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DEVELOPMENT OF A REMOTE NON-CONTACT MEASUREMENT SYSTEM BY COMBINING LASER DOPPLER VIBROMETER AND TOTAL STATION FOR MONITORING OF STRUCTURES

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INTRODUCTION

There are many cable-supported bridges at Honshu-Shikoku Bridge Expressway Company in Japan. This implies a large amount of labor and risky inspections are necessary for maintenance and monitoring of these large structures. It is forecasted that the cost of inspection will be very expensive, and will become a big burden in the future. Cable vibrations are normally measured with an accelerometer, and the condition of the cable is determined based on its natural frequency. However, these methods require the use of many accelerometers and cable connections, including measurement equipment such as amplifiers and a PC on the site. Additionally, installation of the accelerometers at high elevation is unsafe. A large amount of labor and expenditures have already been spent due to the the above-mentioned reasons for the monitoring of the cable member because it is of critical importance. In this research, to improve safety and work of vibration measurement in cable-supported bridges, we developed a remote non-contact measurement system by combining Laser Doppler Vibrometers (LDV) and total station (TS). By using this system, most of existing cable members, girder, and pylon can be monitored quickly, easily and safely.

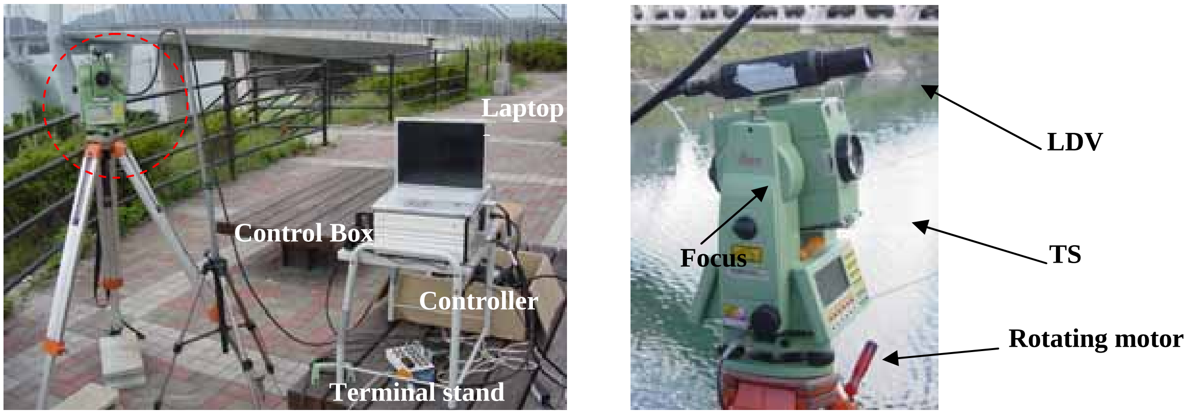


Figure 1. Measurement system by combining Laser Doppler Vibrometer (LDV) and Total Station(TS)

CHARACTERISTICS OF THIS MEASUREMENT SYSTEM

Past measurements using Laser Doppler Vibrometer had the following disadvantages:

1) The measurement system was complicated during installation.
2) During long-distance measurement, it is very difficult to aim at the desired measurement point
3) The system was expensive
4) The scanning angle of the system was limited to ±20°.

But, this system enables the following:

1) Using Total Station, we can confirm the location of the laser in the measurement position.
2) It is possible to save the measurement position using the three dimensional coordinates of the point.
3) Using the rotating motor of the Total Station, the scanning angle of the system is ±90°.
4) It is possible to control the LDV and TS using only one laptop.

Moreover, using prisms, we developed the technique by which the measurement distance was greatly increased. The measurement system is very compact compared with the measurement equipment of the old model, it also simplified the installation, and was able to decrease the amount of work involved for the monitoring of structures, reducing the amount of errors in measurement (refer to Figure1).

MEASUREMENT EXPERIMENT IN OSHIMA BRIDGE AND TATARA BRIDGE

During measurement, the vibration of the cable was measured simultaneously by LDV and accelerometer for comparison. The natural frequency identified with LDV and the accelerometer is shown in Figure 2 and Figure 3 for a typical cable.

