New Measuring Methods for Wheelset Angle of Attack of Railway Vehicle on Curves*

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New measuring methods for the wheelset angle of railway vehicles on board and on the ground have been developed by the Railway Technical Research Institute in Japan. With these methods, the wheelset angle of attack has been measured on curves in field running tests of limited express trains on a narrow-gauge commercial line. The measured results are as follows. (1) The measuring accuracy of these methods attained the targetted levels. (2) The higher the velocity and the larger the curve radius, the smaller the steady angle of attack. The steady angle of attack of the first wheel is 0.28 degrees, and that of the second wheel is 0.02 degrees for a curve radius of 400 m at a velocity of 110 km/h. (3) The measurement and simulation results for the wheelset angle of attack are in agreement.

Key Words: Dynamics of Machinery, Measurement, Railway Vehicle, Wheelset Angle of Attack, Curving

1. Introduction

Curving performance of a railway vehicle is influenced by many factors such as the lateral profile of the wheel and rail, angle of attack between wheelset and rail, curve radius, running velocity, creep force characteristics, primary longitudinal and lateral stiffness, and secondary yawing restraint moment. In particular, side thrust is influenced by the wheelset angle of attack. Therefore, in order to reduce side thrust, it is necessary to measure the wheelset angle of attack as precisely as possible, and to grasp its actual state.

The limit value of 0.8 of the derailment coefficient is based on the assumption that the wheelset angle of attack should be large for safe operation. Therefore, the value of the wheelset angle of attack, if accurately measured, leads to adequate evaluation of the safety margin before derailment. Moreover, it becomes useful for the verification of vehicle dynamics simulation.

In Japan, the vertical load and side thrust of a wheel and lateral displacements between wheelset and bogie have been measured. However, the displacement between wheelset and rail has not been measured. In several countries, some methods have been reported, but these methods have some demerits. Therefore, we have developed new methods to measure the wheelset angle of attack on board and also on the ground. Using these methods in field running tests, we have been measuring Shinkansen and limited express trains on a narrow-gauge commercial line.

This paper presents the measuring methods of the wheelset angle of attack on board and on the ground (section 2), error evaluation imposed in measurement (section 3) and field running test results (section 4). In section 5, the simulation is validated by comparing the simulation results with measurements for wheelset angle of attack.

2. Measuring Methods for Wheelset Angle of Attack

The wheelset angle of attack is defined as the angle between the rail and the wheelset running direction (Fig. 1). There are two measuring methods. One

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is measurement on board and the other is measurement on the ground. By measurement on board, continuous data on a limited number of wheelsets can be obtained, while by measurement on the ground, instantaneous data on all the wheelsets of a train can be obtained. Thus, measurements on board and on the ground have their respective merits and demerits. It is desirable that both measurements be performed during the same running tests to obtain sufficient data.

2.1 Measuring method on board

As methods of measuring the wheelset angle of attack, the mechanical method⁽¹⁾ developed by British Railways and the optical method⁽²⁾ by Swiss Federal Railways have been reported.

In the first method (Fig. 2), two small measuring wheels are attached to the axlebox with levers. These two wheels are pressed to the inside of the rail. The angle of attack can be measured using the information from the angular displacements of the two wheel levers. Unfortunately, the mechanical contacts make it difficult to use this method in high-speed operation.

In the second method, optoelectronic transducers are attached to the axlebox. The transducers and the sensors are attached with a 45-degree angle between them. First, infrared radiation from the transducer is emitted to the side surface of the rail head. Then, the

Fig. 1 Definition of wheelset angle of attack

Fig. 2 British Railways' apparatus for measuring wheelset angle of attack

reflex is received by the sensor, giving information on lateral displacement through variation of the incidence position of the optical axis. Two sets of transducer and sensor are attached in the front and rear positions at a distance from the center of the axle box. The wheelset angle of attack is determined from the difference between the lateral displacements measured. However, the ordinary axlebox does not have enough space for the transducers, and the output signals of the transducers are affected by the disturbance light and the surface condition of the rails.

To solve these problems, we use video cameras attached to the bogie frame, which has sufficient space. The yawing angle between the bogie frame and the rail ψ_t can be measured through analysis of the images obtained by the video cameras.

2.1.1 Yawing angle between bogie frame and rail ψ_t

The video cameras are attached to the bogie frame at the front and rear ends just above the rail (Fig. 3). The two rail images obtained by the front and rear video cameras are combined into one screen. We can measure the yawing angle between the bogie frame and rail ψ_t from the difference between the two rail images η . ψ_t is given by

$$\psi_t = \eta \cdot a / (2c), \quad (1)$$

where a is the ratio of the actual rail width to the image rail width, and $2c$ is the distance between the front video camera and the rear one.

