Clarification of the Effect of High-Speed Train Induced Vibrations on a Railway Steel Box Girder Bridge Using Laser Doppler Vibrometer

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ABSTRACT: The effect of train-induced vibrations and the train speed on local stresses at each part of the steel box girder bridge were studied analytically as well as by field measurement. The results show that vibrations at the lower flange of the main girder increased the local stresses causing damage. Furthermore, the study shows that the vibration depends on the cyclic external load induced by train speed. The measurement system consists of a scanning type vibrometer and a single point type vibrometer and the measurement clarified the non-stationary characteristics of a railway bridge subjected to train-induced vibrations. The data acquired were analyzed to identify the natural frequencies and the changes based on the retrofit in the mode shapes of the railway bridge.

1 INTRODUCTION
At a railway steel box girder bridge, damage was observed on the web of a main girder at the bottom end of a welded vertical stiffener. The cause of the damage is thought to be an increase in the local stress due to vibrations induced by high-speed trains. Thus, parts of the bridge of similar detail were also strengthened and this proved to be effective in preventing further damage. However, the relationship between train-induced vibration and the increase in local stresses remains to be unclear. Similarly, the relationship between train speed and the induced vibrations need to be investigated, including the effects of acceleration on a railway bridge since there are plans of increasing the present speed of trains in service.

In this research, the effect of train-induced vibrations and the train speed on local stresses at each part of the bridge were studied by analysis as well as field measurement. Laser Doppler Vibrometers (LDV) were used in the field measurement of the actual bridge. The LDV is capable of long distance and non-contact measurement and is being considered to be a strong tool in the field of structural health monitoring.

2 THE OUTLINE OF FIELD MEASUREMENT
2.1 Focus bridge for field measurement
The bridge studied for field measurement is a pair of steel mono-box girders with 4 spans. There are cross frames every 3.2m (Sec.C or D), and vertical stiffeners were installed midway between cross frames (Sec.E) as shown in Figure 1 (a). The stiffeners were not welded to the lower flange in the sections where positive moment affects the main girder in order to protect against fatigue damage of the lower flange. In bridges which have similar detail, damage was observed on the web of a main girder at the bottom end of a welded vertical stiffener. The parts of the bridge of similar detail were strengthened such as in Figure 1 (b) using a T-shape member installed between the web and the lower flange using high tension bolts. The trains which pass on the bridge have 16 cars which are 25m long, and having maximum speed of 270km/h at present.
2.2 The outline of the field measurement

Accelerometers and strain gauges were installed in the bridge. Since it is suspected that the cause of high local stresses was local vibration of the web or lower flange of the main girder, accelerometers were installed on both the web and the lower flange of the main girder. The strain gauges were installed on the main girder web 20mm away from the toe of welding between the web and the vertical stiffener. Furthermore, gauges were installed on the lower flange to measure nominal stresses of the main girder as shown in Figure 2. In addition, Laser Doppler Vibrometer was utilized to verify the rationale behind a future monitoring system.

3 THE RESULT OF FIELD MEASUREMENT

3.1 The outline of the bridge for field measurement and trains which pass on the bridge

Figure 3 show examples of acceleration, stress and FFT results from the field data. Figure 3(a) shows that there is one large waveform caused by trains passing on the bridge and there are 17 cycles corresponding to each bogie passing the cross section. It is shown that the dominant frequency is 3.0 Hz, which depends on the 17 cycle waveform. This phenomenon is known as “speed effect by regular loading” which depends on the interval that bogies or train cars pass at constant speed. Figures 3(b), (c) and (d) show the presence of high frequency local vibration and stresses, and the frequencies of these vibrations are 20Hz — 30Hz. Each result shows a dominant frequency and they have the same intervals.

3.2 The relation between vibration and train speed

Figure 4 shows the relation between the dominant frequency of acceleration of the main girder and train speed of 39 trains. This figure shows that the dominant frequency of vibration of the main girder depends on the train speed and it agrees with the relational expression “speed effect by regular loading”. Figure 5 shows the relation between the dominant frequency of acceleration of the lower flange and train speed. This figure shows that the dominant frequency depends on train speed, similar to the vibration of the main girder and that the frequency is an integer multiple of the frequency of the main girder.
Figure 3. The result of field measurement.

(a) Nominal stress of lower flange (S01R).

(b) Acceleration of web (A42L).

(c) Acceleration of lower flange (A42C).

(d) Local stress of web (S42L).

Figure 7. Local vibration-mode.

