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ADVANCED VIBRATION MEASUREMENT SYSTEM FOR BRIDGE USING LASER DOPPLER VIBROMETERS

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Abstract

A visual inspection of bridges mainly has been conducted as conventional maintenance technique. The results may depend on subjectivity. Therefore, the development of quantitative maintenance techniques is required. This paper presents three studies of advanced vibration measurement for bridges using laser Doppler vibrometers (LDV), which it makes possible to conduct high accurate, non-contact and long distance measurement.

At a Shinkansen (Bullet Train) railway steel box girder bridge, fatigue cracks were observed at the bottom end of vertical stiffeners. The objective of this study is to clarify the dynamic behavior of the bridge by vibration measurement using convectional sensors and LDVs.

A new measurement system using LDVs for monitoring Shinkansen RC viaducts will be presented. Ambient and impact vibrations were measured by LDVs compensated for noise in order to eliminate the low amplitude vibrations of the viaduct. The global mode shapes and natural frequencies were identified.

Compact and portable LDV measurement system was developed and applied to tensile force measurement of cables in the Tatara Bridge. The LDV used in this study integrates sensor head and controller into a body and drives by a battery. Measurement system using the LDV was developed in order to be possible to handle by a laptop PC. As the result, the number of working persons for measurement becomes few, due to very excellent movability of the system.

INTRODUCTION

In Japan, continuous investments in infrastructures have formed a huge stock. However, since the infrastructures were constructed rapidly and emphatically in high economic growth period, the number of the degraded ones comes to increase rapidly. Therefore, the development of quantitative and efficient maintenance techniques is required.

Laser Doppler Vibrometer (LDV) is an optical instrument employing laser technology to measure velocity. The characteristics of LDV are the following: first, in comparison with conventional transducers such as accelerometers, non-contact and long distance measurement is possible without adding mass or stiffness to an object. Second, resolution of velocity is very high, and frequency bandwidth is very wide. Third, by attaching a scanning unit of mirror in front of the laser sensor head, measurement on multiple points is made possible. This paper presents three studies of advanced vibration measurement using LDVs in order to monitor bridges.

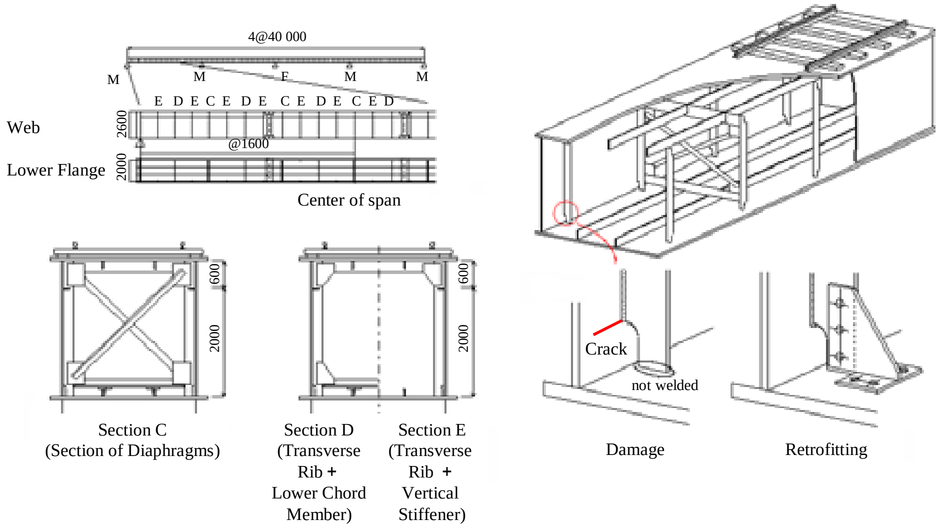
CLARIFICATION ON DYNAMIC BEHAIVOUR OF HIGH-SPEED TRAIN INDUCED VIBRATION OF SHINKANSEN RAILWAY STEEL BRIDGE [1]

Investigated bridge

The investigated bridge has a pair of steel mono-box girders with 4 spans as shown in Fig.1. The stiffeners were not welded to the lower flange in the sections where positive moment affects the girder. In bridges which have similar detail, fatigue cracks were observed on the web of the girder at the bottom end of vertical stiffeners The parts of the bridge of similar detail were retrofitted such as in Fig.1(b) using a T-shape member installed between the web and the lower flange using high tension bolts.