Initially, we expected to encounter difficulty during measurement because of the low-level of the natural frequency as the shape of waves of FFT fell into disorder due to the influence of sag and the entire bridge of Tatara Bridge. But we were able to measure well. The measurement showed that the LDV is very effective in identifying the natural frequency of the cables by non-contact measurement [1].

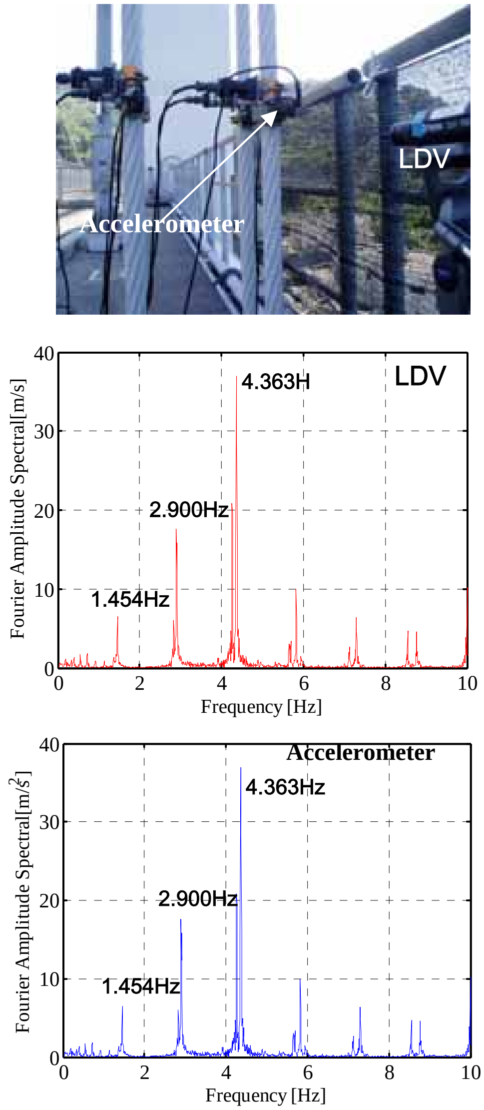


Figure 2. Comparison of the natural frequency in Oshima Bridge hanger rope

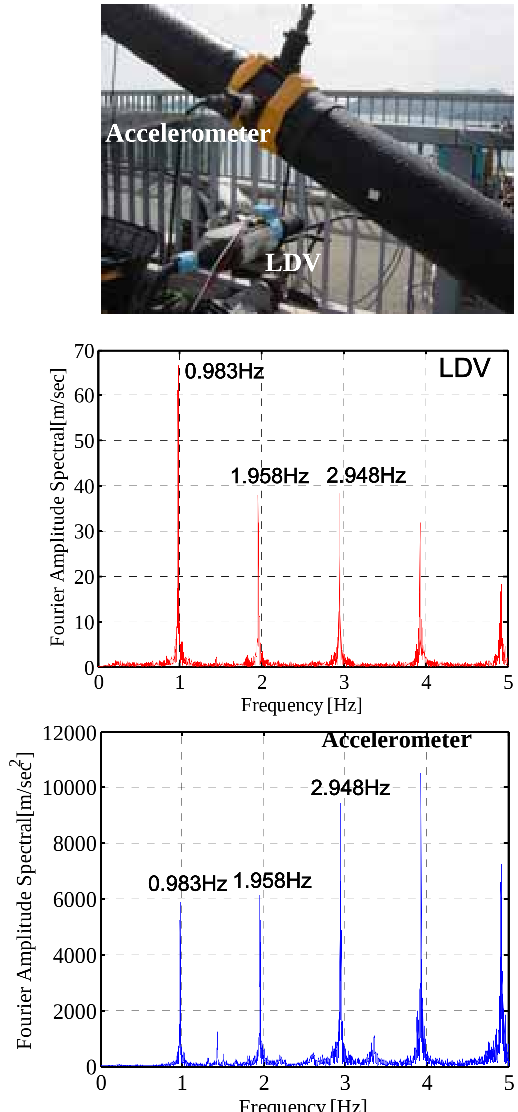


Figure 3. Comparison of the natural frequency in Tatara Bridge stay cables

MEASUREMENT USING LDV AND TS COMBINED SYSTEM IN KOUHEI BRIDGE

When the distance of the measurement point is far away, it is difficult to confirm the irradiation of the LDV's laser spot with the unassisted eye on-site. Thus we developed the measurement system which installed an LDV on the TS, which has a highly accurate, remote measurement position identification ability (shown in Figure 4). TS can absolutely determine the coordinate system. In addition, it is capable of highly accurate positional identification ability of 1mm for 100m distance ahead.

