Research on Vertical Natural Vibration Characteristics of Gravel Aggregate in Ballasted Track

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This paper describes research into the dynamic responses measured on a commercial-line with ballasted track using sensing sleepers and sensing stones both of which were developed by the author, for the purpose of gaining new knowledge that will contribute to measures against track deterioration and effective track maintenance. The research further analyzed the measurement results in terms of the spectral characteristics of ballast behavior and the vertical natural vibration characteristics of ballast layers. The results of the spectral analysis show that the rigid-body vibration mode of sleepers is in a frequency range lower than 100 Hz and also reveal that the elastic vibration modes of ballast layers are in a frequency range as wide as 400 - 800 Hz. This series of analyses suggests the possibility that the dynamic load of a passing train is hard to damp, affected by its resonance. Furthermore, the author performed a full-scale drop-weight impact test and found from the test result that when the impact load works on a ballast layer, unloading causes abrupt release of stress, which led to decreased contact force between particles and a jumping behavior in the ballast layer.

Keywords: ballasted track, spectral analysis, field measurement, natural vibration modes, impact loading test

1. Introduction

While rolling stock is getting more and more sophisticated, the basic structure of ballasted track in railway systems ensuring high speed and safety has hardly changed for the last 150 years. This is because most of the design, construction and maintenance/management of ballasted tracks has been empirically established. The ballasted track is characterized by its structure with a ballast layer sandwiched in between sleepers and a roadbed which significantly reduces the impact loads generated between the wheels and rails. However, this advantage has an adverse effect: Ballasted tracks are structurally prone to deteriorate over time and therefore absolutely require periodic maintenance and repairs. When considering the future of railways, it is impossible to disregard the requirement for frequent maintenance. Hence, there is a desire to improve maintenance methods for the ballasted track based on findings from dynamic investigation of the response characteristics and deterioration factors of the ballast layer.

The dynamic loads induced by running trains are caused by two major factors: one is dynamic load exerted by the passing axle load as a train is running. The frequency characteristics of this depend on the number of axes passing per unit of time, and are limited to a low-frequency domain, ranging from only several hertz to approx. 20 Hz. The other factor is the impact load from the rolling contact between the wheels and rails. This sharp pulse-shaped dynamic load is superimposed with the low-frequency dynamic loads from passing axle loads and is transmitted to the ballast layer. When this waveform is transformed into a frequency domain, it has broadband frequency characteristics ranging between a low frequency and several kilohertz. In other words, the dynamic response measurements of ballast require high-precision measurement of vibration components ranging a broad band from several hertz up to several kilohertz.

However, the sensor outputs used to be contaminated with the noise of tens of millivolts due to the inductive currents of high-voltage overhead lines in the conventional field measurements, which required the use of a low-pass filter to remove such noise. Under the circumstances, it was impossible to ensure measurement accuracy for high-frequency vibration components exceeding 50 - 100 Hz, thus full discussion about these components has not been possible. This paper presents the measurement of dynamic responses of ballasted track with a train passing at the sampling frequency of 10 kHz using the sensing sleepers and sensing stones developed by the author, without a low-pass filter. Using the measurement results, the analysis can be performed to focus on the propagation characteristics of the dynamic loads inside the ballast layer and the vertical natural frequency characteristics of the ballast layer. Moreover, the author performed a drop-weight impact test on a full-scale mockup of a ballasted track to study the response displacements of the ballast immediately after impact load was applied.

2. Identification of natural vibration modes through full-scale testing

(1) Rigid-body and elastic vibration modes

A dynamic load is transmitted to a structure as a wave through the inside of an object, consequently inducing the natural vibration mode specific to the object, which is true for ballasted track composed of crushed stone particle aggregate. Although the ballast layer is a discontinuous structure, it is considered to have natural vibration modes specific to ballast track.

Figure 1 shows the characteristics of the principal natural vibration modes in the vertical direction of the ballast...
layer, one is the rigid-body vibration mode, and the other is the elastic vibration mode. The structure of the ballasted track can be regarded as a single degree of freedom system consisting of sleepers, rails, etc. which constitute the mass of a track structure and also the ballast layer and road bed which constitute the spring rigidity component. The rigid-body vibration modes are the modes in which this single degree of freedom system vibrates vertically and rigidly under the dynamic load of a train, in which case, the ballast layer plays the role of an elastic spring. There are six rigid-body vibration modes in total: Translational and rotational modes respectively along three axes. However, the vertical vibration components are dominant both in the dynamic loads applied to the ballast layer and in the responses of the ballast layer. Therefore, this paper focuses on the translational behavior in a vertical direction. It has been said that this mode exists in the vicinity of approx. 100 Hz [1].