Measurement using conventional sensors

Accelerometers and strain gauges were installed in the bridge for measurement of train induced vibration. Since it is suspected that the cause of high local stresses was local vibration of the web or lower flange of the girder, accelerometers were installed on both the web and the lower flange of the girder. The strain gauges were installed on the girder web 20mm away from the toe of welding. Furthermore, the strain gauges were installed on the lower flange on the girder as shown in Fig.2.



(a) Detail of bridge (b) Retrofitting work (Sec.E)

Figure 1. Investigated bridge

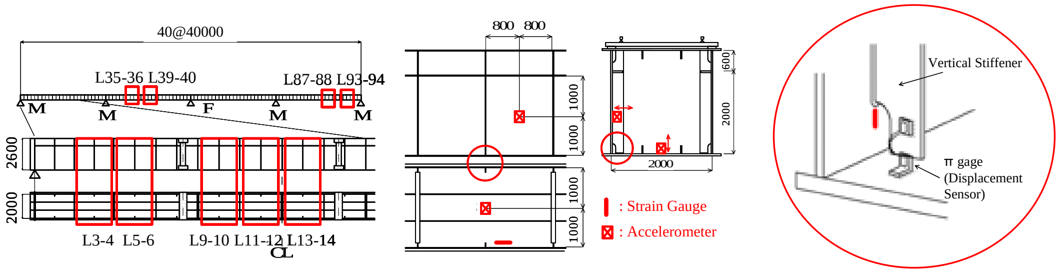
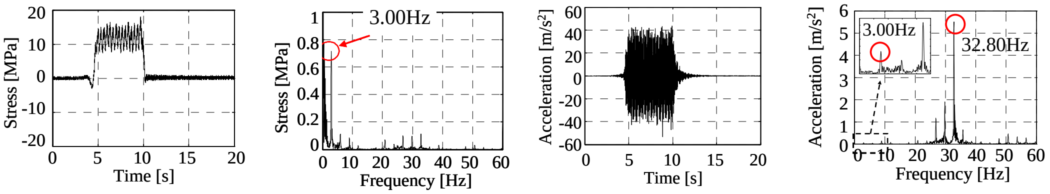


Figure 2. Measurements using conventional sensors



(a) Stress at lower flange

(b) Acceleration at lower flange

Figure 3. Results of measurement by conventional sensors

Measurement results

Fig.3 shows examples of the field data. Fig.3(a) indicates that there is one large waveform caused by trains passing on the bridge and there are 17 cycles corresponding to each vehicle passing the cross section. It is shown that the dominant frequency is 3.0 Hz. This phenomenon is known as “speed effect by periodic loading” [2] which depends on the interval that bogies or train vehicles pass at constant speed. Fig.3(b) shows the presence of high frequency local vibration, and the frequencies of these vibrations are 20Hz to 30Hz.

The relation between vibration and train speed

Fig.4 shows the relation between the dominant frequency of acceleration of the girder and train speed of 39 trains. This figure shows that the dominant frequency of vibration of the girder depends on the train speed and it agrees with “speed effect by cyclic loading”. Fig.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 girder, and that the frequency is an integer multiples of the frequency of the girder.

