

Advanced Vibration Measurement System for Infrastructures using Laser Doppler Vibrometers

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ABSTRACT:

A subjective visual inspection of infrastructures mainly has been conducted as conventional maintenance technique. Therefore, the development of quantitative maintenance techniques is required. This paper introduces three studies of advanced vibration measurement for infrastructures using Laser Doppler Vibrometers.

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 followings: 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 introduces three studies of advanced vibration measurement using LDVs in order to monitor infrastructures.

1. UNDERSTANDING OF HIGH-SPEED TRAIN INDUCED LOCAL VIBRATION OF A RAILWAY STEEL BRIDGE^{1), 2)}

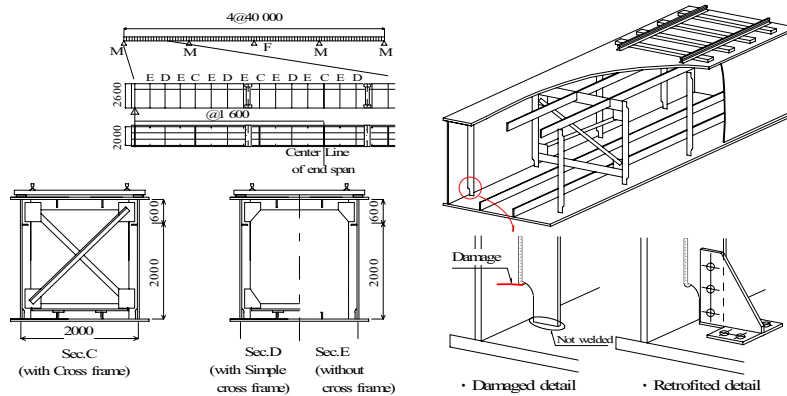
At a railway steel box girder bridge, damage was observed on the web of a main girder at the bottom end of a welded vertical stiffener. The objective of this study is to clarify the cause of the damage

Bridge for measurement

The investigated bridge is a pair of steel mono-box girders with 4 spans as shown in Figs.1. The stiffeners were not welded to the lower flange in the sections where positive moment affects the main girder. In bridges which have similar detail, damage was observed on the

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web of a main girder at the bottom end of a welded vertical stiffener. 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.



(a) Detail of bridge (b) Detail of Retrofitting (Sec.E)
Figure 1: The focused bridge for measurement

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 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. Furthermore, the strain gauges were installed on the lower flange on the main girder as shown in Fig.2.

Measurement results

Figs.3 show examples of the field data. Fig.3(a) shows 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 cyclic loading”³⁾ 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 - 30Hz.

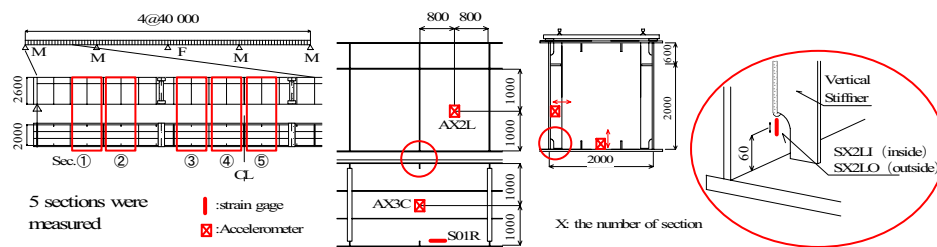
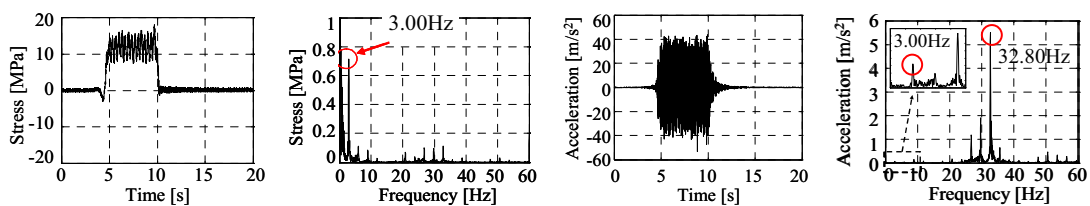


Figure 2: Measurement using conventional sensors



(a) Nominal stress of lower flange (b) Acceleration of lower flange
Figure 3: The results of measurement by conventional sensors

The relation between vibration and train speed

Fig.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 “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 main girder and that the frequency is an integer multiple of the frequency of the main girder.