On the other hand, the elastic vibration mode is a vibration mode where the whole ballast layer stretches vertically as an elastic body. This mode does not occur in a normal-state ballast layer but occurs when the ballast layer is under high confining pressure generated by the train’s weight applied on the layer. This mode is a major factor that induces surface waves in the direction of the track extension. When the train speed has reached the propagation speed of the surface wave, there will be a resonance which affects the traveling stability of trains. Consequently, this mode is also a factor which establishes an upper limit to traveling speed. So far no research has been done to capture this mode, i.e. ballast motion in the frequency domain related to this mode. It should be added that on a real track natural vibration modes that entail bending deformation and torsional deformation of members occur in addition to the above.

(2) Overview of vibration test

The author built a full-scale mockup of a track and investigated the natural vibration characteristics of a ballasted track by performing an impulse excitation test. Figure 2 shows the profile/plain of the mockup and sensor positions.

To build a full-scale track mockup, the author employed new ballast using andesite which complies with the same standard for real track and compacted it sufficiently. For the mockup, type 3 (JIS) sleepers were used, which are widely used for the meter-gauge (1,067 mm wide) conventional lines of Japan Railways. A urethane mat was sandwiched between the mockup and the outer concrete frame to shut off the vibration effect from the concrete frame. To verify the vibration barrier properties, the author installed acceleration sensors on the mockup and concrete frame, vibrated the mockup and ensured that the vibrations were isolated.

The test was performed by vibrating the end of a sleeper with an impulse hammer in three different directions: vertically, laterally and longitudinally. The test record included the acceleration responses at 22 points on the sleeper and some in the ballast layer. The author then obtained the accelerances (by dividing accelerations by excitation forces), which are transfer functions of the acceleration responses to the excitation forces, conducted an experimental modal analysis with consideration for the locational relationship of measuring points, and thus identified the natural vibration frequencies and their mode profiles between the low frequency domain and 1 kHz [2].

(3) Test results

Figure 3 shows the natural vibration frequencies and mode profiles of the ballasted track that were acquired.
from the test results. Though there are 6 modes of rigid-body vibrations as stated above, the figure shows only the rigid-body translational mode in a vertical direction and indicates that the vertical, translational rigid-body vibration mode is generated at 98 Hz, which almost agrees with the previous research results. Besides, six natural vibration modes are found entailing the bending and torsional deformations of sleepers as shown in the same figure.

3. Measurement of dynamic responses on a real track

(1) Overview of field measurement and spectral analysis

The dynamic responses were measured on a ballasted track of a main conventional line in order to identify the natural vibration modes of the ballast layer. The track structure at the measurement site was designed to the standard that allows a running speed higher than 130 km/h [3], consisting of continuous welded rail (CWR) weighing 60 kg/m and prestressed concrete (PC) type 3 sleepers, and located on a solid embankment in a straight section. For spacing between the sleepers, 41-42 sleepers are positioned over a distance of 25 m. The author chose a straight section with optimal track conditions, based on data from an inspection car for that section. The ballast layer at the measurement site is made of new andesite stones with clear-cut edges, and the ballast layer is approx. 30 cm thick. Figure 4 includes an illustration overview of sensor positions. Details of the measurement are described in Reference [4].

(2) Measurement results focused on time history responses

Figure 4 also shows an example of measurement results. This paper focuses on the measured responses for a limited express train at a traveling speed of approx. 120 km/h (the sampling frequency is 10 kHz). This figure shows three types of time history response waveform in response to sleeper vibration accelerations, ballast vibration accelerations and sleeper lower surface loads (dynamic loads acting on the ballast layer), respectively. The following analyses were conducted by obtaining linear spectra through Fast Fourier Transform (FFT) from these time history waveforms and smoothing them at a bandwidth of 20 Hz.

(3) Acceleration responses and displacement responses of ballast

Figure 5 shows the linear spectra related to the accelerations and displacements of the ballast at approx. 10 cm in depth. The acceleration linear spectra in the chart indicates that the high-frequency components above 100 Hz as well as the low-frequency components contribute greatly to ballast response. These high-frequency vibration components are attributable to the sharp kurtosis of the impact loads induced between the wheels and rails. This graph also allows us to recognize the peak profiles of the responses related to the natural vibration modes which are shown in the preceding paragraph. For instance, the graph shows the peak value in the vicinity of 100 Hz because vibrations with the vertical rigid-body vibration mode dominant are generated in the ballast layer in the vicinity of 100 Hz.

