Train Position Detection System by Means of Inertial Sensors Together with a Tachometer Generator

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Generally, tachometer generators are used to calculate the train running distance under on-board units, and transponders are used to detect the train position. However, with this approach the effects of wheel skidding or slipping need to be compensated, which would require a large number of transponders. Therefore, a method is under development using both a tachometer generator and inertial sensors, to calculate train running distances independently of the number of wheel rotations and train position detection, using curved line sections. The results of simulation analyses using managed time-stamped data show that it is possible to compensate train running distance using this method, even when wheel skidding or slipping occurs, and that it is possible to detect train position.

Keywords: running distance calculation, compensation against wheel skidding or slipping, inertial sensor, compensation with line feature points

1. Introduction

Generally, the running distance of vehicles is calculated by counting the tachometer generator pulse. Research has also been conducted with GPS or Doppler sensors as alternatives, however the limitation of GPS is that no satellite signal can be received in tunnel sections, and Doppler sensors present a problem with regards to calibration in terms of installation angle errors [1]. Inertial sensors however, which are proposed in this paper, are small and do not suffer any of the constraints just mentioned.

2. Background

As distance and speed are calculated by integrating the acceleration and angular velocity detected with inertial sensors, periodical processes for error resets have to be considered. In the case of more precise inertial sensors installed in airplanes, reset intervals can be set to a longer time, and any devices to complement inertial sensors may not be required. However, as it is too expensive to install such sensors on railway vehicles, to reduce the integral calculation time using inertial sensors, a method has been developed which combines a tachometer generator and inertial sensors to detect acceleration and angular velocity, whereby only inertial sensors are used during wheel skidding or slipping. Moreover, in recent train control systems, it is required that transponders be settled along lines at such a short interval as to be able to detect train positions in order to calibrate the train location in the on-board unit, which requires a greater number of trackside devices. As such, a method has been developed for detecting positions such as curve sections by combining a tachometer generator and inertial sensors, which removes the need for transponders for the calibration of train location.

In train control systems, the higher the precision of the detected train location the better the train control. At the same time, detecting train position means including the margin for safety distances in the section occupied by the train. This means that the area ‘occupied’ by the train and recognized by the system is actually quite large.

The proposed method is low cost and fairly easily to apply to certain traditionally difficult cases, such as installation of a tachometer generator on short trains with only driving axles and without reduced braking power, in order to avoid the wheel skidding or slipping, etc. Furthermore, this method can be useful for estimating the maximum distance error based on sensor error.

This paper describes a compensation method for wheel skidding or slipping and a position detection method with inertial sensors together with a tachometer generator. The effectiveness of this method is shown through simulation results obtained from data recorded with managed time stamps during test runs.
3. Proposed method

3.1 Distance calculation method with inertial sensors and tachometer generator

For distance calculations in the proposed method, transition conditions between the inertial sensors and the tachometer generator are based on a comparison of the acceleration from both sensors. When the difference exceeds a certain threshold, wheel skidding or slipping are detected and calculations from the tachometer generator are subsequently adapted through the inertial sensors. In the compensation process, the integration of longitudinal acceleration is used, and in order to remove the acceleration of gravity, the pitch angle of a vehicle is calculated. The calculation method is explained in more detail below.

3.1.1 Wheel skid or slip detection

In order to alternate distance calculation between the inertial sensors during wheel skidding or slipping, and the tachometer generator for when there is wheel/rail adhesion, the difference in acceleration between both sensors is compared for diagnosis. Concretely, the longitudinal acceleration detected by inertial sensors ($a_i$) and the acceleration calculated by the tachometer generator ($Ap$) are compared, and when the difference (acceleration reference value) exceeds a threshold ($Ta$), it is recognized as wheel skidding or slipping (1). $Ta$ is given a value in such a way as to avoid misjudgment from gravitational acceleration due to gradients.

$$|a_i - Ap| > Ta$$

This method allows earlier detection of wheel skidding or slipping, since they are detected from the difference in acceleration detected by the tachometer generator and the inertial sensors.

