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VERIFICATION OF HIGH-ACCURACY AND CONTACT MEASUREMENT SYSTEM USING FSF LASER OPTICAL COORDINATE

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Abstract

Technologies that allow the behavior of bridges and structures to be monitored in a non-contact manner are useful in their maintenance. The full-field optical measurement method is one of such technologies and holds great promiseS for the future. The frequency-shifted feedback laser (FSF Laser) optical coordinates measurement system (FSF-OCMS), which allows non-contact measurement of objects, has the feature that its measurement accuracy is distance-independent and also allows dynamic measurement. The FSF-OCMS also has a driving mechanism, which allows full-field measurement by providing laser irradiation direction control. The performance of the FSF Laser has already been verified in short-distance measurement operations. To evaluate the applicability of the FSF-OCMS to the monitoring of bridges and structures, the authors carried out field measurement experiments to verify the device's performance with regard to displacement measurements from long distance and measured the natural frequencies and deflections of bridges in service. It is expected that the establishment of this technology will bring new possibilities for the monitoring of civil engineering structures.

INTRODUCTION

A wide range of measurement operations are performed in the field of construction, including those relating to road structures such as bridges and tunnels, river structures such as dams and revetments, port structures and airport facilities, and infrastructures for waterworks and sewerage systems , and buildings and those relating to disaster prevention and environmental management/protection. Widely used measurement methods include methods that use sensors attached to the object to be measured and methods that use a nondestructive test technology to measure the surface and internal states of the structure. These sensor technology- and nondestructive test technology-based methods provide very accurate numerical data.

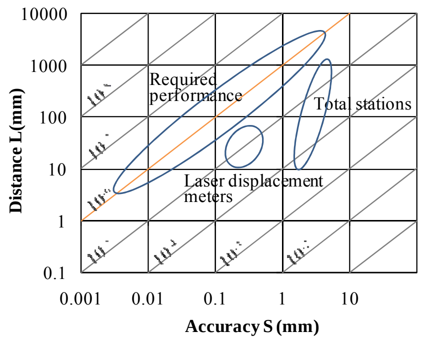


Figure 1: Relationship between the Accuracy and Measurement Distance Requirements in the Construction Field (The figures in the graph are S divided by L.)

The level of performance required of measurement technologies used in the field of construction is by no means lower than those in other industries. This is illustrated in Fig.1, which shows the relationship between the accuracy and measurement distance requirements for displacement measurements. It is not uncommon that the distance (L) to the object to be measured is 100m and the accuracy requirement (S) is 0.1mm, in which case the required performance (S/L) is 10^{-6}. Furthermore, measurement technologies used in the field of construction must be capable of measuring the object in a non-contact manner and at close intervals, in addition to meeting the accuracy requirement. The full-field optical measurement technology is one method to achieve this and holds great promise for the future. The full-field optical measurement technology can be defined as “a technology that makes use of the optical characteristics to obtain 2- and 3-dimensional information on the target object.”

The full-field optical measurement method has the following advantages over measurement methods that use sensors attached to the object to be measured:

1) Measurements can be taken remotely and in a non-contact manner. There is no need to construct a temporary scaffold or install cables for the sensors attached to the target object.

2) Information on multiple points can be obtained quickly. Because it is possible to quickly obtain information on multiple points within the target area, the per-point measurement cost is lower.

3) The measurement data can be visualized in the form of high density 2D and 3D graphical representations.Two- and 3-dimensional measurements can be taken at close intervals and the data can be converted into high density 2D and 3D graphical representations.

Considering that these features make it easier to visualize the state of the target object in the form of high density graphical representations safely and at a low cost, it can be said that the full-field optical measurement technology is a unique technology that is the same with or better than technologies which use sensors attached to the object to be measured and nondestructive test-based measurement technologies.

