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Vibration-based Structural Health Monitoring for Bridges using Laser Doppler Vibrometers and MEMS-based Technologies

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Abstract

This paper describes several studies relating to the development of vibration-based Structural Health Monitoring (SHM) techniques for existing bridges. In the first half of the paper, for the purpose of realizing non-contact and remote measurement of bridges, SHM techniques using laser Doppler vibrometer (LDV) are reported; Firstly, compact and portable LDV measurement system was developed and applied to tensile force measurement of cables in a cable-stayed bridge. Next the system combining LDV with Total Station was developed for automated remote measurement of whole large bridge. In the latter half of the paper, SHM techniques using MEMS (Micro Electro Mechanical System) based technologies, which are expected to realize huge and dense sensor network for structures, are reported; A new wireless LAN accelerometer based on MEMS technology was evaluated and applied to field measurement of bridges.

Keywords: structural health monitoring, bridge, vibration, laser, MEMS

1. Introduction

Through the high level of research interests and activities in structural health monitoring (SHM) in the world, the concept of SHM is incorporated into bridges by installing a lot of sensors (Chang 2006). However, up until now, integrity diagnosis techniques for existing bridges have mainly been conducted by subjective visual inspections. Therefore, there is a strong need to establish objective and effective SHM techniques for existing bridges.

Deterioration or damage of a structure leads to the change of stiffness or mass. The change appears in dynamic characteristics such as natural frequency of the structure. Therefore, vibration-based SHM is quite effective (Fujino *et al*., 2002). Also recent development of measurement technologies is promising for vibration-based SHM.

This paper describes several studies relating to the development of vibration-based SHM techniques for bridges. In the first half of the paper, for the purpose of realizing non-contact and remote measurement of large bridge, SHM techniques using laser Doppler vibrometer (LDV) are reported; at first, compact and portable LDV measurement system was developed and applied to tensile force measurement of cables in a cable-stayed bridge. Next the system combining LDV with Total Station was developed for automated remote measurement of whole large bridge. In the latter half of the paper, SHM techniques using MEMS (Micro Electro Mechanical System) based technologies, which are expected to realize huge and dense sensor network for structures, are reported; A new wireless LAN accelerometer based on MEMS technology was evaluated and applied to field measurement of bridges.

2. Structural Health Monitoring using Laser Doppler Vibrometer

2.1. Laser Doppler vibrometer (LDV)

LDV is an optical instrument employing laser technology to measure velocity based on the Doppler principle. The characteristics of LDV are the followings: in comparison with conventional transducers such as an accelerometer, non-contact and long distance measurement is possible without adding mass or stiffness to an object. Secondly, velocity is measured very high accurately, and frequency bandwidth is very wide. Thirdly, by attaching a scanning unit of mirror in front of the laser sensor head, scanning measurement for multiple points can be realized.

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Figure 1. Equipments of measurement using LDVs.

Figure 2. Portable type LDV.

2.2. Tensile force measurement of cables in cable-stayed bridge

Up until now, researches using LDV have been extensively conducted (Kaito *et al*., 2000, Miyashita *et al.*, 2007, Hernandez *et al*., 2007) in order to develop quantitative SHM technique for civil infrastructures. As one problem in these researches, setting up of equipments requires time-consuming tasks. Since LDV has been utilized for vibration measurement such as a car or a hard disk drive in laboratory environment, equipments do not suite for on-site measurement as shown in Fig. 1. Therefore it has been difficult to measure large structures with for lack of portability.

A LDV used in this study is a commercial product (PDV-100) supplied by Polytec Inc. as shown in Fig. 2. Its sensor head and controller are 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. Since the system has very excellent movability, the number of working persons for measurement becomes few. The specification of the LDV is shown in Table 1. 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 Bridge are measured. A picture of measurement condition is shown in Fig. 3.