3.1.2 Compensation during wheel skidding or slipping

(1) Compensation process

After detection of wheel skidding or slipping is detected, velocity and distance are calculated with longitudinal acceleration ($a_i$) (Fig. 1). Since longitudinal acceleration is affected by the acceleration of gravity ($G \times \sin \theta$) caused by gradients (2), to remove this factor, the pitch angle of a vehicle ($\theta$), which is based on the coordinate system centering on the earth is calculated. In this calculation process, first the points where the adhesion state between wheels and rails is observed are defined as the start point of compensation, and the initial pitch angle ($\theta_0$) is calculated by the difference between the value of $a_i$ and $Ap$ at $t=0$ (3). Then, the pitch angle ($\theta(t)$) is calculated based on the time integration value of pitch angular velocity with inertial sensors, until wheel/rail re-adhesion occurs and is recognized by (4).

$$A_i(t) = a_i(t) - G \times \sin \theta(t)$$

$$\theta_0 = \arcsin \left( \frac{a_i(0) - Ap_0}{G} \right)$$

$$\theta(t) = \theta_0 + \int_0^t \omega_i(t) \, dt$$

where $\omega_i$ : Pitch angular velocity with an inertial sensor

As $\omega_i$ shown in (4) is affected by yaw angular velocity because of cants in curved sections, $\omega_i$ is compensated by (5).

$$\omega_i'(t) = \omega_i(t) - (-\omega_i(t) \times \sin \psi(t))$$

$$\psi(t) = \psi_0 + \int_0^t \omega_i(t) \, dt$$

$$\psi_0 = \arctan \left( \frac{-A_{\psi}}{\sqrt{A_{\psi}^2 + A_0^2}} \right)$$

Since the maximum value of $A_{\psi}$ shown in (7) is 35% (1.23 km/h/s), and this value is 3.5% of the acceleration of gravity, where $A_0$ is less enough than $A_{\psi}$, (7) can be approximated by (8).

$$\psi = \arctan \left( \frac{-A_{\psi}}{A_0} \right)$$

Moreover, since lateral acceleration $A$ is affected by centrifugal force, lateral acceleration with an inertial sensor ($a_0$) has to be compensated as shown in (9).

$$A_{L_0} = -(a_0 - v_0 \times \Omega_0 \times \cos \psi(t))$$

$$a_0 : \text{Lateral acceleration with an inertial sensor at } t=0$$

$$\Omega_0 : \text{Yaw angular velocity on a horizontal plane at } t=0$$

Where $\psi$ is less enough, $\Omega_0 \times \cos \psi(t)$ is approximated as shown in (10).

$$A_{L_0} = -(a_0 - v_0 \omega_0 \psi(t))$$

$$\omega_0 : \text{Yaw angular velocity with inertial sensor at } t=0$$

Equation (8) is changed to (11) by substituting (10).

$$\psi = \arctan \left( \frac{a_0 - v_0 \omega_0 \psi(t)}{A_{L_0}} \right)$$

Since $v_0$ shown in (11) is the value before compensation

$$v_0 : \text{Yaw angular velocity}$$

$$\omega_0 : \text{Roll angular velocity with an inertial sensor}$$

$$\psi(t) : \text{Roll angle}$$

$$\omega_i'(t) : \text{Compensated pitch angular velocity considering yaw angular velocity}$$

$$\omega_i(t) : \text{Yaw angular velocity with an inertial sensor}$$

$$t : \text{Compensation duration}$$

$$A_i : \text{Longitudinal acceleration for attitude sensing at } t=0$$

$$A_{\psi} : \text{Lateral acceleration for attitude sensing at } t=0$$

$$A_0 : \text{Vertical acceleration for attitude sensing at } t=0$$

$$A_{\psi} : \text{Longitudinal acceleration for attitude sensing}$$

$$A_{L_0} : \text{Yaw angular velocity with an inertial sensor}$$

$$Ta : \text{Threshold}$$

$$A_0 : \text{Acceleration of gravity}$$

$$\theta(t) : \text{Pitch angle of a vehicle}$$

$$\theta_0 : \text{Initial pitch angle}$$

$$v_0 : \text{Velocity with a tachometer generator at } t=0$$

$$\psi(t) : \text{Roll angle}$$

$$\omega_i(t) : \text{Pitch angular velocity with inertial sensors}$$
during wheel skidding or slipping, and this value is not affected by these factors, velocity from the tachometer generator can be applied.