This noncontact method utilizing video cameras can be used even in high-speed operation. Even when the optoelectronic transducers give false output under the circumstances of rapid change in daylight or of another object coming into the field of the transducer,

Fig. 3 Method for measuring angle of attack and lateral displacement relative to rail

exact information can be obtained by adding human judgment of the image in this method. Furthermore, in this method, the errors imposed by vertical vibration of the bogie can be compensated using the information on constant rail bottom width.

2.1.2 Yawing angles between wheelset and bogie frame ψ_{w1}, ψ_{w2} Longitudinal displacements between the four axleboxes (first and second, right and left) and the bogie frame are measured with ordinary displacement pickups. With these data, the yawing angles between wheelsets and the bogie frame ψ_{w1} (the first axle) and ψ_{w2} (the second axle) are obtained.

2.1.3 Angles of attack between wheel and rail ϕ_1, ϕ_2 The wheelset angle of attack during curve negotiation is given by the angle AO_1C between the radius direction at the wheelset position OA and the centerline of wheelset CD (Fig. 4).

Wheelset angles of attack ϕ_1 and ϕ_2 are given by

$$\phi_1 = \phi_t + \psi_{w1} + (a/R) \quad (\text{first axle}) \quad (2)$$

$$\phi_2 = \phi_t + \psi_{w2} - (a/R) \quad (\text{second axle}), \quad (3)$$

where ϕ_t , ψ_{w1} and ψ_{w2} are given in sections 2.1.1 and 2.1.2.

R : curve radius

$2a$: wheelbase of the bogie

2.2 Measuring method on the ground

Photoelectric switches are attached directly to the high rail A and the low rail B along curves in the radial direction (Fig. 5). The emitter and detector of each photoelectric switch are located on the opposite sides of the rail. When a wheel passes through this section, light from the emitter is intercepted and the detector gives a pulse signal. Therefore, the wheelset angle of attack is given by

Fig. 4 Yawing angle of bogie and wheelset angle of attack on curve

$$\phi = \tan^{-1} (V\tau/2b), \quad (4)$$

where

τ : time lag between output pulse signals of high rail detector A and low rail detector B,

V : vehicle running velocity,

$2b$: lateral distance between right and left wheel flange tops.

To obtain the vehicle running velocity and to check the dynamic movement of the wheelset, photoelectric switches are also set in a second section 5 cm away from the first section. The vehicle running velocity is also obtained from the time difference between the two pulse signals issued by the first and second axles of the bogie.

This method—utilizing the information on the passage time lag between outer and inner wheels—has already been used in Canada. In Canada⁽³⁾, a laser emitter and detector which are large and located on the ground are used. In contrast, the small, light and shockproof photoelectric switches used in our method can be attached directly to the rail. This direct attachment can eliminate the errors imposed by sinking of the rail, which depends on the running velocity and wheel load. Since no errors are imposed by sinking of the rail, lateral displacement of the wheelset relative to the rail can be determined secondarily from the position of wheels, rail and sensor.

In order to determine the wheelset angle of attack and the lateral displacement of the wheelset, a processing unit was manufactured, with which the time difference of signal pulses between outer and inner wheels and the passage time of each axle can be quickly calculated using the output pulse signal from the sensors.

Fig. 5 Method for measuring angle of attack on the ground

3. Measurement Errors of Wheelset Angle of Attack

3.1 Expected value of wheelset angle of attack

We evaluate measurement errors based on running tests for a Japan Railways (JR) type 381 electric car. The measured result is reported in section 4.

The first wheelset angle of attack is 0.15 degrees and the second one is -0.15 degrees when a bogie with a 2.1 m wheelbase runs tangentially to the track on a 400 m - radius curve, under the assumption that the wheelset is rigidly attached to the bogie. Actually, 0.5 degrees for the first angle of attack and 0.2 degrees for the second one are expected, because the bogie is at an angle to the track tangent and the wheelsets swivel against the bogie.

In the case of decreasing the wheelset angle of attack by varying the primary stiffness or wheel tread profiles, one target is that the wheelset angle of attack of the first axle decreases to the same level as the second axle. In that case, it is necessary for measurement accuracy that the angle difference of about 0.3 degrees between the first and second axles be detected.

3.2 Errors from measurement on board^{(4),(5)}

As for errors from measurement on board, firstly, error from the resolving power of the video camera is considered. In this measurement, since the resolving power for η in Fig. 3 and Eq. (1) is about 1 mm, this error corresponds to 0.016 degrees of ϕ_t in Eq. (1). In addition, since ϕ_t only relates the resolving power for η in Eq. (2) and Eq. (3), the error of the wheelset angle of attack becomes 0.016 degrees.