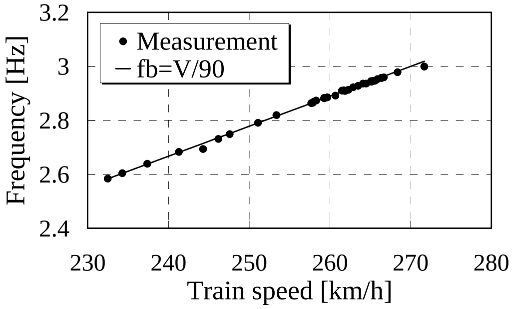


Figure 4. Train speed and dominant frequencies of girder

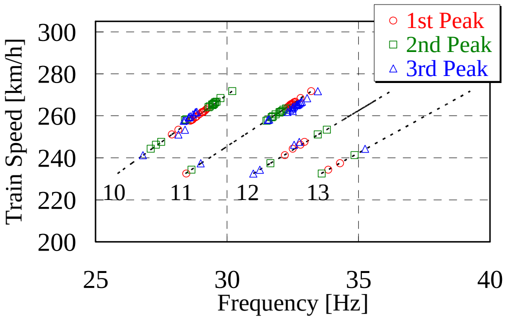


Figure 5. Train speed and dominant frequencies of lower flange

The relation between local vibration and local stresses

Fig.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 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 Fig.7 based on the investigation of the phase between measurements.

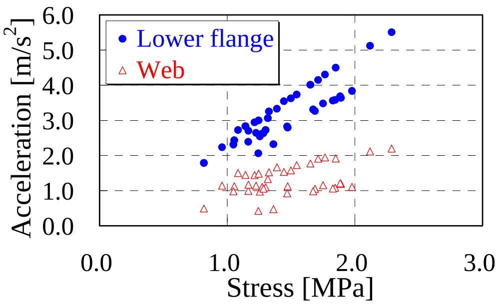


Figure 6. Correlation between stress and acceleration

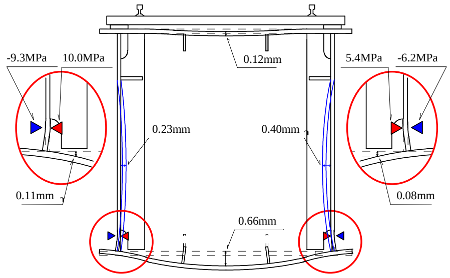


Figure 7. Local mode shape causing local stress

The relation between local vibration and train speed

Fig.8 shows the relation between the Fourier spectral amplitude and the frequency of the lower flange vibration. This figure shows that there are 2 peaks of different frequencies. A peak occurs at 28.65Hz and another one is at 32.80Hz. These 2 peaks identify the natural frequencies of local vibration. Fig.9 shows the relation between the Fourier spectral 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 frequencies at each peak are integer multiples of the frequency of the girder. Thus, it was confirmed that the vibration is larger when the natural frequencies of local vibration are integer multiples of the frequency of the girder induced by periodic loading.

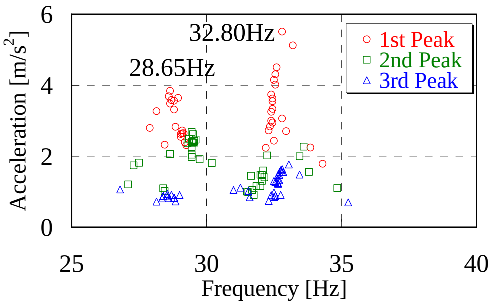


Figure 8. Fourier spectral amplitude and peak frequencies of lower flange

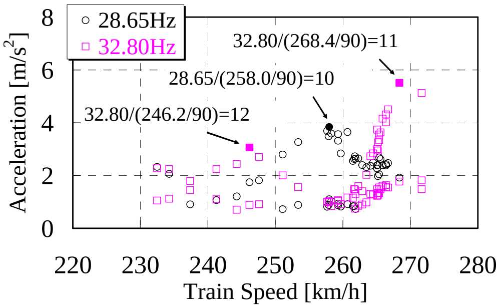


Figure 9. Train speed and Fourier spectral amplitude of lower flange

Measurement using LDVs

The measurement system consists of three scanning type LDVs at three sections and one single point type LDV as shown in Fig.10. The single point typed LDV always measures a referenced point and is used to calculate the phase between measurement points for the identification of mode shapes. Using LDV, measurements of ambient vibration was conducted. During ambient vibration measurement, measurements were conducted before and after retrofitting the bottom part of the vertical stiffeners as shown in Fig.1(b). The objective of the measurement is to identify natural frequencies and mode shapes at the sections before and after retrofitting.

Identification of mode shapes using LDVs

Figs.11 show identified mode shapes based on the ambient vibration measurement. Fig.11(a), (c) and (b), (d) show the mode shapes before and after attaching the stiffener for retrofitting respectively. Notice that although natural frequencies of both modes of Figs.11(a), (b) are the same 29.35 Hz, the mode shapes are greatly different. In Figs.11(c), (d), the natural frequency after retrofitting increases a little.