Moreover, pitch angular velocity is affected by centrifugal forces caused by the roll of the body in curved sections. Therefore, pitch angular velocity shown in (5) is further compensated and represented as (12).

\[ \omega_p(t) = \omega_p(t) + \alpha(t) \times \sin \psi(t) - k \times \alpha(t) \times \sin \psi(t) \]  

(12)

\[ k \] : To the right hand side curve -1, to the left hand side curve +1

(2) Selection of points where to begin compensation

Accurately, at the time of the detection of wheel skidding or slipping, there is no wheel/rail adhesion because the difference between the longitudinal acceleration detected by inertial sensors \((a_x)\) and the acceleration detected by a tachometer generator \((Ap)\) is not zero, and exceeds the threshold \(\Delta a\). If compensation starts at this however, the pitch angle will not be calculated accurately, and the distance error is not ignored. Therefore, compensation must begin ahead of the point where wheel skidding or slipping is detected. The point from which compensation should begin is selected on the condition that the jerking movement is below the threshold in order to reduce the effect of wheel skidding or slipping.

Concretely, the points from where compensation begins are set ahead of the places where wheel skidding or slipping is detected, and are selected on the condition that the longitudinal jerk from the inertial sensors is below the threshold \(J_{\text{th}}\), the jerking movement from the tachometer generator is below the threshold \(J_{\text{tp}}\) and the difference \((J_{\text{th}} - J_{\text{tp}})\) is below the threshold defined to check the synchronization between both sensors. In order to prevent misjudging this selection due to temporary changes, 3 successive checks are made. Moreover, because minor wheel skidding or slipping cannot be detected within the range of jerking thresholds, which may lead to misjudgment, the compensation starting points are selected a certain amount of time before the detection of wheel skidding or slipping.

Applying compensation starting points can reduce distance errors resulting from decreasing differences in inertial sensor acceleration and tachometer generator acceleration due to wheel skidding down slopes and wheel slipping up slopes.

3.1.3 Re-adhesion detection

Re-adhesion between wheels and rails is detected when the acceleration reference value \(|a - Ap|\) is below the threshold and the difference between tachometer generator velocity and compensated velocity from the inertial sensors is below the threshold \(\beta [\text{km/h/s}] \times t [\text{s}], \beta : \text{Acceptable acceleration error}, t: \text{compensation duration}) \) during the compensation process.

3.1.4 Estimation of the maximum distance error

It is a merit that under the proposed system, the maximum distance error caused by wheel skidding or slipping can be estimated from the inherent sensor error. Distance errors during wheel skidding or slipping are \((\Delta d)\) calculated by (13). Though the yaw angular velocity and the roll angular velocity are factored in when compensating the pitch angular velocity, only the pitch angular velocity and the longitudinal acceleration are considered because yaw and roll angular velocities affect little distance errors.

\[ \Delta d = \frac{1}{2} \times \Delta a \times t^2 \]  

(13)

\[ t : \text{Compensation duration} \]
\[ \Delta a: (a) \text{angular velocity error} + (b) \text{acceleration error} + (c) \text{threshold error} \]

Following are the examples of the parameters, in cases where processing cycle is 0.1 sec.

(1) Angular velocity error

0.1 deg/s (0.0615 km/h/s) (100 ms average under stationary setting measurement)

Maximum error during 10 sec 0.615 km/h/s \times 10=0.615 km/h/s

Average error during 10 sec 0.0615/2 \times 10=0.31 km/h/s

(2) Acceleration error

0.1 km/h/s (100 ms average under stationary setting measurement)

(3) Threshold error

Threshold error : 1.23 km/h/s

Though the jerk reference is applied, in consideration of minor wheel skidding or slipping, the error is estimated to be 1.23 km/h/s which is defined by the maximum gradient.

Note that, if \(J_{\text{th}}\), which means the acceleration reference value, is applied to selected compensation starting points, the error caused by the threshold defined by the acceleration reference becomes 2.46 km/h/s in cases where the maximum gradient is 1.23 km/h/s.

(4) Compensation duration

Compensation duration is the time elapsed between the compensation starting point and re-adhesion detection point, and the maximum value is assumed to be 10 sec in consideration of the fact that the duration of about 90 % of wheel skidding or slipping lasts under 10 sec [2].

