Development of a Track Management Method for Shinkansen Speed Increases

We have examined the indicators of appropriate track management that represent the ride comfort when the running speed is increased by introduction of Shinkansen cars for higher speed. As lateral vibration control of rolling stock has successfully brought about good ride quality, we examined vertical vibration control from the perspective of tracks.

Comparing the response characteristics of vibration acceleration of the high speed cars in the 360 km/h speed range obtained from the actual measurement results with the gain of the present track management indicator (40 m-chord versine), we found that those conform to each other. Furthermore, simulation of improvement in ride quality in cases of 40 m-chord maintenance and 60 m-chord maintenance has clarified that the improvement is equal between 40 m-chord and 60 m-chord maintenance with respect to the track maintenance distance. The test using a train also has proved that track maintenance based on a 40 m-chord is effective in improving ride comfort. In these tests, we gained a perspective of ability to deal with control of ride comfort with the present management method based on 40 m-chord versine.

Keywords: Ride comfort, Track management, Response characteristic of car body vibration acceleration, Versine method, Chord, Measurement magnification

1 Introduction

Track irregularity is increased by loads of trains and deformation of structures. Since track irregularity affects ride comfort and running safety of trains, we measure track irregularity to align the tracks upon evaluation with appropriate indicators. We call this work track management.

In general, the more speed increases, the more track irregularity of longer wavelength affects ride comfort and running safety. With the increase of operational speed by the introduction of new high-speed cars, we accordingly examined whether the present track management indicators could be used for the evaluation of ride quality or new indicators that could represent better the effect of track irregularity of longer wavelength would be required.

The running tests of FASTECH360, which is equipped with lateral vibration controllers (active suspension) on bogies, confirmed improvement of ride comfort by more than a few dB compared to an actual train running at 275 km/h (without vibration controllers). Based on those test results, we considered that the present track condition can sufficiently provide good ride comfort in terms of lateral vibration; so, we studied vertical vibration.

First, we compared the track irregularity measurement results measured with 40 m-chord, 60 m-chord and 80 m-chord versine methods to the waveforms of vertical vibration acceleration of cars (with and without ride comfort adjustment). Next, we obtained the response of car body vibration acceleration through frequency analysis and compared it to the measured magnification of the present track management indicator. And by also, simulating track maintenance, we compared improvements in ride comfort per track maintenance length. Finally, we carried out actual 40 m-chord track maintenance to understand the improvement in ride comfort.

2 Background

In order to make appropriate track management for ride quality, we have to pay attention to the following.

* Relationship between ride quality and vibration acceleration of cars
* Relationship between vibration acceleration of cars and track irregularity
* Relationship between track irregularity and track management indicators

2.1 Relationship between Ride Quality and Vibration Acceleration of Cars

The indicator of vibration acceleration of cars applied to railway rolling stock from the perspective of ride comfort is the isosensitivity curve that had been proposed at the Research Committee for Ride Quality Management Standard of JNR based on the ISO 2631 standard (Evaluation of Human Exposure to Whole Body Vibration) applicable to ground vibration etc. The indicator is extended to lower frequencies up to 0.5 Hz to handle vibration under 1 Hz. Using the Ride Quality Filter (Fig. 1) based on that indicator, vibration acceleration of cars is adjusted to see actual ride comfort. Specifically, the logarithms of the actual values of the vibration (average root-mean-square) are indicated in dB (1 m/s² = 100 dB).

2.2 Relationship between Vibration Acceleration of Cars and Track Irregularity

Vertical movement of car body can be explained in the multiple
degree of freedom system model shown in Fig. 2. Characteristics of springs and dampers are for the most part linear. Accordingly, within the range of this modeling, the relationship between vibration acceleration of cars and track irregularity is also linear. Based on that, we applied frequency analysis to the actual values obtained in the running tests to find a linear response function.

2.3 Relationship between Track Irregularity and Track Management Indicators

Since it is inefficient to check track irregularities with surveying instruments such as theodolites, we usually take a straight line of 10 m or other length along the track as a datum (called "a chord") to measure the distance from the center of the chord to the track (called "the versine method", Fig. 3). The chord is set using a track inspection car body or by hand using a string. In addition, we derive the required length of the chord upon those calculation results.

