Improvement in Laser Pulse Methods for Piezoelectric Device Analysis Using Laser Speckle Interferences

Kengo Hara, Yasuaki Watanabe, Ryosuke Nishihara
Graduate School of Systems Design, Tokyo Metropolitan University,
Hachioji, Tokyo 192-0397, Japan
gokenzan85@icloud.com, y.watanabe@ieee.org

***Summary*— Piezoelectric oscillators, which are a type of quartz crystal device that converts pressure and electric power, are used in various electronic devices. Visualizing of the vibration mode of the oscillators is extremely important in design, and one method for doing so is the laser speckle method, in which the surface of the oscillator is irradiated with a laser and the state of vibration is observed from the speckle. In this paper, we focus on the laser speckle pulse method, which has much higher sensitivity than the conventional method, and we obtain basic data on the method, such as the optimum phase angle of the laser pulse with respect to the drive voltage of the oscillator. Since the frequency range of the proposed system is limited only by that of the RF-generator (7GHz) that excites the device under test, the system can be applied to ultra-high frequency devices such as MEMS devices operating in the GHz range.**

Keywords*— *Laser, Resonator, Piezoelectric, thickness-shear,

I. Introduction

Piezoelectric oscillators, which are a type of quartz crystal device that converts pressure and electric power, are used in various electronic devices such as smartphones and PCs. The vibration mode of the oscillators is visualized to evaluate vapor deposition characteristics and device surface conditions, and this is extremely important in design. The laser speckle method, in which the surface of the oscillator is irradiated with a laser and the state of vibration is observed from the speckle, is a method for visualizing the vibration mode of a high-frequency oscillator. Among the types of laser speckle methods, we focused on the pulse method, which is said to have higher detection sensitivity than the conventional method [1]-[10].

This system targets every piezoelectric resonator and is not only so-called quartz crystal units.

II. Measuring principle

In the laser burst method, which is the conventional laser speckle methods, the surface of the oscillator is irradiated with a laser, and the state of vibration is observed from the correlation between the laser speckles when the oscillator is driven and when it is not driven. (see Fig. 1)

In comparison, in the laser pulse method, the oscillator is driven constantly, the laser is applied at the point where the amplitude of the drive voltage is maximum and minimum, and the vibration is observed by correlating the laser speckle[11]. (see Fig. 2) Both the burst method and the pulse method are methods in which the oscillator is irradiated with a laser and the state of vibration is observed from a correlated image of the speckle pattern. The difference between the two methods lies in the two points used to obtain the correlated image.

In the burst method, the correlation image is obtained from speckles when the oscillator is driven and when it is not driven, whereas in the pulse method, the correlation image is obtained from speckles when the amplitude of the drive voltage is maximum and minimum.

Therefore, the image acquired by the pulse method has a larger vibration displacement of the oscillator than the image acquired by the burst method, and the detection sensitivity also increases accordingly.