Under these conditions, the estimated maximum error distance is calculated by

\[ 0.5 \times (0.31 + 0.1 + 1.23) / 3.6 \times 100 = \pm 22.8 \text{ m} \]

In cases where the distance including safety margin is set in consideration of this estimated maximum error distance, braking will be applied for safety by stopping the vehicles even though the re-adhesion point has been misjudged. This estimated maximum error distance depends on the line gradient and sensor performance.

Accumulated errors are rest by detecting transponders distributed in defined positions. It is assumed that sensors are resets every 30 min while trains wait in stations.

3.2 Position detection

To reduce the number of transponders distributed along lines, positions are detected not only using tachometer generators but also inertial sensors. In this proposed system, curved sections are extracted as reference positions. These positions are used as virtual transponders for position detection.
Concretely, the inverse of the radius in curved sections, which is calculated by an on-board unit based on the train speed by a tachometer generator and on the yaw angle velocity by inertial sensors, is compared with a database in which running distances and radii in curved sections are recorded (Table 1) in order to detect positions, and to cancel the elongation of the virtual train length as well as the distance errors caused by the use of a tachometer generator.

When positions are detected, the following diagnoses are applied by using the above mentioned database.

(1) Diagnosis of points where position detection begins

The purpose of this diagnosis is to check whether the point identified to start detection is correct or not.

(2) Diagnosis of straight section length (entrance sides)

This diagnosis checks whether the defined length of straight line shown in the database is detected or not. The section is deemed to be straight if the inverse of the radius is less than the defined value.

(3) Diagnosis of curved section length

(a) Diagnosis of negative or positive of the inverse of the radius

Diagnosis is to check if the positive or negative of the inverse of the radius obtained from the tachometer generator / inertial sensor coincides with the direction of the curve indicated in the database values for an identified point.

(b) Diagnosis of upper thresholds of the inverse of the radius

This diagnosis checks whether the calculated inverse of the radius is less than the defined value in consideration of the upper margin in a curved section, according to the database.

(c) Diagnosis of distance between lower limits of the inverse of the radius

This diagnosis checks whether the length between the lower limits of the inverse of the radius in a curved section, i.e. both on entrance and exit, are less than the defined margin added to the length of the curved section. The GPS position of the entrance and exit can be also checked for further diagnosis. Position detection is obtained from the lower limit of each curve at the exit, and an error distance is calculated to compensate the distance.

(4) Diagnosis of the length of straight sections (exit sides)

This diagnosis checks whether the defined length of straight line in the database has been detected or not. This method is identical to that applied for the entrance to the curve.

Position detection is achieved only when no errors are detected in the course of the above mentioned. In cases where wheel skidding or slipping occurs, the position is not detected because the calculated inverse of the radius may be affected by the tachometer generator. Moreover, as the calculated inverse of the radius will not be correct when the train stops, the position is not detected when the train is running at a speed below the defined value.

4. Verification results

4.1 Verification methods

The test vehicle specifications are shown in Table 2, and the outline of the test line is shown in Table 3. The hardware for the compensation process during wheel skidding or slipping is the same as for electronic interlocking devices. The process cycle is 100 ms. In this verification, the sampling interval of inertial sensors was 10 ms and the sampling interval of tachometer generators was 100 ms.
of changing their pitch angles, they do not affect position detection because position detection is obtained from yaw angular velocity and vehicle velocity.

4.3 Test Results

4.3.1 Distance calculation method with inertial sensors and tachometer generator

(1) Wheel skidding or slipping detection

In consideration of the fact that the maximum gradient of a conventional line is ± 35 ‰, the thresholds for wheel skidding or slipping were set at ± 1.23 km/h/s. It was confirmed that when wheel skidding or slipping on the test line occurred, the value of \( a \), \( -Ap \) changed greatly, and wheel skidding or slipping was detected. Moreover, even in sections with both downward gradients (15.9 ‰) and curved sections (radius 400 m), wheel skidding or slipping was detected and it was possible to identify the point from where compensations should begin.