The measurement method and the outline of the control program are discussed below. STEP1. The reflection tapes are set up in the measured points. STEP2. The laser point is adjusted so that the reflection level of the laser at the measurement point attains its highest level. STEP3. The measurement time is set. STEP4.Aims at each measurement point with TS, and positional information is memorized in TS. TS's measurement time is 0.5 seconds. STEP5. When TS rotates to the position of the saved measurement points, the signal is transmitted to the program from the TS side to the LDV side and an automatic measurement of LDV starts. STEP6. At the stage where an automatic measurement on the LDV side ends,

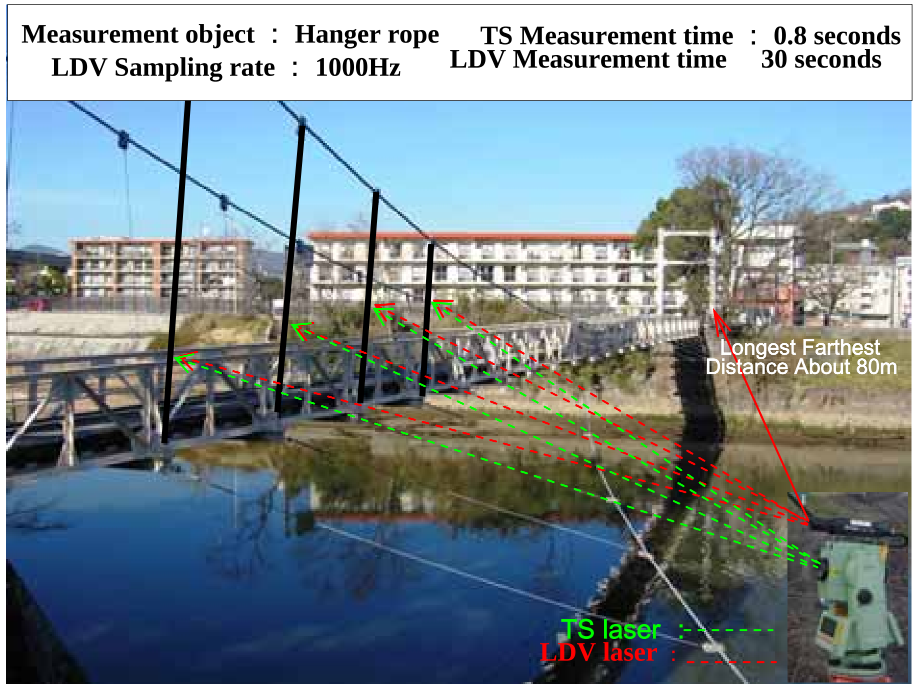


Figure 4. Experiment of LDV and TS combined system in Kouhei bridge

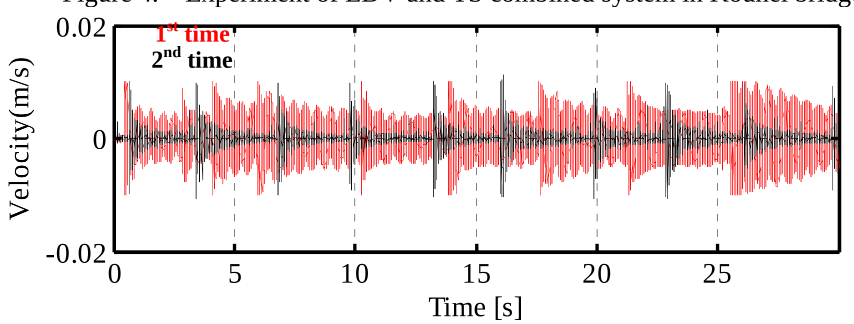
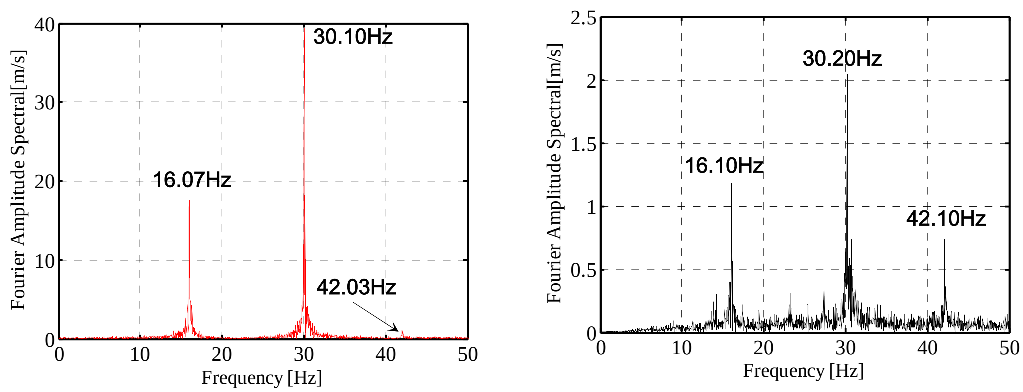


