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# Middle range, rapid strain sensing based on PNC-OFDR and its application to bridge monitoring

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ABSTRACT: Distributed fiber optic sensing is a suitable method for long-term, wide-area monitoring of civil engineering structures such as the ground, tunnels, dams, and bridges. In recent years, distributed strain sensing technologies such as distributed acoustic sensing (DAS) and optical frequency domain reflectometry (OFDR), which can realize real-time monitoring, have made remarkable progress. In particular, OFDR, which performs strain sensing with high spatial resolution, can quantitatively evaluate the strain distribution of civil engineering structures with an accuracy comparable to conventional strain gauges. This method has been limited in its application to structural health monitoring due to its short measurement range. However, by extending the sensing distance, it is evolving into a practical technology for on-site testing. This paper introduces middle-range, rapid strain sensing based on Phase-noise-compensated OFDR (PNC-OFDR) and its application to bridge monitoring. Optical fiber sensors were installed on bridge girders, and the change in strain distribution when the moving load was applied by vehicles was measured using the PNC-OFDR sensing system.

KEY WORDS: PNC-OFDR; bridge monitoring; strain; dynamic strain.

## 1 INTRODUCTION

Distributed optical fiber sensing, in which an optical fiber is installed as a sensor on a target object to measure strain and temperature distribution, is actively applied for long-term, wide-range monitoring of civil engineering structures such as the ground, tunnels, dams, and bridges. For example, ground anchors embedded with optical fiber sensors are installed on on-site slopes, and landslide monitoring is performed by the tension measurement using optical fiber sensors [1]. This monitoring has been carried out over several years, and the measurement data acquired over a certain period are compared quantitatively. The long-term feasibility of the distributed strain sensing using Rayleigh backscattered light spectrum, which is a high-precision measurement technique, was reported. In addition, seafloor fiber optic cables and terrestrial fiber networks (dark fiber) over tens of kilometers are used as sensing fiber to monitor seismic activity [2] and traffic flow [3].

In terms of sensing technology, with the advent of wavelength tunable coherent OTDR [4] and DAS based on phase-OTDR [5] that detect Rayleigh backscattered light with high intensity, high-precision strain sensing on the order of 1$\mu\varepsilon$ and real-time monitoring over the entire length can be performed at the construction site [6]. Currently, distributed fiber optic sensing is utilized to evaluate construction quality and manage safety in the construction field. Strain and temperature distribution data are converted into physical quantities such as displacement and tension force, and construction management based on the sensing data is carried out. For a detailed analysis of the data, it is important to verify that the strain measured by the distributed fiber optical sensing matches the value indicated by a conventional electrical strain gauge. In regard to bridge monitoring, bridge structure shows a variety of responses, from slowly changing static strain to dynamic strain caused by traffic loads. However, few methods can evaluate strain distribution statically and dynamically with a gauge length of a few centimeters, similar to that of a strain gauge. A comparison table of DFOS spatial resolution and sample rate is shown in Figure 1. Brillouin-based sensing technology BOTDR and Rayleigh-based sensing technology TW-COTDR, which have been widely used for structural health monitoring, have a spatial resolution of about 1m or 10cm and are suitable for static sensing. Phase OTDR, one type of DAS, is utilized as a dynamic sensing method to capture vibration distributions with a spatial resolution of several meters. OFDR is both a static and dynamic sensing method [7, 8, 9] with spatial resolution close to that of a strain gauge. Despite its excellent sensing performance, OFDR has been restricted to applications in structural health monitoring due to the sensing distance limited by the temporal coherence of a laser source. Since the sensing

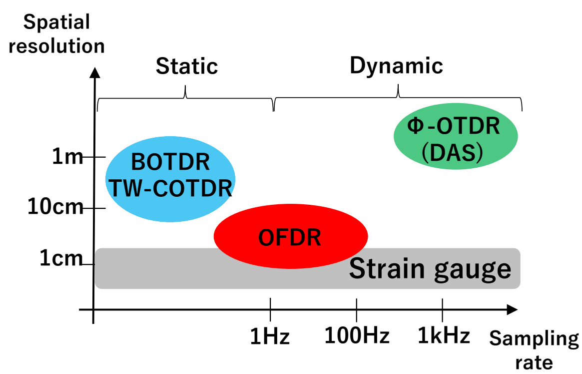


Figure 1. Performance comparison of distributed strain sensing technology.