Table 1. Specification of portable type LDV

Type of Measurement	Velocity
Measurement Range (mm/s)	20 100 500
Velocity resolution (μm/s rms)	<0.05 <0.1 <0.3
Working distance	0.2 to 30 m
Laser safety	Eye safe class II
Analog velocity output	
Output voltage range	±4 V
Frequency range	0.5 Hz-22kHz
Digital velocity output	
Electrical S/P-DIF Interface	24 bit, 48 kSa/s
Frequency range	0-22 kHz
Dimensions	300(L)×63(W)×120(H) mm
Weight	2.6 kg
Operation temperature	+5 to 40°C
Power	11...14.5 V DC, max 15W

Figure 3. Measurement condition.

Tensile force in a cable is related to natural frequency by the following equation.

$$T = \frac{4WL^2}{n^2 g} f_n^2 (n = 1, 2, L) \tag{1}$$

where T is a tensile force in a cable, W is a weight of the cable, L is a length of the cable, g is gravitational acceleration and f_n are nth natural frequencies.

Example of Fourier spectral amplitude calculated from ambient vibration is shown in Fig. 4. The figure indicates the LDV having the ability to identify lower to higher natural frequencies. Fig. 5 shows identified 1st to 12th natural frequencies of each cable. Fig. 6 shows the comparison of 1st natural frequencies measured by the system on Sep. 2006 with ones calculated from measured

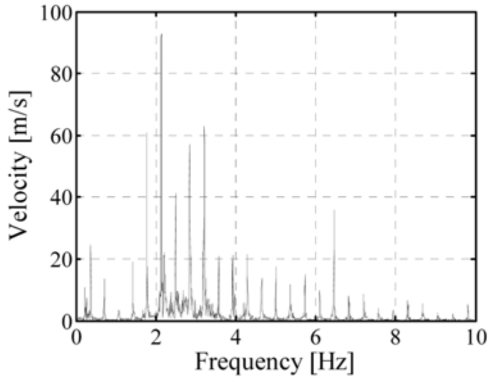


Figure 4. Example of Fourier spectral amplitude of a cable.

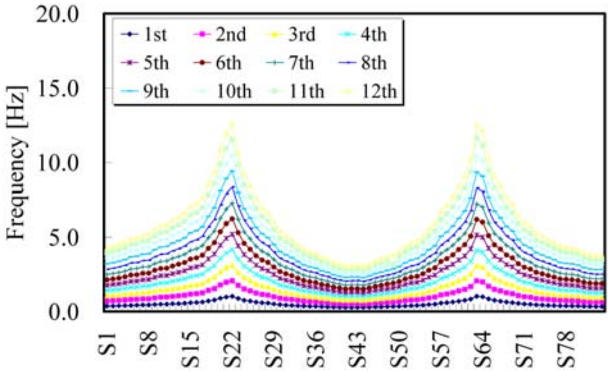


Figure 5. Identified natural frequencies of all cables.

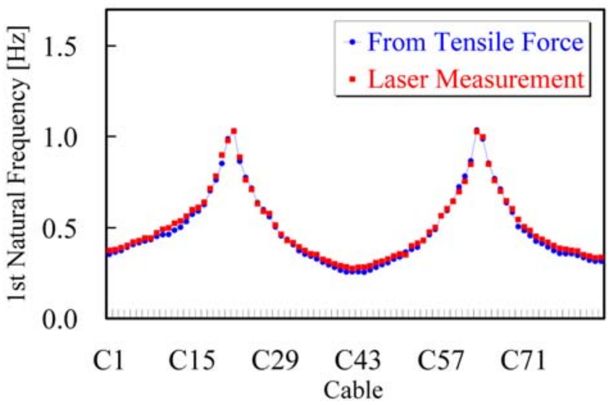


Figure 6. Comparison of natural frequencies.

tensile forces at completion on 1999. Although effect of temperature is not considered in this case, we can recognize good agreement of both results. It spent about 8 hours on the measurement of all 84 cables. Therefore proposed system can be effective in rapid and easily SHM system.