Figure 5. Time-history of Measurement result for hanger rope about 80m away



a) 1st time **b) 2nd time**

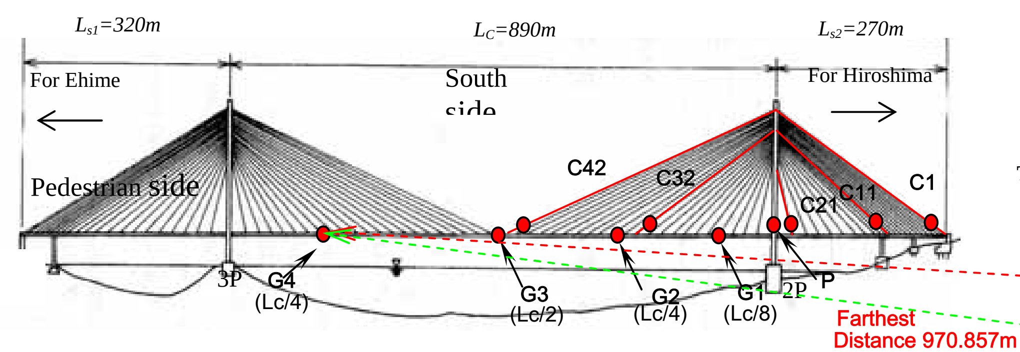
Figure 6. FFT of measurement results for hanger rope

TS moves to the next measurement point. The vibration measurement of all the hanger ropes was executed by repeating steps 5 and 6. LDV's measurement time is 30 seconds. Sampling rate is 1000 Hz. This system can automatically repeat measurement thereafter with the location of the measurement point provided only once. Additionally, there is a feature in place where the LDV and TS can be controlled using one laptop PC. We measured all the hanger ropes twice, validating that repeated measurements can be made automatically.

The vibration measurement result of the hanger rope about 80m away from the system is shown in Figure 5 and Figure 6. In the experiment, the hanger rope was hit to vibrate. The natural frequency of the first time and the second time measurement are in very good agreement, and it is understood that there is reproducibility in the number of peculiar vibrations measured by this system. Moreover, it is confirmed that it is almost the same natural frequency as measured with the accelerometer [1][2]. We could check the effectiveness of this system in Kouhei bridge measurement.

MEASUREMENT EXPERIMENT OF REPETITION IN TATARA BRIDGE

To further confirm the effectiveness of this system, the measurement was done repeatedly for Tatara Bridge's cables, girder, and tower. The outline of the experiment is shown in Figure-7 and Table-1. This system can measure each member in bulk. The measurement points are in ten locations in total. The prism was set up in each measurement location beforehand. In this research, it is shown that we are able to extend the measurement distance of the laser with a prism instead of the reflection tape. The measurement was conducted beginning at 15:00 PM, and repeated at each measurement point 12 times up to 9:00 AM of the following day. The maximum measurement distance is about 970m.



The prism was set up
At each
location.

