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NON-SCANNING MEASUREMENTS FOR DETERMINING IN-PLANE MODE SHAPES IN PIEZOELECTRIC DEVICES WITH POLISHED SURFACES

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Abstract - **Based on laser speckle interference, we developed a non-mechanical scanning method of visualizing the mode shapes of piezoelectric devices with polished surfaces. The best way to obtain positive proof of reliability is by comparing vibrational distribution predicted by analysis and distribution obtained experimentally. This is why a various of methods have been developed and reported for plotting the vibrational distribution of piezoelectric devices.**

At the 2002 International Frequency Control Symposium, we proposed a method of in-plane mode shape visualization, for bulk and surface acoustic wave devices that combined laser speckle interferometry and two-dimensional correlation filtering. We demonstrated that very clear vibrational patterns of in-plane and out-of-plane shapes in high-frequency AT-cut quartz resonators with roughly finished surfaces could quickly be obtained by using this technique.

This paper discusses improvements to our laser speckle-correlation method to measure the in-plane vibrational distributions in piezoelectric devices with polished surfaces. We applied this method to measure the fundamental thickness modes in mesa-shaped AT-cut quartz resonators with polished surfaces, and verified that the mesa structure provides a superior energy-trapping effect that anticipated from computation.

I. INTRODUCTION

Piezoelectric resonant devices are widely used in industrial products. Recent advances in computer technology have enabled the application of finite element analysis (FEA) to their design. In designing them, ensuring the reliability of calculated results is very important. Comparing the mode shape predicted by analysis and that obtained experimentally is the best way of obtaining positive proof of reliability. This is why various of methods of plotting the vibrational patterns of piezoelectric resonators have been developed and reported [1-9]. Almost all methods involve mechanically scanning the entire surface of the device, and the spatial resolution depends on the scanning step size, i. e., it requires long time to obtain high spatial resolution.

We previously proposed various methods to visualize the mode shapes that combined laser speckle interferometry and image processing techniques [10,11]. The involved irradiating a roughly finished device surface with a visible-collimated laser beam, and the field of speckle that was generated above the device was captured by a video camera. The mode shapes were obtained from the difference between the speckle images of the resonator-driven and resting phases. These methods have a great advantage in reduced measurement time.

We reported on three improvements to the methods; (1) introduction of a two-dimensional correlation filter provided very clear, high-contrast mode shape images [12 - 14], (2) in-plane mode shapes could be obtained by operating the laser beam closely parallel to the device surface [15,16], and (3) detection sensitivity was increased by placing a mirror opposite to the laser incident direction [17,18].

This paper describes improvements to the laser speckle method so that it can be applied to devices with polished surfaces. The optical layout and measurement system are described in Section 2. We applied this system to measure the fundamental thickness shear and inharmonic modes in a bi-mesa shaped AT-cut quartz resonator with a polished surface. The experimental results and three-dimensional FEA results for the bi-mesa shaped resonator are in Section 3. Good agreement between experiments and analysis verified that the proposed system can be used to measure the in-plane mode shapes of piezoelectric devices with polished surfaces and that the bi-mesa structure provides superior energy-trapping effects.

II. MEASUREMENT SYSTEM

When a laser beam irradiates a roughly finished resonator surface, a speckle pattern is generated near the surface due to interference between the scattered-light components. The speckle pattern is amplitude modulated by the vibration of the resonator. The mode shapes of the resonator are obtained from the difference between the speckle images of the driven and resting phases.

It is difficult to apply the laser speckle method to devices with polished surfaces because the optical scatter on the surface of the devices is extremely low. However, as devices with gold electrodes, such as quartz resonators, slightly absorb the red component [19], the laser speckle method can be applied by increasing laser power and carefully choosing the incident angle.

Figure 1 shows the optical system for measuring the in-plane mode shapes of polished piezoelectric devices. It consists of a semiconductor laser with a collimate lens and mirror, and it is similar to the previous system [17]. In the present system the mirror is tilted so that the reflection beam from the device returns to the surface of the device. The incident angle of the laser is set to 16 degrees. This angle was selected as the minimum to ensure sufficient scatter intensity on the surface of the device and to eliminate shadow from the device supporters. The angle of the mirror was adjusted to prevent from damaging the semiconductor laser by the returning light.

