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Improvement of estimation accuracy for wheelset angle of attack using a single-wheel creep-force model by taking into account contact phase difference and lateral contact position

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Abstract

The purpose of this study is to improve an accuracy of an estimation method using a single-wheel creep-force model to evaluate a running safety more realistically using an instrumented wheelset. To achieve the purpose, this paper proposes a novel estimation method for a wheelset angle of attack using a Kalman filter. In particular, this paper focuses on the method to improve the estimation accuracy under the situation where creep force is saturated with friction force, which was a problem in previous research, by incorporating contact phase difference into outputs. The validity of the proposed method is verified using simulations. The verification results show that the proposed method managed to obtain estimation results for the angle of attack with quantitative validity regardless of track curve radii. Moreover, the proposed method also managed to estimate the lateral displacement of a contact point at the outer rail side when a wheel and a rail contacted at the flange region while traveling on a circular curve.

Keywords: State estimation, Wheel-rail interaction, Creep force, Angle of attack, Contact position, Kalman filter, Contact phase difference

1 Introduction

Contact force between wheels and rails is important to evaluate running safety of a railway vehicle. One of methods for measuring the contact force is to use a special wheelset, called as an instrumented wheelset, which is generally used to evaluate running safety in Japanese railway vehicles. A value calculated by dividing a lateral force *Y* by a wheel load *Q* acting between the wheel and the rail is called a derailment quotient *Y*/*Q* and is used as an indicator to evaluate running safety. Specifically, when the measured *Y*/*Q* is smaller than the critical derailment quotient calculated by Nadal's formula, it is assumed to be safe. On the other hand, the critical derailment quotient used in the current evaluation does not take into account the effect of contact conditions between wheels and rails, such as an angle of attack and a friction coefficient, which may change for each traveling position. Currently, the critical derailment quotient is determined by considering the combination of the worst possible contact conditions. If the contact conditions can be grasped in detail, it may be possible to evaluate running safety more realistically.

Considering this background, the purpose of this study is to construct a method for grasping the contact conditions between wheels and rails without increasing measurement costs from current level. The authors of this paper considered a method for estimating motion variables of a wheelset such as an angle of attack using a single-wheel creep-force model and an observer based on Kalman filter [1]. Previous study has shown that the proposed method can estimate the change trend of the angle of attack qualitatively in a curved section using the measured values of only a single instrumented wheelset. However, it has also been confirmed that the estimation accuracy decreases under running conditions where creep force is saturated with friction force. Therefore, in this study, we propose a new method to improve the estimation accuracy when creep force is saturated. In this paper, we report the proposed estimation algorithm and the result of validation using simulations.

2 Methods

A single-wheel creep-force model [1] is differential equations for state variables as follows, which are obtained by using two ways of expressions satisfied by creep force.

$$[\dot{y}, \dot{\psi}]^{\boldsymbol{T}} = \boldsymbol{f}(y, \psi, \rho, V, T, Y, Q), \tag{1}$$

where
y: lateral displacement of wheelset
ψ: wheelset angle of attack
ρ: track curvature
T: longitudinal tangential force
Y: lateral fore
Q: wheel load
V: traveling speed.

In previous study [1], an observer was constructed by a Kalman filter of which the state variable vector is $\boldsymbol{x} = [y, \psi]^{\boldsymbol{T}}$**,** the input vector is $\boldsymbol{u} = [\rho, V, Q]^{\boldsymbol{T}}$ and the output vector is $\boldsymbol{y} = [T, Y]^{\boldsymbol{T}}$. Since this model focuses on a single wheel, this observer has the advantage of not having to consider the motion of bogie frames or vehicle car bodies. However, the accuracy for ψ estimated by this model decreases when creep force is saturated with friction force. This is because the inverse function of a creep force model cannot be defined in a saturated region.

To solve this problem without increasing a cost, this paper proposes a novel method which incorporates "contact phase difference" [2] into the output vector. As shown in Figure 1, the contact phase difference $\Delta\theta$ is defined as the difference in the longitudinal position of the contact points between both sides of the wheels and the rails, as an angle around the wheelset axle. Hondo and Noguchi have proposed a method for extracting $\Delta\theta$ from periodic strain signals acquired by the instrumented wheelset [2]. It is known that $\Delta\theta$ depends on ψ and the relationship between $\Delta\theta$ and ψ can be approximately expressed as the following equation (2).

$$\Delta\theta \simeq \psi(\tan\alpha_L - \tan\alpha_R), \tag{2}$$

where

α_L, α_R: contact angle of left wheel or right wheel.