2.3. Automated remote measurement system for whole large bridge

When measurement points are far away from a LDV, it is difficult to confirm the irradiation of the laser during on-site measurements. To improve the situation, the measurement system combining the LDV with a Total

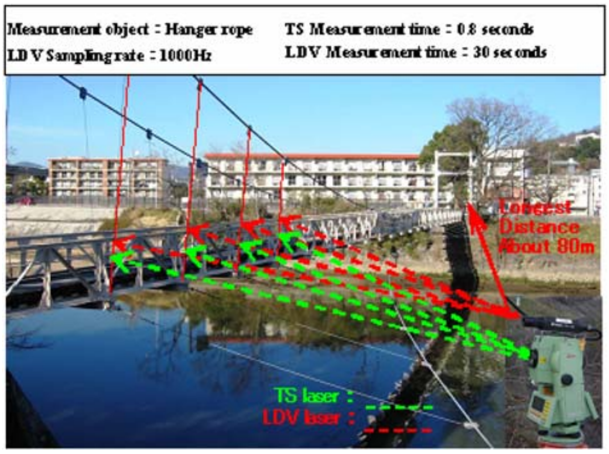


Figure 7. Automated remote measurement system using LDV and Total Station.

Station (TS) for survey was developed as shown in Fig. 7. The LDV is attached on the top of the TS. The TS used in the study posses 1 mm accuracy at 100 m distance. The system has the ability of positioning measurement points high accurately as well as remotely.

Automated remote measurement using developed system is carried out as the following procedures: 1) The reflection objects such as tape or prism are attached on the measurement points, 2) The orientation of the system is adjusted in order that the reflection level of the LDV reaches maximum level, 3) The measurement time is set, 4) Each measurement point is surveyed by the TS, and then the positional information is stored inside, 5) When the TS automatically hits a measurement point using the stored information, data acquisition using the LDV begins, 6) Once vibration measurement using LDV finishes, the TS automatically moves to the next measurement point. After finishing measurement at all points, the system can repeat the measurements automatically.

At a foot bridge, on-site experiment for validation of the developed system was conducted as shown in Fig. 7. The maximum measurement distance to a hanger rope was about 80 m against 30 m in the specification of the LDV. Measurement results of the hanger rope are shown in Fig. 8. It is found that the frequency peaks obtained from both LDV and an accelerometer show good agreement. And also, repeatability of identification on 1st and 2nd natural frequencies was confirmed.

3. Structural Health Monitoring using MEMS-based Technoclogies

3.1. Introduction

A wireless LAN accelerometer utilized in the study is a commercial product (DATAMARK SU100) supplied by Hakusan Corp. in Japan as shown in Fig. 9. Specification of the accelerometer is shown in Table 2. Although it inevitably lacks measured data due to no-checking of data transmission, it has following merits; wireless measurement

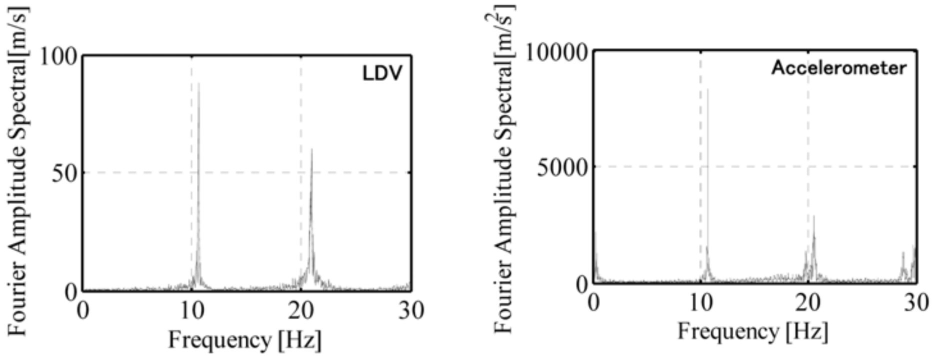


Figure 8. Measurements of the developed system and accelerometer for validation.

