Angle of attack—the tangential angle on the contact point between wheels and rails—is one of the dominant parameters that determine curving performance of railway rolling stock, and it particularly affects lateral force. It is difficult, however, to measure angle of attack on running cars. While many methods of continuously measuring angle of attack have been attempted, there have been only a few examples of measurements where sufficient accuracy was gained. As a part of work to clarify flange climb derailment, we have developed a system that can continuously measure changes in the angle of attack of a vehicle during running using compact, high-performance sensors that have become affordable thanks to the recent sensor technology improvement. We also conducted test runs using that system. The test results demonstrated that the system could detect and measure the attack angle characteristics of rolling stock running on a curve track or a turnout, proving that the system is usable to clarify flange climb derailment.

**Keywords:** Angle of attack, Continuous measurement, Friction coefficient, Sharp curve track, Derailment, Flange climbing

### 1 Introduction

When railway rolling stock runs on a curve track, the wheelsets naturally follow the curve track because of the difference of the turning circles of the left and right wheels due to their tread gradient. In sharp curve tracks, however, outer wheels pass the curve track at the angle of attack to the rail as shown in Fig. 1. Since angle of attack is an important factor to clarify the behavior of a bogie while running in a curve track, many different methods of continuously measuring attack angle of a running vehicle have been studied and proposed1) - 4), but labor required in taking measurements and technical difficulty have kept the number of actual measurement cases low.

It is known that angle of attack as well as lateral force is significantly involved in flange climb derailment. Since angle of attack greatly affects the running distance needed for wheels to completely climb the rail5), it is also a quite important factor in clarifying derailment. In order to assess the safety against flange climb derailment, we have to identify the status of friction between a wheel and a rail at the very moment when the conditions for flange of the wheel to start climbing (hereinafter, “critical derailment state”) are met. Past research showed that high-accuracy measurement of parameters on the border between the wheel and the rail, such as wheel load, lateral force, angle of attack and amount of climbing of wheel, is required to detect the critical derailment state6).

Thus, aiming to make use of the information on continuous change of angle attack for work such as investigating derailment, we have developed equipment for continuous attack angle measurement (hereinafter, “the equipment”) that identifies the critical derailment state essential to finding the limit to flange climb derailment and measures the parameters at the moment when the wheel/rail reaches that status. Using compact and high-performance displacement gauges and other devices that have recently become affordable, the system can stably and continuously measure the angle of attack at the contact point of the wheel and the rail when running in a curve track. This article introduces the system configuration and reports the measurement results of attack angle in different curve tracks including turnouts in test runs.

**Fig. 1 Definition of Angle of Attack**

### 2 Angle of Attack and Running Safety

#### 2.1 Wheel Behavior in Flange Climb Derailment

When wheels run in a sharp curve track at an angle of attack with the flange of the outer wheel pressed against the rail, the flange of the wheel and the rail contact to each other at a position further in the running direction than just under the axle, as shown in Fig. 2. The position of the contact point depends on the shape of the wheel and rail, angle of attack and other geometric conditions. And when conditions such as decreased wheel load and increased lateral force that cause flange climb derailment are present, climbing behavior occurs with the contact point as the fulcrum. Therefore, the further ahead in the running direction the contact point is positioned, the larger the climbing angle is. The running distance until the wheels complete climbing thus becomes shorter. As the contact position and state between the wheels and rails is in constant change when an actual train runs in a sharp curve track, the force applied to the contact point also changes. The train is thus assumed to run while repeating slight climbing and slipping down.

In this context, angle of attack is significantly related to the
time required for a wheel to complete climbing the rail (running distance) in particular among the factors affecting flange climb derailment. Thus, angle of attack is quite an important factor in investigation of flange climb derailment and assessment of safety.

Fig. 2 Behavior of the Outer Wheel in a Sharp Curve Track

2.2 System Performance to Clarify Flange Climb Derailment
In the past, JR East developed a device to continuously measure angle of attack\(^7\) for evaluation of running safety of rolling stock and made measurements using the device. Fig. 3 shows the device and principle by which it measures. This device identifies the edge of the rail according to the amount of laser reflection detected from straightly above the rail by two sensors on each side of the wheel, and it calculates the angle of attack based on the relative position of the identified rail edge. This device was able to measure attack angle in real time even in high-speed running on main lines, yet it needed improvements on the following problems to identify the critical derailment state.

