Optical Fiber Based Multi-Point Laser Vibrometer -Enabling Accurate and Labor-Saving Machinery Monitoring-

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Aging of mechanical equipment that supports social infrastructures is regarded as a problem. However, even with the demand for predictive maintenance using IoT, the expensiveness of highly efficient predictive maintenance systems is forcing a continual reliance on manual inspections. There is also a shortage of skilled workers that are qualified to perform manual inspections, and the inspections are only performed periodically leading to a maintenance short fall. Furthermore, since manual inspections rely on the five human senses, the accuracy of abnormality detection will vary depending on the individual's sensitivity. Consequently, abnormality detection can be delayed and equipment failure occurs, which can lead to long-term system outage and high repair cost.

On the other hand, from the viewpoint of maintenance, failure is avoided by performing regular replacement and maintenance (TBM: Time Based Maintenance) of important equipment in a cycle shorter than the expected life of the equipment albeit an extra cost. OKI is eyeing at unbreakable and unstoppable social infrastructures in which equipment is comprehensively and constantly monitored, and replacement and maintenance (CBM: Condition Based Maintenance, RBM: Risk Based Maintenance) are performed according to condition or failure risk. OKI has contributed to the development of the information society through the manufacturing and sales of optical communication equipment. In a move to expand the field of application, the world-class technology cultivated in the optical communication industry was applied to sensing. The result is the optical fiber based multi-point laser vibrometer introduced in this article.

Optical Fiber Based Multi-Point Laser Vibrometer

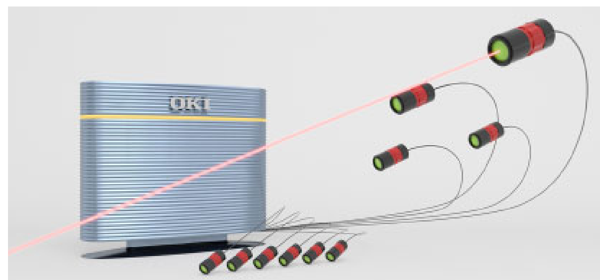


Figure 1. Conceptual Image of Optical Fiber Based Multi-Point Laser Vibrometer

An optical fiber based multi-point laser vibrometer (hereinafter referred to as laser vibrometer) irradiates laser light at multiple vibrating objects to obtain non-contact vibration measurement from multiple points. A conceptual image of the laser vibrometer is shown in **Figure 1**. Vibration is measured by receiving the scattered light generated when an object is irradiated with laser light then detecting the change in wavelength due to the resulting Doppler effect of the vibration. Furthermore, using an optical switch, different optical fibers can be selected in a time-division manner to enable measurement of multiple points (refer to Reference 1 for details on the principle and configuration). A major feature of vibration measurement using a laser is the ability to detect ultrasonic vibrations with high accuracy, which is difficult with a contact-type MEMS (Micro Electro Mechanical Systems) accelerometer. The laser vibrometer that OKI developed was able to measure vibrations of 80kHz, the maximum frequency possible with the test equipment available in the laboratory. In contrast, the MEMS accelerometer has a natural vibration that changes depending on its weight, and it has difficulty in accurately measuring vibrations of 5kHz or more using simple magnet fixtures[1), 2)]. **Figure 2** shows the results of measuring a 10kHz vibration with OKI's laser vibrometer and MEMS accelerometer. Figure 2(a) is the spectral waveform and 2(b) is the time waveform. It can be seen in the spectral waveform, the laser vibrometer detects only pure 10kHz vibration, and the time waveform also shows a noise-free sine wave. On the other hand, the spectral waveform of the MEMS accelerometer shows the generation of harmonics that are integral multiples of 10kHz. This effect causes distortion in the time waveform, and vibrations that are different from the actual one are detected. As shown, the laser vibrometer is able to measure ultrasonic vibration without being affected by resonance.

