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Analysis of Large Amplitude Vibration Mechanism of High-speed Train PRC Girder Bridges Based on Vibration Measurement

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ABSTRACT
Many of railway infrastructure in Japan for high speed train, so called “Shinkansen”, are bridges. It is vital to find and cope with the problems of bridges as soon as possible. Recently, the railway company found some Prestressed Reinforced Concrete (PRC) girder bridges had large amplitude vibration which was not observed in properly designed girders. Girders’ natural frequency estimated by impact test was found to be 13 % larger than the excitation frequency caused by Shinkansen passing in specific velocity. Thus, the large amplitude vibration mechanism cannot be simply explained as resonance. In this paper, we conducted vibration measurement of the large amplitude vibration girders. The result of measured vibration analysis shows the natural frequency becomes lower as amplitude becomes larger, but the natural frequency is still 7 % larger which is too large in terms of analysis error. Then, we took into consideration the effect of Shinkansen vehicles’ weight and conducted eigenvalue analysis using a FEM model introducing those effect. As a result, the natural frequency during Shinkansen passing in the specific velocity becomes close to the excitation frequency. Resonance phenomena occurs at that moment, which is considered as the large amplitude vibration mechanism.

KEYWORDS: *Large amplitude vibration, PRC girder, vibration measurement, amplitude dependency of natural frequency, Shinkansen viaduct*

1. INTRODUCTION

Shinkansen operation plays a significant role in large transportation of human and goods in Japan. The operation disruption makes crucial effect on domestic economy. Therefore, structural characteristics of the infrastructure of Shinkansen should be evaluated properly.

In Shinkansen 29.2 m span PRC girders, which is allowed for clack to occur only during Shinkansen passing in design [1], the large amplitude vibration occurs during Shinkansen passing in specific velocity, which caused the fatigue fracture of a connecter of aerial wiring [2]. In design of only these girders, “impact coefficient” was not set properly. Thus, such a phenomenon does not occur in other girders. The railway company defines the amplitude of vibration larger than 20 mm between maximum and minimum displacement as “large amplitude vibration” [3].

Figure 1.1 shows the dynamic response of two girders with same design during Shinkansen passing in the same velocity; one has the large amplitude vibration phenomena (called “large amplitude vibration girder”), the other does not have it (called “small amplitude vibration girder”). Figure 1.1 shows amplitude increases as Shinkansen passes, the girder bends to the upper, and the large amplitude vibration continues after Shinkansen passing in the large amplitude vibration girder unlike the small amplitude vibration girder.

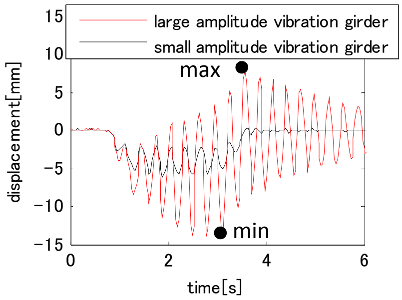


Figure 1.1 Small and large amplitude vibration (velocity: 229 km/h)

Table 2.1 description of measured three girders

	Girder A	Girder B	Girder C
View			
Amp	Large amplitude	Large amplitude	Small amplitude
Measurement date	2014/12/10	2014/10/26-27	2014/12/11

Table 2.2 Measured bridge design

Structural type	Post-tension Tshape PRC 4 main beam
Girder length	30 m
Span	29.2 m
Rails' Radius of curvature	A,B: 4000 m C: ∞
Girder height	1.7 m
Bearing	Rubber (fix-roller)

The railway company conducted impact test on the large amplitude vibration girders to clarify the mechanism [2]. The natural frequency was estimated to be about 3.0 Hz. On the other hand, the excitation frequency by Shinkansen passing under certain velocity causing the large amplitude vibration was estimated to be 2.6 Hz. Large amplitude vibration mechanism was initially thought as resonance, but there is 13% difference between the natural frequency and the excitation frequency, which is too large to ignore as an analysis error. Therefore, the problem does not considered to be simple resonance, and the mechanism or structural characteristics of the girders should be clarified.

Considering the above, the objectives of this paper are as follows. Firstly, vibration measurement on the large amplitude vibration girders in Shinkansen passing under various velocity was conducted and the large amplitude vibration mechanism are clarified by analyzing the measured vibrations and conducting eigenvalue analysis using a FEM frame model. Secondly, by analyzing the large amplitude girders' vibration measured by the railway company for 3 years, long term trend of the structural characteristics is clarified.

