Point Spread Function of Electrical Probe for Measuring Induced Charge on Surface of Piezoelectric Vibrator

Shigetaka Kaga
Nihon Dempa Kogyo Co., Ltd.
Saitama, Japan
kagas@ndk.com

Morio Onoe
Professor Emeritus, University of Tokyo
Tokyo, Japan
m.onoe@ieee.org

***Abstract*— Electrical probe method developed by Fukuyo is an excellent tool to identify various vibration modes of a piezoelectric vibrator.[1][2] Piezoelectrically induced charge of a mode is picked up by a small needle probe embedded in the lower electrode. Mechanical scanning of the vibrator by an X-Y stage allowed to obtain a distribution of induced charge over the surface. Fukuyo measured only the amplitude of induced charge. Ya. Watanabe, et al.[3][4] introduced a network analyzer, which allowed the measurement of phase as well as amplitude and the scanning of frequency. Their works, however, were limited to qualitative observation of distribution pattern.**

This paper presents more quantitative characterization of a probe. An observed value of the input to the network analyzer by electrical probe consists of a desired piezoelectrically induced part and an undesired part caused mainly by stray capacitances. On a circle diagram (vector) plot as a function of frequency, the former part at a resonance is essentially a circle, whereas the latter part is essentially constant, which we call here "reference origin". A reference origin can be directly determined from observed values obtained by a frequency scanning in a narrow range around a resonance itself. [5]

A probe picks up surface charge not only at an infinitesimal point but also at surrounding points due to fringing in electrical field. Its characteristics can be expressed by a spatial point spread function similar to an optical point spread function of a lens. Spatial distribution of surface charge of a main thickness-shear mode usually contains components of high spatial frequency due to effects of high overtones of contour modes, of which observed amplitude are much reduced due to a spread function. In previous papers, an estimation of reference origin were refined and distributions of surface charge analytically obtained were compared with experiments. A good agreement is obtained, when a spread function is taking into an account.[6][7][8]

This paper presents a further refinement of the estimation of reference origin and also details of both theoretical and experimental characterization of point spread function.

I. INTRODUCTION

Electrical probe method developed by Fukuyo is an excellent tool to identify various vibration modes of a piezoelectric vibrator. [1][2] Piezoelectrically induced charge of a mode is picked up by a small needle probe embedded in the lower electrode as shown in Fig. 1. Mechanical scanning of the vibrator by an X-Y stage allowed to obtain a distribution of induced charge over the surface. Fukuyo measured only the amplitude of induced charge. Ya. Watanabe, et al.[3][4] introduced a network analyzer, which allowed the measurement of phase as well as amplitude and the scanning of frequency. Their works, however, were limited to qualitative observation of distribution pattern.

This paper presents more quantitative characterization of a probe. Impedance of a probe is kept as low as possible, so that the probe is accounted to be a part of grounded lower electrode with little disturbance of surrounding electrical field. Hence the input to the network analyzer is essentially proportional to the current flowing the probe. It consists of a desired piezoelectrically induced part and an undesired part caused mainly by stray capacitances. The latter has to be subtracted from the observed value. On a circle diagram (vector) plot as a function of frequency, the former part at a resonance is essentially a circle, whereas the latter part is essentially constant, which we call here "reference origin". The reference origin is a slow varying function of frequency.

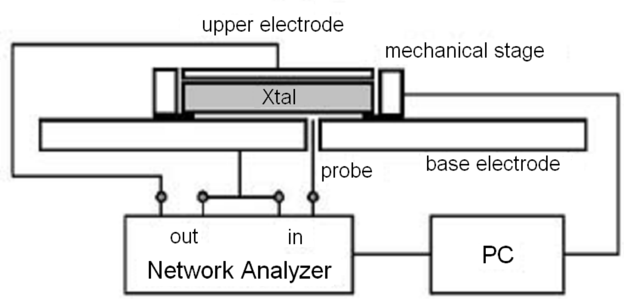


Figure 1. Probe system to pick up piezoelectrically induced charge

Ya. Watanabe, et al. determined a reference origin at each resonance in the following manner. First scan the frequency in a wide range, second remove parts of observed values corresponding to resonances, third approximate remaining values by a polynomial function of frequency and finally calculate an estimated value of reference origin at a particular resonant frequency.[5]

The present paper shows that a reference origin can be directly determined from observed values obtained by a frequency scanning in a narrow range around a resonance itself.