(1) The devices required fine adjustment of the threshold of sensor signals according to surface and abrasion conditions of the top surface of the rail in order to accurately identify the rail edge.
(2) Since the device had the sensors placed in front of and behind the wheel, the measurement accuracy became lower when measuring attack angle near the contact point between the wheel and the rail or when measuring change of curvature at short wavelengths.
(3) Detecting the very moment of transition to climbing or slipping down requires sampling intervals of a couple of millimeters of running distance, equivalent to high-speed sampling at intervals of less than 1 ms in time. However, the sampling measurement period of the device was 10 ms at the shortest.
(4) Due to the difficulty of checking measurement status while running, it was difficult to judge from the measured values whether the sensors were able to correctly detect the rail edge and make correct measurement.

We therefore aimed for performance of the system that overcomes those problems and that secures accuracy and sampling period that enable identification of the critical derailment state.

3. Overview of the System

3.1 Principle of Measurement
The principle of measurement of angle of attack is to measure the distance from two fixed points on the side surface of the wheel to the rail and calculate the angle according to the geometric relation shown in Fig. 4. In order to prevent deterioration of measurement accuracy by relative displacement between the system and the wheel due to factors such as bearing play, this system measures the distance from the axle box to the wheel and to the rail at two points each and determines the difference between the axle box/wheel angle and the axle box/rail angle as the angle of attack.

Fig. 3 Existing Measurement Device for Angle of Attack

\[
\text{Angle of attack} = \tan^{-1} \left( \frac{X_a - X_b}{L} \right)
\]

Fig. 4 Principle of Measurement of Angle of Attack

3.2 Measurement System
Fig. 5 shows the configuration of the system. The system consists of a laser displacement gauge under the axle box and devices that calculate and record angle of attack from measurement data onboard. For distance measurement, we adopted a non-contact sensor (laser displacement gauge) that has been used and showed good results in fixed-point measurement from the wayside. Non-contact sensors up to now did not have good enough accuracy to measure objects such as wheels and rails whose surface condition changes during running, and they had limitations in terms of factors such as placement angle to the object. Those sensors thus have not been used for measuring angle of attack from onboard. But recent advances in sensor technology have made sensors more compact and improved measurement stability as well, and that has enabled measurement from the side of the wheel without interfering with clearance. Thus, we decided to use non-contact sensors for the system.
improves measurement accuracy and eliminates previously required fine setting of threshold values according to the measurement environment. This system only measures distance with the laser displacement gauge without calculating for threshold-based judgment, so it only needs simple calculation. At the performance level of the displacement gauge and computer, the measurement accuracy of angle of attack of the system is estimated to be 0.002 degrees and the shortest sampling period to be 20μs, both of which are sufficient to identify the critical derailment state. Commercially available products are used as components other than the attaching jig, so those can be upgraded with sensors and recorders of higher performance at relatively low cost. However, this system emits a laser beam to the side surface of the rail head to obtain distance information, so it cannot make correct measurements at rail bonds and joints or at rails where objects such as grass are present. Moreover, when the laser target point is off the side surface of the rail head due to factors such as displacement of the system caused by lateral displacement of the wheelset and movement of the axle spring, measurement error becomes larger. To eliminate such incorrect data, the system can check laser emission using a CCD camera synchronized with the attack angle data.

![Image](image_url)

**Wheel rim**

**Side surface of rail head**

**Measuring change wheel to rail distance**

**Devices for data processing and recording**

**Sensor**

**CCD camera**

4. Measurement Results

Installing the equipment to JR East’s series 209 test train (MUE-Train, Saya 209-8), we carried out test runs in a depot yard and on a main line.

4.1 Running on a Curve Track on a Main Line

We carried out test runs in the section between Yotsukaido and Narita Stations on the Sobu/Narita Line. The running speed in a curve track section was mainly low (10–30 km/h), a strict condition in terms of flange climb derailment.