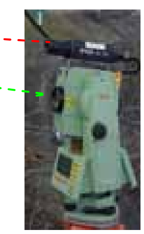


Figure 7. Measurement locations in Tatara Bridge

Table 1. The measurement order and distance from instrument

Order	1	2	3	4	5	6	7	8	9	10
Measurement Point	C1	C11	C21	P	G1	G2	C32	C42	G3	G4
Distance (m)	50.844	124.865	278.383	302.288	390.968	525.719	529.526	725.841	800.252	970.857

Table 2. Comparison of the natural frequency from past measurement

Member	1st Natural Frequency (ambient vibration)	
	Measured in the past (by accelerometer)	1st time in 2006.9 (by LDV)
C1-cable	0.371Hz	0.373Hz
C11-cable	0.496Hz	0.495Hz
C32-cable	0.415Hz	0.417Hz
G3-Girder	0.102Hz	0.103Hz

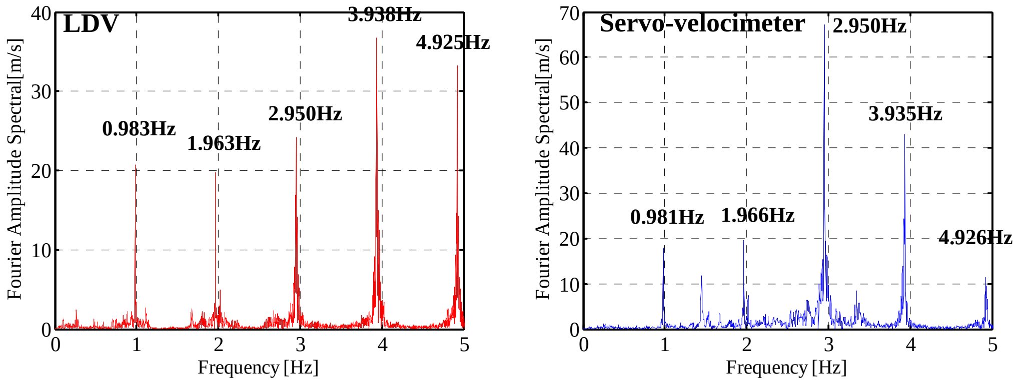


Figure 8. Comparison of the natural frequency (C21)

Comparison with natural Frequency measured with servo type sensor

The natural frequencies of ambient vibration measured by servo- accelerometer in the past are shown in Table 2. The natural frequenies measured by LDV and the servo-velocimeter in cable C21 are shown in Figure 8 (a) and (b), respectively. It can be seen that the natural frequency measured for the first time from these results is in good agreement with the natural frequency remotely measured by LDV. This shows that our system is capable of accurately remotely measuring vibration of structures.

Repeatability of measured natural frequency

The natural frequencies measured from the 1st time to the 12th time are shown in Figure 9 to Figure 12. Measurement point is C1, C32, C42, and G4. These natural frequencies were measured by this system. It is easy to see the identified natural frequencies from these figures, also that the natural frequencies from low-level to higher-order are in good agreement.

Next, the rate of change of the natural frequencies were calculated by using the following equation.

$$\left|\frac{F_i - F_{ave}}{F_{ave}}\right| \times 100 = F_c(\%)$$

F_i : natural frequency of each time

F_{ave} : natural frequency of average in each measurement point

F_c : change of natural frequency ratio

As a result, it is understood that the natural frequency measured has a rate of change within 4%. The result is shown from Figure 13 to Figure 16. This observation naturally follows because the Tatara bridge is under use, and natural frequency changes will be small due to temperature change according to the change in the weather, wind, and traffic load. It is thought that this rate of change originates from these external factors [3].

We have shown that this system has both mobility and accuracy for possible practical use from these results to measure the natural frequency of the members of a large structure.