2. VIBRATION MEASUREMENT OF LARGE AMPLITUDE VIBRATION GIRDERS

The railway company conducted single point vibration measurement of the displacement on the large amplitude vibration girders [2]. In this chapter, multi-point vibration measurement of the large amplitude vibration girders was conducted and the structural characteristics of those are clarified by analyzing measured vibrations and identifying the modal shape. A small amplitude vibration girder was also measured to compare the difference of amplitude between the large and small amplitude vibration girders. Responses of the girders under 74 Shinkansen passing in velocity from 190 km/h to 250 km/h were measured for 4 days.

2.1. Measured girders

Table 2.1 shows specification of the measured three girders. These girders' design are the almost same as shown in Table 2.2, which can avoid difference of the design affecting on amplitude.

2.2. Measuring Instrument

To identify the modal shape, two RSV-150 which are laser doppler vibrometer and manufactured by Polytec shown as Figure 2.1 were used. The laser doppler vibrometer is useful under such a condition in this measurement that it's hard to access the surface or the back of the girder because of high pier height or heavy traffic under the girder.

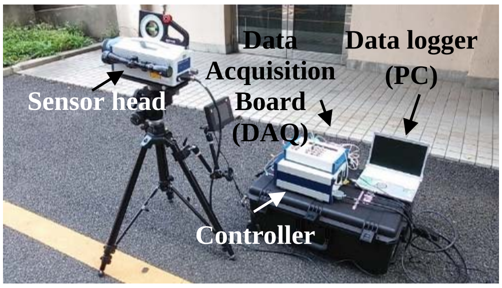


Figure 2.1 RSV-150 used in the vibration measurement

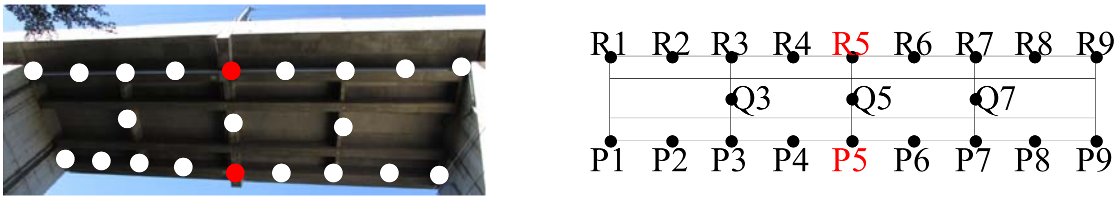


Figure 2.2 Measured points (Reference point: R5 (girder A and B), P5 (girder C))

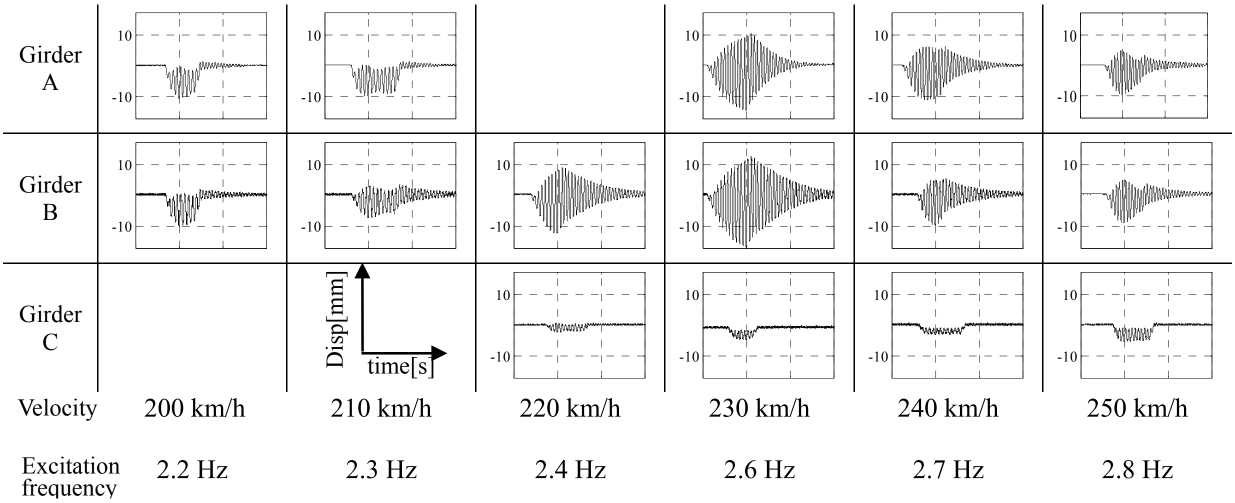


Figure 3.1 Displacement in each girder under typical Shinkansen velocity (Sampling frequency: 500 Hz)