The FSF-OCMS, originally developed by TOHOKU University, was based on full-field optical measurement technology provides high performance measurements, in the field of reverse engineering industrial inspections, digital archiving, civil engineering. This system allows non-contact long range measurement, and high-accuracy at the long distance, and also dynamic measurement. This system also employs a couple of ultra high-resolution direct-drive motors, which allows full-field measurement by providing precise laser beam steering. For example, the performance in short-distance measurement was shown in Figs.2, 3 and 4. To evaluate the applicability of this system to the monitoring of bridges and structures, the authors carried out measurement operations on the site to verify this system’s performance with regard to displacement measurements from long distance and measured the natural frequencies and deflections of bridges in service. This paper reports on the results of the evaluation.

Figure 2: Mock Board

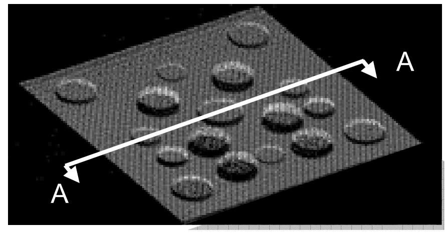


Figure 3: Three-Dimensional Representation of Coordinate Points

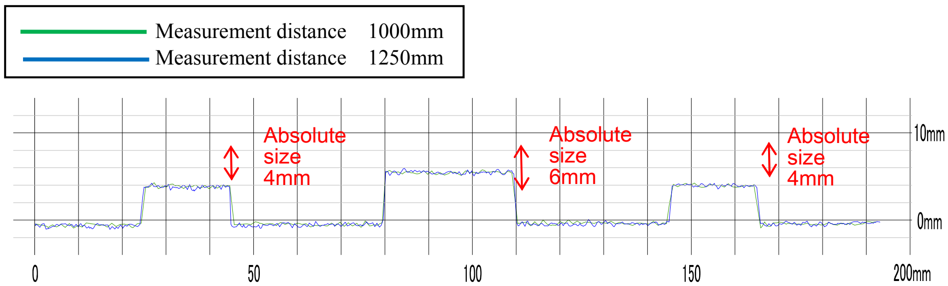


Figure 4: Measurement Results（ A-A section ）

MEASURING PRINCIPLE AND CONFIGURATION OF THE FSF LASER

The basic scheme of the FSF Laser is shown in Fig.5. The light wave radiated from laser medium rotates clockwise followed an isolator and feedback with constant frequency-shift by first-order diffraction of an acoustic-optic frequency shifter in every round-trip. This produces a comb of linearly chirped frequency components (Fig.6). Splitting this frequency-chirped light into the probe light and reference light are re-combining after giving optical path differences using an interferometer. Multiple beat signals obtained from optical heterodyne detection of these lights are proportional to the path differences in its frequencies. By extracting the distance information contained in the beat signals through signal processing, high-accuracy long-distance measurement can be achieved [1, 2, 3,].

The FSF-OCMS is made up of a light source section, a signal processing section and a display section. The signal processing and display sections are combined into a single unit. Fig.7 shows the external appearance and configuration of the device.

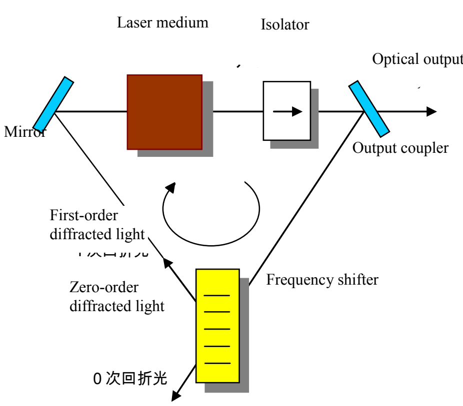
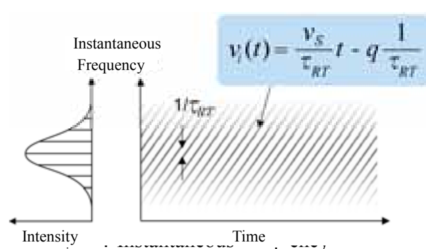


Figure 5: Basic configuration of an FSF laser.