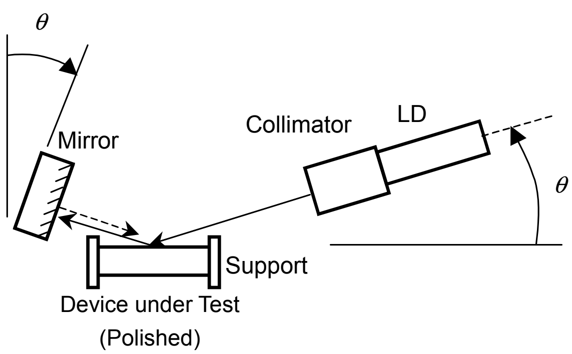


Fig. 1 Optical configuration for polished devices.

Figure 2 is a block diagram of the measurement system. The vibrational patterns were obtained as the reciprocals of correlation coefficients between the images for driven and resting phases [12 - 14]. This system was improved so that the frequency synthesizer's output frequency automatically traces out the resonant frequency of the device using the network analyzer.

The semiconductor laser with the linear polarization generates a visible range beam and its wavelength is 630 nm and its optical power is 10 mW. The polarization of the beam is orthogonal to the direction of the vibrational displacement being measured. The spatial resolution of the images was 640 x 480 pixels. Pairs of images, i. e., the resonator-rested phase and resonator-driving-phase, were accumulated fifty times, a task that took about 20 sec. The kernel, for calculating the correlation between the two accumulated images consisted of 4 x 4 pixels, which was sufficiently smaller than the wavelength of the acoustical standing wave on the resonator surface.

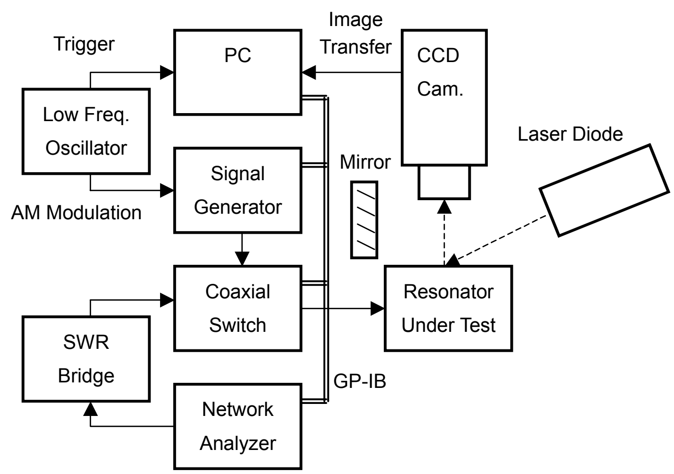


Fig. 2 Block diagram of measurement system.

III. Experimental Results

Figure 3 shows the structure of the bi-mesa shaped piezoelectric resonator [20]. We used 8.3 MHz bi-mesa shaped AT-cut quartz with a polished surface for the experiment. Table 1 shows its electrical equivalent parameters and dimensions.

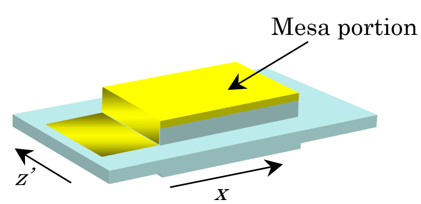


Fig. 3 Bi-mesa rectangular AT-cut quartz resonator.

Table 1 Equivalent parameters and dimensions of mesa-shaped resonator.

Equivalent parameters			Dimensions [mm]					
f_s [MHz]	R_1 [?]	Q	$L(x)$	$W(z')$	$D(y')$	L_{mesa}	W_{mesa}	D_{mesa}
8.297	43	5.0E4	5.94	3.44	0.20	3.00	2.50	0.005

Figure 4 has an actual image of the bi-mesa resonator obtained with the optical system in Fig. 1. The rectangular part at the center is the bi-mesa portion. The white spots on the image are dust adhering to the surface and they correspond to the non-moving area because they create large scattering around themselves and bring on saturation of the CCD device. We can see from the figure that optical scattering is produced by the proposed optical system even if devices have polished surfaces.