Fig. 6 shows the relation between the angle of attack and the curve track radius. Here, the curve track radius is the values converted from 10 m-chord versines of the track measurement data on the measurement day nearest to the test day. Fig. 6 also shows the angle of attack calculated with the derailment coefficient ratio estimation formula to evaluate the validity of the measurement values. The attack angle measurement values were 0.2–0.4 degrees in an R400 curve and 0.3–0.5 degrees in an R300 curve track. In a curve track of a radius less than R400, the change of the attack angle in relation to the change of the curve track radius tended to be larger. The tendency conformed with the values calculated in the derailment coefficient ratio estimation formula and past measurement values too; therefore, we believe that the measurement method of this system is valid.

![Image](image_url)

**Fig. 6 Curve Track Radius and Angle of Attack**

4.2 Running on a Turnout in a Depot Yard

We measured the angle of attack at passing a turnout in a depot yard. More specifically, we made measurements of the angle of attack while running in the direction of turning out on a route that has both of a No. 8 simple turnout (T50NK8-101, hereinafter, “No. 8 turnout for main lines”) and a No. 8 turnout for service lines (T50NK8-201), it is assumed that flange climb derailment can easily occur at those turnouts.

Fig. 7 shows an example of the results of the attack angle measurement at approx. 20 km/h on the No. 8 turnout for main lines and the No. 8 turnout for service lines in the direction of turning out. The horizontal axis is the running distance and the toe of the tongue rail is the 0 m point for convenience. In principle, the sensors cannot correctly detect the side surface of the rail top at the toe of the tongue rail and the crossing with system, so measurement was incorrect. But, the image of the CCD camera showed that the sensors detected around the center of the side surface of the rail head at the lead rail. Thus, the measurement values were valid. In these measurements, the maximum angle of attack measured was approx. 1.2 degrees on the No. 8 turnout for main lines and approx. 1.4 degrees on the No. 8 turnout for service lines along the curve track radius of the lead rail. A characteristic of the angle of attack generated was that the angle was almost constant on the lead rail of the No. 8 turnout for main lines while the angle decreased once on the tongue rail and then increased on the lead rail of the No. 8 turnout for service lines. From this, we estimate that an angle of attack at approx. 2 degrees occurs the moment the outer wheel passes the straight part and contacts the toe of the tongue rail while running on the No. 8 turnout for service lines that has a straight tongue rail in the direction of turning out. That 2-degree angle of attack is equal to the angle of incidence of the outer wheel at that moment. Then, the angle of attack decreases on the straight part of the tongue rail as the wheelset turns out, increasing again on the curved part to the value according to the curve track radius of the lead rail.
4.3 Consideration on Flange Climb Derailment and Angle of Attack

In the investigation after the derailment in the yard of Oku Station on the Tohoku Line in February 2008, evidence of climbing of wheels was found from the point 8 m from toe of the tongue rail of the No. 8 turnout for service lines. Further investigation clarified that the derailment coefficient of the outer wheel became largest just short of that point. In our measurement of angle of attack on a turnout of the same type, we found that the angle of attack became largest at around 8 m from the tongue rail in the lead rail section. In this measurement, the point measured and the vehicle were different from those of the derailment, but the turnout was of the same type. Therefore tendencies of angle of attack should be the same. It would be therefore highly likely that the derailment point was the point where both the derailment coefficient and the angle of attack became large.

5 Conclusion

We developed a system that can make continuous onboard measurement of angle of attack, an important factor of flange climb derailment, and we conducted test runs. Comparison of the test results to past measurement results and calculation results by the derailment coefficient ratio estimation formula proved the validity of measurement with the system.

For safety assessment of flange climb derailment, identifying the friction coefficient between the wheel flange and the rail is essential. The friction coefficient is considered very difficult to measure, yet it has been shown that the critical derailment state can be identified by continuously measuring angle of attack as well as wheel load, lateral force and wheel climb amount. And the friction coefficient can be obtained from measurement values at that moment. We are planning to further research estimation of the friction coefficient in the critical derailment state in sharp curves of around R100 using the wheel climb amount measurement device and the angle of attack continuous measurement system developed this time in addition to conventional measurement of wheel/rail contact force.

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