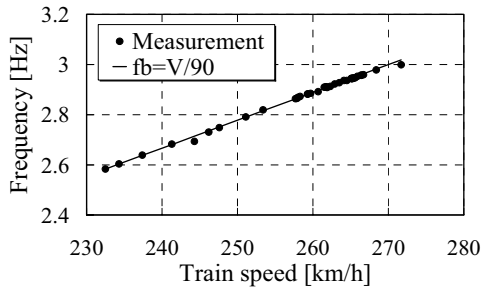


Figure 4: Train speed and frequencies of main girder

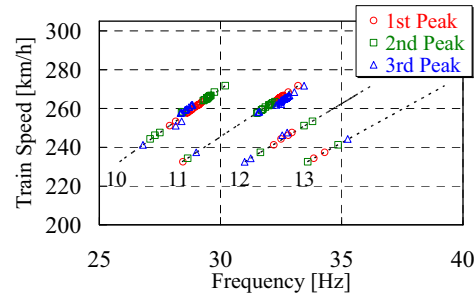


Figure 5: Train speed and frequencies of lower flange

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 stress and acceleration.

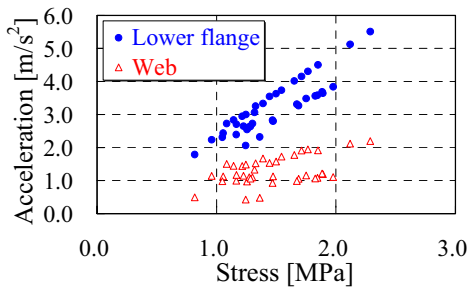


Figure 6: Correlation between stress and acceleration

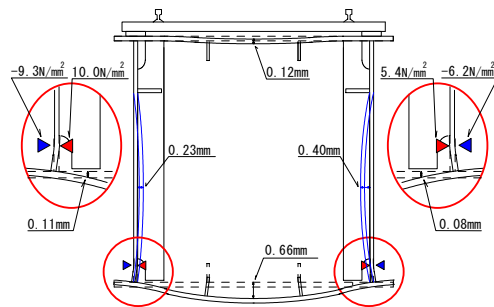


Figure 7: Local mode shape causing local stress

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 28.7Hz and another one is at 32.8Hz. 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 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 cyclic loading.

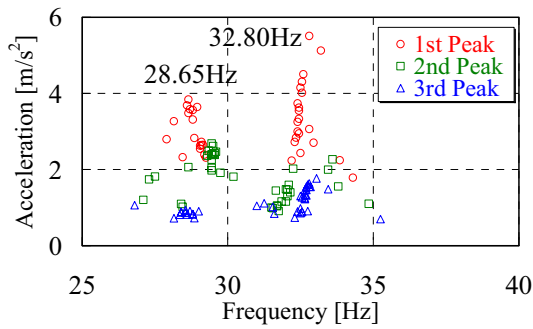


Figure 8: Fourier spectral amplitude and peak frequencies of lower flange

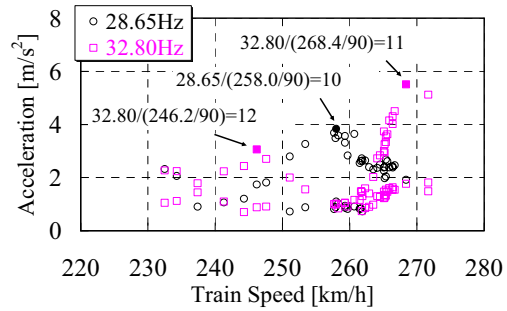


Figure 9: Train speed and Fourier spectral amplitude of lower flange

Measurement using LDVs

The measurement system consists of three scanning type LDVs at three sections and one single point type LDV. 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. 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.10 show identified mode shapes based on the ambient vibration measurement Figs.10(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.10(a), (c) are the same 29.3 Hz, the mode shapes are different. In Figs.10(b), (d), the natural frequency after retrofitting increases a little.