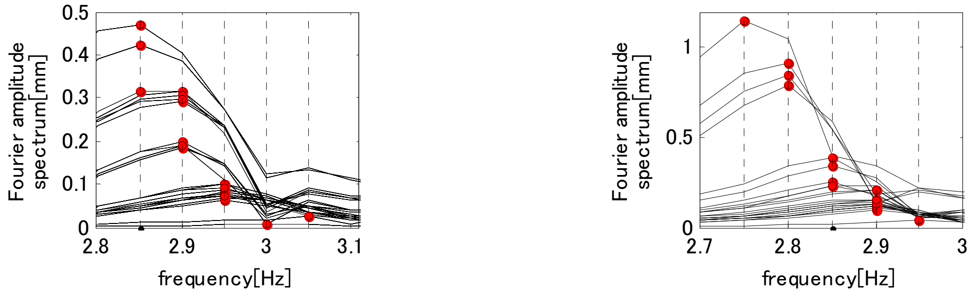
2.3. Measurement way

Figure 2.2 shows measured points.R5 in girder A and B, P5 in girder C were selected as “reference point”. One RSV-150 always measured vibration on the reference point in any Shinkansen passing. The other RSV-150 measured vibration on a point except for the reference point, called “moving measured point”, which was moved after every Shinkansen passing. Vibrations of the fixed reference point and the moving measured point were measured simultaneously.

3. VIBRATIONS ON REFERENCE POINT

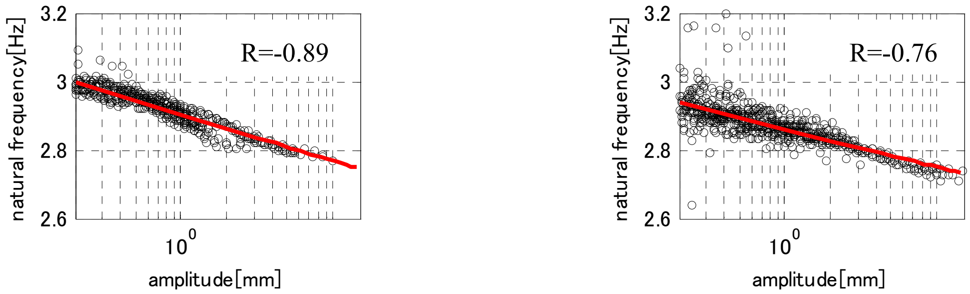
In this chapter, the structural characteristics of the large amplitude vibration girders and the mechanism is examined by analyzing the vibrations on the reference point.

Figure 3.1 shows the vibrations on the reference point under typical Shinkansen’s velocity/excitation frequency. In girder C the amplitude seems stable regardless of Shinkansen’s velocity. On the other hand, in girder A and B amplitude becomes larger when the Shinkansen’s velocity becomess closer to about 230 km/h, about 2.6 Hz in excitation frequency. This result does not conflict with the railway company’s impact test.



(a) girder A (b) girder B

Figure 3.2 Fourier amplitude spectrum in each girder's free vibrations



(a) girder A (b) girder B

Figure 3.3 relationship between logarithm of amplitude and natural frequency (red line: linear regression line)

3.1. Examining structural characteristics and mechanism of large amplitude vibration by estimating natural frequency

The vibration after Shinkansen passing seems free vibration as shown in Figure 3.1, which means natural frequency can be easily estimated. Whether the large amplitude vibration mechanism is resonance or not can be quantitatively evaluated by comparing the natural frequency estimated from the free vibration with the excitation frequency of 2.6 Hz causing the large amplitude vibration. The natural frequency was estimated by discrete Fourier transform. In this analysis, we extracted such free vibration that the length is 20 second and first 3 wavelength is cut to avoid Shinkansen passing affecting on the free vibration.