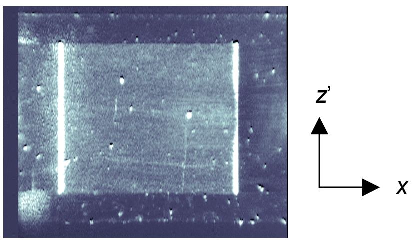
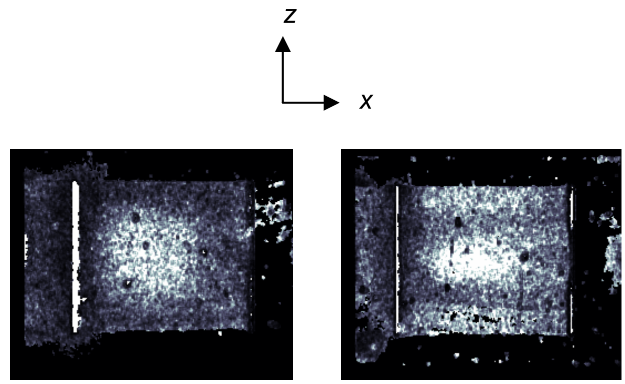


Fig. 4 Optical scattering image of the mesa-shaped resonator having polished surfaces.

Figures 5(a) and 5(b) have the experimental results for the fundamental thickness shear (1, 1, 1) and inharmonic modes (1, 1, 3). The numbers in parentheses indicate overtone, wave number along the x axis, and wave number along the z' axis. Because of displacement detection sensitivity, the resonator driving level for the (1, 1, 1) and (1, 1, 3) modes were + 9 dBm and + 15 dBm, respectively. We can see from these figures that in-plane vibrational displacement is trapped at the center of the mesa portion, i. e., the bi-mesa structure has a very large energy trapping effect.

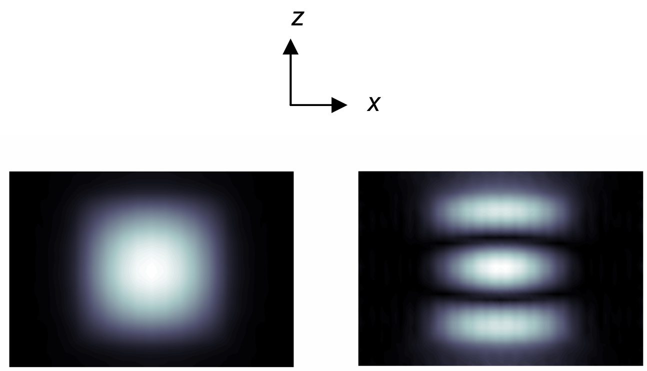
To verify the experimental results in Fig. 5, we analyzed the in-plane vibrational displacement of the (1, 1, 1) and (1, 1, 3) modes in a bi-mesa AT-cut quartz resonator with the same dimensions using three-dimensional finite element analysis.

Figures 6(a) and 6(b) have analyses for (1, 1, 1) and (1, 1, 3) modes. The results correlates well with the experimental results, i. e., the proposed optical system can measure in-plane mode shapes even if devices have polished surfaces.



(a) (b)

Fig. 5 Experimental results for mesa-shaped resonator. (a):fundamental thickness-shear(1, 1, 1) mode, (b):nearby inharmonic(1, 1, 3) mode.



(a) (b)

Fig. 6 Analyses using finite element method for mesa-shaped resonator. (a):fundamental thickness-shear(1, 1, 1) mode, (b):nearby inharmonic(1, 1, 3) mode.

IV. Conclusion

The optical system and method described in this paper enable the visualization of in-plane mode shapes of piezoelectric resonant devices with polished surfaces. The basic principle of the method can be applied to piezoelectric devices operating at any frequency. The detection sensitivity can be improved with increased laser power or decreased laser wavelength. We are currently in the process of alternating this and will report on results in the near future.

REFERENCES

[1] R. J. Williamson, ”Non-destructive means for determining mode shape in thickness-shear resonators,” Proc. 44th Annu. Symp. Freq. Control, pp.436-449, 1990.

[2] W. J. Spencer: Physical Acoustics (Academic Press, New York, 1968) Vol. 5, Chap. 3.

[3] Y. Watanabe, H. Sekimoto and Y. Oomura, “An improved method for determination of surface charge distribution of weak spurious modes in quartz plates,” Jpn. J. Appl. Phys. Vol. 34 , Pt. 1, No. 1, pp.200-204, 1995.

