Fiber Optic Vibration Sensor for Environmental Monitoring

Naoki Yamashiro **Yoshihiro Kanda**
Hitoshi Murai

Fiber optic vibration sensors that use existing fiber optic cables laid for communication have the advantage of being able to collectively and accurately measure vibrations over a wide range along the cables[1), 2)], and in recent years, they have been attracting attention as a means of environmental monitoring[3)]. For example, the optical communication cables already buried along railway lines and highways can be utilized to measure mobile objects or detect equipment abnormalities, hence contribute to the maintenance, management and improvement of aging social infrastructures. Therefore, OKI has been researching and developing ϕ-OTDR type[4)] fiber optic vibration sensors[5), 6)] in addition to the already commercialized fiber optic temperature and strain sensors.

Fiber optic vibration sensors are largely divided into intensity type or phase type based on their measurement methods. In general, the intensity type has a simple device configuration but poor measurement accuracy while the phase type is more complicated in configuration but provides higher accuracy. OKI has been working with both types of fiber optic vibration sensors to meet the needs and usage environments of various customers.

This article provides introduction to fiber optic vibration sensor technology and the progress of sensor research and development through verification tests with customers.

Fiber Optic Vibration Sensor using Rayleigh Scattered Light

A typical fiber optic vibration sensor measures the Rayleigh scattered light generated in the optical fiber[7)]. **Figure 1** is a conceptual diagram showing the principle of this fiber optic vibration sensor. It is known that when light enters an optical fiber, a small amount of scattered light is reflected back from the scattering point to the incident end, and this scattered light is called backscattered light. There are several types of backscattered light. Among them, the scattered light caused by the non-uniformity of the quartz glass that makes up the optical fiber is called Rayleigh scattered light. Since this light has the highest intensity among the backscattered lights, it is suitable for detecting optical fiber vibration with high degree of sensitivity. Furthermore, backscattered light is generated by the incident light pulse at each point of the optical fiber. Therefore, the point where the backscattered light is generated can be determined from the time it takes the incident light pulse to enter the fiber and backscattered light reaches the incident end.

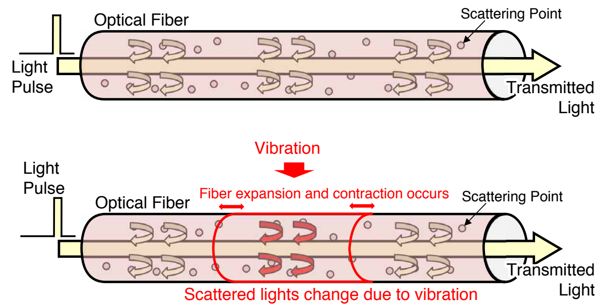

Figure 1. Principle of Fiber Optic Vibration Sensor

When vibration is transmitted to an optical fiber, the optical fiber expands and contracts due to that vibration. A fiber optic vibration sensor measures the changes in scattered light caused by the expansion and contraction, and calculates the vibration transmitted to the optical fiber. At that time, the fiber optic vibration sensor is largely divided into two types depending on whether attention is given to the intensity change or the phase change of the scattered light. **Table 1** summarizes these characteristics.

Table 1. Characteristics of Fiber Optic Vibration Sensors

	Intensity Type	Phase Type
Device Configuration	Simple	Complex
Cost	Low	High
Measurement Sensitivity	Low	High
Measurement Linearity	No	Yes

The intensity-type fiber optic vibration sensor is relatively simple in configuration and low in cost, but it has low measurement sensitivity, and vibration strength and magnitude of the measurement result are not necessarily proportional (no linearity). On the other hand, the phase-type fiber optic vibration sensor has relatively high measurement sensitivity and the obtained measurement results are proportional to the vibration strength. However, a mechanism for measuring the phase must be configured into the device, and a mechanism for solving a problem called fading, which is unique to the phase type, is also required. As a result, phase-type fiber optic vibration sensors are costly.

