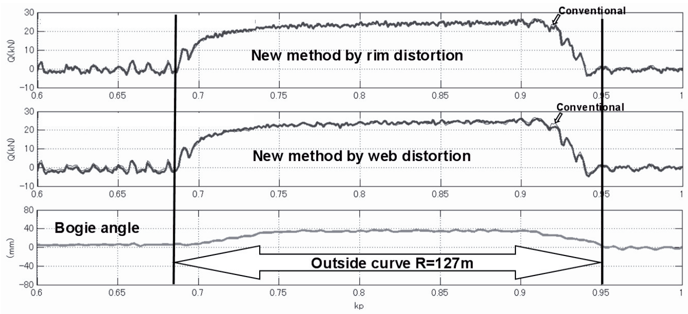
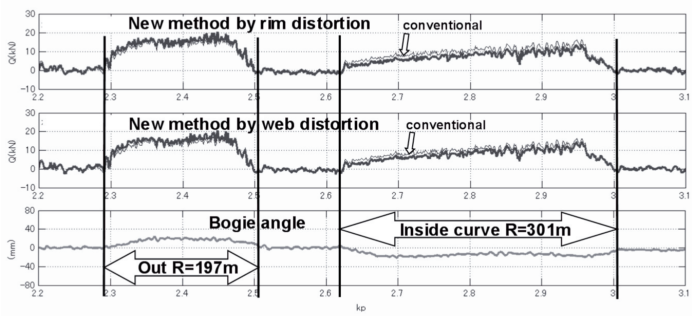


Fig. 17 Relationship between new method and conventional method



(a) outside curve R=127m



(b) outside curve R=197m to inside curve R=301m

Fig.18 Comparison between new method and conventional method in lateral force measuring measured "wheel distortion" by the new method and "lateral force" by the conventional method. The results by both methods almost agree with each other, and the proposed new method can obtain the lateral contact force correctly. The values by both methods are proportional and the displacement of wheel web is 0.09mm for lateral force of 10kN. As the resolution of inductive displacement sensors used in this measurement is 0.002mm, the measurement is possible enough although the sensitivity is rather low.

For the second stage of verification we carried out train running tests on a commercial subway line. Train running tests were carried out by using 3-car EMU on a branch line of Tokyo Metro. This branch line has 4 stations and its length is about 3.2km. It has several sharp curves of both direction, and minimum radius of curve is 127m. The test bogie was installed in the front vehicle and various measurements are carried out mainly on the leading wheelset. The test train ran at normal speed same as commercial operation.

Some improvements were done compared with stand tests. For example, bearings were changed to no-lateral-clearance type, and gap sensors were fixed more rigidly by using keys.

Fig. 17 shows the relationship between the "lateral forces" obtained by the conventional method and the compensated "wheel rim distortion" obtained by the new method. Both values have good correlation to each other.

By using the relationship in Fig. 17, lateral contact forces are calculated from the new method. Fig. 18(a) shows the comparison between the conventional method and the new method in an outside curve of 127m radius. Both values agree very well at every moment. Fig.18(b) shows another example at 197m radius outside curve to 301m radius inside curve. Both value agree well in 197m radius outside curve, but the value from the new method is lower than conventional one in 301m radius inside curve

Thus, concerning inside wheel the value from the new method is a little smaller than the conventional method.

(d) Measurement of vertical and longitudinal contact force

To compare with the lateral contact force, vertical contact force (wheel load) and longitudinal contact force are easier to be measured without using of slip rings and radio telemeters. Non rotating parts of the truck are chosen for those measurements.

For vertical contact force detection, following locations are tried.