Therefore, the error from measurement on board is within 0.02 degrees.

However, the video camera can only take interrupted images in each frame cycle (interval of one image) of 1/30 sec. Six images are necessary in a response cycle when investigating the dynamic response of the wheelset angle of attack to track irregularity. Therefore, the detectable response value of the wheelset angle of attack is limited below about 5 Hz $[=1/(6 \times 1/30)]$. However, most responses to track irregularity are considered to be below 5 Hz. Consequently, this method seems to allow investigation of the response to track irregularity of the wheelset angle of attack with no problems.

3.3 Errors from measurement on the ground⁽⁶⁾

For primary error from measurement on the ground, errors from attaching the sensor to the rail and from the characteristics of the sensor are considered. Then, by showing the equation for calculating these errors, the errors for each factor are evaluated using lateral track irregularity of 0-p 1 mm for a 10 m

chord, curve radius 400 m and running velocity 110 km/h, which are the conditions in the actually measured section discussed in section 5.

The errors due to attachment are as follows.

(1) Errors from discrepancy between radial direction of track as regulated by T-square (2 m chord, Fig. 6) and by axes of emitter and detector

Using errors $\Delta\sigma_i$ and $\Delta\sigma_o$ (mm) against the radial direction of the track indicated in Fig. 7, errors of wheelset angle of attack $\Delta\phi(^{\circ})$ are calculated with

$$\Delta\phi = (\Delta\sigma_o - \Delta\sigma_i) / 2b \times (180/\pi) (^{\circ}), \quad (5)$$

where $\Delta\sigma_o$ and $\Delta\sigma_i$ are negative on the left side of the track radial line in the figure, positive on the right side, and $2b$ is the lateral distance (mm) between wheel flange tops. In this measurement, the sum of size errors for sensors, attachment of sensor (metallic plate) and T-square warp $\Delta\phi$ is 0.022 degrees from Eq. (5), because each error of $|\Delta\sigma_i|$ and $|\Delta\sigma_o|$ is 0.2 mm at maximum; $\Delta\sigma_o - \Delta\sigma_i = 0.4$ mm, $2b = 1\,020$ mm.

(2) Errors from T-square warp

With the discrepancies between the T-square and the radial direction $\Delta\sigma_{ti}$ and $\Delta\sigma_{to}$ in Fig. 8, the error of the wheelset angle of attack $\Delta\phi(^{\circ})$ is calculated with

$$\Delta\phi = (\Delta\sigma_{to} - \Delta\sigma_{ti}) / l_{tv} \times (180/\pi) (^{\circ}), \quad (6)$$

where the signs of $\Delta\sigma_{to}$ and $\Delta\sigma_{ti}$ are the same as that of term (1), and l_{tv} is the length (mm) of the vertical

Fig. 6 Plate attached to rail in curve radius direction regulated by T-square

Fig. 7 Discrepancy between radial direction of track regulated by T-square and axis of emitter and detector

bar of the T-square.

In this measurement, since the T-square is arranged so that $\Delta\sigma_{to} - \Delta\sigma_{ti}$ is within 0.5 mm, the error of the wheelset angle of attack becomes 0.022 degrees, since $\Delta\sigma_{to} - \Delta\sigma_{ti} = 0.5$ mm and $l_v = 1\,285$ mm.

(3) Errors from discrepancy between actual radial direction of track and that regulated by T-square

When the amplitude of lateral track irregularity is a_t (mm) as a maximum in the section of measuring point $\pm l_t/2$ (mm), the discrepancy between the actual radial direction of the track and that regulated by the T-square is the error of the wheelset angle of attack $\Delta\phi$, which is shown in Fig. 9. It is calculated with

$$\Delta\phi = (2a_t/l_t) \cdot (180/\pi) (^{\circ}). \quad (7)$$

In this measurement, since the location is selected so that the amplitude of lateral track irregularity for a 10 m chord is within 1 mm in the section of measuring point ± 1 m, the error of the wheelset angle of attack $\Delta\phi$ is 0.057 degrees, since $a_t = 1.0$ mm and $l_t = 2\,000$ mm.

Next, errors from characteristics of the sensor are considered.