τ_{RT} : Cavity Round Trip Time

V_s : Frequency Shift

q : Integer

t : Time

Figure 6: Schematic of a comb chirped frequencies.

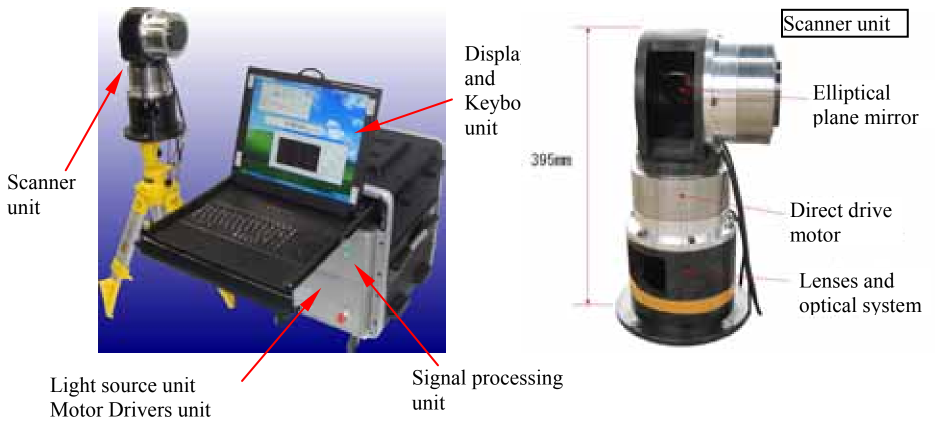


Figure 7: Configuration of the FSF Laser Optical Coordinate Measuring System.

Figure 8: A Prism Target Controlled by high-resolution Position Stage.

Table 1: Specifications of the Total Station

Distance measurement range	1.3 to 2700m (single-element prism)
Distance measurement accuracy	±(2mm+2ppm・D) (single-element prism)
Smallest value that can be displayed	0.1mm
Angle measurement accuracy	Within 2”

VERIFICATION OF THE FSF-OCM’S LONG DISTANCE DISPLACEMENT MEASUREMENT

We conducted a ranging experiment to compare the FSF-OCMS and a total station (TS), specifications shown in Table 1, on optical paths of 50, 100, 200, 300, and 500-meters at a riverside. The target is a retro reflector prism displaced 2-mm steps by a positioning stage (Fig. 8), resolution of less than 10 μm. Fig.9 shows the results of the 500-m distance measurement of FSF-OCMS and TS. Both results are in good agreement with stage displacement. Fig.10 shows a distribution of the ranging data from the FSF-OCMS (400 points/sec×10 seconds = 4000 points) for the 2mm prism position at the 500m stand position in the form of a histogram.

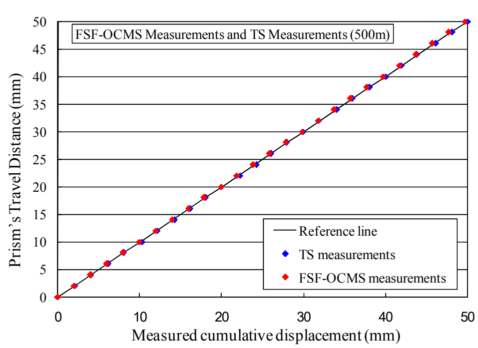


Figure 9: Travel Distances of the Prism and the Corresponding Displacement Measurements.

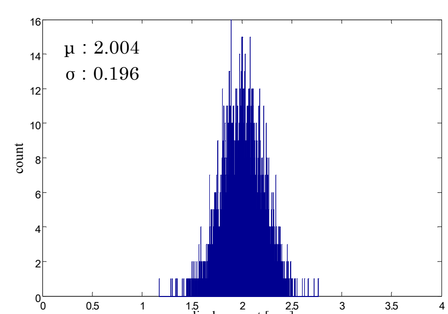


Figure 10: A Histogram of the FSF-OCMS data.