When looking at the ballast displacement, its amplitude is extremely small in the high-frequency domain. For instance, the displacement amplitude is only 1/1000 μm at the frequency of approx. 800 Hz which is equivalent to the natural frequency of the third mode of bending of the sleeper. This means that the vibration components in the high-frequency domain are not transmitted by rigid-body vibrations around the center of gravity of the ballast, but the dynamic loads are transmitted through the elastic un-
dulation propagation attributable to the local deformation behavior and sliding behavior at the tips of the edges at the contact points between the ballast stones. On the other hand, the displacement amplitudes in the low-frequency domain at several hertz to 20 Hz is three orders larger than those in the high-frequency domain. Consequently, the loads in the low-frequency domain is mainly transmitted through the rigid-body rotational and/or translational vibrations of the ballast.

(4) Rigid-body vibration mode and load transmission characteristics

This paragraph describes the investigation into how the rigid-body vibration mode affects the dynamic response characteristics of ballasted track, using field measurement data. Figure 6 shows the graph of the displacement amplification ratio between sleepers and the ballast. This graph shows the displacements, however, the acceleration amplification ratios will form the same curve. The graph shows that the amplitude of the vibration components at frequencies of more than approx. 100 Hz reduces to one-third to one-fifth of the original amplitude when starting on the lower surfaces of the sleepers and reaching the ballasted layer. This fact indicates that the ballast layer acts in a way which damps the high-frequency vibration components. On the other hand, for the vibration components at the frequencies below approx. 100 Hz where rigid-body vibrations are dominant, the amplification ratio is almost one in the vicinity of 40 Hz for instance, which means that the ballast is less effective for damping vibration components in the low-frequency domain where rigid-body vibrations are dominant.

(5) Elastic vibration mode and load transmission characteristics

Figure 7 shows the accelerance in relation to the acceleration responses of the ballast layer to the lower surface loads of the sleeper under a passing train. The accelerance curve in this graph represents a transfer function of acceleration responses against the load responses in a frequency domain. The data is standardized so that the maximum value may be one in the graph, so that a gentle slope appears in the broadband frequency domain between 400 and 800 Hz. The author infers that this shape is caused by the effect of the elastic vibration mode where the ballast layer stretches vertically as an elastic body. Besides, in the vicinity of this frequency range there are natural frequency modes where the bending vibrations and torsional vibrations of sleepers are dominant, such as the second vertical bending (424 Hz), the first torsion (524 Hz), the second horizontal bending (628 Hz) and the third vertical bending (805 Hz) of sleepers. They are all in the high-frequency domain. The vibration components disperse immediately at frequencies below approx. 100 Hz with larger displacement amplitudes, with steep tangent slope, in the domain where the displacement amplitudes are small in the vicinity of the origin that is a frequency domain not less than approx. 20 Hz. This fact indicates that the ballast layer is sufficiently rigid against dynamic loads, with elastic behavior dominant, in the 20 Hz or higher frequency domain where the displacement amplitudes are smaller. However, the graph also indicates that as the displacement amplitude increases, the slope of the curve decreases abruptly, which indicates that the vibration components at frequencies lower than 20 Hz with larger displacement amplitudes lead to a decrease in the rigidity of the ballast layer while nonlinear behavior is dominant.

(6) Relationship of displacement amplitudes to stress amplitudes

Figure 8 plots the relationship between the stress amplitude applied to the ballast layer and the displacement amplitudes of the ballast layer. The numerical values in the graph represent the frequencies providing the plotting points. The values between 5 and 22 Hz show the frequencies. For a higher-frequency range, the points are mostly concentrated in an area near the origin. The slope of the curve in the graph represents the dynamic rigidity of the ballast layer. According to the graph, linearity can be mostly recognized between the load amplitudes and the displacement amplitudes, with steep tangent slope, in the domain where the displacement amplitudes are small in the vicinity of the origin that is a frequency domain not less than approx. 20 Hz. This fact indicates that the ballast layer is sufficiently rigid against dynamic loads, with elastic behavior dominant, in the 20 Hz or higher frequency domain where the displacement amplitudes are smaller. However, the graph also indicates that as the displacement amplitude increases, the slope of the curve decreases abruptly, which indicates that the vibration components at frequencies lower than 20 Hz with larger displacement amplitudes lead to a decrease in the rigidity of the ballast layer while nonlinear behavior is dominant.