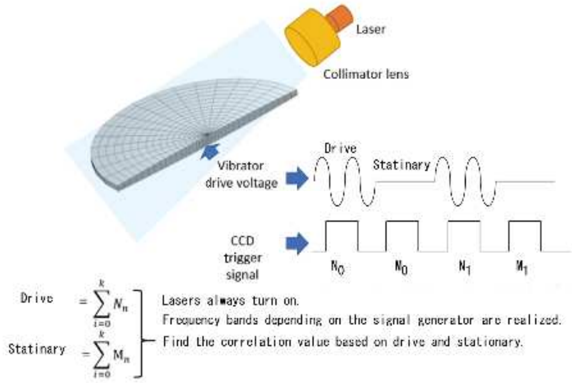

Fig. 1 Experimental diagram of laser burst method

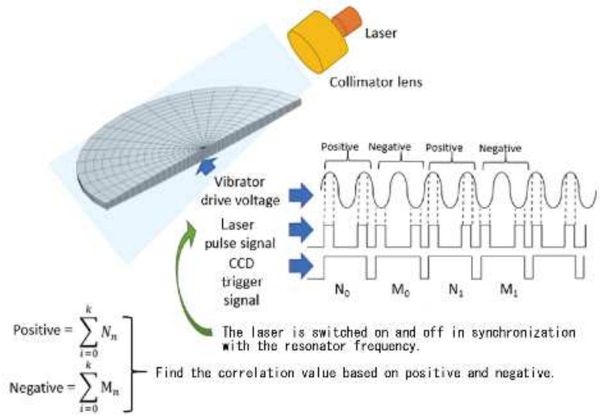

Fig. 2 Experimental diagram of laser pulse method

According to previous studies, there is a demerit to the pulse method in that the frequency of the driving voltage of the oscillator is limited to 7GHz (@ this point) at the maximum, but it has been found that the pulse method can obtain a correlated image with excellent contrast even though the drive voltage of the vibrator is 15 dBm lower than that of the burst method. However, the problem with the pulse method is that the optimum duty ratio of the laser pulse and the phase angle with respect to the drive voltage is unknown. In this study, we measured the relationship between the drive voltage of the vibrator and the phase angle of the laser pulse in the pulse method.

III. MEASURING SYSTEM

In the correlation image, the larger the vibration displacement, the higher the brightness. Fig. 3 shows the pulse method measurement system used in this study. The following is the measurement procedure used in this study[12]-[16].

1) Measure the resonance frequency of the quartz crystal oscillator using a network analyzer.

2) Use a signal generator to drive the quartz crystal oscillator with a constant voltage and resonance frequency.

3) Apply a laser pulse to the surface of the oscillator at an incident angle of 10°, and acquire a speckle pattern 20 times each measurement using a CCD camera at a certain phase angle and at a phase angle shifted by 90° from that phase angle.

4) Correlate the collected images with the reciprocal of the correlation function to obtain a correlated image of the speckle pattern.

5) Specify a central 50 × 50 pixel area for the 512 × 680 pixel correlation image, and take the average of the reciprocals of the correlation function (1/correlation value) in the area.

6) Verify the detection sensitivity by comparing the 1/correlation values at each phase angle.

To suppress noise, the CCD camera was kept at a low temperature of about −10 ℃, and the measurement was performed with the air conditioning in the laboratory turned off.

In the correlation image, the larger the vibration displacement, the higher the brightness. Equation 1 shows the correlation function used in this study[17]-[22]. Because the analysis was insufficient in USE2021 paper[23] the detail was placed in this equation.

To evaluate the detection sensitivity, the 1/correlation value was averaged in the central 50 × 50 pixel area of the obtained 512 × 680 pixel correlation image. (see Fig.4) The correlation value is a numerical value of 0 to 1 indicating the similarity of data. When the value is close to 0, two pieces of data have no similarity, and when it is 1, they are exactly the same. The 1/correlation value, which is the reciprocal of the correlation value, is given as 1 to ∞, and if the value is large, the observed vibration displacement is also large, and the detection sensitivity is high. The phase angle at which this value is maximized was set as the optimum point. The oscillator was driven at a resonance frequency of about 6.397 MHz, which was achieved by measuring with a network analyzer. In addition, the laser output was kept constant for measurement and wavelength is 630 nm.

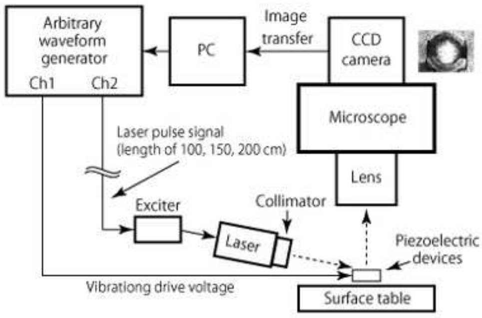

Fig. 3 Schematic of measurement system

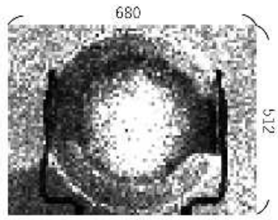

Fig. 4 Averaged in central 50 × 50 pixel area of obtained 512 × 680 pixel correlation image

IV. RESULTS

The purpose of this study was to obtain the data that is the basis of the pulse method, which is said to have a higher detection sensitivity than the burst method. To confirm the significance of the pulse method, the vibration of the crystal oscillator was observed by the burst method and the pulse method, and the detection sensitivities of the two methods were compared. Fig. 5 shows a comparison of the 1/correlation values