A probe picks up surface charge not only at an infinitesimal point but also at surrounding points due to fringing in electrical field. Its characteristics can be expressed by a spatial point spread function similar to an optical point spread function of a lens. Spatial distribution of surface charge of a main thickness-shear mode usually contains components of high spatial frequency due to effects of high overtones of contour modes. A spread function reduces the observed amplitude of these high spatial frequency components.

In previous papers, distributions of surface charge were analytically obtained and compared with experiments. A good agreement between analyses and experiments was obtained, when a spread function is taking into an account. Estimation of reference origin was obtained removing DC component of observed values in Fourier domain.[6][7][8]

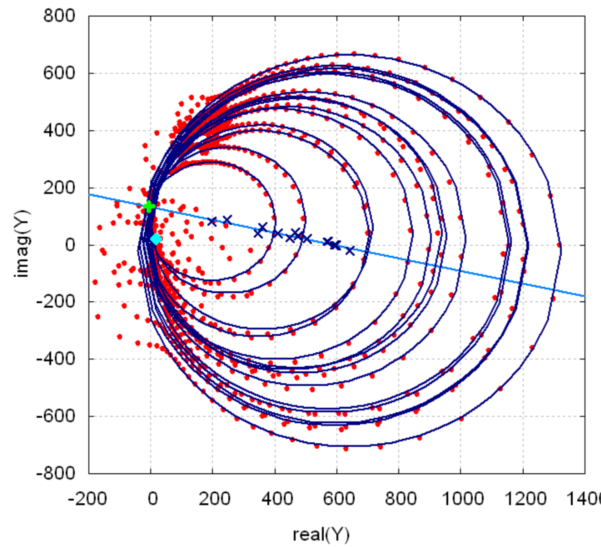
This paper presents a further refinement of the estimation of reference origin and relationships between geometrical configurations of a probe and its point spread function. A calibration scale is made of a quartz Z-cut (non-piezoelectric) with various electrode patterns deposited on its surface. It performs a similar role to a test chart for an optical lens for evaluating a point spread function. A probe is easily calibrated by the use of the calibration scale.

II. Estimation of Reference Origin

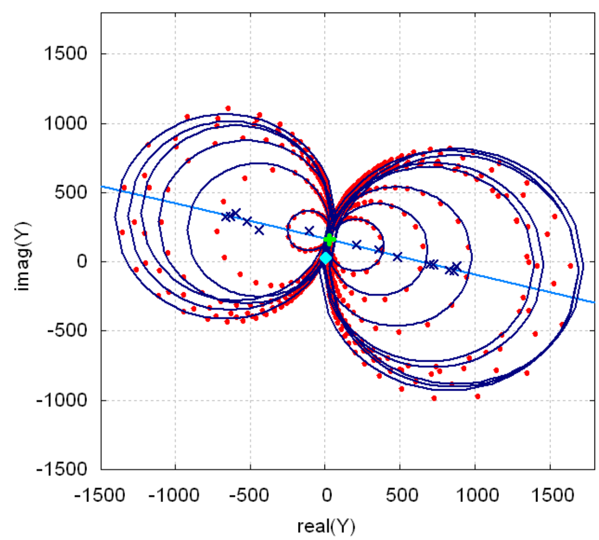
Movements of a mechanical stage is slow in time. Hence a frequency scanning in a narrow range can be completed at each point of mechanical scanning with no extra time. This allows to draw circle diagrams of several spurious modes with only one mechanical scan. The use of circle diagrams allows a sensitive detection of any irregularity during mechanical scan.

