Inertial Measurement Processing Techniques for Track Condition Monitoring on Shinkansen Commercial Trains

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Abstract
We have developed three inertial measurement processing techniques to measure the longitudinal level of tracks using the devices mounted on the commercial shinkansen trains. Two of them, labeled as the "Frequency variable difference filter" and the "Speed variable moving summation", employ digital processing, while the other employs analogue processing applying a frequency variable low-pass filter. Through a series of the simulation tests, the above all methods were found to be capable of deriving a 10 m versine longitudinal level directly from the measured acceleration with high precision without causing any waveform distortion. An experimental prototype of a digital inertial device applying the "Frequency variable difference filter" that can help to minimize the processing load was produced, and its reliability was investigated. As a result, the output by means of the proposed prototype revealed good correlation with the data collected from an existing track geometry car. After the successful test results were obtained, the devices have so far been manufactured and installed in six N700 commercial trains. The repeatability was also found to be excellent, thus the device is expected to detect even a slight change of the track.

Key words : Track Condition Monitoring, Inertial Measurement, Track Geometry Recording, 10 m Versine, Difference Filter, Moving Summation

1. Introduction
Track condition monitoring is essential to enhance the safety and reliability of high-speed and high-density transportation. To meet this demand, the car body acceleration of commercial trains has been measured every day since the inauguration of the Tokaido shinkansen line in 1964. Car body acceleration measurement devices are now installed in four 700 series shinkansen train sets in order to check the track condition several times a day. If the measured accelerations exceed the predetermined target values, the measured values and locations of them are automatically reported to the train control centre and track maintenance depots. Table 1 shows the main features of the track condition monitoring system called RAIDARSS 2+.

In the near future, track condition monitoring that references car body acceleration will become more difficult because recent shinkansen vehicle is equipped with high-performance suspension and is therefore not responsive to track irregularity. To solve this problem, a new measurement device which is able to measure vertical track irregularity that is calculated using double integration of the axle-box acceleration, was developed. This paper describes
new inertial processing techniques developed for the new RAIDARSS system.

2. Former Inertial Measurement Unit

Inertial measurement is based on a simple law where double integration of the acceleration indicates a position on an accelerometer. For example, the vertical position of a wheel can be found by using double integration of the axle-box acceleration. The result provides the longitudinal level due to the wheel being continuously in contact with the rail (Fig. 1).

On the other hand, for the measurement of the track alignment, the change of the clearance laterally existing between the wheel flange and the rail needs to be taken into account and thus needs to be measured by means of sensors.

![Fig. 1 Inertial track measurement in longitudinal level](image)

### Table 1 Main features of RAIDARSS 2+

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic reporting</td>
<td>Exceeded values and locations are automatically reported to the train control center and track maintenance depots.</td>
</tr>
<tr>
<td>Wheel diameter adjustment</td>
<td>Wheel diameters are automatically revised by wheel pulse and position detection cell information.</td>
</tr>
<tr>
<td>Opposite train sensing</td>
<td>Opposite trains are detected by optical sensors.</td>
</tr>
<tr>
<td>Data acquisition</td>
<td>10 runs of operation data are stored on PCMCIA card.</td>
</tr>
<tr>
<td>Telecommunications</td>
<td>Setting change and data transmission are available via mobile phone.</td>
</tr>
</tbody>
</table>

2.1. Analogue inertial measurement unit

In 1974, the first system adopting the inertial method was mounted on a 961-type shinkansen test train. A practical system called HISTIM (High-Speed Track Inspection Machine) was installed as an additional method of track recording and has been in operation on the track geometry cars on the Tohoku and Joetsu shinkansen lines since 1985.

The three types of inertial systems shown in Table 2 were put to practical use on the Tokaido shinkansen line. Currently, several TRASC (TRack State Confirming machine) and RARO (RAil surface pROfile measuring machine) are in operation(1).

2.2. waveform distortion of analogue systems

The conventional inertial system shown in Table 2 uses an analogue integral circuit. If an input signal has a slight offset, the output of an analogue integrator is completely saturated in the vicinity of the power supply voltage, and therefore cannot function as an integrator. To avoid saturation, a high-pass filter is added before the integrator. Figure 2 shows the frequency response of the high-pass filter used in TRIPS. The cut-off frequency varies with vehicle speed to maintain the cut-off wavelength at a fixed value of 120 m over the distance domain.