1) Strain of the side frame of the truck
2) Deflection of primary suspension spring

For longitudinal contact force, although it is also important for the safety and the performance of the railway vehicles, especially in curving conditions, it is rarely measured up to now

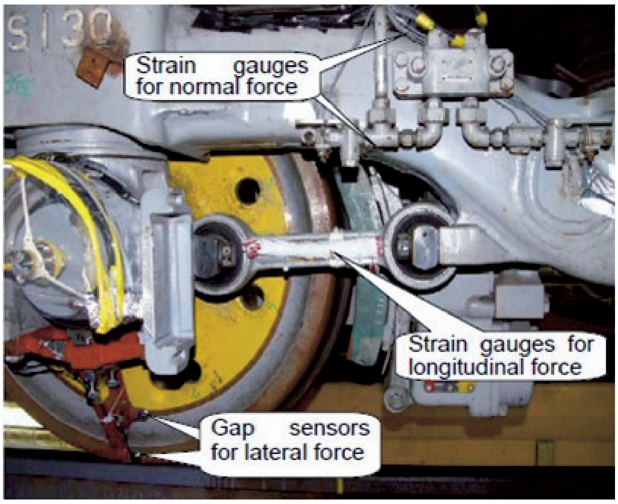


Fig.19 Sensors and gauges attached on bogie frame

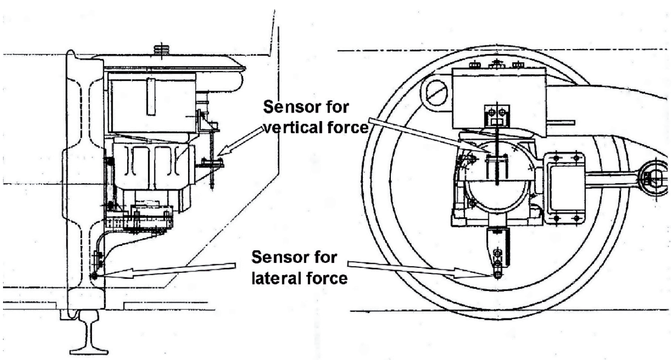


Fig.20 Improved system for practical use

because of difficulty of measuring method. Some times, for the purposes of research, longitudinal contact force is calculated from the measured torsional strain of axle. It is very difficulty to find the space to attach strain gauges on practical axle especially on driving axle. In the new measurement method, the lever link of axle box support is chosen. Strain gauges are attached on the link. Strain caused by push and pull tension of the link is proportional to the longitudinal contact force. After calibration, the longitudinal contact force can be measured easily. Fig. 19 shows the layout of strain gauges for vertical and longitudinal contact force measurement.

Now we plan the improved system for practical use of the measurement of contact forces shown in Fig.20, and carried out more practical running test on commercial lines.

4.2 Measurement from Track Side

Vertical and lateral contact forces can be measured from track side by attaching strain gauges on rail. Basically, the measurement uses the theory of rail sheering stress detecting. For vertical contact force, strain gauges are attached on the web of rail, and for lateral contact force, strain gauges are attached on the bottom of rail. Fig. 21 and Fig. 22 show the position of train gauges attached and the circuit of vertical and lateral contact force measuring bridge respectively.

The advantage of contact force measurement from track side is the same with that of displacement. It can measure all of the wheels those pass over the section. Fig. 23 shows the ratio of vertical and lateral contact forces of every wheel measured from the same train as shown in Fig. 8. The result shows the high rail of 29th wheelset has the highest derailment coefficient. This is the same position with the derailed train.