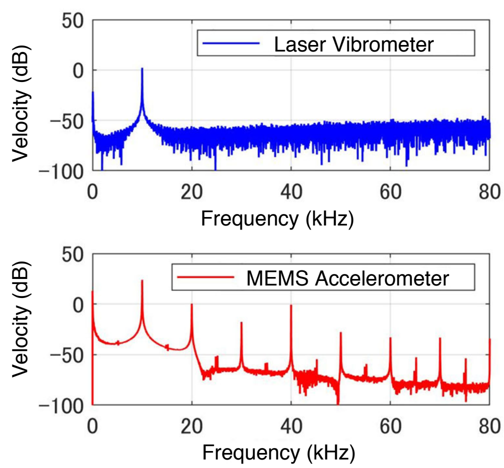


Figure 2(a) Spectral Waveform

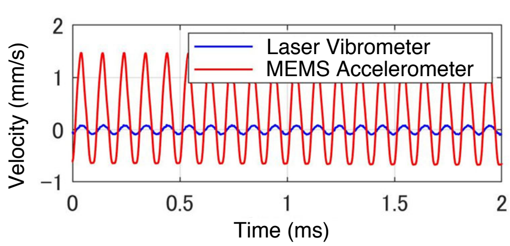


Figure 2(b) Time Waveform

Figure 2. Comparison with MEMS Accelerometer

Conventionally, a bandwidth up to about 10kHz is generally used for detecting signs of failure in an industrial rotating equipment. However, it has been reported that measurements up to the ultrasonic region of 30kHz is necessary to detect early failure signs[3)]. Therefore, it is considered that early failure detection can be expected using the laser vibrometer, which is capable of high accuracy detection in the higher frequency region.

Next, the value provided by OKI's laser vibrometer will be described from the perspective of equipment management. Multi-point measurement enables multiple facilities at an establishment to be comprehensively managed using a single system. Also, as the number of measurement points increases, the cost per point is reduced (Refer to Reference 1 for the evaluation results of multi-point measurements).

Furthermore, since the main unit and sensor heads are connected via optical fiber, it can be easily extended, which aids in the comprehensive early prediction of failure at a large-scale manufacturing site or plant. **Figure 3** shows the results of measuring 1kHz vibrations over optical fibers stretching 200m and 600m, respectively, between the main unit and sensor heads. Some noise is generated in the high frequency band, but it is suppressed to a sufficiently low level. A sharp peak is detected at 1kHz for both fiber lengths, and it is considered that highly accurate vibration measurement is possible even when the length of the optical fiber is extended.

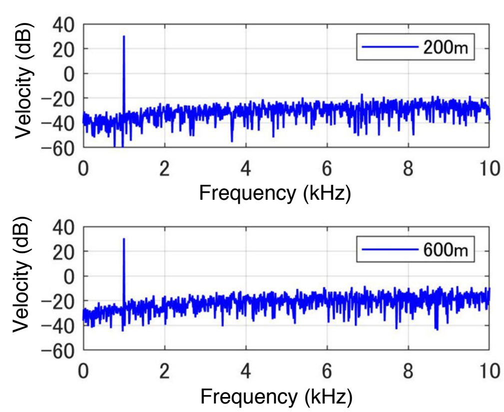


Figure 3. Measurement Results of Extended Optical Fiber

The market for vibrometers is growing mainly in the manufacturing industry, but its deployment is not progressing due to cost and difficulty in installation.

However, in addition to the previously mentioned features that conventional vibrometers lack, OKI's laser vibrometers do not require power supplies for the on-site sensors and data communication environment that are often required for IoT. This expands the possible areas of deployment. **Figure 4** shows some of the industries where the laser vibrometer can be deployed.

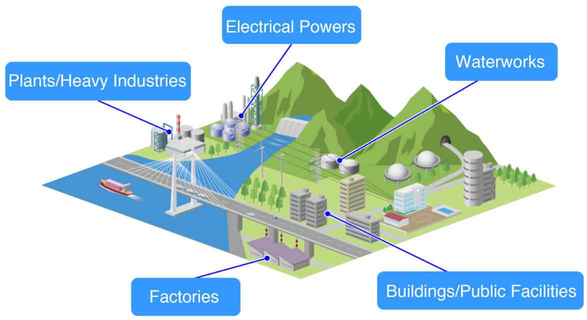


Figure 4. Possible Industries for Deployment

Table 1 summarizes the features of OKI's laser vibrometer and the values they provide.

