Multi-Point Laser Doppler Vibrometer

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Expectations for predictive maintenance technology to prevent catastrophic failures of plant equipment and improve operating efficiency at production sites have increased in recent years[1]. OKI is developing a laser Doppler vibrometer capable of monitoring vibrations at multiple points (hereinafter, multi-point laser Doppler vibrometer) as one solution to meet these expectations. This article describes the basic configuration and operational results of the proposed multi-point laser Doppler vibrometer and the measurement results of actual vibrations generated in a plant.

Conventional Predictive Maintenance and Issues

Presently, sensor systems that detect temporal variations in temperature and vibration of equipment and provide advance notice of possible change in equipment state are beginning to appear on the market[2, 3]. Typical plant equipment in which a catastrophic failure cannot be tolerated is a rotating machine such as a pump or a compressor. Generally, the measurement frequency band of vibration required for identifying the state of a rotating machine is specified as 10Hz to 1kHz[4], and the measurable upper frequency limit of most monitoring systems currently on the market is 1 to 3kHz[2, 3].

However, there is a research report that suggests the measurement frequency band of 10kHz to 30kHz is the optimal frequency for detecting early failure signs in an industrial rotating machine[5]. In fact, for industrial pumps, there have been reports of cases where the predominant frequency indicating a sign of failure was measured at a much higher frequency[6] than the conventionally specified criterion[4]. For early detection, it may be desirable to raise the monitoring frequencies of vibrations up to higher values (OKI considers an upper limit of 30kHz to 50kHz).

A typical vibrometer currently in use utilizes a MEMS (Micro Electro Mechanical Systems) accelerometer that detects acceleration from a change in capacitance between the movable and fixed parts of the sensor element. Such a contact-type vibrometer is attached to the measurement target either permanently with screws or detachably with magnets. According to interviews OKI has conducted with manufacturing sites, the detachable attachment method was clearly more favorable for the ease of maintaining plant equipment. However, since the vibrometer has a natural frequency of its own, it has been reported that the accurately measurable upper frequency limit is about 5kHz[7]. Therefore, in order to accurately measure vibrations of 30kHz to 50kHz, a non-contact method of measurement is considered desirable.

Table 1 summarizes the general specifications of non-contact vibrometers on the market. Among them, the eddy current vibrometer and the capacitance vibrometer detect displacement of the target object by electromagnetic action, and the vibration of the object is determined from the displacement value. However, the target area is limited to metal, and the measureable distance to the target is short. Laser displacement meters allow distances of up to several dozen centimeters, but the measurable frequency is less than 10 kHz, which is smaller than the frequency OKI is considering. The laser Doppler vibrometer has sufficient distance and measurable frequency, but at several million yens, the extremely expensive cost makes it difficult to use for monitoring plant equipment. The reason for the expensive cost is considered to be the high cost of lasers having good phase noise characteristics, which is essential for coherent detection.

Table 1. Classification of Non-contact Vibrometers

	Eddy Current Vibrometer	Capacitance Vibrometer	Laser Displacement Gauge	Laser Doppler Vibrometer
Principle of Measurement	Displacement calculated from magnetic field	Displacement calculated from capacitance	Displacement calculated by triangulation	Displacement or velocity calculated from optical phase
Measureable Distance	< several dozen mm	< 10mm	< several dozen cm	< 5 - 10m
Frequency Range	1Hz - 10kHz	1Hz - 10kHz	1Hz - 10kHz	Up to several MHz

According to Nikkei's 2017 news article "Nippon Paper Industries Develops 'e-musen junkai' (e-wireless patrol) System that Constantly Monitors the Temperature and

Vibration Acceleration of Equipment with a Wireless Sensor," needs exist for "monitoring vibrations of many machinery at low cost."[8)] However, due to the expensive nature of the laser Doppler vibrometer, it is impractical in terms of cost to implement multiple laser Doppler vibrometers to measure vibrations of multiple points.

In an effort to remedy this issue, OKI is attempting to develop a multi-point laser Doppler vibrometer capable of monitoring vibration at multiple points by attaching multiple sensor heads to one expensive laser. In this way, OKI plans to play a part in the vibration based predictive maintenance technology.

Principles of a General Laser Doppler Vibrometer

The laser Doppler vibrometer is a device that measures vibration without contact using the Doppler effect of light. Doppler effect is a phenomenon in which the observed frequency of the scattered wave changes depending on the motion states of the wave (light or sound wave) source and the observer. **Figure 1** shows the Doppler effect of light. When an object is irradiated with light, scattered light is generated. If the object is in a vibrating state at that time, the wavelength of the scattered light changes due to the Doppler effect. Therefore, the vibration can be detected by measuring the change in wavelength of the received scattered light.