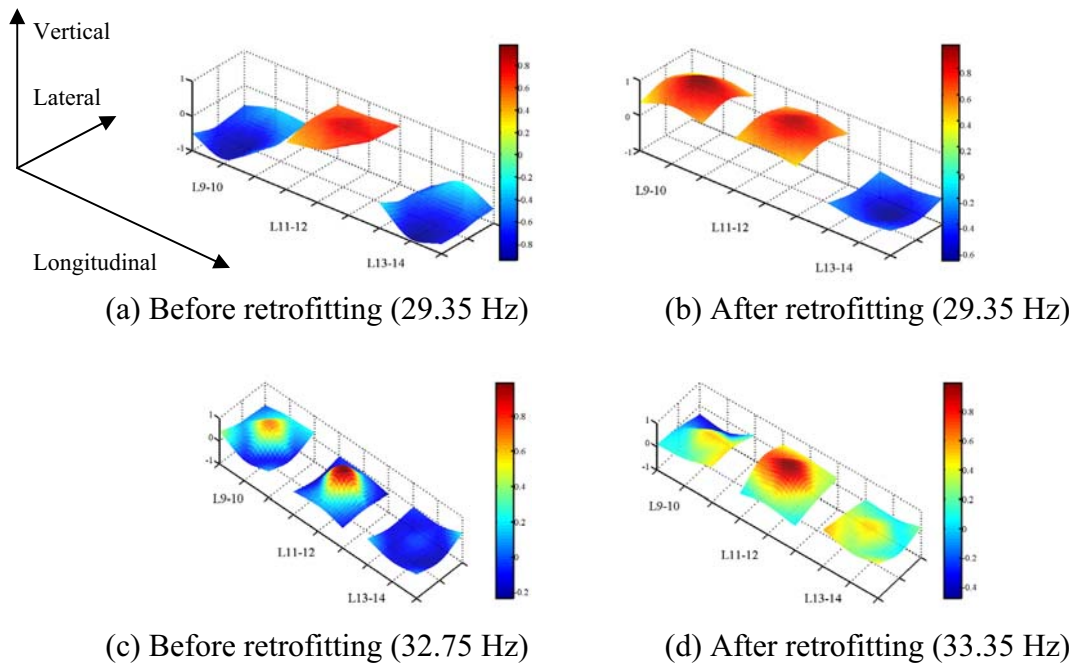


Figure 10: Identified mode shape from ambient vibration data using LDV

2. DEVELOPMENT OF THREE-DIMENSIONAL VIBRATION MEASUREMENT SYSTEM USING LDVS ^{4), 5)}

The objective of this study is to develop vibration measurement system using three LDVs, which makes possible to measure three-dimensional behavior of an object high accurately and spatially high densely. Since developed system can clarify the three-dimensional local deformation of structures caused by train/traffic-induced vibration, it can contribute to the preventive maintenance and the improvement of functionality in existing infrastructures.

Problem in one-dimensional vibration measurement using LDV

When only one LDV is used and the laser beam is perpendicular to the measurement surface, the velocity component perpendicular to the surface can be measured with very high accuracy. However, if the laser beam is not perpendicular to the surface, the accuracy of the velocity decreases depending on the laser beam angle.