Along with the research and development of the intensity type, which is expected to reduce the price of the sensors, OKI has been working to simplify and lower the cost of the phase type in an aim to spread environmental monitoring using fiber optic vibration sensors on a nationwide scale.

Development of Simple Phase-Type Fiber Optic Vibration Sensor

Typically, phase-type fiber optic vibration sensors are known to suffer an effect called fading, in which points that cannot be measured stochastically occur. **Figure 2** shows a conceptual diagram of fading. In the figure, the horizontal axis indicates the distance from the incident end of the optical fiber to the scattering point, and the vertical axis indicates the intensity of the scattered light. The backscattered light that the fiber optic vibration sensor observes is the result of interference between scattered lights generated at countless scattering points within the optical fiber. Therefore, the observed intensity of the scattered lights changes randomly depending on whether the scattered lights interfere constructively or destructively. The result can be seen in **Figure 2** where the scattered light intensity takes on a jagged shape that varies randomly with position. As described above, in a fiber optic vibration sensor, there are points where the intensity of the scattered lights are stochastically weak and become buried in noise. At these points, the phase of the scattered light cannot be measured accurately, and in turn, the vibration cannot be measured. This is the basic principle of fading.

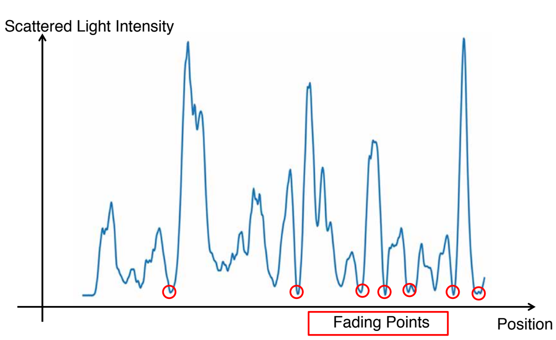

Figure 2. Conceptual Diagram of Fading

Well-known methods to solve the fading problem include frequency multiplexing of the light source, which utilizes the fact that the fading point changes randomly depending on the frequency of the light source; or alternately inputting an unmodulated optical pulse and an optical pulse in which half of the pulse is phase-modulated in the opposite phase to create a situation in which at least one of the optical pulses does not experience fading. However, these methods either require multiple light sources that differ in frequencies or special phase modulation devices, which increase cost. Therefore, OKI has proposed the adaptive gauge length method[6] that only utilizes signal processing as low-cost alternative to solving the fading problem.

Figure 3 shows a conceptual diagram of this method. In the figure, the concept of the adaptive gauge length method is added to the conceptual diagram of **Figure 2**. The basic concept of this method is based on the idea that if the phase at a point with weak intensity cannot be accurately measured, phase from a nearby point with high intensity should be substituted.

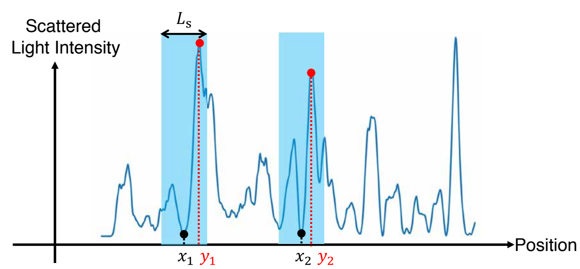

Figure 3. Conceptual Diagram of Adaptive Gauge Length Method

In general, a phase-type fiber optic vibration sensor extracts vibration information applied between two points by calculating the phase difference of scattered light at these two points. The distance between these two points is called the gauge length. Assume now that the scattered light intensity is weak and fading is occurring at points x_1 and x_2 in **Figure 3**. In the adaptive gauge length method, instead of using the phases of these points, the phases from points with the highest scattered light intensity in the vicinity of the fading points (search range L_S) is used. Thus, in **Figure 3**, the phases at y_1 and y_2 are respectively used instead. As a result, the signal processing changes the gauge length from x_2-x_1 to y_2-y_1, hence the method is called the adaptive gauge length method. Although the adaptive gauge length method has a disadvantage that the position accuracy becomes ambiguous, it has the feature of being able to eliminate the influence of fading.