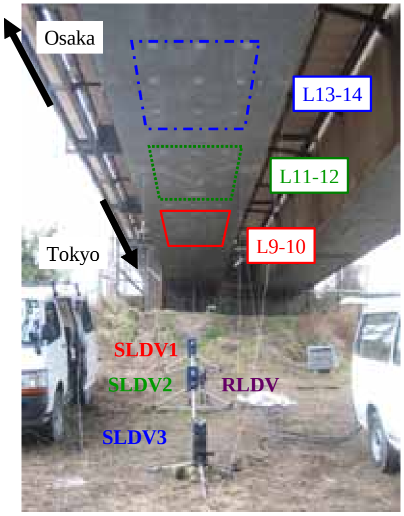
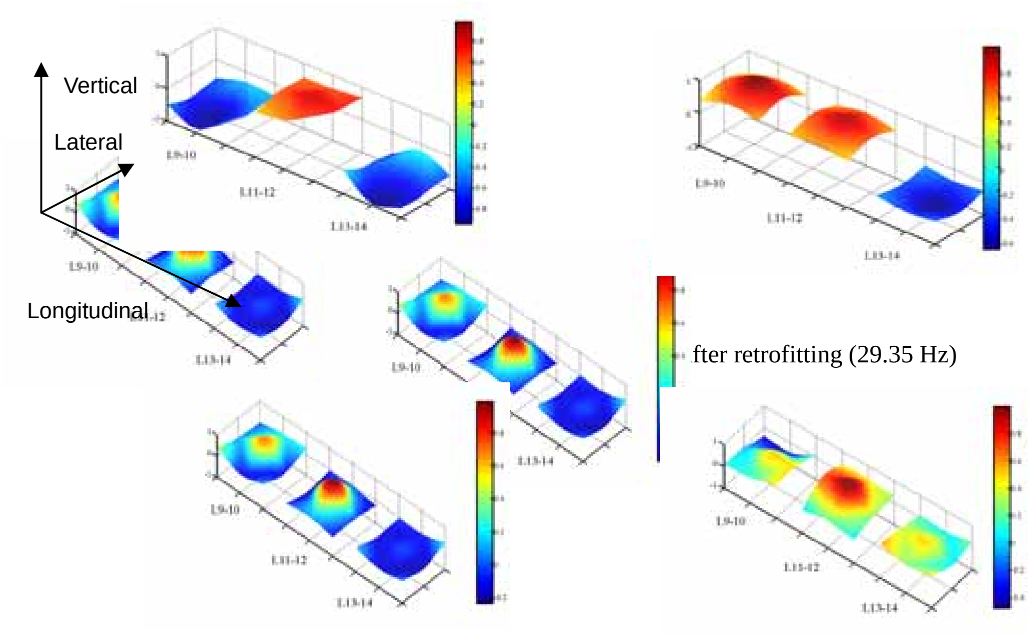


Figure 10. Vibration measurement of steel railway bridge using LDVs



fter retrofitting (29.35 Hz)

(c) Before retrofitting (32.75 Hz)

(d) After retrofitting (33.35 Hz)

Figure 11. Identified mode shapes from ambient vibration data using LDV

DEVELOPMENT OF MONITORING TECHNIQUE FOR SHINKANSEN RC VIADUCT USING LDV [3]

Background

Integrity evaluation for a RC viaduct of Shinkansen has been conducted by the impact vibration test proposed by Nishimura [4]. Here, global 1st natural frequency of the viaduct identified from impact test in lateral direction by 30kg weight mass has been utilized. However, there are some defects in this method; it requires dangerous works at high level and a lot of times, and it is difficult to access the viaduct after disaster, such as, when an earthquake occurs. Therefore, in this study, a new monitoring technique using LDV taking place of conventional technique was investigated.