As seen in the figure, the high-pass filter has a nonlinear phase shift. This distorts the output waveform so that the output signal does not agree with the track profile on the ground. Another issue is that the measured waveforms of alternate directions are largely different. Figure 3 shows a comparison of the original track profile and the output signals from 300X-TRIPS.
Table 2  Inertial system in use on the Tokaido shinkansen line

<table>
<thead>
<tr>
<th></th>
<th>TRASC (Track Data Confirming system)</th>
<th>TRIPS (Track Information Processing System)</th>
<th>RARD (Rail surface deformation measuring device)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>25</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mounted on</td>
<td>Track survey control car</td>
<td>High-speed test train 300X</td>
<td>Ultrasonic rail inspection car</td>
</tr>
<tr>
<td>Frequency</td>
<td>Every morning</td>
<td>Monday &amp; Tuesday</td>
<td>2 times a year</td>
</tr>
<tr>
<td>Track parameters</td>
<td>Longitudinal level (RL), Gauge, CrownHolz</td>
<td>Longitudinal level (RL), Gauge, CrownHolz</td>
<td>Rail surface irregularity (vertical RL)</td>
</tr>
<tr>
<td>Wavelength band</td>
<td>0.5 – 100 m</td>
<td>0.5 – 120 m</td>
<td>0.02 – 2 m</td>
</tr>
<tr>
<td>Maximum operating speed</td>
<td>70 km/h</td>
<td>443 km/h</td>
<td>49 km/h</td>
</tr>
</tbody>
</table>

Fig. 2  Frequency response of the H.P.F. used in TRIPS

Fig. 3  Waveform distortion of analogue inertial system (300X-TRIPS)
2.3. Distorted waveform correction using a phase compensation filter

Since the waveform distortion is oriented from the clear characteristic of the analogue high-pass filter, the distortion can be corrected by reversing the phase of the output signal (2), (3). Figure 4 (a) shows the phase compensation filter for TRIPS. The phase here is opposite that of the original signal without changing the amplitude. Figure 4 (b) shows the impulse response function (filter coefficient) calculated from Fig. 4 (a) by inverse Fourier transform. The compensated waveform from 300X-TRIPS and original track waveform restored from a conventional track geometry car are compared in Fig. 5. These results confirm that a phase compensation filter is able to correct waveform distortion.

3. Inertial Mid-chord Offset Method

In 1995, Takeshita suggested a method of overcoming the waveform distortion problem inherent with inertial measurement (4), (5). This method uses the 10 m versine characteristic to stabilize the double integration (Fig. 6).

Although the "inertial mid-chord offset method" is both simple and clever, it has been thought that realization of complete "integration and mid-chord offset composite calculation" was difficult for the following reasons.

- Because the input acceleration has a larger value at higher frequencies, A/D conversion causes quantization noise due to insufficient resolution.
- The integral characteristic must be changed with respect to the speed in the distance domain. The versine characteristic, meanwhile, must be changed with respect to the speed in the time domain. The subject of how to coordinate these two characteristics still remains.

The latter problem is difficult to solve by changing the many coefficients of the high-order digital filter in real time. Because of the above reason, the inertial mid-chord offset measurement device in practical use first calculates the double integration using an analogue circuit,
and then passes the resulting signal through a digital filter to perform phase compensation and versine calculation(6).

4. Digital Integration Using a High-Pass Filter

This section describes digitization of the inertial measurement unit as a means of eliminating waveform distortion. As with saturation in an analogue integrator, an offset of the input data gains in number of bits by digital integral calculus, the bit width of the processor will shorten immediately. To avoid this problem, as in analogue devices, a high-pass filter is necessary before the integrator. Waveform distortion can be eliminated in digital processing because it is easier for a digital filter to achieve the linear phase characteristic. Figure 7 shows the processing flow using a digital high-pass filter, and Fig. 8 shows a comparison with track geometry car data.