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distance is generally less than 100 m, OFDR has been widely used for laboratory use in civil engineering. On the other hand, in the field of telecommunications, a PNC (phase noise compensation) algorithm for demodulating the coherence of a laser source has already been verified, and PNC-OFDR, which implements the PNC algorithm in OFDR, has succeeded in measuring with a spatial resolution of 5 cm over a distance of 40 km [10]. However, this PNC-OFDR has not been confirmed for strain and temperature measurements performed in structural health monitoring. The authors expected that PNC-OFDR would be a practical strain sensing technology for on-site structural health monitoring and developed a distributed strain analyzer based on PNC-OFDR (Figure 2). This paper describes an overview of the PNC-OFDR based strain measurement system and reports its application to static and dynamic strain measurements on an actual bridge.

Figure 2. PNC-OFDR based distributed strain analyzer and a laptop PC for data processing.

## 2 PNC-OFDR BASED STRAIN SENSING SYSTEM

### 2.1 *Rapid sensing with a fast wavelength-swept laser source*

OFDR, known as a high-precision strain measurement method, incorporates a wavelength-tunable laser source with excellent coherence. Most of these tunable laser sources sweep the output wavelength slowly by motor drive and are used for the static strain analyzer that samples data over several seconds. Recently, Anritsu released a new high-speed wavelength swept light Source [11]. This laser realizes both high-speed wavelength-sweeping using a MEMS (Micro-Electro-Mechanical System) scanning mirror and high coherence, contributing to middle-range fiber sensing. Especially, sweep repetition frequency, which corresponds to the time interval in strain sensing, reaches 150 Hz. According to the Nyquist theorem, the maximum observable frequency is 75 Hz, making it possible to measure dynamic strain caused by traffic vibrations. Besides, another feature of this system is the short data acquisition time. Acquisition time per one shot is 2 msec. This property is similar to taking photographs that are resistant to subject blur using a high-speed camera and is believed to be suitable for stable static and vibration (dynamic strain) monitoring of infrastructure structures that are subjected to live loads. Figure 3 shows about data sampling when measuring static and dynamic strain with this system. The laser wavelength is swept periodically with a 15 nm width, and dynamic sensing can be performed by arbitrarily setting the time interval in synchronization with the sweep period. It is also possible to perform long-term static strain sensing, such as creep monitoring.

### 2.2 *Extending the sensing distance by the PNC algorithm*

In distributed strain sensing using Rayleigh scattered light, reference and measurement data are obtained, and the relative strain variation is output. Strain is calculated from the spectral correlation to each segment, corresponding to the distributed fiber optic sensor gauge. Figure 4 shows a schematic diagram of OFDR-based distributed strain sensing. The data for the entire length of the optical fiber is converted into spectral data

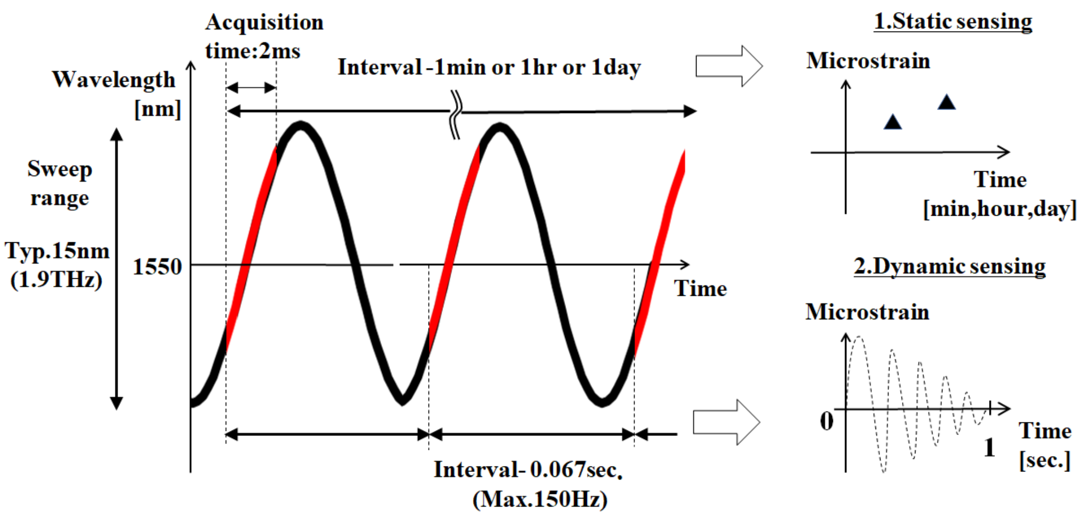


Figure 3. Static and dynamic strain sensing using with a fast wavelength-swept laser source.