The measurement gain by the versine method, namely the ratio to the actual track irregularity (called "measurement magnification") depends on the chord length and the wave length of the track irregularity. Based on the track irregularities \( u_1, u_2 \) and \( u_3 \) in Fig. 3, the track irregularity \( v \) according to the chord at the point \( u_2 \) is:
\[
v = u_2 - \frac{u_1 + u_3}{2}.
\]

Then, given that the shape of the track is a sine wave with the amplitude \( a \), the wave length \( \lambda \), and the chord length is \( L \),
\[
u = a \sin \left( \frac{2\pi x}{\lambda} \right),
\]
\[
u = a \sin \left( \frac{2\pi (x + L/2)}{\lambda} \right),
\]
and the measurement magnification is:
\[
v/u_2 = 1 - \cos \left( \frac{\pi L}{\lambda} \right).
\]

Fig. 4 shows the relationship between the wavelength of the track irregularity and the measurement magnification per chord length. When the wavelength is equal to the chord length, the measurement magnification is a maximum of double; and as the wavelength becomes longer than that, the measurement magnification decreases. Such a characteristic of the versine method is suitable for track irregularity control focusing on the wavelength range with large response of car body vibration acceleration.

For present ride quality control of Shinkansen, we use the track irregularity of a 40 m-chord and a 20 m-chord (maintenance values for long wavelength tracks). But the higher the running speed is, the more the track irregularity of longer wavelengths affects vibration acceleration of cars. For such wavelengths, the measurement magnification with the present wavelength standard decreases. So, we examined if a longer chord length is required or if the present chord length can handle that when running speed is increased.

Fig. 5 shows vertical track irregularity measured on the versine method with a 40 m-chord, a 60 m-chord and an 80 m-chord (vertical irregularity) and actual waveforms of vertical vibration acceleration of cars (with and without ride quality adjustment).

When looking at the area in the square in Fig. 5, we can see the tendency that the longer the chord length is, the larger the value of track irregularity becomes. That means that the longer the chord length is, the larger the measurement magnification becomes in relation to the track irregularity of longer wavelength as shown in Fig. 4.

On the other hand, vertical vibration acceleration of cars is not particularly large in that area. In particular, the gap tends to be larger for track irregularity with larger chord length. This tendency is more remarkable for vertical vibration acceleration of cars with ride comfort adjustment.
Those results suggest that a longer chord length does not demonstrate a particular advantage as an index for ride quality.

4.1 Overview
As explained above, the reason why the versine method is used as the standard indicating track irregularity is compatibility to vibration acceleration of cars. So, we compared the response of vibration acceleration of high-speed cars and the measurement magnification of the present versine method (with a 40 m-chord).

4.2 Response of Vibration Acceleration of High-Speed Cars and Present Cars
By frequency analysis of the vibration acceleration of high-speed cars obtained in running tests and the track irregularity measured with a track inspection car in the same period, we calculated the response of vibration acceleration of cars to the track irregularity by frequency (Fig. 6). The test train was FASTECH360S (E954). Comparing the results to those of the E2 series train, which is now in operation, the response is lower in a wide frequency band. That indicates improvement in ride comfort from the perspective of rolling stock.

4.3 Response of Car Body Vibration Acceleration and Measurement Magnification of Track Irregularity
Applying ride quality adjustment in Fig. 1 to the response of car body vibration acceleration in Fig. 6, we can obtain the response of vibration acceleration of cars with ride quality adjustment. Next, to take into account of the effect of running speed, we replaced the frequency (X-axis) with the wavelength of the track irregularity corresponding to 275 km/h for E2 series and to 360 km/h for FASTECH. To discuss whether the present 40 m-chord versine method can handle the obtained response of vibration acceleration of cars per wavelength of track irregularity (with ride quality adjustment), we compare obtained results with the 40 m-chord measurement magnification in Fig. 7. The measurement magnification is shown so that it contacts the response of vibration acceleration of E2 series cars at 275 km/h at the wavelength of 39 m. Fig. 7 shows that all the values of response of vibration acceleration of high-speed cars at 360 km/h are under the measurement magnification curve. Hence, the measurement magnification with a 40 m-chord is considered adequate to control the vibration of high-speed cars.