(7) Dynamic stiffness of ballast layer

The author investigated the causes for the ballast layer being significantly deformed and insufficiently resistant to the vibration components in the low-frequency domain below 20 Hz. Figure 9 shows the dynamic spring constants of the ballast layer that were calculated from measurement data. A dynamic spring constant is the result of dividing load amplitude by displacement amplitude in a frequency domain and means the dynamic rigidity of a ballast layer. If the value of the dynamic rigidity is large, this means
the ballast is hard to move and cannot be easily deformed, and vice versa if the value is close to zero. Generally, the dynamic rigidity increases in proportion to the frequency in domains where the frequency is higher than a certain degree, which is represented by a straight line in a double logarithmic chart.

The chart shows that the dynamic rigidity forms a straight line subject to the vibration components higher than approx. 20 Hz in a double logarithmic chart, where dynamic rigidity has a tendency to vary almost directly with the first power of the frequency. On the other hand, where the frequency is lower than 20 Hz, the tendency appears for the dynamic rigidity to vary almost exactly with the square of the frequency. Thus it can be concluded that ballast behavior under the threshold value of around 20 Hz is determined by physical factors, which differs from factors coming into play above the threshold. Ballast behavior in the low-frequency domain is discussed in the following chapter.

4. Full-scale impact loading test

(1) Overview of test

The author performed a drop-weight impact test using a full-scale ballasted track mockup, dropping a weight from a given height and applying sharp pulse-shaped impact loads directly on the track. Figure 10 shows an overview of the test. The test setup consists of a 30 cm thick ballast layer built by new andesite ballast on concrete roadbed, and a track structure built by using three PC type 3 sleepers and rails weighing 60 kg/m. A steel weight frame positioned on the sleeper at the center was repeatedly dropped from the given height to apply sharp pulse-shaped impact loads to the track structure. The measurement data, namely, magnitudes of impact load, sleeper displacements, and the acceleration responses of sleepers and ballast, were recorded by sampling the data at 10 kHz. This paper discusses the measurement results of displacement responses of sleepers out of the above data.

(2) Time history responses of sleeper displacements

Figure 11 (a) shows the time history responses of sleeper displacements immediately after impact loading. This is an average curve of the test results from loading approx. 4000 times, excluding the initial loading (first 1000 times). The downward displacements in this chart mean the compressions of the ballast layer, and the upward displacements mean the extensions of the ballast layer. Figure 11 (b) is a close-up of the chart, focused on the period immediately after loading. The average impact loads on the ballast on the left and right rails totaled 217 kN.

According to this chart, when an impact load is applied, the ballast layer deforms instantaneously due to elastic compression, and the compression reaches a maximum in 0.71 ms and then returned to the pre-loading position in 1.1 ms. Thus it takes only about 1 ms for the ballast layer to be compressed and be restored. The load and sleeper displacement response during that time period include almost no vibration components of a frequency below 40 Hz.

The sleeper jumps on occasion following the compression and restoration of the ballast layer. The jumping speed is approx. 6 times as high as the compression speed.
Though it is impossible to make a definitive statement based only on the results of this test, it is possible that the different slopes of dynamic rigidity curves are attributable to the upward stretching motions generated in the ballast during unloading. It also can be easily inferred that the decrease in the particle-to-particle contact force and abrupt stretching motions in the ballast layers as described above cause a flow or lateral spreading in the ballast layer.

5. Conclusion

This research investigated the natural vibration characteristics of the ballast layer and their transmission characteristics for dynamic loads through spectral analysis using field measurement results and vibration tests using a full-scale track mockup. The research results can be summarized as follows:

The results indicate that the rigid body vibration mode of the ballast layer belongs to the low-frequency domain below 100 Hz, and that low-frequency components of the dynamic loads exerted by passing trains are hard to damp. Furthermore, it is also found that the elastic vibration mode of ballast layer falls within the broad frequency domain ranging between 400 and 800 Hz. Moreover, results revealed that in the vicinity of the frequency of the elastic vibration mode, there are natural sleeper vibration modes where the bending and torsional behaviors of the sleeper are dominant, and the resonance at these frequencies makes it hard for the impact load components to be damped around these frequencies.

The results of the full-scale impact loading test on the simulated ballast layer indicate that the abrupt release of stress during unloading causes a decrease in particle-to-particle contact forces and abrupt stretching motions in the ballast layer. These ballast behaviors are one of the factors that cause flows or lateral spreading in the ballast layer.

Natural vibration modes such as the rigid-body and elastic vibration modes of the ballast layer play a role in the deterioration of ballast, as it wears and flows. In the future, the author intends to conduct full-scale tests and numerical analyses, to clarify and gain more detailed insight into the mechanism involved in this process, and to evaluate countermeasure effectiveness.

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