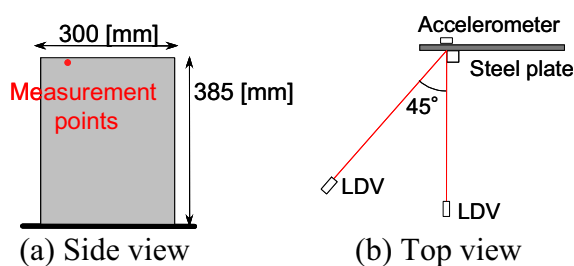
To investigate this problem, a simple experiment was conducted. Figs.11 show the experimental set up. First, a steel plate with an attached accelerometer was hit by a hammer. Then, a LDV measured the velocity of the plate from the direction making an angle of 45° with respect to the normal axis.

Fig.12 shows the comparison. The solid blue line is the velocity computed from the acceleration and the thin red dot line is the velocity from the LDV. Comparing these two velocities, their amplitudes are different, because the laser beam angle is not perpendicular to the surface. In order to obtain the vibration component perpendicular to the surface, compensation on laser beam angle is necessary such as Eq. (1).

$$V_m = V \cos \theta \quad (1)$$

where V_m is the velocity perpendicular to the surface, V is the velocity measured by the LDV and θ is the laser beam angle of the LDV.

The green thick dot line in Fig.12 is the velocity compensated by Eq. (1). Comparing the solid and thick dotted lines, their amplitudes agree well. Therefore, when only one LDV is used, it is necessary to install the LDV perpendicular to the surface to conduct accurate measurements. However, during field measurement using LDV, it is difficult to satisfy such a condition.



(a) Side view (b) Top view
Figure 11: Configurations of a LDV in one-dimensional vibration measurement

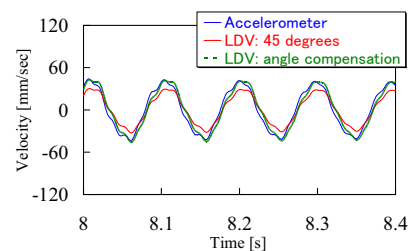


Figure 12: Measurements of 1D vibration measurement using a LDV

Three-dimensional measurement principle using LDVs

The principle of three-dimensional measurement involves a geometrical transformation of coordinates as shown in Fig.13. Three-dimensional vibration components of the body are determined from measurements of the three LDVs by premultiplying by a transformation matrix consisting of the direction cosines of the laser beam angles.

$$\begin{Bmatrix} V_x \\ V_y \\ V_z \end{Bmatrix} = \begin{bmatrix} \cos \alpha_1 & \cos \beta_1 & \cos \gamma_1 \\ \cos \alpha_2 & \cos \beta_2 & \cos \gamma_2 \\ \cos \alpha_3 & \cos \beta_3 & \cos \gamma_3 \end{bmatrix}^{-1} \begin{Bmatrix} V_1 \\ V_2 \\ V_3 \end{Bmatrix} \quad (2)$$

where V_x, V_y, V_z are vibration components of the body in each axes, V_1, V_2, V_3 are vibration components measured by each LDV and $\alpha_i, \beta_i, \gamma_i$ ($i=1,2,3$) are the laser beam angles of each LDV.

Fundamental investigation of three-dimensional measurement

As fundamental study, three multiple points type LDVs having a scanning system (SLDV) are set at parallel to a measurement surface. The surface was vertically irradiated with each LDV when input voltages are 0 [V]. Therefore, laser beam angles for the measurement points are directly obtained from mirror angles.

The developed system was applied to three-dimensional vibration measurement for a steel railway bridge. A tri-axial accelerometer was attached on the surface of the main girder for the purpose of validation. Fig.14 shows the setting of the SLDVs and the measurement axes of the accelerometer. Each SLDV was set parallel to the main girder and ground. Figs.15 show the comparison in each axes concerning time histories. These are free vibration components after a train passes through the railway bridge. Since both measurements agree well in each axis, the system can be applied to on-site measurement.