Figure 8. Relation between FFT amplitude and frequencies of lower flange vibration.

Figure 9. Amplitude ratio of lower flange vibration in each mode.

Figure 10. Relation between FFT amplitude of lower flange and train speed.

Figure 4. Relation between train velocity and frequencies of main girder.

Figure 5. Relation between train velocity and frequencies of lower flange.

Figure 6. Relation between local vibration and local stress.
3.3 The relation between local vibration and local stresses

Figure 6 shows the relation between local vibration and local stresses. This figure shows that there is a strong correlation between local stresses and the lower flange vibration, and that local stresses and web vibration correlate poorly. Thus, it was confirmed that the cause of high local stresses is local vibration of the lower flange. The vibration-mode inducing local stresses can be seen in Figure 7 based on the investigation of the phase between stress and acceleration.

3.4 The relation between local vibration and train speed

Figure 8 shows the relation between the FFT amplitude and the frequency of the lower flange vibration. This figure shows that there are 2 peaks of different frequencies. A peak occurs at 28.7Hz and another one is at 32.8Hz. These 2 peaks identify the natural frequencies of local vibration. The mode shapes of these 2 peaks were identified using cross-spectral analysis. It is shown in Figure 9 that these 2 peaks correspond to local vibration modes. Lastly, Figure 10 shows the relation between the FFT amplitude of the lower flange vibration and the train speed in each mode. It is shown that each mode has each peak at a certain speed and that the frequency at each peak is an integer multiple of the frequency of the main girder. Thus, it was confirmed that the vibration is larger when the natural frequency of local vibration is an integer multiple of the frequency of the main girder induced by regular loading.

4 FIELD MEASUREMENT USING LASER DOPPLER VIBROMETER

4.1 Laser Doppler Vibrometer (LDV)

Laser Doppler Vibrometer (LDV) is an optical instrument employing laser technology to measure velocity of points on a vibrating object. Velocity is measured based on the Doppler effect, which induces a frequency change between the radiation laser and the reflected laser.

The characteristics of the LDV are: first, compared with conventional transducers such as accelerometers, non-contact and long distance measurement (up to 100 m) is possible without adding mass or stiffness to an object. Second, resolution of velocity is very high (0.1µm/s) and bandwidth is very wide (0 – 35kHz). Therefore, in situations when the installation of the measurement devices is difficult, it is possible to measure high frequency components of small vibration such as ambient vibration. Third, by attaching a scanning mirror unit in front of the laser sensor head, measurement on multiple points (±20 degrees) is made possible. The specification of the LDV used in this research is shown in Table 1.

As an application of the LDV system consisting of one scanning type LDV and one single point type LDV to real structures, Kaito et al. applied the vibration measurement system to steel and reinforced concrete girders of existing viaducts. The mode shapes were identified and the quality of measurement was quantitatively evaluated (Kaito et al., 2001).

4.2 Measurement system

The measurement system consists of three scanning type LDVs (named SLDV) and one single point type LDV (named RLDV). The single point type LDV always measures a reference point and is used to calculate the phase between measurement points for the identification of mode shapes. The system is controlled by one desktop PC using a LabVIEW program, which can control the scanning mirrors of the SLDVs and record measurement data.

Figure 11 shows the measurement sections and points used during field measurement. There are 3 measurement sections which include the center of the girder and each SLDV is positioned below each section. In Figure 11 numbers 1 to 9 at each section refer to the measurement points by the SLDV and vibration measurement is conducted at each point by scanning from points 1 to 9. Measurement reference point measured by RLDV is the ‘R’ point in Figure 11, which is not a nodal point in the first and second modes of vibration of the sections. At each measurement point, reflection tapes attached to magnets were installed to increase the reflectivity of the steel surface. Figure 12 shows the measurement set-up of the LDV. In Figure 12, trains pass coming from Osaka going to Tokyo.
Using LDV, measurements of ambient vibration and train-induced vibration were conducted. During ambient vibration measurement, measurements were conducted before and after retrofitting the bottom part of the vertical stiffeners as shown in Figure 1 (b). The objective of the measurement is to identify natural frequencies and mode shapes at the sections before and after retrofitting. Ambient vibration measurement was done at nine measurement points as shown in Figure 11 when trains do not pass the section. Sampling frequency is 1000 Hz and the sampling point number is 20000 at each point.