The results of the digital operation agree with data from the track geometry car, and waveform distortion does not occur. However, because several thousand points from the filter coefficient are repeated, this processing can still overload even today’s fast processors. Furthermore, a problem occurs with the lower limit speed, as described below. The cut-off frequency of the high-pass filter is set at 0.5 Hz. This is equivalent to a wavelength of 200 m at a vehicle speed of 360 km/h, and a wavelength of 50 m at 90 km/h. Therefore, when track irregularity is measured up to a wavelength of 50 m, the desired wavelength band cannot be achieved at speeds less than 90 km/h. The problem can be theoretically solved by using a lower cut-off frequency. However, resolving the lower limit speed problem is difficult because more filter coefficients are necessary, and this increases the processing load.

![Fig. 6  Inertial mid-chord offset method](image)

![Fig. 7  Processing flow for digital integration using H.P.F.](image)

![Fig. 8  Digital integration with H.P.F. (10 m versine)](image)
5. Digital Processing Techniques for "Integration and Mid-chord Offset Composite Calculation"

As noted above, two integrators require two high-pass filters for stable operation. If the 10 m versine characteristic could be divided into two filters and thus utilize the more stable integration, the high order high-pass filter would not be necessary. Based on this idea, this section introduces two digital techniques to realize "integration and mid-chord offset composite calculation".

5.1. Division of 10 m versine characteristic

The 10 m versine method is expressed by Eq. (1):

\[ y(\xi) = x(\xi) - \frac{x(\xi - 5) + x(\xi + 5)}{2} \]  

Where,

\( y(\xi) \) : measured 10 m versine signal.
\( x(\xi) \) : original track profile on the ground.

From Eq. (1), a transfer function for a 10 m versine measurement on the z-plane yields Eq. (2). In this equation, the sampling distance is 1.0 m and an output delay of 5 m to satisfy the law of causality.

\[ H_{10}(z) = -\frac{1}{2} + z^{-5} - \frac{1}{2}z^{-10} \]  

Furthermore,

\[ H_{10}(z) = -\frac{1}{2} \left( 1 - 2z^{-5} + z^{-10} \right) \]
\[ = -\frac{1}{2} \left( 1 - z^{-5} \right)^2 \]  

Equation (3) shows that a characteristic of the 10 m versine consists of two difference filters and one multiplier. Figure 9 shows a block diagram of the 10 m versine method, and Fig. 10 shows the characteristics of a difference filter.
5.2. Frequency variable difference filter

As shown in Fig. 10, because the difference filter, which is divided from a 10 m versine characteristic, exhibits a high-pass characteristic and the DC (0 Hz) gain is zero, allowing this filter to utilize integration stabilization\(^{(3)}\). Since the difference filter operates by taking the difference between the input signal and its delayed signal, the processing load is very light. Furthermore, a variable frequency filter can easily be used by changing the delay corresponding to the vehicle speed. With a sampling frequency of 1.0 Hz, the characteristics of the 10 m versine method in the time domain yields Eq. (4).

\[
H_{10}(z) = -\frac{1}{2} \left(1 - z^{-L}\right)^2 \tag{4}
\]

Where \(L = 5/v\), and \(v\) is the vehicle speed (m/s). Equation (5) is the transfer function for the simplest digital integrator on the \(z\)-plane.

\[
H_I(z) = \frac{1}{1 - z^{-1}} \tag{5}
\]

Using Eqs. (4) and (5), the "integration and mid-chord offset composite calculation" is expressed as Eq. (6).

\[
H_{DI}(z) = H_{10} \cdot H_I = -\frac{1}{2} \left(\frac{1 - z^{-L}}{1 - z^{-1}}\right)^2 \tag{6}
\]

In this paper, this digital inertial measurement technique is called the "Frequency variable difference filter". Figure 11 shows a block diagram of this processing technique. This system, mainly composed of adders with a single multiplier, can maintain quite low CPU loading condition.