Estimation of the reference origin has been further improved by estimating approximate admittance circles based on all the data of each mechanical scan position. Since reference origin is essentially constant during a narrow frequency scanning, a desired piezoelectrically induced part of a circle diagram can be obtained as follows: first fit an approximate circle to measured data obtained at scan position, estimate the center of the circle, third repeat the procedures first and second for other position, forth obtain a best fit of a line through centers of circles and fifth intersections of the line with circles yield the reference origin, whereas an intersection of the line on the other side of each circle yields the point of resonance.

Fig. 2 (a) shows an experimental plot of circle diagrams of the main (1,1,0) mode and estimation of reference origin. Fig. 2 (b) shows an experimental plot of circle diagrams of the (5,1,0) mode and estimation of reference origin. The sample is an AT-cut vibrator (x: 22.0 mm, y': 0.552 mm, z': 27.0 mm). Circles are various position in mechanical scan along the X axis. Only a few circle diagrams are shown here in order to avoid congestion. It can be seen that their reference origins coincide at the intersection of each circle and DC component is a little away from suitable reference origin.



(a) main (1,1,0) mode



(b) (5,1,0) mode

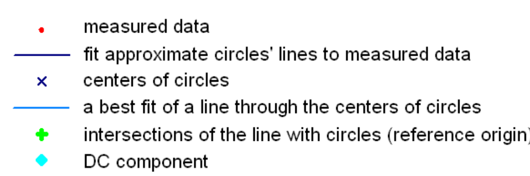


Figure 2. Circle diagrams of main (1,1,0) mode (a) and (5,1,0) mode (b)

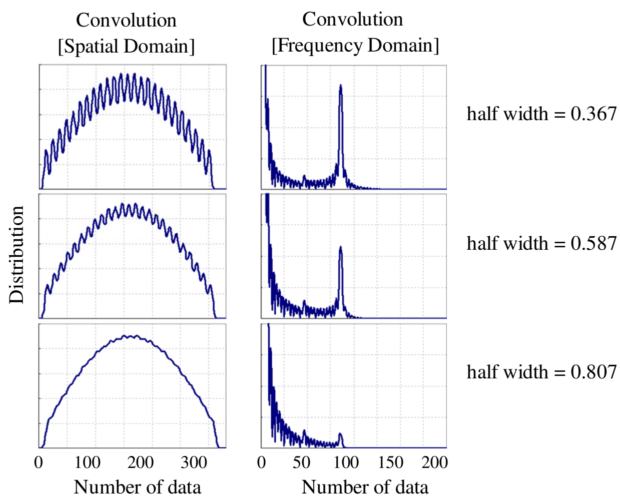


Figure 3. Effect of half width of PSF

III. Point Spread Function (PSF)

A probe picks up surface charge not only at an infinitesimal point but also at surrounding points due to fringing in electrical field. Its characteristics can be expressed by a spatial PSF similar to an optical PSF of a lens. Spatial distribution of surface charge of a main thickness-shear mode usually contains components of high spatial frequency due to effects of high overtones of contour modes. A PSF reduces the observed amplitude of these high spatial frequency components.

In previous papers, distributions of surface charge were analytically obtained and compared with experiments. A good agreement between analyses and experiments was obtained, when a spread function is taking into an account. Fig. 3 shows analytically effect of half width of PSF. The larger of half width (PSF), the smaller the high spatial frequency component.

IV. Test Scale for Calibrating a Probe

A calibration scale shown in Fig. 4 is made of quartz Z-cut (non-piezoelectric). A group of comb electrodes are deposited on its surface (Fig. 4). It performs a similar role to a test chart for evaluating a PSF of an optical lens. Fig.5 shows geometrical configuration of a comb electrode. Dimensions of each comb electrode are listed in Table 1.