Figure 9. Wireless tri-axial MEMS based accelerometer.

Table 2. Specification of wireless LAN Accelerometer based on MEMS technology

Type	Electric capacity
Frequency	0.1 to 50 Hz
Channels	3
Range	±1.5 G
Resolution	18 bits
Sampling rate	100 Hz
Wireless LAN	IEEE 802.11 b
Transfer rate	11 Mbps
Distance	About 100 m (Outside)
	About 60 m (Inside)
Battery	6 V
Size	147×25×5 mm
Weight	About 850 g including batteries

at about 100 m distance on outside, tri-axial measurement, synchronized measurement between sensors and battery driven (about 10 hours). Wireless measurement can eliminate a lot of works and time such as needed in connecting cables. Also, tri-axial measurement can capture local three-dimensional behavior. Therefore the accelerometer is greatly effective device for quantitative SHM.

At first, in order to verify the applicability of the accelerometer to real structures, performance evaluation test was conducted. Then, the technique identifying whole mode shapes of a bridge from partially identified mode shapes using the accelerometers is proposed and validated by on-site measurement.

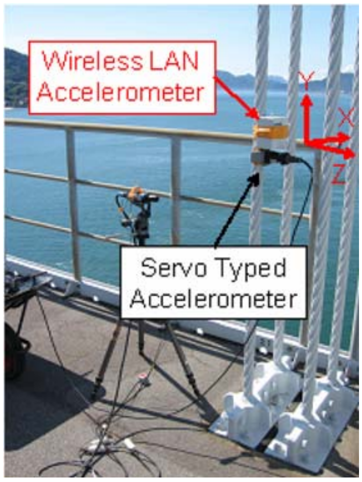


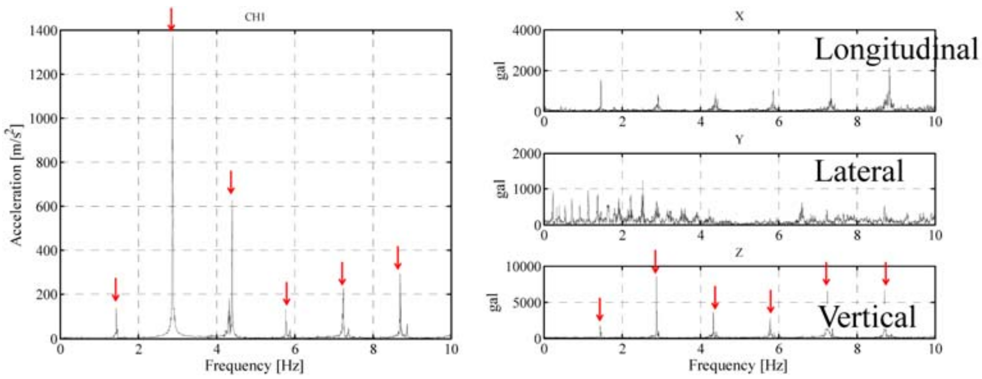
Figure 10. Performance evaluation test.

3.2. Performance evaluation of sensor

3.2.1. Investigation on fundamental performance

At first, fundamental performance of the wireless accelerometer was evaluated. As shown in Fig. 10, the wireless accelerometer and a servo type accelerometer for validation were attached on a hanger cable of a suspension bridge. Ambient vibration measurement was conducted, and then their corresponding Fourier spectral amplitudes (FSAs) were compared as shown in Fig. 11. Frequencies giving peak of FSA correspond to natural frequencies of the cable. We can recognize the agreement of both natural frequencies.