It can be seen from the figure that the measurement data shows a normal distribution with a mean (μ) of 2.00mm and a standard deviation (σ) of 0.196mm, even at a distance of 500m. This result demonstrates that the FSF Laser is capable of measuring displacements very accurately irrespective of the distance. The FSF Laser far exceeds other sensor-based devices in terms of accuracy, as is demonstrated by the S/L value of 3.9×10^{-7} (which more than satisfies the performance requirement for measurement technologies used in the field of construction shown in Fig.1) achieved in this study for a long distance of 500m. Furthermore, the measurement data of 400 points/sec was able to be acquired in this accuracy.

EXPERIMENT TO MEASURE THE NATURAL FREQUENCIES OF BRIDGES IN SERVICE

Figure 11 shows the experimental place of a composite girder bridge and a truss bridge of Asa-bridge (Hiroshima Japan). The span length and the height of the bottom of the girder of the composite girder bridge were 23.0-m and 5.7-m, respectively, and the truss bridge was 73.8-m and 7.0-m, respectively. Measuring points were taken at the centers of the spans with optical reflective sheet for the FSF-OCMS.

The FSF-OCMS was placed on the ground directly below the girder (Fig.12). A high-sensitivity contact-type displacement meter, specifications shown in Table.2, was attached on top of a scaffold constructed and come in contact with the bottom surface of the girder. Both displacement data were taken for a 5 minutes with 200 samples per second. Fig.13 shows results of FFT (Fast Fourier Transform) of the measurement data in the truss bridge. The natural frequencies obtained from the FSF-OCMS are identical with the contact-type displacement meter.

Fig.11: The Composite Girder and Truss Bridges.

Figure 12: The Scanner Unit Setup on the Ground.

Table 2: Specifications of the High-Sensitivity Displacement Meter.

Type	CDP-50
Capacity	50mm
Rated output	Strain 10000×10^{-6}
Nonlinearit	0.1％RO

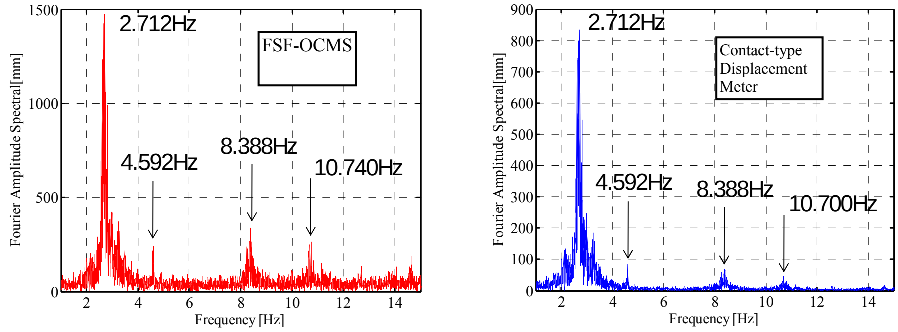


Figure 13: FFT Results (Truss Bridge).

EXPERIMENT TO MEASURE DEFLECTION OF BRIDGES IN SERVICE

Deflections of the composite girder and truss bridges were measured using the same method as for the natural frequency measurement experiment. Fig.14 shows the deflections of the girders of the composite girder and truss bridges measured with vehicles traveling over the bridges, and Fig.15 shows the correlation diagrams created by plotting the peak deflection measurements from the FSF-OCMS and the contact-type displacement meter that had been selected randomly. The measured deflections of the girders are deflections relative to the averages of all measurements. The deflection measurement results show that the FSF-OCMS measured deflections of the girders of the composite girder and truss bridges with vehicles traveling over the bridges down to less than 1mm. In addition, the measured peak deflections from the FSF-OCMS are identical with those from the contact-type displacement meter. The above-mentioned results demonstrate that the FSF-OCMS is capable of measuring deflections of girders of a bridge with vehicles traveling over the bridge at a very high accuracy and in a non-contact manner.