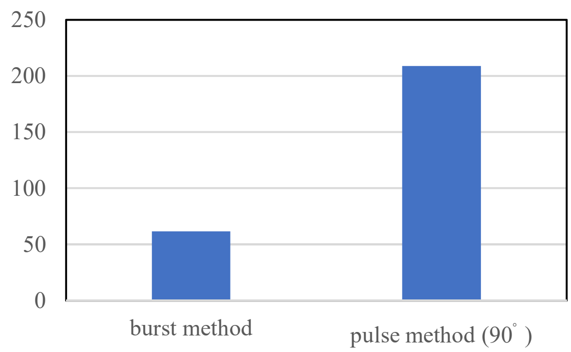

Fig. 5 1/correlation of burst and pulse methods

$$\rho(i_0, j_0) = \frac{\sqrt{\sum_{i=i_0-(M/2)}^{i_0+(M/2)} \sum_{j_0-(N/2)}^{j_0+(N/2)} \left|a_{i,j} - \overline{a}\right|^2 \sum_{i=i_0-(M/2)}^{i_0+(M/2)} \sum_{j_0-(N/2)}^{j_0+(N/2)} \left|b_{i+l,j+m} - \overline{b}\right|^2}}{\sum_{i=i_0-(M/2)}^{i_0+(M/2)} \sum_{j_0-(N/2)}^{j_0+(N/2)} \left(a_{i,j} - \overline{a}\right)\left(b_{i+l,j+m} - \overline{b}\right)} \quad (1)$$

in the central portion of the correlation images acquired by the pulse and burst methods with the driving voltage of the oscillator kept constant. The pulse method was measured when the phase angle of the laser pulse with respect to the driving voltage of the oscillator was 90°. According to Fig. 5, it can be seen that the burst method had a 1/correlation value of about 50, while the pulse method showed a very high detection sensitivity of 200 or more. This meant that the pulse method has a detection sensitivity about four times higher than that of the burst method.

Next, to investigate the optimum phase angle of the laser pulse, the phase angle of the laser pulse with respect to the driving voltage of the oscillator was changed in 10° increments from 0° to 180° for measurement. The measurement was performed with conditions other than the phase angle constant, such as the magnitude of the drive voltage, the resonance frequency, and the duty ratio of the laser pulse; at the length of a laser pulse signal was 100 mm. (see Fig. 4)

Fig. 6 shows the relationship between the phase angle of the laser pulse and the 1/correlation value, that is, the phase angle and the detection sensitivity. As can be seen, the detection sensitivity was low near the phase angle of 0°, it increased as the phase angle approached 90°, it began to decrease after 90°, and it became the lowest near 180°. Therefore, in this measurement, the optimum phase angle was around 90°. At the optimum phase angle, the 1/correlation value was as high as about 200, similar to the result for the pulse method in Fig. 2.

However, the 1/correlation value was very low near 0° and 180°, which are the farthest from the optimum phase angle, which means that the state of vibration could hardly be observed. The detection sensitivity of the pulse method was lower than that of the burst method at a point separated from the optimum phase angle by 70° or more as seen in Figs. 5 and 6. Therefore, it was confirmed that it is important to perform the measurement near the optimum phase angle when observing vibration with the pulse method.

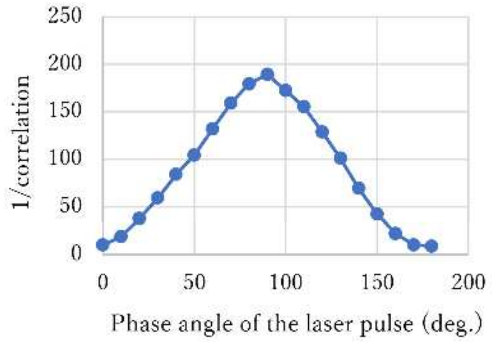

Fig. 6. 1/correlation with pulse method, phase difference: 0~180(deg.)

On the other hand, we will verify the case where the laser pulse signal cable is changed from 100 to 200 cm.(see Fig. 3) These characteristic impedances are 50Ω. Fig. 7 shows the results of setting the laser pulse signal cable lengths to 100, 150, and 200 cm in Fig. 3. From this, as you can intuitively understand, you can see how the phase shift amount shifts to the left by extending the length of the signal cable. It is also determined that the longer the signal cable, the larger the maximum amplitude tends to be.

This is not the case for 50Ω cables, but the termination resistance may be different. This time, only the experimental results will be simulated.

V. Conclusions and Discussions

By comparing the detection sensitivities of the pulse method and the burst method, the superiority of the pulse method was reconfirmed. In addition, the pulse method requires a shorter measurement time than the burst method. The optimum phase angle was obtained through measurement by changing the phase angle of the laser pulse with the pulse method.