5.3. Speed variable moving summation

The polynomial division within the parenthesis in Eq. (6) becomes a moving summation expressed as follows when \(L = 5\).

\[
\frac{1 - z^{-5}}{1 - z^{-1}} = 1 + z^{-1} + z^{-2} + z^{-3} + z^{-4} \tag{7}
\]

In the time domain:

\[
\frac{1 - z^{-L}}{1 - z^{-1}} = 1 + z^{-1} + z^{-2} + \cdots + z^{-(L-1)} \tag{8}
\]

Therefore, the "integration and mid-chord offset composite calculation" yields Eq. (9) in the time domain.

\[
H_{MS}(z) = -\frac{1}{2} \left(1 + z^{-1} + \cdots + z^{-(L-1)}\right)^2 \tag{9}
\]
The above equation shows that while changing the width depends on vehicle speed the moving sum performed completely agrees with the "integration and mid-chord offset composite calculation". In this paper, this processing technique is labeled as the "Speed variable moving summation". Figure 12 shows a block diagram of the digital inertial operation using the "Speed variable moving summation" algorithm. Even with only one multiplier, this algorithm has more adders than the above-mentioned "Frequency variable difference filter".

6. Analogue Inertial Measurement That Eliminates Wave Distortion

This section discusses the possibility of an analogue device with a linear phase property that eliminates waveform distortion. The gain of the "integration and mid-chord offset composite calculation" in Fig. 6 can be considered a type of low-pass filter, being very similar to a Bessel filter. A Bessel filter is a type of analogue filter with a maximally flat group delay. A low-pass Bessel filter is characterized by its transfer function:

\[
G(s) = \frac{S_n(0)}{S_n(s)}
\]

\[
S_n(s) = (2n - 1) S_{n-1}(s) + s^2 S_{n-2}(s) \tag{10}
\]

where \(s\) is a complex variable (= 2\(\pi\)f), \(f\) is the normalized frequency and \(n\) represents of the order of the filter. The frequency response functions and filtered signals of an 8th-order low-pass Bessel filter and "integration and mid-chord offset composite calculation" are compared in Figs. 13 and 14. Since good compatibility is shown, if the amplitude and cut-off frequency of the Bessel filter can vary according to vehicle speed, an analogue inertial measurement unit with no waveform distortion will be realized. Figure 15 shows a circuit diagram of a device that achieves this idea. Amplitude change using a variable gain amplifier (VGA) and cut-off frequency using variable resistance can be adjusted according to vehicle speed.

![Fig. 12 Block diagram of "Speed variable moving summation"](image)

![Fig. 13 Comparison of Bessel filter and "integration and mid-chord offset composite calculation"](image)
7. Test Results

Since the information from RAIDARSS system will be used in the speed reduction judgment of train operation, the on-board device must be highly reliable. Therefore, seeking minimal device degradation and temperature influence, it is desirable that the digital circuits used offer easily obtainable stable performance. For this reason, because of its lighter processing load it was decided to use the "Frequency variable difference filter" for the new on-board processor and a prototype device was produced. Figure 16 shows the data processing flow of the prototype device. Test results from the prototype are shown in Fig. 17. For comparison, measurement signals from an existing track geometry car are shown in the figure. There are the good correspondences between the signals.

After successful test results were obtained, the devices able to measure car body accelerations and vertical track irregularities were manufactured and installed in six N700 train sets during the fiscal year 2008. The results of the repeatability tests carried out for 3 weeks are shown in Fig. 18. In spite of the varied train sets and running speed, good correspondence was obtained among 22 different signals, which indicates good repeatability of the device. It can be seen that rapid track geometry degradation occurs in this section. Although the growth rate of the track irregularity is small every day, the good repeatability of the device can identify even the slight change of the track.

From those test results, it can be concluded that the new digital inertial processing techniques exert sufficiently high precision.
8. Conclusion and Future Topics

- Two digital processing techniques and one analogue device were developed to achieve inertial measurement on shinkansen commercial trains.
- An experimental prototype of a digital inertial device applying the "Frequency variable difference filter" with small hardware load was made. As a test result, the output of the prototype achieved good correlation with data from the existing track geometry car.
- With the "Speed variable moving summation" techniques, an extremely simple "integration and mid-chord offset composite calculation" was realized.
- Though thought to be difficult, it was shown that an analogue inertial measurement unit that eliminated waveform distortion was possible.
The new product was installed in six N700 train sets. They have good repeatability and it enables identifying a slight change of the track.

The new track condition monitoring system named RAIDARSS 3 including wide area network and data management software will start working in FY 2009 (Fig. 19).

References