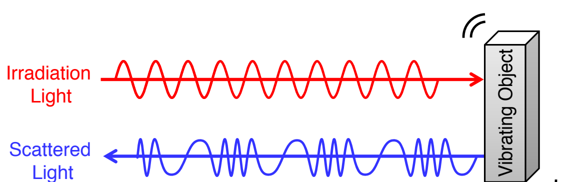


Figure 1. Doppler Effect of Light

Figure 2 shows the configuration of a general laser Doppler vibrometer[9)]. The continuous light output from the laser source is split using a beam splitter. One of light is used as probe light for irradiating the measurement target, and the other is used as reference light for interfering with the scattered light. The probe light passes through another beam splitter, exits from the sensor head into space, and irradiates the object to be measured. Part of the scattered light generated from the measurement target is captured by the sensor head and is injected into the optical phase detection circuit. In the optical phase detection circuit, the scattered light is interfered with the reference light and a vibration component derived from the Doppler effect is obtained. Thereafter, the vibration component passes through a photodetector and an analog-to-digital converter before reaching the signal processing circuit where the phase of light, that is, vibration information is obtained.

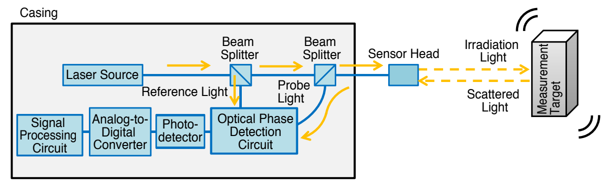


Figure 2. Configuration of a General Laser Doppler Vibrometer

Overview of the Multi-point Laser Doppler Vibrometer and Evaluation Results

In order to enable measurements of vibrations at multiple points with one laser, OKI proposes using multiple sensor heads and switching the incidence of the probe light to each sensor head in a time-division manner. An optical switch is a device capable of accomplishing such an operation. Using a 1xN optical switch, the probe light is switched to N ports in a time-division manner and emitted from the sensor head making it possible to measure vibrations at multiple points (N points). The configuration of the multi-point laser Doppler vibrometer is shown in **Figure 3**.

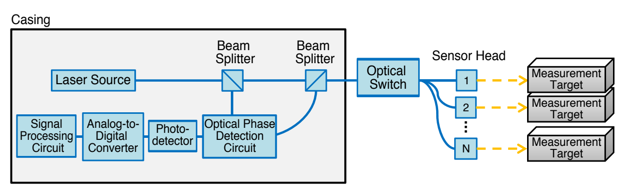
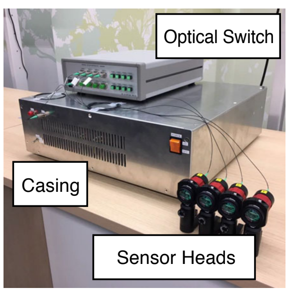


Figure 3. Configuration of the Multi-point Laser Doppler Vibrometer

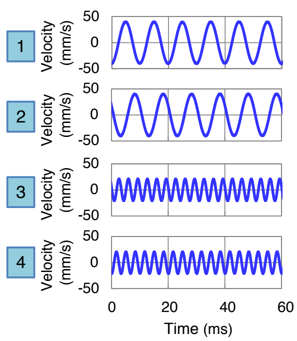
An experimental system was developed to evaluate the basic operation of the aforementioned multi-point laser Doppler vibrometer. First, to evaluate multi-point measurements, four points of vibration were measured using a 1x4 optical switch and four sensor heads. Irradiation lights from sensor heads 1, 2, 3, and 4 were directed at measurement targets vibrating at frequencies of 100Hz, 100Hz, 300Hz, and 300Hz, respectively. Diffuse reflector plates having a reflectance of 5% were used as measurement targets, and the distance from the sensor heads to the measurement targets was 50cm. **Figure 4** shows the experimental system and the evaluation results.

From the results of **Figure 4(b)**, it can be seen that the desired vibrations were measureable with all the sensor heads, and that multi-point vibration measurements are possible.

Next, in order to examine the detectable frequency range, measurement was taken using one of the four sensor heads. Generally, vibration is expressed using frequency and displacement/velocity/ acceleration, and can be defined by points on a tripartite graph with horizontal axis and vertical axis representing frequency and velocity, respectively, as shown in **Figure 5**. From the evaluation, it was determined that vibrations in the range of the shaded area shown in **Figure 5** are measureable. The region outside the shaded area is a region that could not be evaluated due to operational restrictions such as with the vibration generator. The above findings show that OKI's multi-point laser Doppler vibrometer is capable of measuring high frequency vibrations (30kHz to 50kHz) required for detecting changes in the state of plant equipment through the use of multi-point measurements.