Figure 3.2 shows Fourier amplitude spectrum of the measured free vibrations of the large amplitude vibration girders. According to the Figure 3.2, the dominant frequency monotonically increases as Fourier amplitude spectrum decreases, which means the natural frequency can increases in free vibration as amplitude decreases in free vibration. Figure 3.3 shows the relationship between each cycle's amplitude and the reciprocal of each cycle's wavelength which is regarded as instantaneous natural frequency. In this analysis, the free vibrations were processed by a low pass filter with 4 Hz cut off frequency to remove high frequency noise. According to Figure 3.3, the large amplitude vibration girders clearly have amplitude dependence of natural frequency. Linear regression analysis shows the logarithm of amplitude and natural frequency have strong correlation as shown in Figure 3.3. The linear regression lines were calculated as Eq. 3.1 and Eq. 3.2 in girder A and B, respectively, which enables to estimate natural frequency from amplitude.

Girder A: $$f_n = -0.0582 \log \sigma + 2.90 \quad (3.1)$$

Girder B: $$f_n = -0.0476 \log \sigma + 2.86 \quad (3.2)$$

f_n is natural frequency (Hz), σ is amplitude (mm). According to Eq. 3.1 and Eq. 3.2, the natural frequency decreases to about 2.75 Hz to 2.80 Hz at the amplitude of 15 mm which is the measured maximum displacement, but still there is about 7% difference from the excitation frequency of 2.6 Hz causing the large amplitude vibration. Therefore, the large amplitude vibration mechanism cannot explained only as the amplitude dependency of natural frequency.

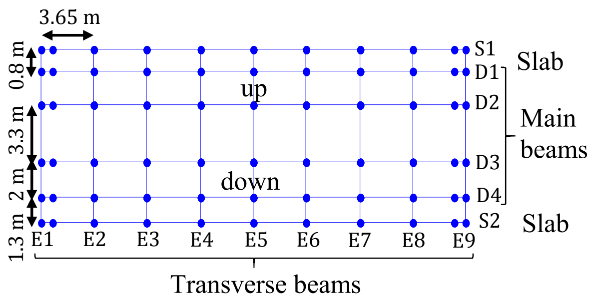


Figure 4.1 FEM frame model (same in girder A and B)

Table 4.1 the second moment of area of each component

beam	the second moment of area (m^4)
S1	1.04×10^{-3}
S2	1.69×10^{-3}
D1~D4	0.378~0.395
E1, E9	0.415
E2,E4,E6,E8	6.80×10^{-3}
E3, E7	0.119
E5	A: 0.168/ B: 0.182

Table 4.2 material characteristics of each component

		Main beam	Transverse beam slab
Young's modulus (N/m^2)	Concrete	3.1×10^{10}	2.8×10^{10}
	PC tendon	2.0×10^{11}	
	Reinforcing rebar	2.1×10^{11}	----
Unit weight (kg/m^3)		2500	
Poisson's ratio		0	0.2

3.2. Evaluating mechanism of amplitude dependency of natural frequency

The amplitude dependency of natural frequency can be caused by crack. As we refers in chapter 1, in PRC girders' design, crack is allowed to occur in the large amplitude vibration girders only during Shinkansen passing. If girders vibrate in large amplitude, the crack can open and then effective sectional area decreases, which leads stiffness decreasing. If stiffness decreases, natural frequency can also decrease. On the other hand, if girders vibrate in small amplitude, the crack may not open and effective sectional area increases, stiffness can increases, and natural frequency can increases.

According to the Figure 3.2, the natural frequency converges to 3.00 Hz and 2.95 Hz in girder A and B, respectively. This result does not conflict with railway company's impact test. This is because natural frequency is estimated by vibration with sufficiently small amplitude in impact test.

4. EIGENVALUE ANALYSIS USING FEM FRAME MODEL

In the last chapter, we found natural frequency could decrease as amplitude increases, but the natural frequency decreases to 2.75 Hz~2.80 Hz at the smallest, which is still significantly larger than excitation frequency of 2.6 Hz causing the large amplitude vibration. On the other hand, Shinkansen's vehicle weight can also decreases the natural frequency. To estimate the natural frequency considering Shinkansen's vehicle weight as well as amplitude dependency of natural frequency, FEM frame model was made and eigenvalue analysis was conducted.