(2) Compensation process

The points from where compensation should begin were determined through the method described in section 3.1.2. The threshold of the jerking movement was set to \( |Ji - Jp| < 0.05 \text{ km/h/s/0.1 s} \), considering a resolution where \( Jp \) was 0.15 km/h/s/0.1 s and the resolution of Ji was 0.1 km/h/s/0.1 s.

Figure 3 shows an example of wheel skidding on a test line. The error distance caused by wheel skidding or slipping is shown in Fig. 4. Error distances are based on the distances between transponder detection triggers. These distances are calculated by the tachometer generator without wheel skidding or slipping. The error rate is calculated as: (measured distances – distances between transponders) / distances between transponders × 100.

Although there are some cases where compensation occurs for a longer period than the assumed 10 sec, the error is within about ± 2 ‰.

In curved sections which are also on a slope, re-adhesion detection is difficult when there is no pitch compensation. However, detection is possible if the pitch angular velocity is compensated by the yaw angular velocity and the roll angular velocity. (Fig. 3, Fig. 4)

Note that among the 44 points where wheel skidding or slipping was detected, 4 points incorrectly detected wheel skidding or slipping. The reason for this is that minor wheel skidding or slipping which can’t be detected leads to an incorrect compensation start point setting, which should actually begin after wheel skidding or slipping is detected, on the basis of the jerking movement reference. To avoid this type of error therefore, the compensation start point selection process is shifted to a predefined time prior to wheel skidding or slipping. Based on test results, this predefined time was set to 2.1 sec, which is the minimum time necessary to avoid incorrect positioning when the process involving the jerking movement reference is applied. Applying these measures to all detection points demonstrated that re-adhesion was correctly detected at all the points except one. However, extending the predefined time as suggested above is a problem, since it lengthens the compensation time. Therefore, given that re-adhesion cannot be detected within the predefined time, when the
maximum compensation time expires, the system issues a brake command to guarantee system safety. Furthermore, to guarantee availability, during the measuring process where several points are selected to begin compensation, compensation at these points occurs simultaneously, and the re-adhesion point detected first is selected.

Note that, it is expected that the error distance will be reduced if the jerking movement reference is added to the selection process in order to make detection of the re-adhesion point more precise.

4.3.2 Position detection

Simulated analyses confirmed that for test sections where detection points had been settled, the recorded outputs of sensors were able to compensate train positions. Detection positions were set in sections where the curve radii were between 300 m and 500 m, considering the speed of the above mentioned special test vehicle. However, in the case of conventional trains which can run faster, for sections with larger radii, detection positions can be also set. As an example, the profiles of the calculated inverse of the radii in curved sections are shown in Fig. 5. Five detection positions were set along the 8 km test line. The results of three test runs showed that the errors were within 10 m. Based on this profile, a database was created containing the running distances and the radii of curved sections. By applying this position detection, it is expected that the maximum safety distance which is calculated on the basis of a 2 % error margin vis-à-vis the running distance (8 km), can be reduced from 180 m without any position detection points, to 80 m with five position detection points. Note that this safety margin includes the margin (20 m) for wheel skidding or slipping, which is assumed to occur once between position detection points (Fig. 5).
5. Conclusions

Tachometer generators are used to calculate train running distance on on-board units. However, compensation is required to offset the effects of wheel skidding or slipping. A method was by means of both a tachometer generator and inertial sensors to calculate train running distances independent of the number of wheel rotations. The results of simulation analysis using managed time stamped data showed that it is possible to compensate the train running distance with this proposed method, using both inertial sensors on 6 axles (acceleration on 3 axles and angular velocity on 3 axles) and a tachometer generator, even where there is wheel skidding or slipping in curved sections which also have a gradient.

To achieve these results however would require the installation of a large number of transponders along lines at set intervals to detect train positions to calibrate its position in the on-board unit. As such, this paper proposed a method for detecting train position in curved sections by combining a tachometer generator and inertial sensors which would remove the need for transponders. The effectiveness of the proposed method was demonstrated through simulation results. The next step in this research will be to apply the method in actual line tests.

Although availability of the proposed method remains to be examined, it can be applied to short trains with only driving axles and without reduced braking power. The benefits of this method are that it is low cost and compact. Moreover, the maximum error distance can be estimated based on the sensor errors.

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