(a) Experimental System



(b) Results

Figure 4. Evaluation of Multi-point Measurement

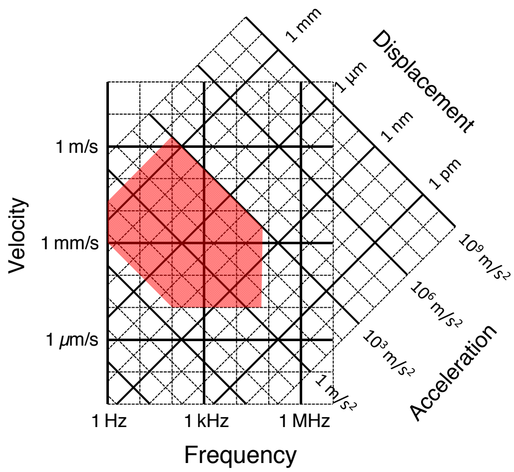


Figure 5. Measureable Range

OKI's multi-point laser Doppler vibrometer has three features. The first is the use of the optical coherent detection and signal processing technologies, which OKI has cultivated in its work with optical communication and laterally deployed across the company. This also allows the use of inexpensive optical communication devices. For example, by applying digital signal processing to optical communication, it becomes possible to simplify the photodetector, and reduce size and cost.

Second, since the light source used is in the communication wavelength band that has less adverse effect on the eyes than visible light, it can be amplified to a higher power compared to visible light. As a result, sensitivity is 100 times greater than conventional systems[10]. Therefore, it is possible to extend the measurable distance or measure the vibration of an object with a small reflectance.

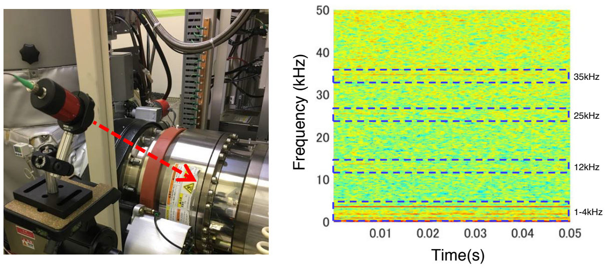
Third, the use of inexpensive optical switches enables inexpensive multi-point measurements. This makes it possible to collectively detect vibrations of equipment spread out across the plant using a vibrometer installed at a single location. The above features are summarized as follows.

(1) Use of optical communication technology: Downsizing and cost reduction are possible
(2) Use of communication wavelength band laser source: Extends measuring distance and expands target type
(3) Use of optical switch: Multi-point measurement is possible with only a small increase in cost

Demonstration experiment: Vibration measurement of a vacuum pump

A turbo-molecular pump, a kind of vacuum pump, is a rotating machine that is essential at a semiconductor production site. However, due to the non-magnetic material and high surface temperature of the pump, vibrations are difficult to measure using conventional contact-type sensors. Therefore, a laser Doppler vibrometer that OKI developed was tested on the turbo-molecular pump to measure vibrations.

Figure 6 shows the experimental image and the results. As shown in **Figure 6(a)**, the light emitted from the sensor head was directed at the side of the turbo-molecular pump. Results were displayed on a spectrogram diagram to visualize the vibration characteristics. As can be seen from the results shown in **Figure 6(b)**, multiple vibrations were observed (1, 2, 4, 12, 25, and 35kHz) during the steady state. Among them, the vibration at 4 kHz is large, and it is considered to be the vibration that characterizes the state of the turbo-molecular pump. In future work, vibrations of various parts of the turbo-molecular pump will be measured using a multi-point laser Doppler vibrometer in an attempt to find distinctive vibration characteristics for detecting state changes.



(a) Experimental Image (b) Measurement Results

Figure 6. Vibration Measurement of a Turbo-molecular Pump

Future Prospects

This article described OKI's work on a laser Doppler vibrometer. The multi-point laser Doppler vibrometer can measure high-frequency vibrations without contact and at low cost and high sensitivity. It can be expected as a new predictive maintenance method. The demonstration experiment will be continued, and work will proceed with development to enable measurement of several dozen to several hundred vibrations. OKI aims to play a part in the predictive maintenance of plant equipment combining its machine learning algorithm[11] with the multi-point laser Doppler vibrometer. ◆◆

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TIPS 【Glossary】

Optical switch
Refers to a device for switching the light's optical path or turning on/off the light. An optical switch having M input ports and N output ports is called an MxN optical switch.

Tripartite graph
The relationship between the three vibration elements of displacement, velocity, and acceleration with respect to frequency is expressed in a single diagram. It is also called a vibration specification conversion table.

*1) e-musen junkai (e-wireless patrol) is a registered trademark of SAKURAI CO., LTD.