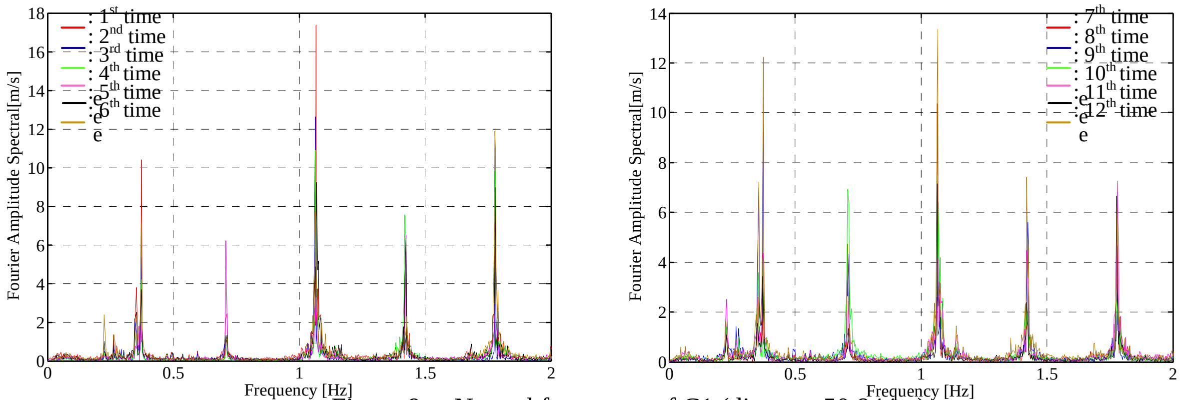


Figure 9. Natural frequency of C1 (distance 50.844m)

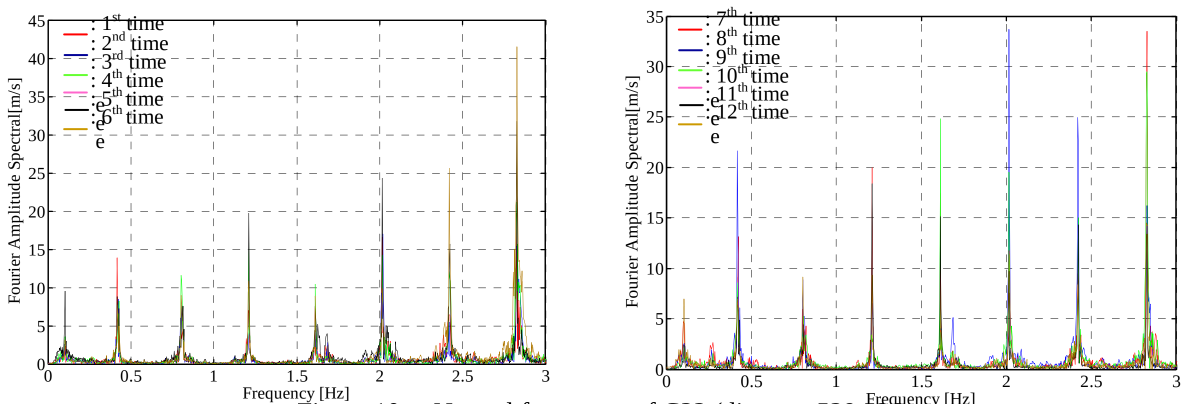


Figure 10. Natural frequency of C32 (distance 529.526m)

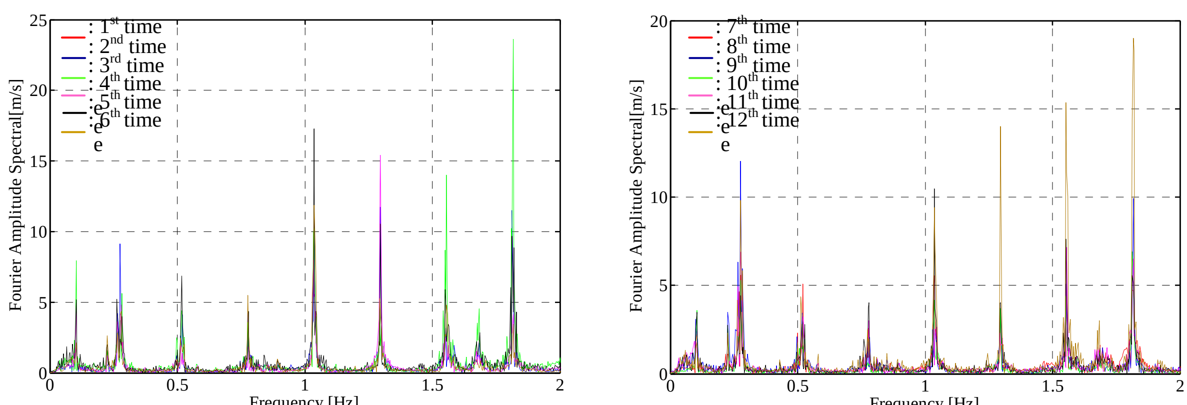


Figure 11. Natural frequency of C42 (distance 725.841m)