4.1. FEM frame model

The structure of the FEM frame model, the second moment of area and material characteristics are shown in Figure 4.1, Table 4.1 and Table 4.2, respectively. These are referred by *Tetsudou Kouzoubutsutou Sekkei Hyoujun Dou Kaisetu* [4]. Now, in the main beams the second moment of area changes depending on the location of the sections because PC tendon is located different place in each section. Furthermore, E5 component in girder B is bigger than that in girder A, which is introduced only in girder B.

4.2. Modal shape identification

Using the measured data, modal shape was identified to calibrate the FEM frame model. The identification procedure of the modal shape is as follows.

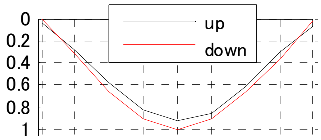
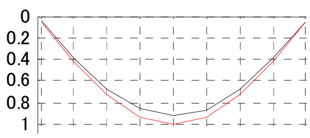
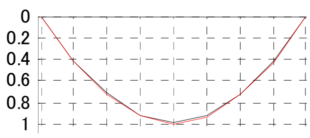
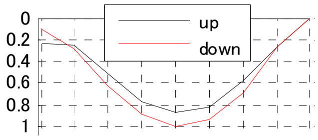
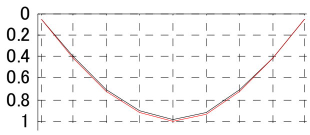
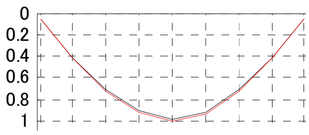
	Identified modal shape (measured data)	Analyzed modal shape (after calibration)	Analyzed modal shape (before calibration)
girder A	 natural frequency: 3.00 Hz up-to-down girder ratio: 0.92	 natural frequency: 3.01 Hz up-to-down girder ratio: 0.92	 natural frequency: 3.22 Hz up-to-down girder ratio: 0.99
girder B	 natural frequency: 2.95 Hz up-to-down girder ratio: 0.86	 natural frequency: 2.95 Hz up-to-down girder ratio: 0.98	 natural frequency: 3.17 Hz up-to-down girder ratio: 0.98

Figure 4.2 Identified modal shape and analyzing modal shape before/after calibration

Firstly, two free vibrations on the reference point and every moving measured point were extracted. Secondly, by conducting discrete Fourier transform to the free vibrations, the ratio of amplitude on the reference point and that on another moving measured point at the natural frequency were calculated. Finally, by normalizing amplitude at the reference point, modal shape could be estimated. In this paper, primary bending mode was distinguished and could be easily identified.

4.3. Calibration of FEM frame model based on identified modal shape

In calibration of the FEM frame model by using the identified modal shape, we focused on the natural frequency and the up-to-down girder ratio. As Figure 4.2 shows, analyzed modal shape before calibration has higher natural frequency and smaller up-to-down girder ratio than identified modal shape. The shape of the primary bending mode strongly depends on the stiffness of four main beams, therefore we changed them by trial and error as the natural frequency and the up-to-down girder ratio had good agreement with identified them.

As for the model of girder A, by decreasing the stiffness of D3 and D4 by 28%, they had good agreement with the identified them. As for the model of girder B, it was hard to make up-to-down girder ratio of the model have good agreement with the identified one. Thus, by decreasing the stiffness of all main beams to 15%, only natural frequency had good agreement with the identified one.

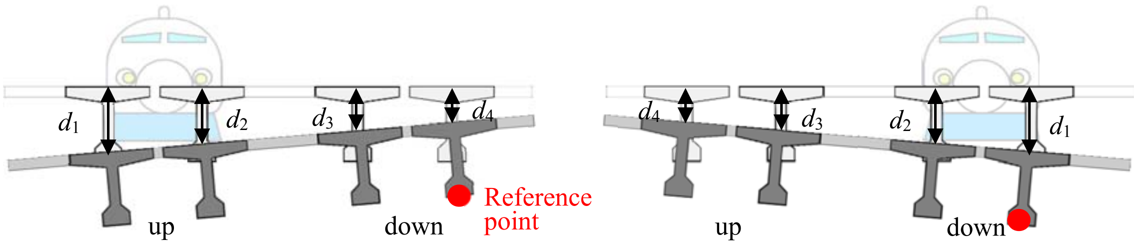
4.4. Estimating natural frequency under existence of Shinkansen’s vehicle weight

By introducing the Shinkansen’s vehicle weight and the amplitude dependency of natural frequency to the model, how much the natural frequency decreases is clarified in this chapter. In reality, the large amplitude vibration phenomena occurs only when Shinkansen passes on the up-side, therefore Shinkansen’s vehicle weight is introduced on the up-side.