α_L and α_R are determined from the wheel shape data as a function of the lateral displacement s_L or s_R of the left or right contact point. If α_L and α_R are constant, ψ and $\Delta\theta$ are in a proportional relationship. Therefore, the inverse function of Equation (2) can be defined even if the creep force is saturated, which is expected that the estimation accuracy is improved. However, since α_L and α_R change according to the change of s_L or s_R as described above, it is necessary to estimate them at the same time. In this study, the time derivatives $\dot{s}_L$ and $\dot{s}_R$ are assumed to be locally proportional to the lateral velocity $\dot{y}$. On the basis of this assumption, the following differential equations are integrated with Equation (1) so as to estimate the lateral contact positions:

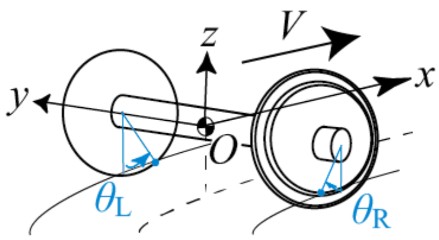
$$\dot{s}_i \simeq a_i \dot{y} \tag{3}$$

$$\dot{a}_i \simeq 0, \tag{4}$$

where

i: wheel index $(i = L, R)$.

Equation (4) gives the time derivative of the factor of proportionality a_i in Equation (3), and the change of a_i is assumed to be a quasi-static process in this study.



$\Delta\theta = \theta_L - \theta_R$:Contact phase difference

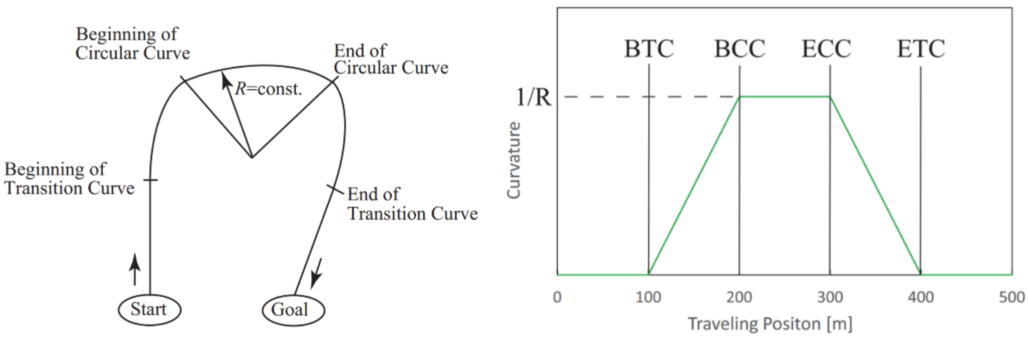
Figure 1: Definition of contact phase difference $\Delta\theta$.

3 Results

The validity of the proposed method is verified using the simulation software “Simpack”. Figure 2 shows an alignment of the test track used for the simulations. The simulations were performed with various curve radii R of the circular curve and the influence of R on the estimation accuracy was investigated. The friction coefficient and traveling speed were set to 0.4 and 10 km/h, respectively. Random noise was superimposed on the simulated wheel / rail contact force data, which was used as the measured values in the proposed method. The observer was designed using an unscented Kalman filter to consider the non-linearity of the system.

Figure 3 shows the relation between R set in the simulations and the estimated values of ψ, and also indicates the RMSE (Root Mean square Error) of the estimated values against the simulated values during the circular curves. The estimated values are obtained by two methods: conventional and proposed method. In the conventional method, the contact phase difference is not considered. Figure 3 shows that the proposed method can improve the accuracy compared with the conventional method. While the RMSE in the conventional method is 0.33 deg when R is equal to 100 m, the RMSE in the proposed method is 0.02 deg.

Figure 4 shows the relation between R and the estimated values of lateral contact position s_i and its RMSE. Figure 4(a) shows that the maximum RMSE of the outer rail side was about 1 mm when R is equal to or smaller than 800 m. However, it was also confirmed that when R is larger than 800 m, the RMSE increases. In this region, the contact point is located closer to the center of the tread, where the variation of the contact angle α_i is small. Since s_i is indirectly estimated as the function of α_i in the proposed method, the estimation accuracy decreases when R is large. Figure 4(b) shows that the estimated value for the inner rail side was not accurate for the same reason. On the other hand, the estimation accuracy of ψ is not directly affected by the estimation accuracy of s_i since it is important to estimate α_i accurately. Since the estimation error of α_i was not so large in the region closer to the tread center, the RMSE of ψ was small despite the inaccurate estimation of s_i in this verification.