Fig 6 shows an effect of PSF. Spatial distribution of electrical potential of a comb electrode is rectangular (a). Spatial distribution of current induced in a probe (c) loses components of high spatial frequency due to a PSF (b). (c) is obtained as a convolution of (a) and (b). The shape of PSF can be approximated by a Hanning (raised cosine) window.

Conversely a half width can be estimated from measured distribution (c). Fig.7 shows a comparison between measured distribution of each comb and calculated convolution.

The gap between comb electrodes and a probe is 380 µm for the first and the second column and 35 µm for the third and the fourth column. The half width used in calculation is 1.25 mm for the second column and 0.625 mm for the fourth column. A good agreement between measured and calculated distributions is obtained.

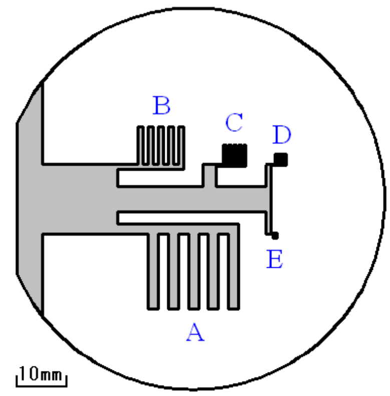


Figure 4. The test plate of Z-cut of quartz crystal (non-piezoelectric)