The aim of train-induced vibration measurement is to clarify the vibration phenomena at the steel girder when trains pass. The measurement is conducted at the nine points in Figure 11 by scanning mirrors and the measurement signal of RLDV is set as the triggering signal. Because the manner of triggering is pre-trigger, it is possible to acquire measurement data before the trigger activates. Sampling frequency is 1000 Hz and sampling point numbers are 2400, 800 and 4000 at point 1, points 2 – 8 and point 9, respectively. The sampling numbers at point 1 and 9 are larger than those at the other points in order to measure the vibration when a train enters the bridge and the free vibration after it passes. Focus trains are the same trains as the vibration measurement with the accelerometer and the strain gauge that was discussed in section 2 and 3.

4.3 LDV measurement results

Train-induced vibration measurements using LDV at point 5 (see Figure 11) are shown in Figures 13 and 14. In Figures 13 (a) and 14 (a), the topmost figure shows the time-history at section L9-10 measured by SLDV1, the second from the top L11-12 by SLDV2, the third from the top L13-14 by SLDV3 and the bottom figure L11-12 by RLDV. In Figures 13 (b) and 14 (b), the topmost figure shows the cross spectrum between RLDV and SLDV1 measurements, the sec

Table 1. Specification of LDV.

<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Single Point Type</th>
<th>Scanning Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>He-Ne</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave Length</td>
<td>633 [nm]</td>
<td></td>
</tr>
<tr>
<td>Laser Output / Class</td>
<td>30 [m]</td>
<td>100 [m]</td>
</tr>
<tr>
<td>Measurement Distance</td>
<td>1mW/II</td>
<td>2.3mW/IIIa</td>
</tr>
<tr>
<td>Resolution of Velocity</td>
<td>0.1 [µm/s]</td>
<td>0.5 [µm/s]</td>
</tr>
<tr>
<td>Frequency Bandwidth</td>
<td>0 - 35k [Hz]</td>
<td>0 - 35k [Hz]</td>
</tr>
<tr>
<td>Velocity Range</td>
<td>1,5 [mm/s/V]</td>
<td>1,5,25,125 [mm/s/V]</td>
</tr>
<tr>
<td>Mirror Angle</td>
<td>-</td>
<td>-20 - +20 [degree]</td>
</tr>
<tr>
<td>Resolution of Angle</td>
<td>-</td>
<td>0.01 [degree]</td>
</tr>
</tbody>
</table>

Figure 11. Measurement sections and points. Figure 12. Field set-up of the LDVs.
ond from the top between RLDV and SLDV2, and the bottom figure between RLDV and SLDV3. Train velocities in Figures 13 and 14 are 258.0 [km/h] and 266.7[km/h], respectively. 258.0 [km/h] correspond to n = 10 in Mode A in Figure 9 and 266.7[km/h] correspond to n = 11 in Mode B in the same figure. These measurements were simultaneously taken using LDV and accelerometers in Figure 9.

Time history at point 5 shows the waveform when a train passes through the girder. Cross spectrum plots show the dominant frequency components excited by the train-induced vibration. At each section, the same frequency component is excited for the same train. In Figure 13 (b) the frequency component 28.8 Hz is excited when the train passes while in Figure 14 (b) the frequency component 32.5 Hz is the one excited. It is clear that the excited frequency components depend on the train velocities.

4.4 Identification of mode shapes using LDV

The method of identifying mode shapes using LDV will now be explained. First, cross spectrum is calculated between the measurements at the reference point by the single point type LDV (RLDV) and the measurements by the scanning type LDV (SLDV). Natural frequencies are identified based on the peaks of the cross spectrum amplitude. Next, as for mode shapes, amplitude ratios are determined based on the ratio of the Fourier spectrum by SLDV to the Fourier spectrum by RLDV corresponding to the identified natural frequency. Then, phases of the mode shape are identified based on the cross spectrum. The amplitude ratios become positive when the phase of the cross spectrum is between −90° and +90° and become negative when the phase of the cross spectrum is between +90° and +180° or between -180° and -90°. This method makes it possible to identify the dynamic properties of a structure not only with a stationary case such as ambient vibration but also with a non-stationary case such as train-induced vibration.

Figure 15 show identified mode shapes based on the ambient vibration measurement using LDV at the three sections shown in Figure 11. Figure 15 (a) shows the mode shape before attaching the stiffener for retrofitting and Figure 15 (b) shows the mode shape after attaching the stiffener. Notice that although natural frequencies of both modes are the same 29.3 Hz, the mode shapes are different. Mode shapes before retrofitting (Figure 15 (a)) show positive, positive and negative at the center of each section, respectively, similar to Mode A (28.65 Hz) in Figure 9.
Identification of mode shapes was conducted from train-induced vibration measurements using LDV based on the method explained in section 4.4. Because the resolution of the frequency is 1.25 Hz, the dominant frequency component in Mode A is 28.75 Hz, near 28.65 Hz. Shown in Figure 14, peaks of the cross spectrum occur at 28.75 Hz. Similarly in mode B the dominant frequency component is 32.5 Hz. To utilize the data when a train passes, measurement taken from points 1 to 6 were adopted.