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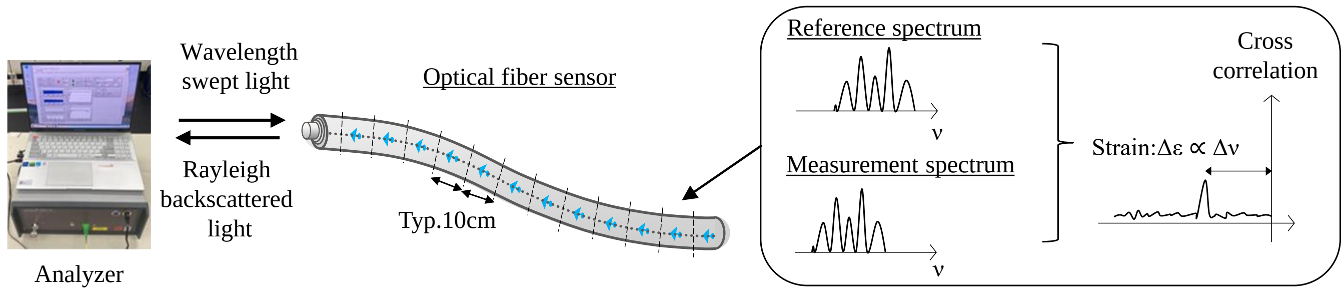


Figure 4. Schematic diagram of OFDR-based distributed strain sensing.

for each gauge, and strain is calculated by multiplying the strain coefficient by the spectral shift frequency that shows the cross-correlation peak. Since this measurement method utilizes the repeatability of the spectrum, it is particularly important to perform a linear wavelength sweep to reproduce the spectrum. To achieve high spectral correlation, wavelength sweep correction is performed, which resamples the raw data based on clock timing with a constant wavelength interval. While this wavelength sweep correction works well up to the coherence length of the source, further correction algorithms are required to go beyond the distance limit of the source. The analyzer implements a PNC algorithm to extend the sensing distance to 1,000 m [12], over 70 times the coherence length of the swept laser. Table.1 shows the measurement specifications of the PNC-OFDR based strain sensing system.

Table.1 Specifications of PNC-OFDR based strain sensing system.

| | |
|---|---|
| Sensing distance [m] | 1000 |
| Acquisition time [ms/shot] | 2 |
| Max. sampling rate [Hz] | 150 |
| Strain resolution [με] | 1 |
| Spatial resolution [cm] | 0.5～10 |

## 3 APPLICATION TO BRIDGE MONITORING

By applying this sensing technology to bridge monitoring, it is expected to capture the distribution of static strain changes used to evaluate seasonal variations, as well as the dynamic strain response subject to moving vehicles. In addition to identifying stress variations that indicate structural strength and the location of damage, it may be possible to obtain information useful for the maintenance and management of civil engineering structures, such as estimating traffic loads. In this study, we report the results of measuring the strain distribution when vehicles are stopped and passing through an existing bridge with optical fiber sensors installed on the bottom of the bridge girder. The applicability of PNC-OFDR sensing system to bridge maintenance was verified.

### *3.1 Bridge monitoring methods*

These tests were conducted on the prestressed concrete bridge of the Atami Beach Line (Figure5.). Figure 6. shows the layout of the optical fiber sensors and strain gauges installed on the bottom of the girder. 0.9 mm tight-buffered single-mode fiber was used as the optical fiber sensor, and it was firmly bonded with epoxy glue to the concrete surface on the bottom of the girder closest to the mountain side.

First, a load test was conducted in which a vehicle was placed at the center of the bridge span to measure the static strain. Three vehicles with different weights were used for quantitative static strain evaluation. Then, as a dynamic load test, a 20-ton truck runs at a speed of 60 km/h on the road close to the mountain side. The strain distribution was output with a sampling interval of 5 cm and a spatial resolution of 10 cm. In the dynamic loading test, the sampling rate was set to 5 Hz.

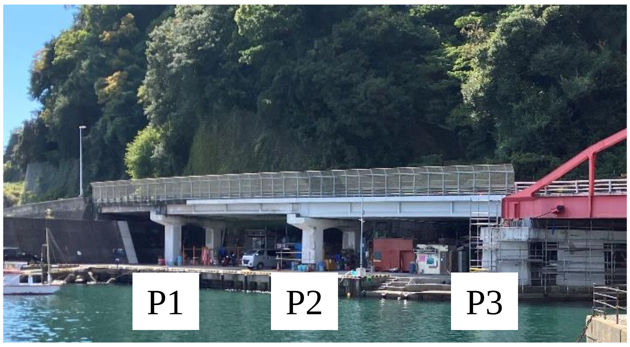


Figure 5. PC bridge of the Atami Beach Line (Testing site).