Shinkansen’s vehicle weight should be introduced as distributed load. Then, concentrated loads calculated by a weighted average considering the location of the rails and the main beams were introduced at the each lattice point.

As for amplitude dependency of natural frequency, stiffness lowering rate in each main beam depending on displacement during Shinkansen passing was introduced as follows.

Firstly, we estimated displacement d (mm) in each main beam. As Figure 4.3 shows, the displacements in each main beam are not constant in assuming Shinkansen passes on the up-side. The displacement of the outmost beam of the up line (d_1) when Shinkansen passes on the up-side (Figure 4.3(a)) is considered to be equal to that of the outmost beam of the down-side when Shinkansen passes on the down-side (Figure 4.3(b)) because the girder’s shape is almost symmetry. The latter displacement can be easily estimated from the vibration data on the reference point locating at center of the outmost main beam of the down-side. The displacement of the out most beam of the down-side (d_4) when Shinkansen passes on the up-side can be directly estimated from the vibration data on the reference point. The displacement of middle two main beams (d_2, d_3) are calculated as a slope of the displacement was linear.



(a) Shinkansen passing on the up-side (b) Shinkansen passing on the down-side

Figure 4.3 Assumption of displacement of main beams

Secondly, we estimated the extent of the stiffness decreasing in each main beam. Assuming main beams held Eq. 3.1 and Eq. 3.2, natural frequency can be calculated from the estimated displacement in each main beam. Furthermore, stiffness is proportional to the square of natural frequency from general beam theory [5]. Therefore, stiffness lowering rate β was calculated by Eq. 4.1.

$$\beta = \left(\frac{f_n}{f_0}\right)^2 \tag{4.1}$$

f_n is the estimated natural frequency (Hz), and f_0 is the natural frequency in sufficiently small amplitude (Hz). As mentioned in chapter 3, f_0=3.00(Hz) and f_0=2.95(Hz) in girder A and girder B, respectively.

By conducting eigenvalue analysis using the FEM frame model which was calibrated based on the measured data and introduced Shinkansen's vehicle weight and the amplitude dependency of natural frequency, the natural frequency decreases to 2.60~2.62 Hz in girder A, and 2.58~2.60 Hz in girder B, which are almost same as the excitation frequency of 2.6 Hz causing the large amplitude vibration. In short, the large amplitude vibration mechanism is concluded as instantaneous resonance during Shinkansen passing.

5. LONG TERM TREND OF STRUCTURAL CHARACTERISTICS

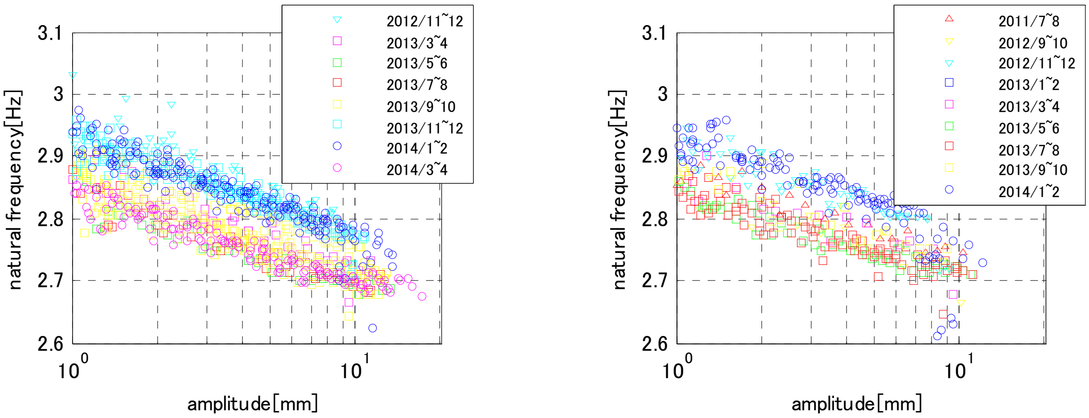
Until the last chapter, the large amplitude vibration mechanism is clarified. In this chapter, the long term trend of the structural characteristic of amplitude dependency of natural frequency is also estimated by analyzing the vibration data measured by railway company for past 3 years for future prediction of the structural characteristics.