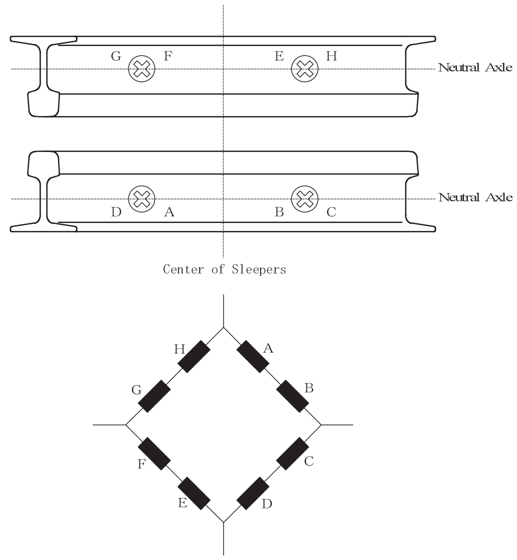


Fig. 21 Vertical contact force measurement from track side

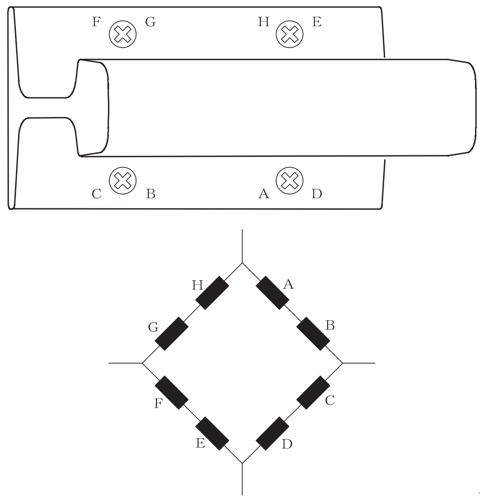


Fig.22 Lateral contact force measurement from track side

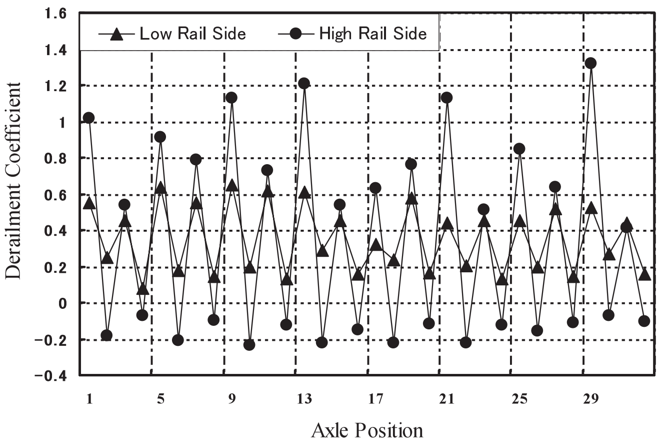


Fig.23 Sample of contact forces measurement result [7)]

- Variation in a train-set -

Conventionally, in order to improve the sensitivity of the measurement, strain gauges are attached in very close distance. One pick value can be obtained from the measurement. This has disadvantage if the surface of rail or wheel is not smooth and the contact forces may vary in high frequency. This problem is solved by extending the span of strain gauges. Fig. 24 shows the state of strain gauges in practical measurement. Contact forces can be measured continuously within the span.

This method is extended to measure the contact forces not only span within one sleeper but continuously for numerous spans of sleeper including the span across the sleeper. Fig. 25 shows the theory and layout of strain gauges in order to realize the measurement. Fig.26 shows the principle of the compensation of this new method. We have acquired the patent from the Patent Office of Japan for this method.

By applying this method, the dynamical changes of contact forces can be measured accurately. Fig.27 shows an example of measurement by this method, where we successfully caught the high frequent contact force vibration that initiate rail corrugation.

Fig.24 Strain gauges on rail in practical measurement

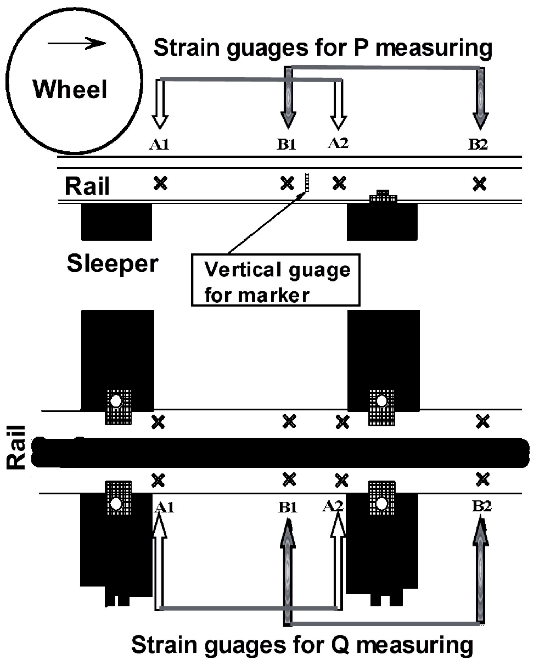


Fig.25 Principle of "continuous measurement along rail" for contact forces PQ [5)]