(a) Track diagram (b) Track curvature

Figure 2: Test track diagram.

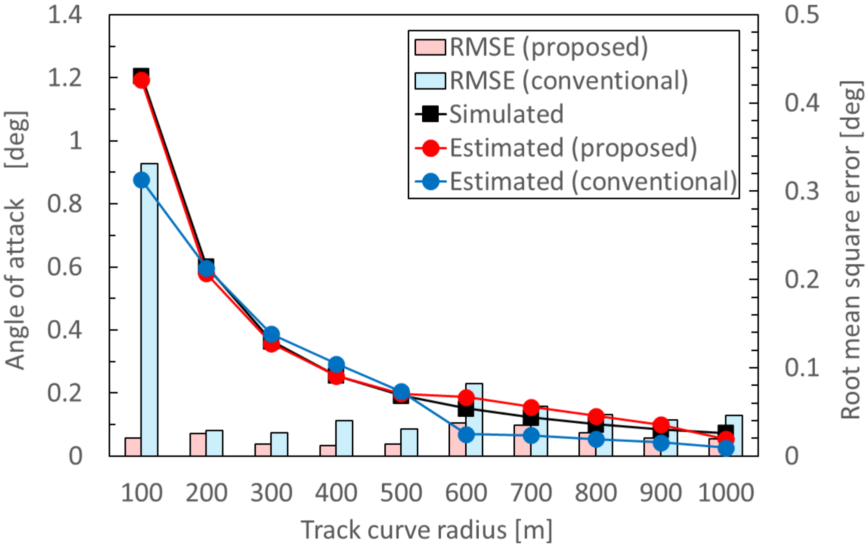
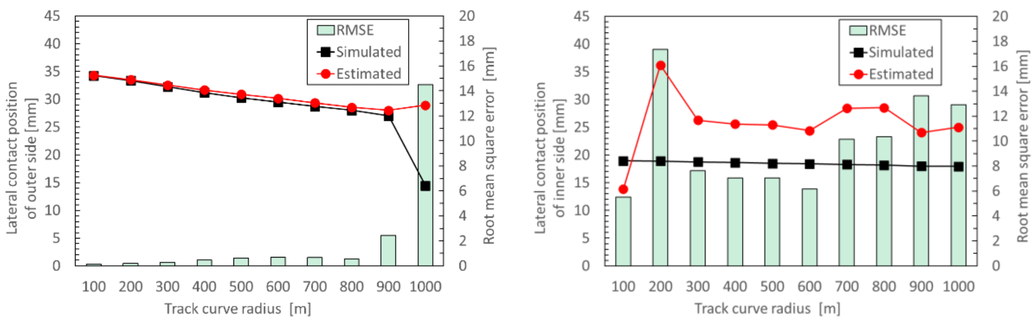


Figure 3: Relation between the curve radius and average of the estimated angle of attack ψ during the circular curves.



(a) Outer side (b) Inner side

Figure 4: Relation between the curve radius and average of the estimated lateral displacement s_i of contact point during the circular curves.

4 Conclusions and Contributions

This paper proposed a novel method for estimating the wheelset angle of attack using a Kalman filter for the purpose of improving the accuracy of evaluation for running safety using an instrumented wheelset. In particular, this paper focused on a method to improve the estimation accuracy when creep force is saturated with friction force, which was the problem in previous research, by incorporating the contact phase difference into the outputs. The following results were obtained by the verification using the simulations.

- The estimation accuracy for the wheelset angle of attack was improved by incorporating the contact phase difference and the lateral contact position into the state observer.

- When the wheel contacts with the rail in the flange region, the estimated contact position was in agreement with the simulated results. However, when the contact point is in a region closer to the tread center, the accuracy decreased because the sensitivity of the contact angle to the lateral contact position is small. In spite of this fact, the estimation accuracy for the wheelset angle of attack is not so decreased since it is not directly affected by the estimation accuracy of the lateral displacement of the contact point.

Future works are as follows.

- Verification under various running conditions considering the change of contact geometry (e.g. rail wear and slack) and the running states (e.g. traveling speed, friction coefficient and superelevation)
- Verification using actual measurement data

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