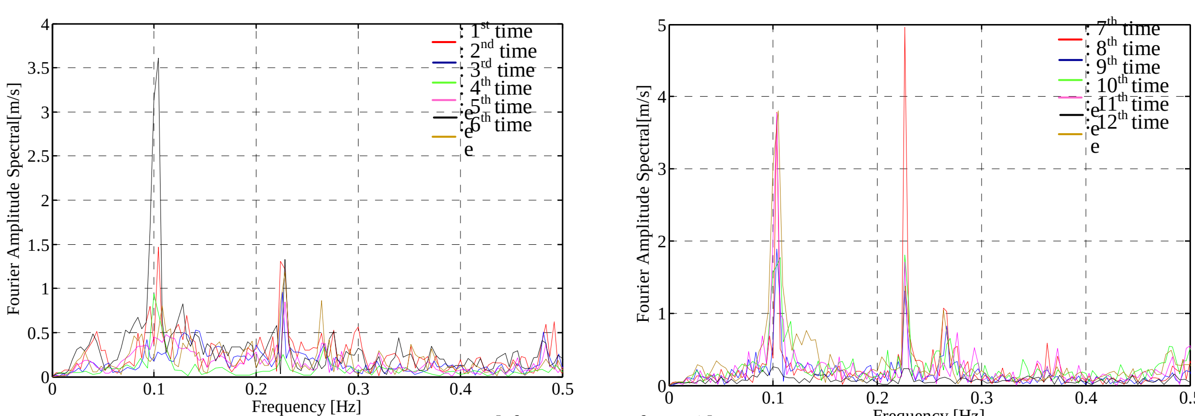


Figure 12. Natural frequency of G4 (distance 970.857m)