(4) Errors from difference in response time of sensor between high-rail and low-rail sides

When the delays of response time for rise and fall of the sensor pulse on the high-rail side are $\Delta t_{ou}(s)$ and $\Delta t_{od}(s)$, respectively, those on the low-rail side are $\Delta t_{iu}(s)$ and $\Delta t_{id}(s)$, respectively, and the running velocity of the train is V (km/h). The error of the wheelset angle of attack $\Delta\phi$ is calculated by substitut-

Fig. 8 Errors from T-square warp

Fig. 9 Errors from track irregularity

ing the following equations for σ_o and σ_i in Eq. (5).

$$\sigma_o = (10^3 V/3.6) \cdot (\Delta t_{ou} + \Delta t_{od})/2 \text{ (mm)}$$

$$\sigma_i = (10^3 V/3.6) \cdot (\Delta t_{iu} + \Delta t_{id})/2 \text{ (mm)}$$

As for the characteristics of the sensor used in this measurement, since $\Delta t_{ou} - \Delta t_{iu}$ and $\Delta t_{od} - \Delta t_{id}$ are within 10 μ s, the error of the wheelset angle of attack $\Delta\phi$ is 0.017 degrees, since $\Delta t_{ou} - \Delta t_{iu} = 10$ μ s, $\Delta t_{od} - \Delta t_{id} = 10$ μ s and $V = 110$ km/h.

The errors from measurement on the ground are summarized in Table 1, which shows that the total of all primary errors is within 0.12 degrees when the error from the characteristics of the sensor is the value at the running velocity of 110 km/h.

When considering the relative difference among trains or between the first and second axles, the errors from the sensor set can be eliminated. In that case, the errors become one figure smaller and within 0.02 degrees.

4. Measurement Results of Field Running Tests

The field running tests were performed⁽⁷⁾ using a JR type 381 limited express test train on a JR narrow-gauge commercial line (curve radius 300 to 800 m). The test section was about 66 km long, and 12 tests in total were performed at velocities of 70 to 130 km/h. In these tests, an arc wheel profile⁽⁸⁾ was adopted instead of the ordinary 1/20 conic profile. The rail profile called 50 N⁽⁹⁾ was used in the test section.

In these tests, the side thrust and vertical load of wheels, accelerations and displacements were measured in addition to the wheelset angle of attack and lateral displacement relative to the rail. The wheelset angle of attack was measured on board at the front bogie of the head car. Figure 10 shows the video camera boxes attached to the bogie frame.

The wheelset angle of attack was also measured at 6 points on the ground (Fig. 11) on a 400 m-radius curve. Measurements were made at 6 points in order to determine whether the wheelset angle of attack is constant or varies in the curve. The points were located at 6 cm intervals to determine whether or not wheelsets vary in a short period, and at 12 m intervals

Table 1 Classification of errors from measurement on the ground

From sensor set			From sensor	Sum of primary errors
Set to rail	T-square warp	Lateral irreg.	Response delay	
0.022°	0.022°	0.057°	0.017°	0.118°

to determine variation over a long period. The 6 cm intervals also enable detection of the running velocity when the train passes the measuring points. Figure 12 shows the photoelectric switches attached to the rail, while Fig. 13 shows the processing unit for the wheelset angle of attack. The worn rail profiles in some test sections were measured. Then, from these data numerical functions were derived and introduced into the vehicle dynamics simulation program.

The results measured on board and on the ground are as follows.

4.1 Results measured on board

One example of a wave form of the wheelset angle of attack and other angles are shown in Fig. 14. The 0 value of the wheelset angle of attack is the value at the starting point of the running test section.

Fig. 10 Lens box of video camera in measurement on board

Fig. 11 Location of sensors when measuring wheelset angle of attack at 6 points on the ground

Fig. 12 Emitter and detector in measurement on the ground

That is, at this point, the values of ϕ_t , ϕ_{w1} , ϕ_{w2} and a/R in Eqs. (2) and (3) are defined as 0.

Yawing angles between wheelset and bogie frame (ϕ_{w1} and ϕ_{w2}) are small compared with the yawing angle between bogie frame and rail ϕ_t . ϕ_{w1} and ϕ_{w2} have the sign opposite to ϕ_t , and ϕ_{w1} is larger than ϕ_{w2} . This means that a steering moment is generated on the wheelsets, and this moment is larger on the first wheelset than on the second wheelset. ϕ_{w1} and ϕ_{w2} are 2 to 5 times those of the Shinkansen measured previously.

The mean values of ϕ_1 and ϕ_2 in Fig. 14 in the curve section are defined as a steady wheelset angle of attack. This steady wheelset angle of attack is used for comparison with simulation results in section 5.