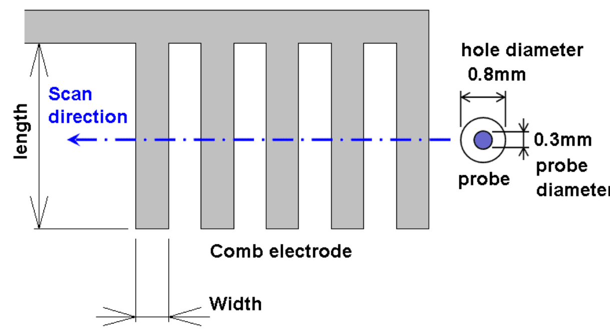


Figure 5. Comb electrode and probe

TABLE I. Size of Comb Electrodes

	length	width
A	15.0	2.0
B	7.5	1.0
C	3.75	0.5
D	1.88	0.25
E	0.75	0.1

unit : mm

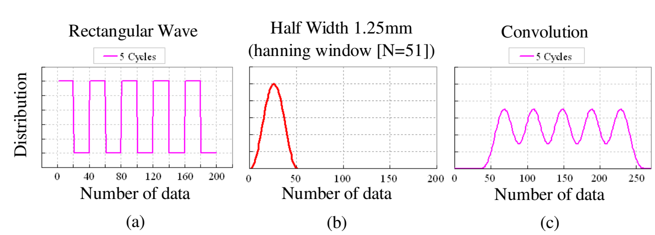
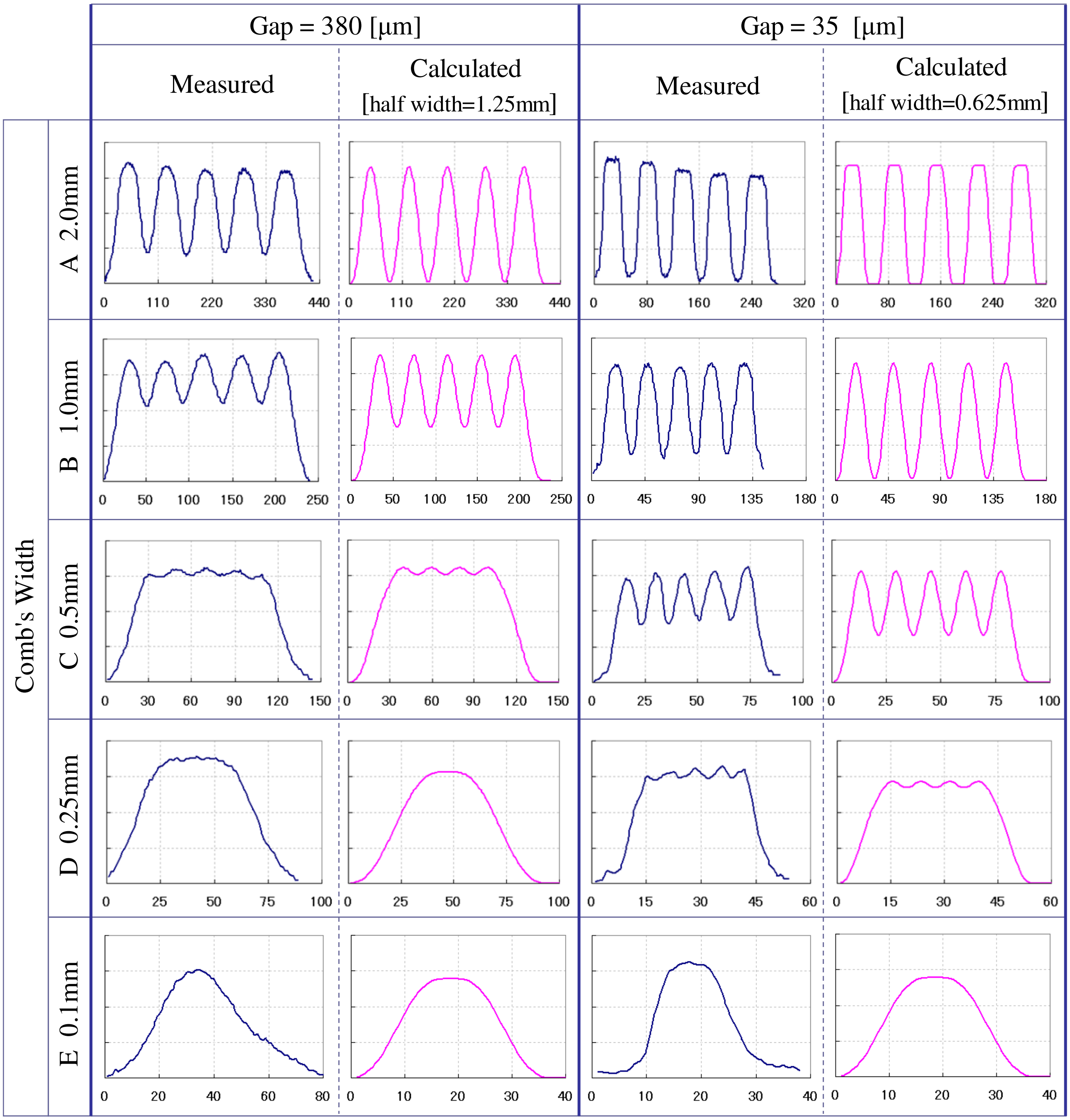


Figure 6. Effect of PSF



Vertical axis : Distribution, Horizontal axis: Index number proportional to mechanical scanning distance

Figure 7. Comparizon of measured and calculated distributions of piezoelectrically induced charge