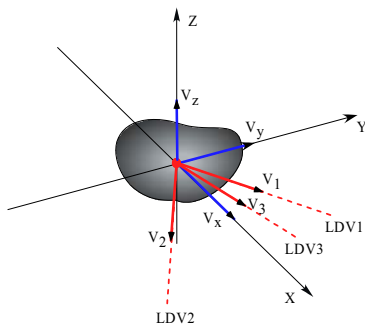


Figure 13: Three-dimensional vibration measurement using LDVs

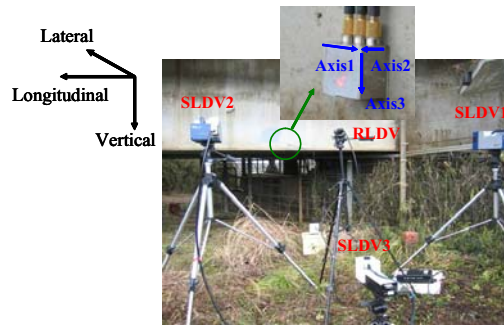
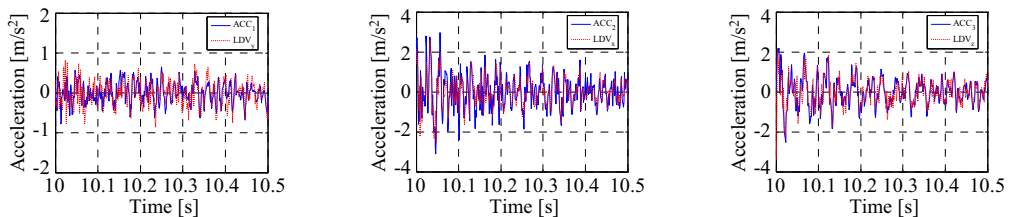


Figure 14: Configuration of field measurement



(a) Horizontal In-Plane (b) Horizontal Out-of-Plane (c) Vertical In-plane
Figure 15. verification of three-dimensional vibration measurement

3. DEVELOPMENT OF REMOTE NON-CONTACT MEASUREMENT SYSTEM BY COMBINING LASER DOPPLER VIBROMETER AND TOTAL STATION

In this Research, a non-contact measurement system which combines a LDV and a total station (TS) was developed. This system is capable of measuring a lot of cable members for long-span cable supported bridge applications, since it is especially suited for remote non-contact vibration measurements.

Measurement in Oshima and Tatara Bridges

The measurement was conducted by measuring the ambient vibration of the cables using conventional accelerometers and LDV simultaneously. Typical cable vibration frequency plots obtained from the LDV and the accelerometer data are shown in Figs.16 and 17.

At first, there was some concern that it will be difficult to determine the natural frequency of the cables in Tatara bridge due to the influence of sag and the contamination of the recorded data with many low-frequency vibrations. However, we were able to get good results, verifying the effectiveness of the LDV in identifying the natural frequency of cable elements.