The graph in **Figure 4** shows the effect of this method. The horizontal axis indicates the distance from the incident end of the optical fiber, the vertical axis indicates the measurement time, and the color intensity indicates the change in the light's phase due to vibration. **Figure 4(a)** shows the measurement results of the fiber optic vibration sensor without fading countermeasures, and **Figure 4(b)** shows the effect of signal processing using the adaptive gauge length method on the results of **Figure 4(a)**. In this example, an optical fiber with a total length of about 11km was used, and a 100Hz vibration was applied at a point around 10km.

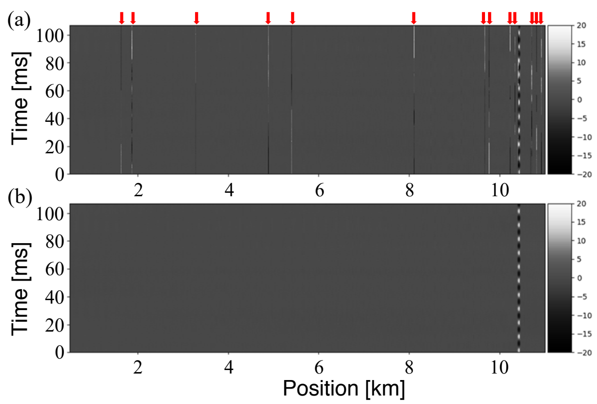

Figure 4. Effect of Adaptive Gauge Length Method

In **Figure 4(a)**, it can be seen that the 100Hz vibration was measured as a striped pattern near the 10km point, but vertical noise lines are seen at other points indicated by the arrows in the upper part of the figure. These noises are caused by fading. Although there are no actual vibrations at these points, they appear as vibration noise because the phase cannot be measured accurately. On the contrary, in **Figure 4(b)**, it can be seen that the 100Hz vibration was measured in the same way as in **Figure 4(a)**, but noises due to fading have been eliminated.

Measurement Sensitivities of Intensity-Type and Phase-Type Sensors

To verify the use of fiber optic vibration sensors in environmental monitoring, OKI has been conducting vibration measurement tests using existing optical fibers along railway lines and highways. The tests revealed that the intensity type is capable of measuring heavy objects such as trains, but it sometimes experiences difficulty measuring vibrations generated by cars, which are relatively lighter compared to trains. As an example, results of vehicle measurements conducted at the ITS test course on the grounds of OKI's Honjo Plant will be presented. **Figure 5** shows an outline of the vehicle measurement test. In the test, a 200m optical fiber was placed directly alongside the lane of the test course, and a vehicle was driven over the lane to try to measure the vibration from the vehicle. The measurement results from the intensity-type and phase-type fiber optic vibration sensors are shown in **Figures 6(a)** and **6(b)**, respectively. The horizontal axis of the graph indicates the distance from the incident end of the optical fiber, and the vertical axis indicates the measurement time. The moving speed of the vehicle can be estimated from the inclination of the vibration position over time on the graph indicated by the red arrows.