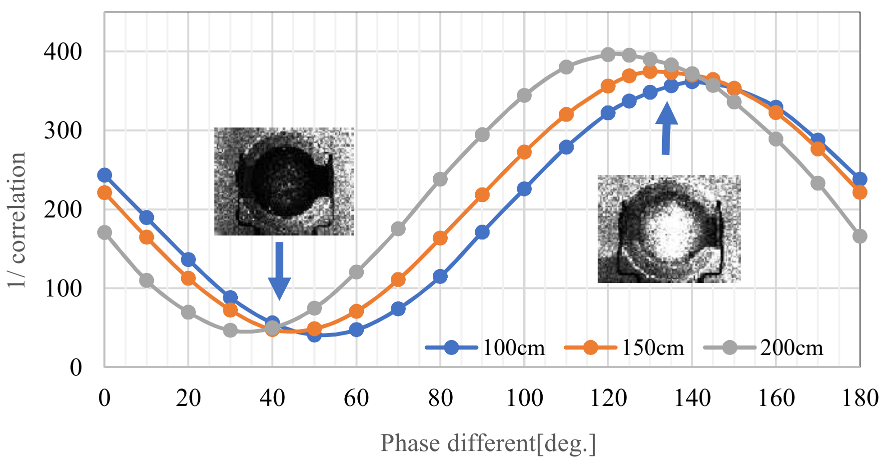

Fig.7 1/correlation values by exchange laser cable lengths (Phase different 0~180[deg.])

The optimum phase angle was obtained through measurement by changing the phase angle of the laser pulse with the pulse method. However, the optimum phase angle also changes depending on changes in conditions such as the degree of the insertion blocking, the length of the coaxial cable, and changes in the resonance frequency. Therefore, the optimum phase angle was 90° in the measurement of this study, but it was observed that the optimum phase angle will be different if the measurement conditions are changed.

The detection sensitivity was lower than that of the burst method when the measurement was performed at an angle of 70° or more from the optimum phase angle with the pulse method. It is thought that this is because the pulse method acquires an image only when the laser pulse is irradiated and obtains a correlated image of the speckle pattern.

At the optimum phase angle, the laser pulse is applied to the surface of the oscillator at the point where the vibration displacement of the oscillator is maximum to acquire an image, so the detection sensitivity is high. When the phase angle is deviates from the optimum phase angle, an image is accordingly acquired at a point where the vibration displacement is small. Therefore, it is thought that images of the points where the vibration displacement is extremely small are acquired at 0° and 180°, which are the farthest from the optimum phase angle, and the vibration is hardly observed. To perform measurement with a high detection sensitivity using the pulse method, it is necessary to perform measurement at or near the optimum phase angle.

The duty ratio of the laser pulse also affects the detection sensitivity of the pulse method. When the duty ratio of the laser pulse is increased, the laser irradiation time becomes longer, so it becomes easier to observe the speckle pattern in the image acquired by the CCD camera. Conversely, if the duty ratio of the laser pulse is lowered, the entire image becomes dark, and it becomes difficult to observe the speckle pattern. Therefore, when the duty ratio is lowered, the detection sensitivity tends to be low regardless of the phase angle, and when it is high, the sensitivity tends to be high.

When measuring at a phase angle away from the optimum phase angle, increasing the ratio of the laser pulse also increases the sensitivity. However, by increasing the ratio and lengthening the laser irradiation time at the optimum phase angle and its vicinity, an image is also acquired when the vibration displacement is small, resulting in a decrease in detection sensitivity. Therefore, the optimum laser pulse duty ratio changes depending on the phase angle. If the optimum phase angle can be adjusted, it is not necessary to change the duty ratio for measurement.

In the current pulse method, it is necessary to identify the optimum phase angle of the laser pulse for each measurement before performing the measurement, and it takes time and labor to observe the vibration with a high detection sensitivity. However, the pulse method takes less time from the start of measurement to the acquisition of the correlation image than does the burst method. Further, by setting the phase angle at or near the optimum phase angle, it is possible to acquire a correlated image having excellent contrast even if the driving voltage of the oscillator is made lower than that of the burst method. In this study, the problem with the pulse method and its superiority when compared with the burst method were clarified. Obtaining detailed data on the optimum phase angle of the laser pulse in the pulse method and the simulations are future tasks.

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