Next, since MEMS-based sensor is often insufficient in measurement resolution, the performance for ambient vibration measurement of a bridge was evaluated. The wireless accelerometer was put on the Tatara Bridge, and then ambient vibration measurement was conducted. Fig. 12 shows time histories in three measurement directions and their corresponding FSAs. Measurement directions in the figures up to down are longitudinal, lateral and vertical directions respectively. We can recognize from



(a) Servo type Accelerometer (b) Wireless accelerometer

Figure 11. Comparison of Fourier spectral amplitudes (Arrows indicate natural frequencies).

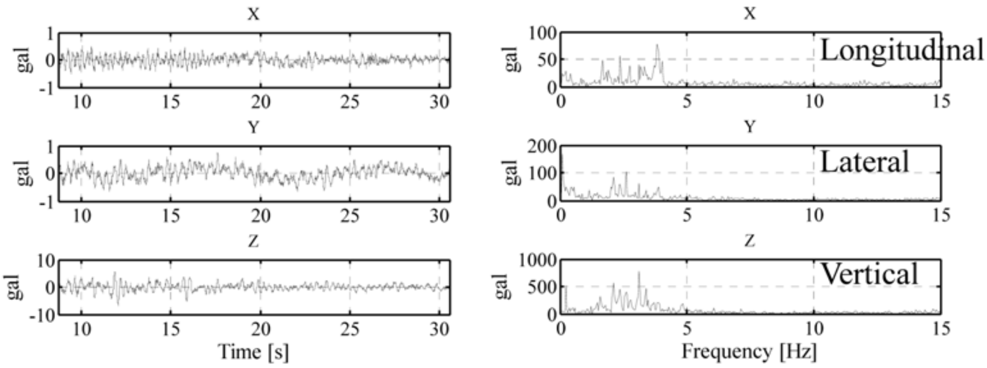
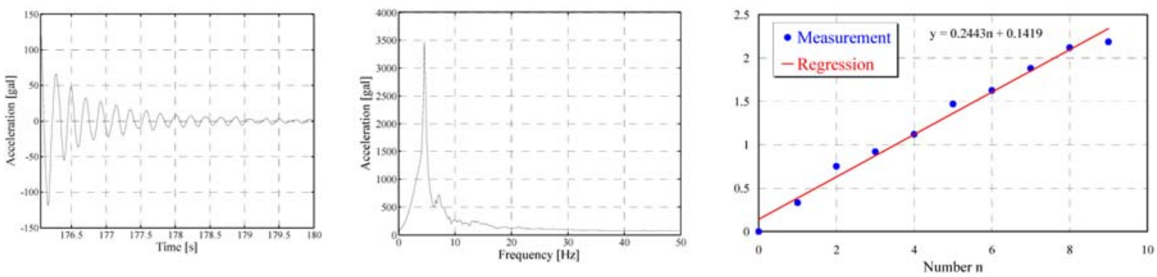


Figure 12. Measurement results by a wireless LAN accelerometer.



(a) Free vibration response (b) Fourier spectral amplitude (c) Logarithmic damping ratio

Figure 13. Simple modal testing using wireless accelerometer.

time histories that the wireless accelerometer can acquire ambient vibration of bridge. Previous modal testing at the Tatara Bridge identifies 1st lateral and vertical natural frequencies as 0.102 Hz and 0.227 Hz. As shown in Fig. 12, 1st natural frequencies in lateral and vertical directions are identified as 0.091 Hz and 0.228 Hz using the sensor. Therefore, it is found that the wireless accelerometer makes possible to measure ambient vibration of bridge.