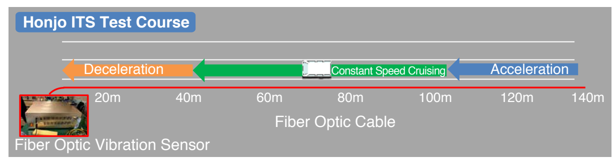

Figure 5. Schematic of Vehicle Measurement Test at Honjo Test Course

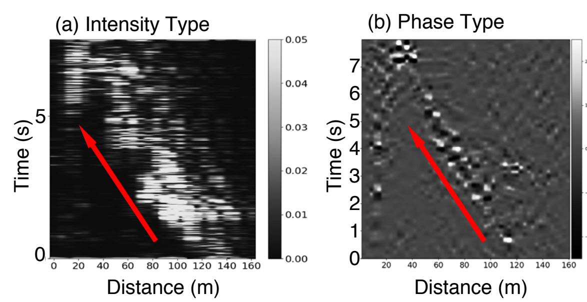

Figure 6. Measurement Results from Cruising Vehicle

In **Figure 6(a)**, the range in which the vibration is generated spans several tens of meters in the horizontal direction surpassing the actual length of the vehicle. This shows that the intensity type is less accurate than the phase type in pinpointing the position of the vehicle, and there are situations where measurement of vehicle vibrations is difficult. However, verification tests with OKI's customers also revealed that the phase type requires signal processing technology that can display vehicle vibrations in real-time, and the need for even higher sensitivity in order to measure vibrations of lighter, slower-moving vehicles. Therefore, OKI made improvements to the phase-type fiber optic vibration sensor.

Figure 7 shows the results of a similar measurement test at the Honjo ITS test course using the improved phase-type sensor.

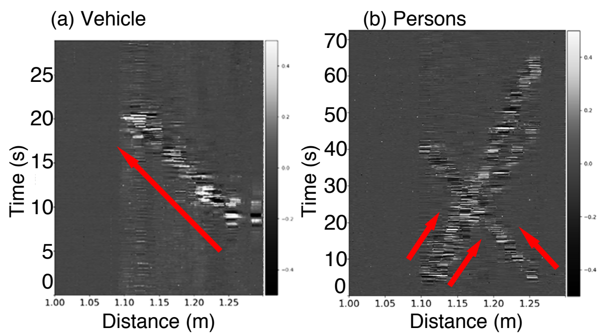

Figure 7. Measurement Results from Improved Phase-Type Fiber Optic Vibration Sensor

Figure 7(a) shows the result of vibration measurements taken from a vehicle cruising in the same manner as the test case of **Figure 6(b)**. **Figure 7(b)** is the measurement result when two people ran in one direction and another person ran in the opposite direction near the installed fiber optic cable. Comparing **Figures 6(b)** and **7(a)**, it can be seen that the improved method suppresses the ambient noise and measures the vehicle's trajectory more clearly. Moreover, the fact that the trajectories of two people running at different speeds in one direction and the trajectory of another running in the opposite direction can be confirmed in **Figure 7(b)** shows that even weak vibrations can be measured.

Conclusion

OKI has been working on the research and development of environmental monitoring with fiber optic vibration sensors that utilizes existing fiber optic cables. This article introduced an overview of OKI's work that has been conducted through verification testing with customers on both intensity-type and phase-type sensors. Future work will involve real-time AI processing based on the obtained vibration information, which will create even more value by enabling detection of events such as accidents, traffic jams, and wrong-way driving on highways. Through co-creation, OKI will continue to take on challenges of technological development that meet customer needs.◆◆

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Authors

Naoki Yamashiro, Sensing Technologies R&D Department, Innovation Promotion Center

Yoshihiro Kanda, Sensing Technologies R&D Department, Innovation Promotion Center

Hitoshi Murai, Sensing Technologies R&D Department, Innovation Promotion Center

TIPS【Glossary】

Φ-OTDR
(Phase-sensitive Optical Time Domain Reflectometry)
A method that measures the vibration transmitted to the optical fiber by receiving Rayleigh scattered light, which is one of the backscattered lights generated when a light pulse enters the optical fiber.

Rayleigh scattered light
One of the scattered lights generated by the optical fiber. It is generated due to density fluctuations in the medium and has the same frequency component as the incident light.

Adaptive gauge length method
A measurement method that eliminates the effects of fading. Instead of using the phase at a point where the scattered light intensity is weak, phase from a nearby point with high intensity is substituted.