Figures 16 (a) and (b) show the identified mode shapes for Mode A and Mode B, respectively. At the center of the mode shapes (point 5) in Figure 16 (a), signs are positive, positive and negative at L9-10, L11-12 and L13-14, respectively. In Figure 16 (b), signs are positive, positive and positive at L9-10, L11-12 and L13-14, respectively. These results agree with the signs in Figure 9. This proves that it is possible to identify the mode shapes based on the non-contact vibration measurement using LDV, which is simpler compared to the conventional measurement with accelerometers.

5 ANALYTICAL STUDY

In this section, an analytical study for train-induced vibration phenomena is conducted using a simple analytical model. The analytical model consists of a superimposed spring-mass model using identified natural frequencies based on the measurement at the focus section (L11-12). Input forces for the model are applied by the impulse force based on the interval of train wheels. Output response is equal to the superposition of unit impulse response functions based on equations shown below. In this model, the output depends on the train velocities. Acceleration response can be determined by taking the numerical derivative of the output response twice.

\[
g(t) = \sum_{k=1}^{M} \frac{1}{m_{k}h_{k}} \sum_{l=1}^{N} \left[ e^{-\alpha_{l}(t-\tau_{kl})} \sin \left\{ b_{l} \left( t - \tau_{kl} \right) \right\} + e^{-\alpha_{l}(t-\tau_{kl})} \sin \left\{ b_{l} \left( t - \tau_{kl} \right) \right\} \right] \]

\[
a_{l} = \xi_{l} \omega_{0l} \quad b_{l} = \omega_{0l} \sqrt{1 - \xi_{l}^{2}}
\]

\[
\tau_{w} = 3.6\left( d_{p} + 25(k-1) \right)/V + c \quad (p = 1, 2, 3, 4)
\]

\[
d_{1} = 2.5, d_{2} = 5.0, d_{3} = 20.0, d_{4} = 22.5
\]
where $M$ is the number of adopted natural frequencies, $N$ is the number of the train bogies, $m_i$ are the mass, $\xi_i$ are the damping ratio, $\omega_i$ are the natural frequency, $c$ is the time lag before applying the input force and $V$ is the train velocity. In this study, $M = 2$, $N = 16$, $(m_1, m_2) = (1,1)$, $(\xi_1, \xi_2) = (0.02, 0.02)$, $(\omega_0, \omega_0) = (2\pi \times 28.65, 2\pi \times 32.8)$, $c = 0.5$ and $V = 258.0, 266.7 \text{ [km/h]}$. $d_i (i = 1, 2, 3, 4)$ are the intervals of the train wheels. The natural frequencies were determined from Figure 8.

Figure 17 shows the Fourier spectrum of the measurement with accelerometer at L11-12 for mode A ($V = 258.0 \text{ km/h}$) and mode B ($V = 266.7 \text{ km/h}$). Figure 18 shows the Fourier spectrum of the analytical model. Comparing plots, the distributions of frequency components agree well. Thus, this analytical model can explain the train-induced vibration phenomena qualitatively.

6 SUMMARY AND CONCLUSIONS

- At a main girder, the cyclic external loads of the bogies generate forced vibration and the frequency is proportional to the train velocity.
- Frequencies of local vibration at a web or lower flange of the main girder are integer multiples of the frequency of the external cyclic load. It was shown that the amplitude of the local vibration increases when the frequency of the local vibration is an integer multiple of the external cyclic load.
- Vibration at the lower flange has a localized effect on the stresses at the bottom of the vertical stiffener.
- A measurement system consisting of three scanning type LDVs and one single point type LDV has been developed. It was proven that the system can identify mode shapes of three sections of a steel box girder bridge.
- The change of mode shapes of the section is identified based on the ambient vibration measurement using LDV before and after retrofitting of the vertical stiffeners.
- Mode shapes are identified based on the train-induced vibration measurement using LDV. The mode shapes correspond to the signed amplitude ratio solved using accelerometers.
- Simple analytical model can explain the train-induced vibration phenomena qualitatively.

REFERENCES