Table 1. Laser Vibrometer Features and Provided Values

Features	Provided Values
Non-contact	• Improved ease of installation • Vibration measurement over a wide band • Vibration measurement of moving objects • Vibration measurement of high and low temperature objects
Digital processing of optical signals	• Vibration measurement of long-distance irradiation
Multi-point measurement	• Comprehensively continuous vibration monitoring • Centralized management of the entire facility equipment • Cost reduction per each measurement point
Optical fiber method	• Additional power supply near the measurement target is not required • Data communication environment near the measurement target is not required • Vibration measurement covering a wide area

Experiment and Results

Among the provided values listed in **Table 1**, this section presents the experimental results of the multi-point measurement. The object for measurement was an air conditioning pump in an OKI facility. The points selected were near the pump bearings for a total of four measurement points. For convenience, the measurement points were numbered 1 thru 4 starting with the point closest to the bearings. Upon evaluating the spectrum of vibration speed at each measurement point, ultrasonic vibrations between 10 and 30kHz, which is difficult to measure accurately with the MEMS accelerometer, were detected at each point.

However, there were large differences in the results depending on the measurement point, and two examples of such measurement results are shown in **Figure 5**. For example, vibrations detected around 9kHz and 23kHz at measurement point 1 and around 13kHz at measurement point 2 were stronger than other points. From this, it was considered difficult to identify the equipment state from the measurement of a single point. Therefore, in order to judge the state of the rotating equipment with high accuracy, it is necessary to acquire vibration measurement from multiple points and carefully verify the correlation and tendency of those data. Through combining such data analysis methods, a more reliable decision result can be obtained.

OKI has already commercialized ForeWave® *1), a waveform analysis engine that can detect abnormal vibrations at an early stage by sensing the transition tendency of vibration data with high accuracy[4]. The next section will describe the results of using ForeWave to detect abnormal vibrations from the data acquired with the laser vibrometer that OKI developed.

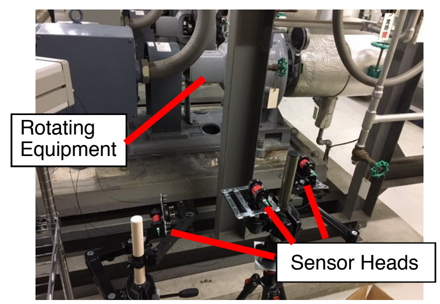


Figure 5(a) Measured Object

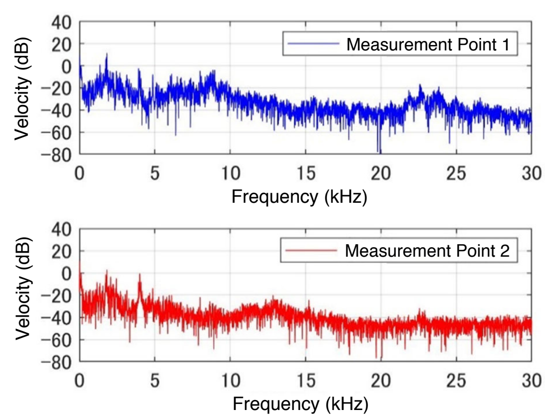


Figure 5(b) Measurement Results (Spectrum)

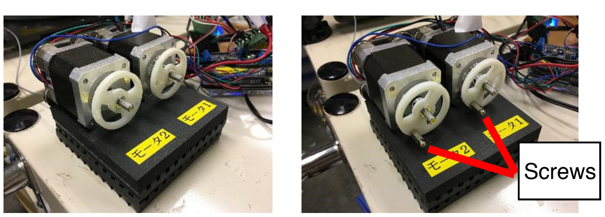
Figure 5. Vibration Measurement Experiment of Rotating Equipment

*1) ForeWave is a registered trademark of Oki Electric Industry Co., Ltd.