Measurement system

Due to large stiffness of Shinkansen RC viaduct, amplitude level of ambient vibration becomes very low. Also, lower frequency components based on the external disturbances affect vibration measurement. The noise components due to the external disturbances should be eliminated in vibration measurement using LDV because vibration of the tripod setting LDV affects the measurement. In this study, measurement is compensated using the method proposed by Uehan et al [5]; a servo typed velocimeter put on the LDV measures the vibration of the LDV itself. Then, the velocity measured by the velocimeter is subtracted from the one measured by the LDV.

On-site measurement

During on-site measurements, a total of 11 points on the surface of an RC viaduct were selected, two per column and three on the main beam. Fig. 12 shows the location of the measurement points, whereas Fig. 13 shows the equipment set up on the field. The equipment was set up about 30 m facing the viaducts. The data acquisition system was set at a sampling rate of 1000 Hz. The left most measurement point on the beam was chosen as the reference. Once all of the measurement point coordinates were identified for scanning, the vibration at each point was measured in succession using the SLDV for 10 min per point, continuously. Thus, the record consists of ambient and train-induced vibration data which were separated during analysis.

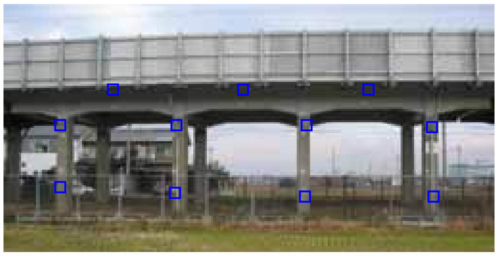
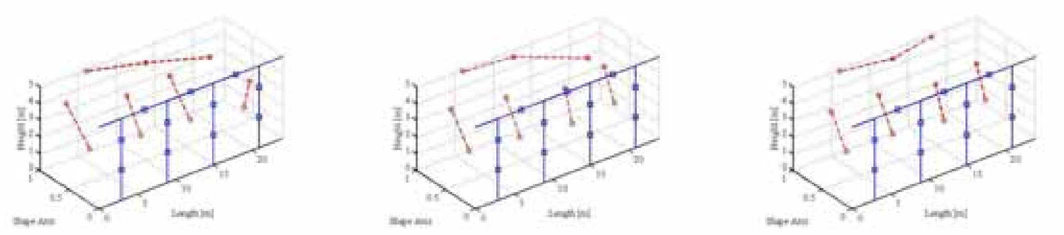


Figure 12. Location of measurement points

Figure 13. On-site measurement setup

Modal characteristics of viaduct

After eliminating external disturbances by the servo typed velocimeter attached on a LDV, global mode shapes of a viaduct were identified using cross spectrums calculated between measurement and referenced points. Averaged cross spectrums identified natural frequencies of the viaduct as 2.833Hz, 2.933Hz and 3.033Hz. In general, a viaduct has three mode shapes in longitudinal, lateral and vertical directions respectively. In order to distinguish identified natural frequencies, it is necessary to identify mode shapes. Fig.14 shows identified mode shapes corresponding to each natural frequency. Although the mode shape at 3.033Hz corresponds to the one in lateral direction, it is difficult to interpret the mode shapes at 2.833Hz and 2.933Hz. Actually, a close examination of the identified mode shapes [6] reveals that they are a combination of torsional and lateral modes. The phenomenon can be explained by dynamic structure interaction between adjoining viaducts due to the presence of the continuous rails.



(a) 2.833Hz

(b) 2.933Hz

(c) 3.033Hz

Figure 14. Global mode shapes of a viaduct (□: Measurement points, ○: Mode shapes)

TENSILE FORCE MEASUREMENT OF CABLES USING PORTABLE LDV

Up until now, research using LDV have been extensively conducted [1], [3] and [6] in order to develop quantitative SHM techniques for civil infrastructures. As one problem in this research, setting up of equipments requires time-consuming tasks. Because LDV is assumed to be utilized for vibration measurement such as a car or a hard disk drive in laboratory environment, constitution of equipment does not suite for on-site measurement as shown in Fig.15. Therefore, it has been difficult to measure large structures with moving all equipment.

A LDV used in this study is a commercial product (PDV-100) supplied by Polytec Inc. as shown in Fig.16. Its sensor head and controller is integrated into a body and driven by a battery. Measurement system using the LDV was developed in order to be possible to handle by a laptop PC. Because the system has very excellent movability, the number of working persons for measurement becomes few. Another characteristic of the LDV is to have not only analog output but also digital output.