[4] T. Adachi, M. Okazaki and Y. Tsuzuki, ”Improvements of laser interferometric measurement system of vibration displacements,” Proc. 37th Annu. Symp. Freq. Control , pp.187-194, 1983.

[5] Y. Hirose and Y. Tsuzuki, “Measurement method of VHF elastic vibrations by optical fiber interferometric sensing,” Proc. 43rd Annu. Symp. Freq. Control, pp.360-364, 1989.

[6] Y. Watanabe, H. Sekimoto, Y. Kitada, Y. Omura, “Measurement and analysis of surface charge distribution in rectangular AT-cut quartz resonators,” Trans. IEICE-A, Vol.J77-A No.3 pp.285-291, 1994 [in Japanese].

[7] Y. Watanabe, M. Koyama. H. Sekimoto and Y. Ohmura, ”Precise determination of the optimum supporting position of an SC-cut quartz resonator using a semiconductor pulsed-laser system,” Jpn. J. Appl. Phys. 34, pp.2617-2619, 1995.

[8] Y. Watanabe, K. Niikura, G. Yuan, S. Goka and H. Sekimoto, ”Visualization of mode shapes in piezoelectric resonators using an electrostatic microphone,” Jpn. J. Appl. Phys. Vol. 38, p.938-939, 1999.

[9] S. Hertl, E. Benes, L. Wimmer and M. Schmid: Proc, ”Investigation of quartz crystal thickness shear and twist modes using a new non-interferometric laser speckle measurement method," 39th Annual Freq. Control Symp., pp.535-544, 1985.

[10] Y. Watanabe, Y. Shikama, S. Goka, T. Sato and H. Sekimoto, “Visualization of mode shapes in piezoelectric resonators using image processing,” Proc. of 15th European Frequency and Time Forum, Vol. CH2007, pp361-364, 2001.

[11] Y. Watanabe, Y. Shikama, S. Goka, T. Sato and H. Sekimoto, ”Mode shape measurement of piezoelectric resonators using image processing technique,” Jpn. J. Appl. Phys. Vol. 40, pp.3572-3574, 2001.

[12] Y. Watanabe, T. Sato, S. Goka and H. Sekimoto, ” Application of Two-dimensional Correlation Filters to Laser-Speckle Interferometry,” Technical Report on IEICE, US2002-1,2002. [in Japanese]

[13] Y. Watanabe, T. Sato, S. Goka and H. Sekimoto, ”Visualization of Mode Shapes in Piezoelectric Devices Using Laser-Speckle Interferometry and Two-Dimensional Correlation Filter,” Proc. of 31st EM Symposium, IEEJ, pp.79-82, 2002 [in Japanese]
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[14] Y. Watanabe, T. Tominaga, T. Sato, S. Goka and H. Sekimoto, “Visualization of mode patterns of piezoelectric resonators using correlation filter,” Jpn. J. Appl. Phys., Vol.41, Pt.1, No.5B, pp.3313-3315 , 2002.

[15] Y. Watanabe, T. Sato, S. Goka and H. Sekimoto, “Visualization of mode shapes in piezoelectric devices using two-dimensional correlation filter,” Proc. of 2002 IEEE International Frequency Control Symposium, pp.55-60, 2002.

[16] Y. Watanabe, T. Sato, S. Goka and H. Sekimoto, “Measurement of in-plane and out-of-plane mode shapes in piezoelectric devices using laser speckle interferometry,” Acoust. Sci. & Tech. Vol.23, No.5 pp.284-285, 2002

[17] Y. Watanabe, T. Sato, S. Goka and H. Sekimoto, “Non-scanning means for determining vibrational distribution in BAW and SAW devices,” Proc. of 2002 IEEE International Ultrasonics Symposium, 2002.

[18] Y. Watanabe, T. Sato, S. Goka and H. Sekimoto, “Measurement of In-Plane Vibrational Patterns in Piezoelectric Devices Using Laser Speckle Interferometry,” Proc. of USE2002, pp.329-330, 2002 , [in Japanese]

[19] K. Sato, “Fascinated with gold stones,” Shokabou, 1990 [in Japanese]

[20] S. Goka, H. Sekimoto, Y. Watanabe and T. Sato, “Frequency-temperature characteristics of stepped bi-mesa-shaped AT-cut quartz resonators”, Proc. of 2002 IEEE International Frequency Control Symposium, pp.91-95, 2002.