Abnormal Vibration Detection Using ForeWave

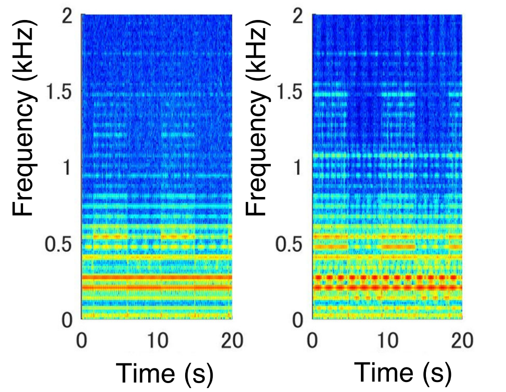
ForeWave automatically extracts feature components from the acquired vibration data and applies machine learning, which enables it to quickly detect more complicated abnormalities. ForeWave already has a proven track record detecting abnormal vibrations in combination with conventional MEMS accelerometers[5). ForeWave's abnormality detection is a two-step process of learning and evaluation. ForeWave learns normal and abnormal vibration data in advance and creates an evaluation model. This model is then used to determine the normality or abnormality of newly acquired data.

This section describes the evaluation results of ForeWave's abnormal vibration detection based on the data acquired with the laser vibrometer. A jig consisting of two stepper motors was used to simulate equipment vibrations (**Figure 6**). A screw was attached to the blade of one of the motors, and the slight vibration change made with the weight of the screw simulated abnormal vibration. **Figure 7** shows the spectrograms of the normal and abnormal vibrations obtained with the laser vibrometer. High-intensity vibrations were detected in the bands 1kHz and below, and change in intensity about every one second was also detected during abnormality. An evaluation model was created from the acquired data, and normality/abnormality of the evaluation data was differentiated. **Table 2** shows the number and breakdown of vibration data used for learning and evaluation. The results of the evaluation showed that all twenty evaluation data were correctly differentiated as normal or abnormal, and the abnormality detection rate was 100%. Based on the evaluation, it was determined that the abnormal vibration detection using ForeWave can be sufficiently applied to the laser vibrometer. Taking advantage of the laser vibrometer's wideband characteristics, future work will proceed with demonstration experiments aimed at detecting abnormality at an even earlier stage.



Normal　　Abnormal

Figure 6. Stepper Motors



(a) Normal Vibration　　(b) Abnormal Vibration

Figure 7. Mesurement Results (Spectrogram)

Table 2. Details of Vibration Data Used for Learning and Evaluation

	Number	Data Details
Learning	100	50 normal + 50 abnormal
Evaluation	20	10 normal + 10 abnormal

Future Prospects

This article described the multi-point laser vibrometer that OKI is developing. In the multi-point vibration measurement of a rotating equipment, there were variations in the results at several points. Consequently, it is necessary to obtain measurement from multiple points and analyze the data in order to determine the equipment state with high degree of accuracy. It was also shown that abnormal vibration can be detected using a laser vibrometer and ForeWave combination. OKI's future plan is to take advantage of the high precision and wideband characteristics provided by the multi-point laser vibrometer and develop a predictive failure detection technology for the stable operation of important social infrastructures, which can be greatly affected if a failure occurs. Furthermore, in aim to expand deployment, OKI's expertise in silicon photonics will be utilized to develop an ultra-compact laser vibrometer for mounting on drones and service robots.

Conclusion

OKI is engaged in innovation activities, that is, new business creation activities, upon the innovation management system called Yume Pro. With the vision of solving social issues listed in the SDGs, OKI aims to create businesses while verifying the hypotheses of the values that the company can provide to society. This article is the result of the authors making hypotheses, developing technologies for achieving the values provided, and testing the hypotheses. ◆◆

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TIPS 【Glossary】

Doppler effect
A phenomenon in which the observed frequency of waves change as the source of vibration or the observer moves.