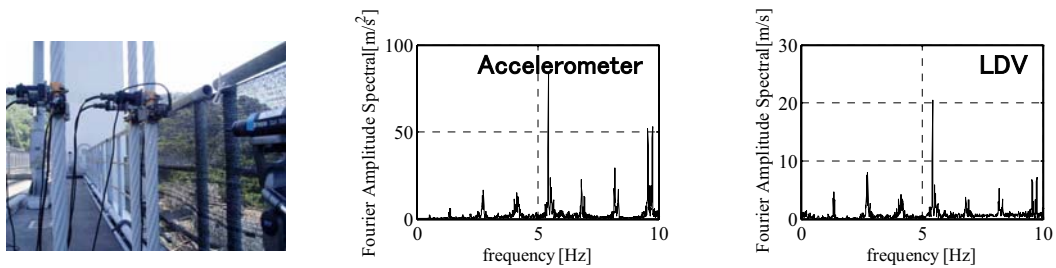


Figure 16: Comparison of the frequency plots from Oshima Bridge hanger rope

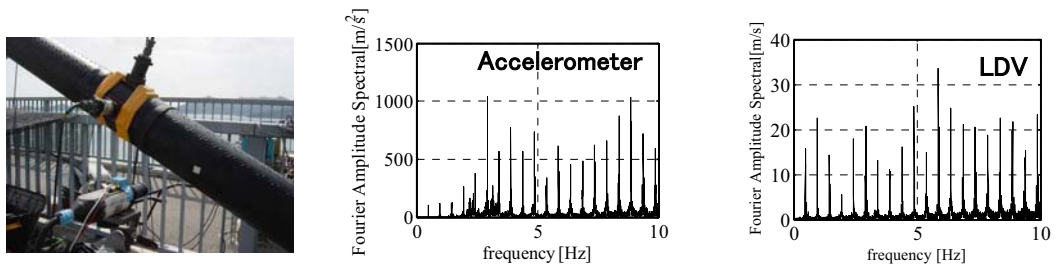


Figure 17: Comparison of frequency plots from a Tataru Bridge Cable

Combined LDV and TS system

When the measurement points are located far from the LDV, it is difficult to confirm the irradiation of the LDV's laser point during on-site measurements. To improve this situation, the measurement system with the LDV attached to a TS, having a highly accurate, remote measurement position identification ability, was developed. The TS poses 1 [mm] accuracy for 100m distance, making it possible to determine the exact position of any point (see Fig.18).

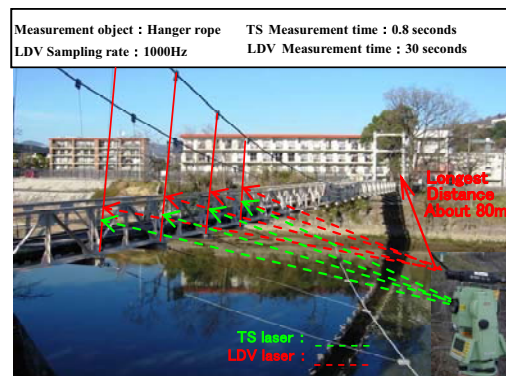


Figure 18: Combined LDV and TS system

The measurement consists of the following steps: 1) The reflection tapes are attached at the measurement points, 2) The orientation of the system is adjusted so that the reflection level of the LDV reaches maximum level, 3) The measurement time is set, 4) Each measurement point is identified with the TS and positional information is stored, 5) When the TS automatically aims at a measurement point using the stored position information, the data acquisition program detects a signal and automatically records vibration from the LDV, 6) Once the vibration measurement using LDV finishes, the TS automatically moves to the next measurement point. Once the coordinates of the points are identified, this system can repeat the measurements automatically.

At Kohei bridge in Hiroshima city, automatically repeated vibration measurement of hanger ropes was conducted. The measurement of a hanger rope from a distance of about 80m using LDV is shown in Fig.19. Moreover, the result of this hanger rope using an accelerometer is shown in Fig.20. It can be seen that the frequency peaks obtained from both sensors are in good agreement. Also, we are confirming that there is no change in the first and second natural frequencies for repeated measurements.

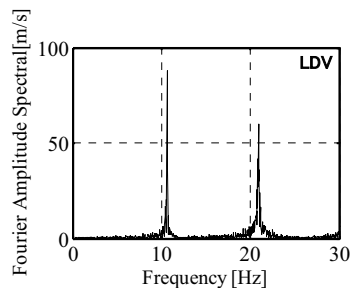


Figure 19: Measurement from about 80m distance using LDV

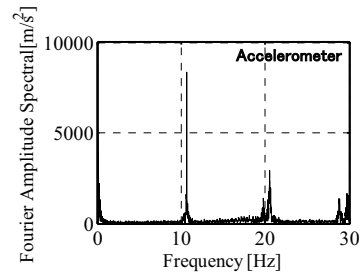


Figure 20: Measurement using accelerometer

CONCLUSIONS

This paper introduces three studies of advanced vibration measurement using LDVs for the purpose of monitoring infrastructures: 1) Understanding of high-speed train induced local vibration of a railway steel bridge. 2) Development of three-dimensional vibration measurement system using LDVs. 3) Development of remote non-contact measurement system by combing LDV and total station.

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