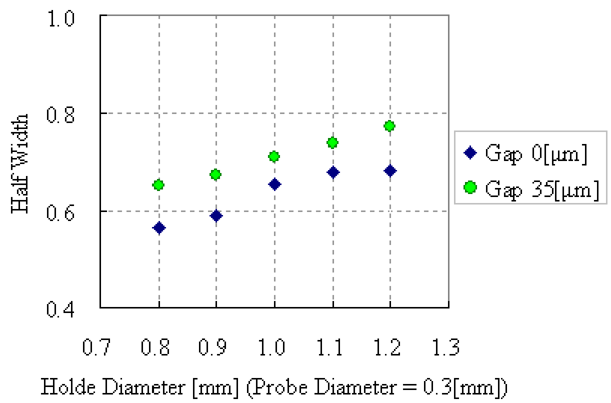


Figure 8. Effect of hole diameter and gap

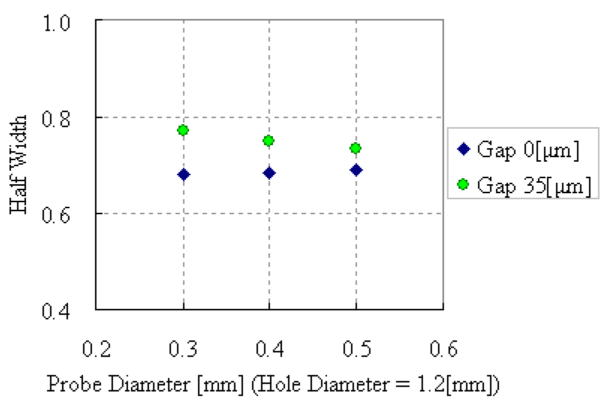


Figure 9. Effect of probe diameter and gap

V. HALF WIDTH OF PROBES OF VARIOUS GEOMETRICAL CONFIGURATION

Effects of various geometrical configuration of probes on half width are determined by the method described in the previous section. Fig.8 shows half width as function of the diameter of a hole surrounding a needle of 0.3 mm in diameter. The parameter is a gap between comb electrodes and the probe, which is chosen as 0 (close contact) and 35 μm. The larger the hole diameter, the broader the half width.

Fig.9 shows half width as function of the diameter of a needle. The diameter of a hole surrounding a needle is 1.2 mm. The needle diameter has little effect on the half width.

These observations agree with FEM analysis of electrostatic field around the probe by Dr. Yo. Watanabe of Ricoh. [9]

VI. CONCLUSION

Characteristics of electrical probe for measuring piezoelectrically induced charge on the surface of a vibrator quantitatively evaluated.

First an improved method to estimate reference origin of circle diagram of admittance is presented.

Second effects of geometrical configuration of a probe on its point spread function are determined using a calibration scale of a group of comb electrodes.

ACKNOWLEDGMENT

The authors thank Mr. Okazaki, Mr. Oita, Mr. Kamijo and Mr. Ikoma (Nihon Dempa Kogyo Co.) for their constant support and encouragement and Dr. Yo. Watanabe of Ricoh Co., for his FEM analysis of electrostatic field around the probe.

REFERENCES

[1] H. Fukuyo, "Researches in modes of vibrations of quartz crystal resonators by means of the probe mehtod," Bull. Tokyo Inst. Tech., series A , no. 1, 1955.

[2] I. Koga and H. Fukuyo, "Vibration of thin piezolelctric quartz plate (especially on R1-cut (AT-cut) rectangular plate)," J. Inst. Comm. Eng. vol. 36, pp. 59-67, 1953. (in Japanese)

[3] Ya.Watanabe, H. Sekimoto, Y. Kitada and Y. Oomura, "Two-dimensional charge patterns of spurious modes in rectangular AT-cut quartz plates," Proc. Ultrasonics Symp., pp. 571-574, 1993.

[4] Ya.Watanabe, H. Sekimoto, Y. Kitada and Y. Oomura, "Measurement and Analysis of Charge Distributions induced on Rectangular AT-Cut Quartz Resonators," Trans. Inst. Comm. Eng. J77-A, pp 285-292, 1994. (in Japanese)

[5] R. D. Mindlin, "High frequency vibrations of crystal plates," Quart. Appl. Math. vol. 19, pp. 51-61, 1961.

[6] R. D. Miundlin and D. C. Gazis, "Strong resonances of rectangular AT-cut quartz plates," 4 th US Nat. Congress Appl. Mech., pp. 305-310, 1962.

[7] M.Onoe and S. Kaga, "Several Extensions of Mindlin-Gazis's Analysis of Rotated Y-cut of Quartz,": Proc. Frequency Control Symp. pp. 10-18, 2008.

[8] M. Onoe and S. Kaga, "Characterization of Electrical Probe for Measuring Induced Charge on Surface of Piezoelectric Vibrator," Proc. Symp. Ultrasonic Electronics, vol. 29, pp. 109-110, 2008.

[9] Yo. Watanabe, Ricoh Co. Ltd., private communication.