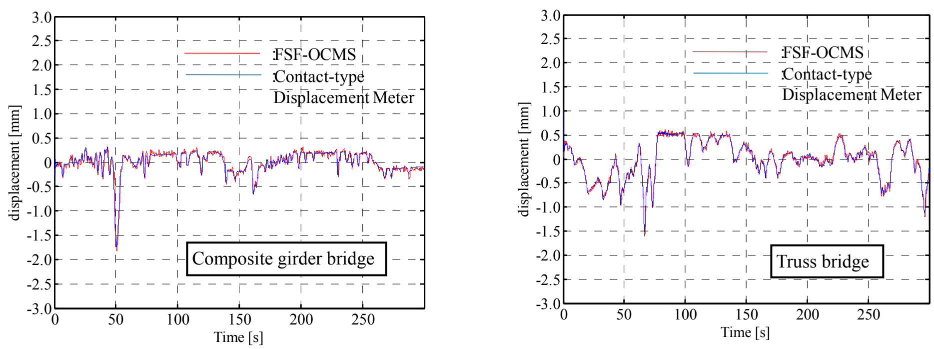


Figure 14: Deflections Measured at the Centers of the Spans of the Girders of the 2 Bridges with Vehicles Traveling over the Bridges

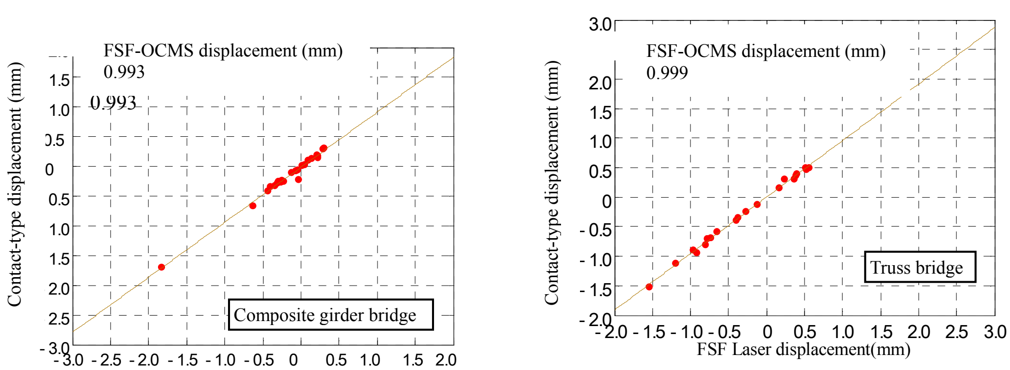


Figure 15: Peak Deflection Correlation Diagrams

CONCLUSIONS

The FSF-OCMS employs a unique measuring principle that allows measurements to be made from long distance at a high accuracy and in a non-contact manner. In this study, the authors verified that the system was capable of measuring displacements of objects located far away from it at a high-accuracy and in a non-contact manner and of measuring the natural frequencies of bridges and deflections of bridges with vehicles traveling over them. On the basis of these results, it can be said that the FSF-OCMS is well suited to be used as a new monitoring technology for bridges and structures.

The authors believe that the establishment of the FSF-OCMS technology as a full-field optical measurement technology will bring new possibilities for the monitoring of civil engineering structures by introducing high-accuracy 2- and 3-dimensional monitoring capability.

GRATITUDE

We would like to express our gratitude to the personnel of the Ohta River Office of the Ministry of Land, Infrastructure and Transport and the Hiroshima City's North Asa Ward Office who kindly permitted us to use state- and city-owned land for our experiments.

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