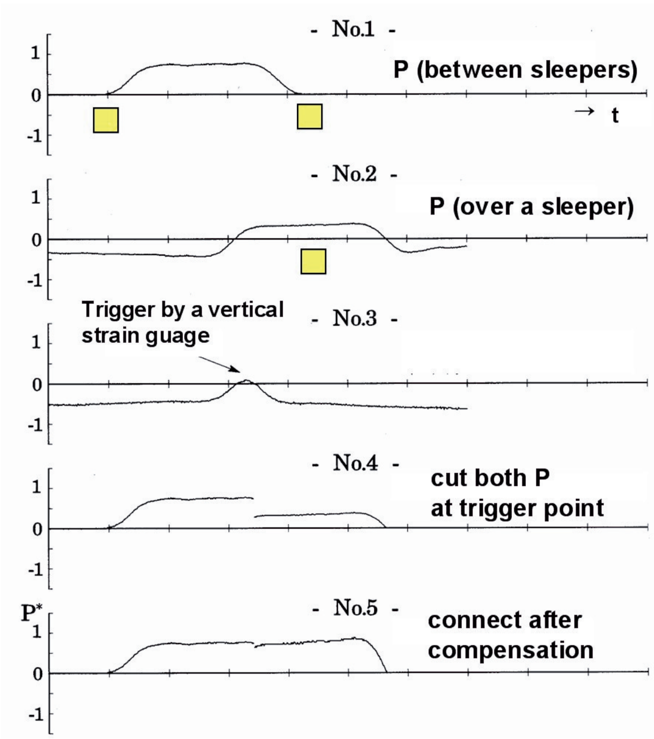


Fig.26 Principle of compensation in "continuous measurement along rail"

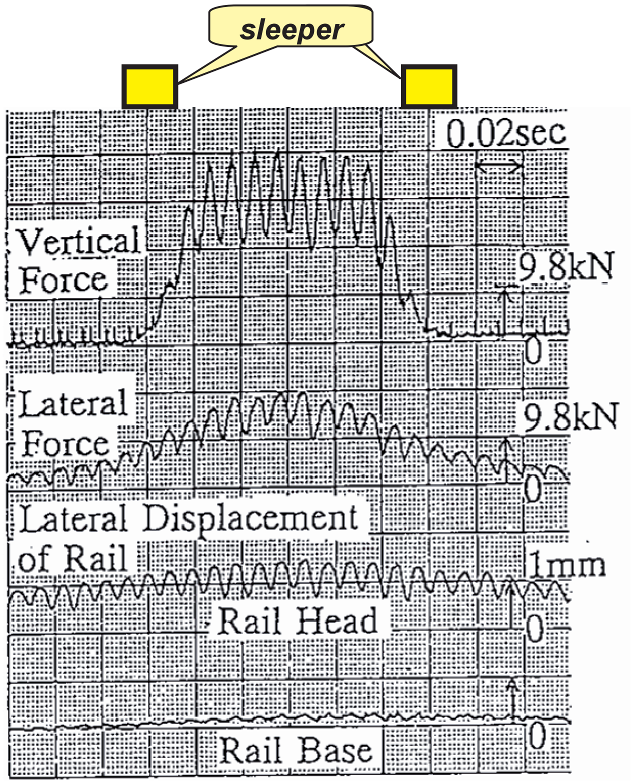


Fig.27 Measuring sample of "continuous measurement along rail"
- High frequent contact force vibration along rolling wheel
= corrugation initiator -

5 CONCULSION

We developed several new measuring methods of wheel/rail contact parameters from on-board and from wayside, and verified the accuracy of these methods.

As for the measurement of lateral displacement and attack angle between wheel and rail, we successfully obtained new methods from on-board and wayside by using non-contact gap sensors. By using these methods we became to be able to take the relative position of wheel/rail easily even for passenger service trains.

As for the measurement of contact forces and derailment coefficient, we succeed in measuring these parameters without special PQ wheelsets, which needs strain gauges on the wheel and slip rings or telemeters for data transmission. This new method can realize the continuous monitoring of the derailment coefficient from on-board on commercial service lines.

In addition we developed a new wayside measuring method that can measure wheel/rail contact forces continuously along rail direction. This method can measure high frequent contact force vibration along rolling wheel and find corrugation initiators.

The understanding of characteristic values of contact between wheel and rail is very important for the prevention of derailment accident, the improvement of railway vehicles and infrastructure and the reduction of maintenance work. These new measuring methods described in this paper will be useful for improvement of safety, maintainability and performance of railway operation.

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