Figure 5.1 shows the amplitude dependency of natural frequency in every 2 months analyzed in the same way as Figure 3.3. This figure indicates there is some seasonal dependency of natural frequency, especially in winter natural frequency increases and in summer decreases.

Then, we extracted the amplitude at the same level to avoid the effect of the amplitude dependency. Figure 5.2 shows the average natural frequency in the each amplitude in the measurement date, which actually indicates the natural frequency decreases in summer and increases in winter. Furthermore, Figure 5.2 also indicates that average temperature of the measurement date and the natural frequency have strong negative correlation, R=-0.91 and R=-0.73 in girder A and girder B, respectively. Comparing natural frequency in amplitude of 1.5~2.5 mm in winter with that in amplitude of 5.5~6.5 mm in summer, the difference is about 0.2 Hz which cannot be ignorable. This result tells us that environmental condition is also important to comprehend the structural characteristics.

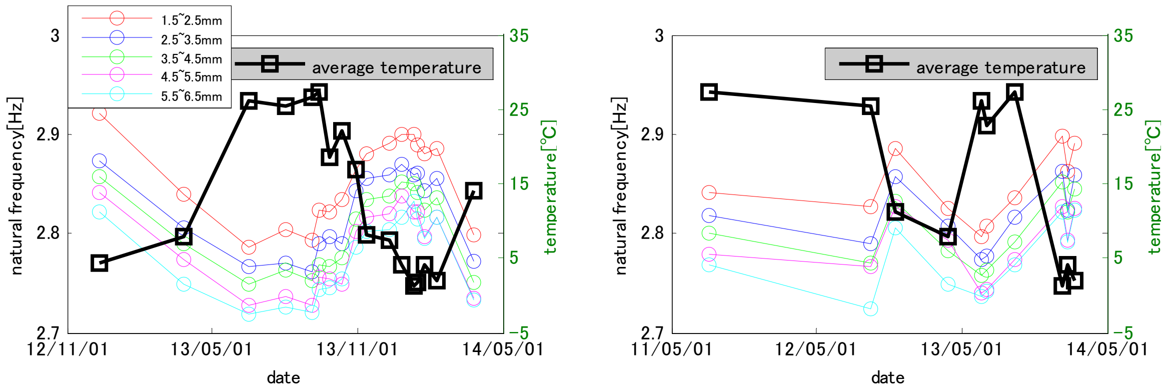
6. SUMMARY

Some Shinakansen PRC viaducts were found to have the large amplitude vibration phenomena which can affect Shinkansen operation and structure itself. According to the multi-point vibration measurement conducted by us, the large amplitude vibration phenomena occurs under Shinkansen's velocity of 230 km/h, the excitation frequency of 2.6 Hz, which does not conflict with the investigation preliminarily conducted by the railway company. Furthermore, we observed the natural frequency of the large amplitude vibration girders decrease by 0.2 Hz at most in large amplitude which shows the girder has nonlinear dynamic property. This reason is considered to be a crack allowed to occur in design in the PRC structure in large amplitude. However, the large amplitude vibration mechanism cannot be explained only as the nonlinearity of the natural frequency because there is still non-



(a) girder A (b) gider B

Figure 5.1 The season change of the natural frequency



(a) girder A (b) girder B

Figure 5.2 natural frequency in each amplitude level in each measurement date

ignorable difference between the natural frequency and the excitation frequency causing the large amplitude vibration phenomena. To consider not only the amplitude dependency of natural frequency but also Shinkansen's vehicle weight, the FEM frame model was developed. By conducting eigenvalue analysis using the calibrated model introduced Shinkansen's vehicle weight and amplitude dependency of natural frequency, the natural frequency can decreases to the excitation frequency causing large amplitude vibration phenomena during Shinkansen passing, which is considered to be the large amplitude vibration mechanism. Furthermore, this paper looked into the long term trend of the structural characteristics as well, and found the natural frequency varies depending on the season clearly. This result implies that to comprehend the structural characteristics of the large amplitude vibration girders, the environmental condition of the measurement is also important.

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