The developed system was applied to tensile force measurement of cables in the Tatara Bridge. All 84 cables on one-side at the Tatara Bridge are investigated. Measurement condition is shown in Fig.17. Example of Fourier spectral amplitude calculated from ambient vibration is shown in Fig.18. The figure indicates the LDV having the ability to identify lower to higher natural frequencies. Fig.19 shows identified 1st to 12th natural frequencies of each cable. Fig.20 shows the comparison of 1st natural frequencies measured by the system on Sep. 2006 with ones calculated from measured tensile forces at completion on 1999. Although effect of temperature is not considered in this case, we can recognize the agreement of both results well. It spent about 8 hours on the measurement of all 84 cables. Therefore, a proposed system can be an effective solution for rapid and convinient SHM system.

Figure 15. Equipments for LDV measurement

Figure 16. Portable typed LDV

Figure 17. Measurement condition

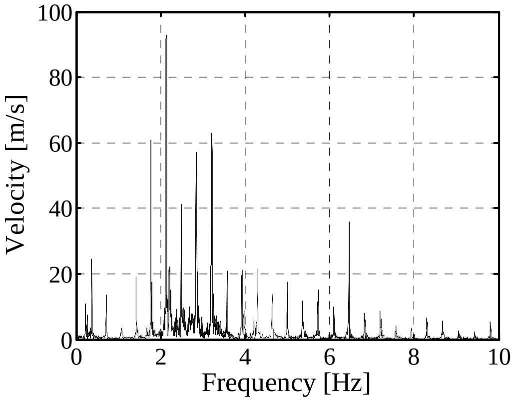


Figure 18. Example of Fourier spectral amplitude of a cable

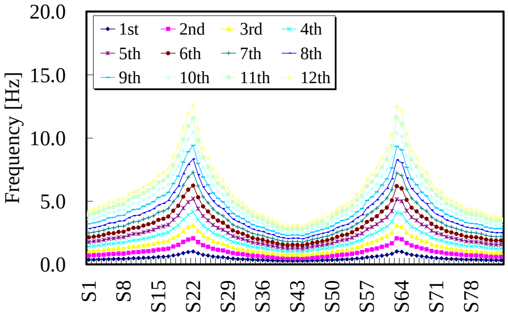


Figure 19. Identified natural frequencies of all cables

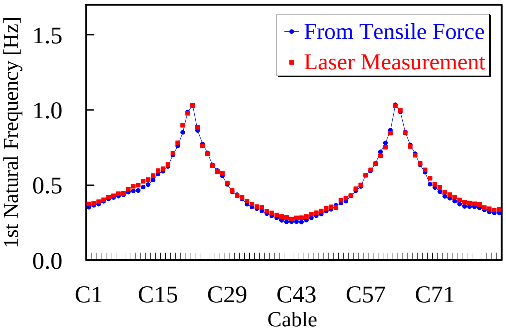


Figure 20. Comparison of 1st natural frequencies

CONCLUDING REMARKS

This paper presents three studies of advanced vibration measurement for bridges using laser Doppler vibrometers (LDVs). The followings conclusions can be drawn.

1. In a Shinkansen (Bullet Train) railway steel box girder bridge, fatigue cracks were observed at the bottom end of vertical stiffeners. In order to clarify the dynamic behavior of the bridge, vibration measurements using convectional sensors and LDVs were conducted. It was found that local vibration of a lower flange caused local stress in the web of a girder at the bottom end of vertical stiffeners

2. A new measurement system using LDVs for monitoring Shinkansen RC viaducts was proposed to replace of conventional impact-based monitoring. It was found that there ware three global mode shapes of a viaduct. One is a lateral mode and the others are a combination of torsional and lateral modes based on the presence of the continuous rails.

3. Compact and portable LDV measurement system was developed and applied to tensile force measurement of cables in the Tatara Bridge. The number of working persons for measurement becomes few due to very excellent movability of the system. The proposed system can be an effective solution for rapid and convenient SHM system.

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