Let us consider what that means based on Fig. 8. Assuming that response of vibration acceleration of cars 1 and 2 contact the 40 m-chord measurement magnification at wavelengths 1 and 2 respectively, the ratios are both 1:α. Accordingly, if the track irregularities measured with a 40 m-chord are equal at wavelengths 1 and 2, the values of response of car body vibration acceleration are equal too.

Thus, if the track that is maintained to have fixed track irregularity measured with a 40 m-chord as shown in Fig. 7, we can say that the vibration acceleration applicable to high-speed cars is less than that of E2 series cars at 275 km/h (at wavelength of 39 m) at any track irregularity wavelength.

4.4 Conclusion
By comparing response of vibration acceleration of cars and measurement magnification measured with chords, we concluded
5.2 Calculation

5.2.1 Simulation of Track Maintenance
Since vertical track irregularity, that we checked this time, is adjusted by inserting filling etc. under the rails, the maintenance is done basically only by lifting up and we do not consider lowering rails. We set the starting point and ending point of the track maintenance at the location where the track irregularity is enough small to confirm that maintenance is done correctly. Taking into account of those limitations, we thus modeled practical track maintenance.

The present track maintenance threshold is 7 mm for vertical track irregularity measured with a 40 m-chord. This time, based on the possibility of further improvement in ride quality, we made estimation of track maintenance with a 40 m-chord and a 60 m-chord for locations of track irregularity of larger than 5 mm.

5.2.2 Estimation of Improvement in Ride Quality
We estimated improvement in ride quality as follows; first we obtained frequency components of track irregularity using FFT (fast Fourier transformation) and multiplied the response of vibration acceleration of FASTECH cars by the ride comfort filter per frequency. Considering the total of the squares of those multiplied values as the vibration acceleration force of cars in that section, we figured out the difference before and after track maintenance.

Fig. 9 shows an example. The upper diagram represents an actual track irregularity waveform (estimated upon the data taken by a track inspection car. Called "restored waveform"), and the bottom diagram represents the estimated vibration acceleration of cars. The car body vibration acceleration is calculated by applying convolution integral in the time domain, based on the amplitude and phase of the response of vibration acceleration of FASTECH cars. Here we consider that the track is linear after the track maintenance and no track irregularity remains other than at the center and the both ends. Fig. 9 shows the estimated vibration in the track maintenance section can be eliminated; that is, this simulation assumes no residual vibration acceleration of cars.

5.3 Calculation Results
We carried out a case study on the track irregularity of a 10 km-long high-speed test section on the Tohoku Shinkansen line. In 10 intervals...
a 40 m-chord track irregularity exceed 5 mm, and in 20 intervals with a 60 m-chord. All of the former 10 intervals were included in the latter 20 intervals. The main reason is that the track irregularity measured with a 60 m-chord tends to be larger than the values measured with a 40 m-chord. For the purpose of comparison, Fig. 10 shows the relationship between the track irregularities in that case study section measured with a 40 m-chord and a 60 m-chord. The figure shows the tendency that the track irregularity measured with a 60 m-chord is larger by approx. 1 mm.

Fig. 10 Relationship between Track Irregularity Measured with a 40 m-Chord and a 60 m-Chord in the Case Study Section

Fig. 11 shows the relationship between maintenance thresholds and track maintenance lengths when maintaining all points where the measured values exceed maintenance threshold values. Of course, the more severe the maintenance threshold is, the longer the track maintenance length is. The results of 60 m-chord maintenance are simply the left shift of the results of the 40 m-chord maintenance. That can be explained by the tendency that the track irregularity measured with a 60 m-chord is larger by approx. 1 mm.

Fig. 11 Track Maintenance Threshold and Length of Track Maintenance

Fig. 12 shows the comparison results of 40 m-chord measurement and 60 m-chord measurement to see the change of ride comfort improvement under certain track maintenance length according to the track maintenance threshold. The results of 40 m-chord maintenance almost overlaps the result of 60 m-chord maintenance. Thus, 40 m-chord maintenance and 60 m-chord maintenance are equal in terms of the ride quality improvement with respect to the length of track maintenance.