3.2.2. Investigation on identification of dynamic characteristics

This section introduces the study that dynamic characteristics of a bridge were identified by simple modal testing using the wireless accelerometer. Investigated bridge is a foot-bridge made from glass. The accelerometer was put on the centre of the bridge, and then time history with human walking excitation was measured. Free vibration part in measured data was extracted as shown in Fig. 13a), and then its corresponding FSA was calculated as shown in Fig. 13b). As a result, 1st natural frequency in vertical direction was identified as 4.6 Hz. Next, after logarithmic damping ratio was calculated from free vibration as shown in Fig. 13c), damping ratio was identified as 0.038. Finally Fig. 14 shows the result adjusting a spring-mass model by one degree of freedom using identified natural frequency and damping ratio to measurement. Curve fitting data (dot line) agrees well with measurement (solid line).

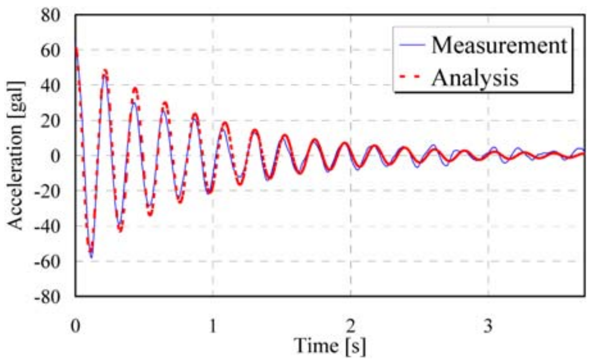


Figure 14. Comparison of analysis with measurement.

3.3. Identification of mode shapes using only two sensors

In general, mode shape is effective for local damage detection in SHM (Shon *et al*., 2003). However, a bride is spatially large structure. Therefore, it is necessary to install a lot of sensors on the bridge in order to identify mode shapes. When the limitation of the number of sensors prevents synchronized measurement on whole bridge, there is a technique identifying whole mode shapes of a bridge from partially identified mode shapes. In this section, identification technique of mode shape for whole bridge using two wireless accelerometers is proposed, and then its validity is verified at on-site.

The principle of proposed technique is shown in Fig. 15. At first, a synchronized measurement of ambient vibration using two accelerometers is conducted, and then cross spectrum between two measurement points is calculated from time histories. Cross spectrum can eliminate noise components without correlation and emphasize same components. Natural frequencies are identified by peak values of amplitude of cross spectrum. Next, after Fourier spectral amplitudes at a natural frequency are obtained, the ratio of Fourier spectral amplitudes is calculated. Here either two points at Unit 1 is set to become a referenced point. When the phase of cross spectrum ranges from −90 degrees to +90 degrees, the phase between measurement and referenced point becomes same. Otherwise the phase becomes opposite. After finishing measurement at Unit1,

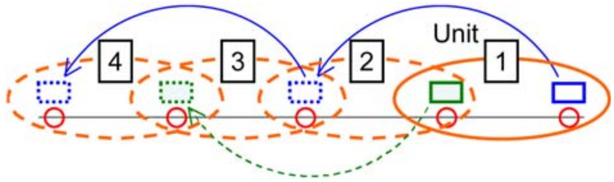


Figure 15. Identification procedure of mode shape.