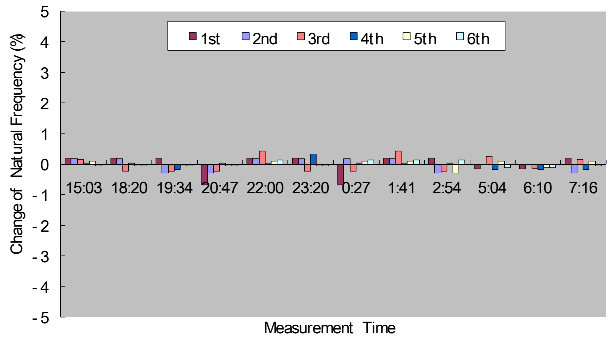


Figure 13. Change of natural frequency from average of C1

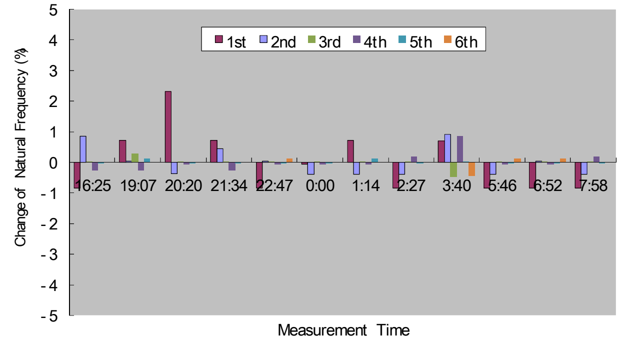


Figure 14. Change of natural frequency from average of C32

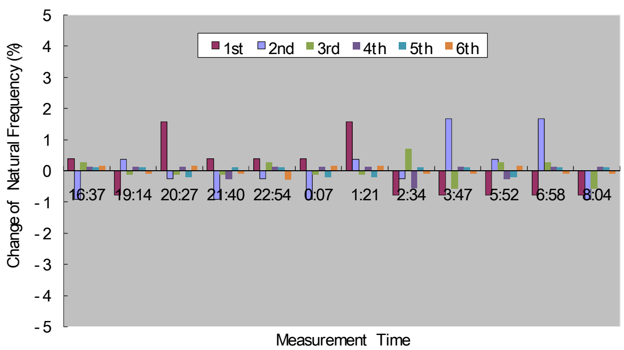


Figure 15. Change of natural frequency from average of C42

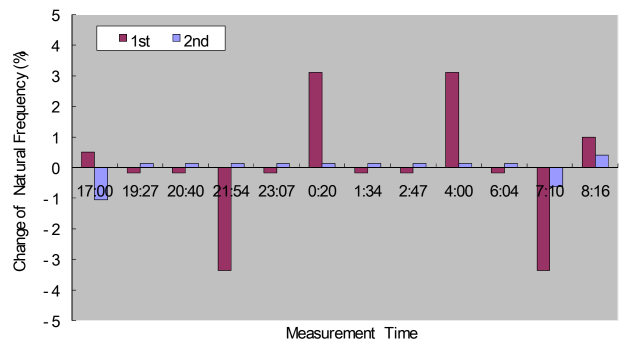


Figure 16. Change of natural frequency from average of G4

The prism was set up on the surface of the steel plate

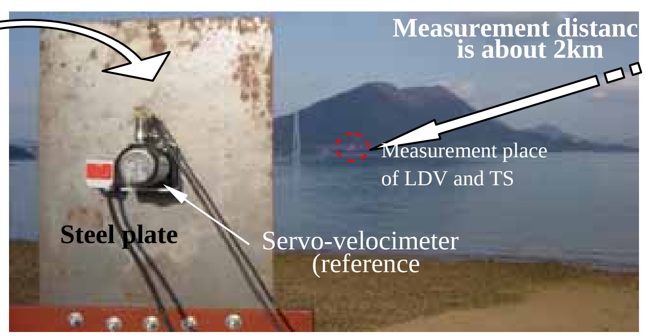


Figure 17: Long distance measurement experiment

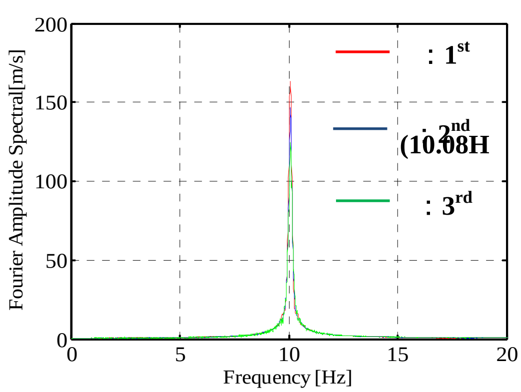


Figure 18. Natural Frequency using LDV (2km ahead)

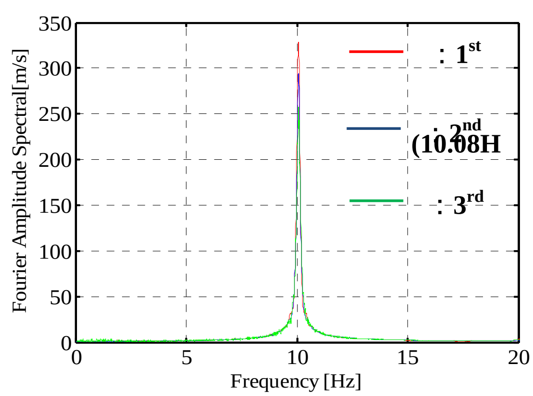


Figure 19. Natural Frequency using Servo-velocimeter

EXPERIMENT USING STEEL PLATE

In order to determine the maximum distance by which we can measure the vibration of a structural member using this system, we measured a steel plate placed 2 km away. This steel plate was fixed to an I type section of about about 60 kgf weight. Moreover, the prism is set up at the center of the surface of the steel plate. The outline of the measurement experiment is shown in Figure-17. The measurement experiment was conducted using a servo-velocimeter at the same time as measuring with LDV.

It can be seen that the natural frequency measured by the servo-velocimeter is the natural frequency of the steel plate which, when compared with the LDV measurement, are in perfect agreement, even though the steel plate is 2 km away in Fugure 18, Figure 19. Note further, that there is no change in the measured frequency with additional measurements using the LDV, verifying the capability of the system to measure vibration of structures at super-remote distances away.

CONCLUSIONS

This system measured the natural frequencies from low-level to higher-order and confirmed that the vibration measurement can be done remotely with the change rate of about 4% from repeated measurements on Tatara bridge members.
Moreover, this system is shown to be capable of identifying the natural frequencies from a distance of 2km. It is therefore, possible to measure the natural frequency of the stay cables, hanger ropes, towers and girder, etc. at highly remote distances of long span cable-supported bridges. A super-remote vibration measurement system capable of reducing the amount of labor of current vibration measurement work and increase safety through the combination of an LDV and TS was developed.

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