The effect of the track maintenance of more than 5 mm vertical track irregularity measured with a 40 m-chord accounts for approx. 10% of the total sections of track maintenance distance, namely a little less than 1 dB. With 60 m-chord vertical maintenance, such track maintenance accounts for approx. 30% of the total sections of track maintenance distance and a little more than 1 dB. Fig. 12 clarifies that the difference comes from the difference of the length of track maintenance.

5.4 Conclusion
Since the calculation results proved that the 40 m-chord maintenance and 60 m-chord maintenance are equal in terms of the improvement in ride quality in the length of track maintenance, we gained a good perspective that the present track management with a 40 m-chord could handle high speed operation.

It would be appropriate to set the maintenance threshold for 60 m-chord maintenance as the threshold for the 40 m-chord maintenance plus 1 mm. When aiming for further improvement in ride quality of high-speed trains, the present vertical track maintenance threshold of 7 mm should be made smaller. In that case, the vertical track maintenance threshold of 6 mm for 40 m-chord maintenance is almost equal to 7 mm for 60 m-chord maintenance, and 5 mm for 40 m-chord maintenance is almost equal to 6 mm for 60 m-chord maintenance. The effect of applying a more severe 5 mm threshold to the present 7 mm threshold is estimated as approx. 1 dB at the maximum.

6 Tests for Confirmation of the Effect of Track Maintenance

6.1 Overview
The track maintenance simulation explained in Chapter 4 assumes that no vibration acceleration of cars remains after track maintenance. In order to confirm that assumption, we compared the vibration acceleration before and after the present track maintenance to confirm that no vibration acceleration remains after the maintenance and ride comfort is sufficiently improved.

6.2 Test Method
We carried out 40 m-chord maintenance in the high-speed running test section, to identify the improvement in ride quality. We carried out track maintenance where vertical track irregularity exceeded 5 mm. This is the lowest value for planning track maintenance, since the 40 m-chord dynamic adjustment standard after track maintenance (the tolerance in track maintenance inspection when measured by a
track inspection car) is +/–4 mm.

There were seven track maintenance intervals, named A to G respectively.

6.3 Test Results
Fig. 13 shows the ride comfort levels regarding vibration acceleration of cars (without ride comfort adjustment) in the track maintenance intervals. The levels were calculated in the 1 – 10 Hz band that is related to track irregularity and the effects of elastic vibration of cars and vertical curves were excluded.

Among the track maintenance intervals A – G, intervals A, D, F and G were those where ride comfort before track maintenance originally was not poor. In intervals B, C and E where ride comfort was poor, we could find the improvement by track maintenance.

There is a vertical curve (gradient transition) between intervals C and D and vertical steady lateral acceleration occurs there, but that does not affect ride comfort in the 1 – 10 Hz band.

Since the ride comfort after track maintenance in all of intervals A – G was less than 80 dB, we can consider that car body vibration was eliminated.

Consequently, we could confirm the effect by the track maintenance in locations of more than 5 mm vertical track irregularity measured with a 40 m-chord in the intervals where ride comfort before track maintenance was poor; that is, ride quality after track maintenance was improved in all intervals.

6.4 Conclusion
We were able to confirm reduction of vibration acceleration of FASTECH cars at 360 km/h by 40 m-chord maintenance. Those results gave us a good perspective that the present track maintenance can meet high-speed operation.

After achieving good ride quality by lateral vibration control in the FASTECH high-speed running tests, we examined ride quality control for vertical vibration.

Obtaining the vibration acceleration characteristics of high speed cars by measurement, we examined the adequacy of the measurement magnification of 40 m-chord and other chord measurement. Since we expect that the vibration acceleration of FASTECH cars in the 360 km/h range (with ride comfort adjustment) could be equal to or less than the maximum vibration acceleration of E2 series cars at 275 km/h in the frequency domain even under the present track management with a 40 m-chord, it was suggested that the 40 m-chord management could be applied.

The simulation of improvement in ride quality by 40 m-chord maintenance and 60 m-chord maintenance proved to be equal in terms of the ride quality improvement with respect to the length of track maintenance. That simulation results gave us a good perspective that the present 40 m-chord management could handle further track maintenance.

We found that the present 40 m-chord maintenance could sufficiently improve ride comfort of high-speed trains. That result gave us a good perspective that the present track maintenance can be applied to high-speed operation.

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Fig. 13 Result of 40 m-Chord Vertical Maintenance