Fig. 13 Processing unit of wheelset angle of attack measured on the ground

Fig. 14 Values of angle of attack measured on board during curving ($R=400$ m, $V=110$ km/h)

4.2 Results measured on the ground

Figure 15 shows the wheelset angle of attack measured on the ground for both type 381 test trains and type 381 commercial trains. The arrows in this figure represent the deviations of the data. The type 381 test train has bolsterless-type bogies with arc profiles. Moreover, the primary longitudinal stiffness is low (less than half the conventional value) and the wheelbase is shorter (2.3 m $\rightarrow$ 2.2 m)⁽¹⁰⁾. The wheelset angle of attack of the first axle is about 30% smaller in the test train than in the commercial train.

5. Comparison between Measurements and Calculations

Since wheelset angle of attack can be measured, as mentioned in section 4, we compare the calculations from the simulation program described in the literature⁽⁸⁾ with the measured wheelset angles of attack and verify them.

Figure 16 shows the wheelset angles of attack measured on board and on the ground for curves with radii of 400 m, 300 m and 800 m. The values measured on board show the mean values⁽⁷⁾ of the wheelset angle of attack of the first and second axles in the front bogie of the head car. The values of the wheelset angle of attack measured on the ground are averages⁽⁷⁾ of 6 sections and all test runs. From these figures, the following has been determined.

(1) Results from both measurement on board and that on the ground are nearly identical if their respective errors are considered. Characteristics for the steady wheelset angle of attack for running velocity from both sources are also nearly identical.

(2) The higher the velocity and the larger the

Fig. 15 Values of angle of attack measured on the ground during curving

curve radius, the smaller the steady wheelset angle of attack.

(3) The steady wheelset angle of attack of the first axle is 0.28 degrees, and that of the second axle is 0.02 degrees for a curve radius of 400 m at a velocity of 110 km/h.

The simulation results corresponding to the measurements are shown with solid and dashed lines.

In the case of the 400 m radius (Fig. 16, top), the dashed line is the simulation value for the first and second wheelset angles of attack when the secondary

Fig. 16 Comparison between measurements and calculations ($R=400$ m, 300 m, 800 m)

yawing restraint moment is only due to the air spring, and the friction coefficient between wheel and rail is 0.3. The solid lines in Fig. 16 represent the values when the secondary yawing restraint moment of 10 kNm acts in addition to the air spring, and the friction coefficient between wheel and rail is 0.15.

The dashed lines in Fig. 16 represent values slightly smaller than measured values for the steady wheelset angle of attack. By contrast, the solid lines are in good agreement with the measurements.

The friction coefficient between wheel and rail is usually considered to be about 0.3. However, it may be decreased to about 0.15 by the influence of weather. Because the bogie is bolsterless, the secondary yawing restraint moment is considered to be within 10 kNm.

Therefore, the calculations under actual conditions seem to provide values somewhere between the dashed line and the solid line.

The measurements on curves of 300 m and 800 m radius (lower two figures) are compared with the calculations (solid line). From these three figures, it is seen that the measurements and the calculations are identical, except that the steady wheelset angles of attack of the first and second axles are slightly smaller in the calculations than in the measurements on a curve of 300 m radius.

Therefore, the measuring method of the wheelset angle of attack, the computer simulation program and the value of the wheelset angle of attack calculated by simulation are all considered to be valid.

6. Conclusions

In the previous sections, the measuring method of wheelset angle of attack, the error evaluation used in measurement, field running test results and the verification of simulation results by field running test were presented. They are summarized as follows.

(1) We have developed new methods to measure the wheelset angle of attack on board and also on the ground. The error from measurements on board is within 0.02 degrees and that on the ground is within 0.12 degrees. Relative errors among trains or between the first and second wheelsets are within 0.02 degrees.

(2) Results from both measurement on board and that on the ground are identical if their respective errors are considered. Characteristics for the steady wheelset angle of attack for running velocity from both sources are also nearly identical. The higher the velocity, the smaller the steady wheelset angle of attack.

(3) For the type 381 test train measured on

board, the larger the curve radius, the smaller the steady wheelset angle of attack. The steady wheelset angle of attack of the first axle is 0.28 degrees, and that of the second axle is 0.02 degrees for a curve radius of 400 m at a velocity of 110 km/h.

(4) For the type 381 test train which has arc wheel profiles, the primary longitudinal stiffness is low (less than half the conventional value) and the wheelbase is shorter (2.3 m→2.2 m). The wheelset angle of attack of the first axle is about 30% smaller in the test train than in the commercial train.

(5) The measured wheelset angles of attack are nearly identical to the simulation results calculated using adequate parameters. Therefore, the measuring method of wheelset angle of attack, the computer simulation program and the value of wheelset angle of attack calculated by simulation are all considered to be valid.

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