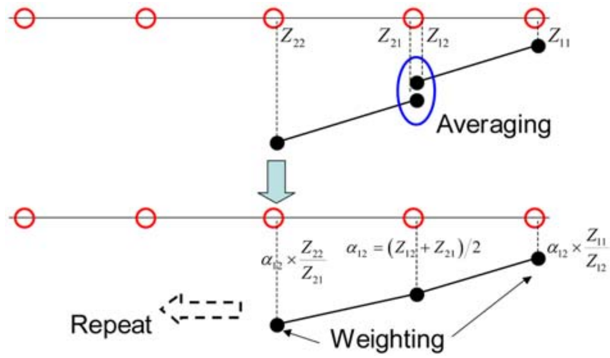
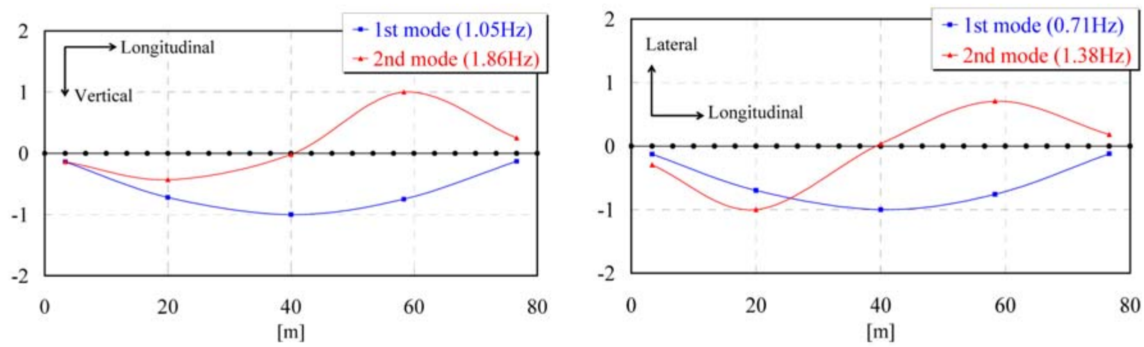


Figure 16. Connection of partial mode shape.

Unit 2 is formed by remaining one accelerometer at same point and moving the other to next measurement point. Also at Unit2 partial mode shape is identified by signed Fourier spectral amplitudes similar to Unit 1.

Figure 16 shows the method connecting partial local mode shapes identified at Unit 1 and 2. At first, averaged Fourier spectral amplitude at same point between Unit 1 and 2 is calculated. Then, weights for each measurement point are calculated based on the averaged and original Fourier spectral amplitude, and original ones are modified. Thereafter above procedure is repeated at each Unit formed by the movement of accelerometer. Finally whole mode shapes of a bridge are identified from partial mode shapes. When higher whole mode shapes are needed, it is better to shorten the distance of movement of accelerometer and increase the number of total Unit.

Investigated bridge for validation of the proposed method is a foot bridge, which is a suspension bridge and its length is 80 m. In the validation, since it is aimed to



(a) Vertical direction (b) Lateral direction

Figure 17. Identified mode shapes.

identify 1st and 2nd mode shapes of the bridge, 5 measurement points are set to become same intervals to the span. As a result, the number of Units becomes 4. Sampling frequency is fixed to 100 Hz due to the specification of the accelerometer. And measurement time at each Unit is set to become 15 to 20 minutes.

From measurements at each Unit, natural frequencies are identified as the followings; 1st lateral mode is 0.71 Hz, 2nd lateral mode is 1.38 Hz, 1st vertical mode is 1.05 Hz and 2nd vertical mode is 1.86 Hz. Figure 17 shows identified mode shapes in lateral and vertical directions using proposed method. It is found from the results that expected mode shapes are obtained by the method. Since proposed method enables the identification of mode shapes simply and at a low cost, this method becomes effective for the validation of analytical model and its updating.

4. Concluding Remarks

This paper describes several studies relating to structural health monitoring techniques based on vibration measurement using laser Doppler vibrometer (LDV) and MEMS-based technologies. The followings can be concluded.

1) 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 a result, the number of working persons for measurement becomes few due to very excellent movability of the system.

2) The system combining a LDV with a Total Station (TS) was developed for the purpose of automated remote measurement for whole large bridge. The LDV is attached on the top of the TS. The system has the ability of positioning measurement points high accurately as well as remotely.

3) A new wireless LAN accelerometer based on MEMS technology was evaluated and applied to field measurement of bridges. At first, fundamental performance of the accelerometer was evaluated. It was confirmed that the accelerometer made possible to measure ambient vibration of a bridge. Then, using the accelerometer, dynamic characteristics of a bridge were identified by simple modal testing. Finally, the method identifying mode shapes of a bridge using only two accelerometers were proposed. Herein, whole mode shapes are identified from partial mode shapes. Its validity was verified by on-site measurement.

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