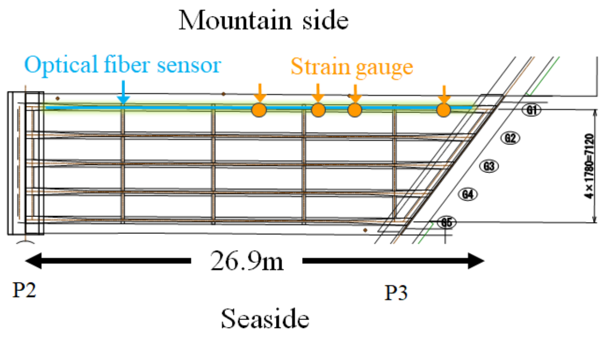


Figure 6. Location of the strain gauges and installed fiber sensors during the load test.

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### *3.2 Results*

Figure 7 shows the strain distribution on the bottom of the girder when cars were placed at the center position between P2 and P3. The results of the strain gauges measured at the same time were also plotted. The downward direction on a vertical axis represents tensile strain value. Tensile strain due to deflection at the bottom of the girder can be seen. The strain increases in proportion to the vehicle weight, and the strain gauge and DFOS values match well. The relationship between the strain at the center of the span and the vehicle weight is shown in Figure 8. This linear correlation indicates the elastic response of the bridge girder. These results suggest that DFOS could be used to detect overloaded vehicles that cause damage to road bridges.

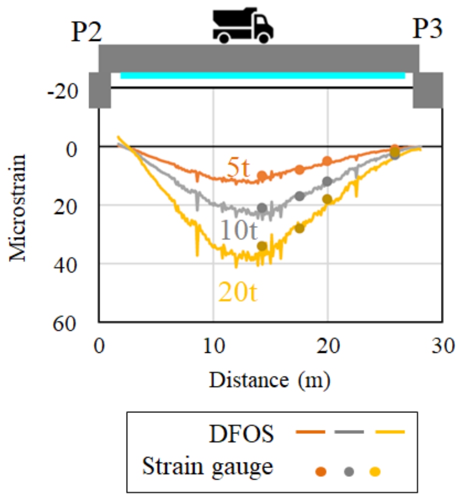


Figure 7. Strain distribution in static loading tests.

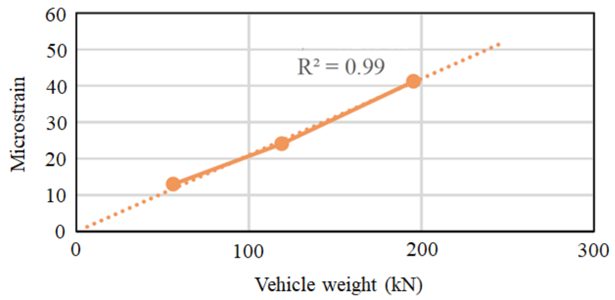


Figure 8. Relationship between strain at the center of span and vehicle weight.

Figure 9. shows the dynamic strain distribution when a 20-ton truck was running as a dynamic loading test. The strain distribution according to the vehicle position can be confirmed. At a speed of 60 km/h, it takes about 1.6 seconds to pass through the 26.9 m span. Strain distribution changes over a period of 1.6 seconds, and the dynamic strain caused by the vehicle movement is accurately captured by the PNC-OFDR based strain sensing system. Strain values at the center of the span observed in the static and dynamic loading tests were nearly equal, suggesting the possibility of dynamic weight monitoring such as the bridge weigh in motion.

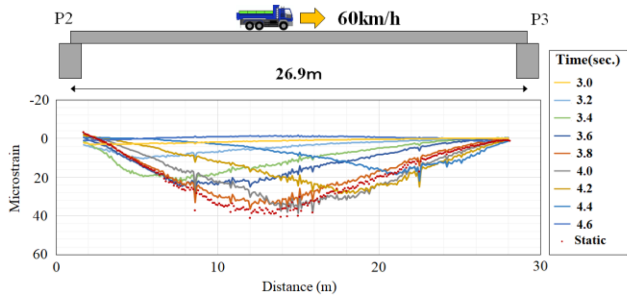


Figure 9. Dynamic strain distribution during vehicle movement with 5Hz sampling.

## 4 CONCLUSION

We investigated a PNC-OFDR based strain sensing system equipped with a high-speed wavelength-swept laser source and its application to bridge monitoring. This system can obtain static and dynamic strain distribution with the same accuracy as a strain gauge. Currently, the sensing distance of this system has been extended to 1000m.

We will continue to develop PNC-OFDR so that it will become a sensing technology necessary for quantitative evaluation of civil engineering structures, such as bridges.

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