# Tactile Sensor Based on Piezoelectric Resonance

G. Murali Krishna and K. Rajanna

*Abstract*—We discuss here the realization of tactile sensors based on the principle of change in piezoelectric resonance frequency with the applied pressure. An array of electrodes has been adopted on either side of the PZT material to have independent resonators. The common areas sandwiched between the electrodes and excitable at resonance frequency of the PZT material are used to form the sensitive area of the tactile sensor. The electrodes were deposited using sputtering technique. Tactile sensors with $3 \times 3$, $7 \times 7$, and $15 \times 15$ array of electrodes are developed with different electrode dimensions and separation between the electrodes. The tactile sensor has been interfaced to computer for the convenience of automatic scanning and making it more user interactive. The tactile sensors developed with different spatial resolution were tested for different shaped objects placed in contact with the sensor. The $3 \times 3$ matrix tactile sensor showed relatively poor spatial resolution, whereas the $15 \times 15$- matrix tactile sensor showed improved spatial resolution. The sensor with $7 \times 7$ matrix elements was tested for its sensitivity to different extents of applied force/pressure. The output response study carried out on the sensors indicated that these sensors can provide information not only about the extent of force/pressure applied on the object, but also the contour of the object which is in contact with the sensor.

*Index Terms*—Piezoelectric resonance and robotics, tactile sensor.

## I. INTRODUCTION

**T**OUCH and tactile sensors are devices which measure the parameters of contact between the sensor and an object. Touch sensing is basically the process of detection and measurement of a contact force at a defined point. A touch sensor can also be restricted to binary information, namely touch and no touch, whereas tactile sensing is the process of detection and measurement of the spatial distribution of forces perpendicular to a predetermined sensory area, and the subsequent interpretation of the spatial information. A tactile sensing array can be considered to be a coordinated group of touch sensors [5]. Robotic and industrial automation are the potential application areas, which have generated considerable interest for the development of these sensors. However, there are several other possible application areas for tactile sensors, namely agriculture, food processing, bio-medical [16], [10], entertainment, and future domestic and service industries. Different types of principles have been explored in realizing the tactile sensors. They are based on mechanical [12], [6], [14], resistive [17], [8], ca-

pacitive [4], magnetoresistive [7], fiber-optic [7], piezoelectric [1], [11], and surface acoustic wave (SAW) [15] techniques. In our present work, we have used the principle of change in the piezoelectric resonance frequency of poled ceramic lead zirconium titanate (PZT) with the applied stress. We have adopted an array of electrodes to have independent resonators. The tactile sensor developed is interfaced to computer and automated to test its output behavior. The response of the tactile sensor has been tested for different shapes of objects placed in contact with the sensor. The sensor is also tested for different extents of pressure applied over the object placed in contact with the sensor.

## II. EXPERIMENTAL

### A. Principle

When an applied frequency to a piezoelectric material is equal to its mechanical resonance frequency, then the material is said to be in piezoelectric resonance. Some oscillator circuits, when suitably connected with piezoelectric material, will give output frequency at the mechanical resonance frequency of the material. The resonance frequency of the resonating material is given by the following: [2]

$$f_o = \frac{1}{2t} \sqrt{\frac{K}{\rho}} \qquad (1)$$

where
$t$      thickness of the piezoelectric material;
$f_0$      natural mechanical resonance frequency of first order;
$K$      stiffness constant of the material;
$\rho$      density of the material.

The area between the electrodes that is oscillating at the mechanical resonance frequency of the piezoelectric material is the active area. For a given material, if the stiffness constant and density of the material are kept constant, then the frequency becomes a sensitive parameter of thickness. When force/pressure is applied on the active area, strain on the active area occurs and the resonance frequency changes [3]. The change in resonance frequency $\Delta f$ is given by [13]

$$\frac{\Delta f}{f_o} = \frac{f - f_o}{f_o} = AF \qquad (2)$$

where
$f$      resonance frequency after the application of pressure;
$\Delta f$      change in the resonance frequency;
$A$      constant;
$F$      applied force.

If stiffness constant $K$ and density $\rho$ of a given material are constant, then from (1)
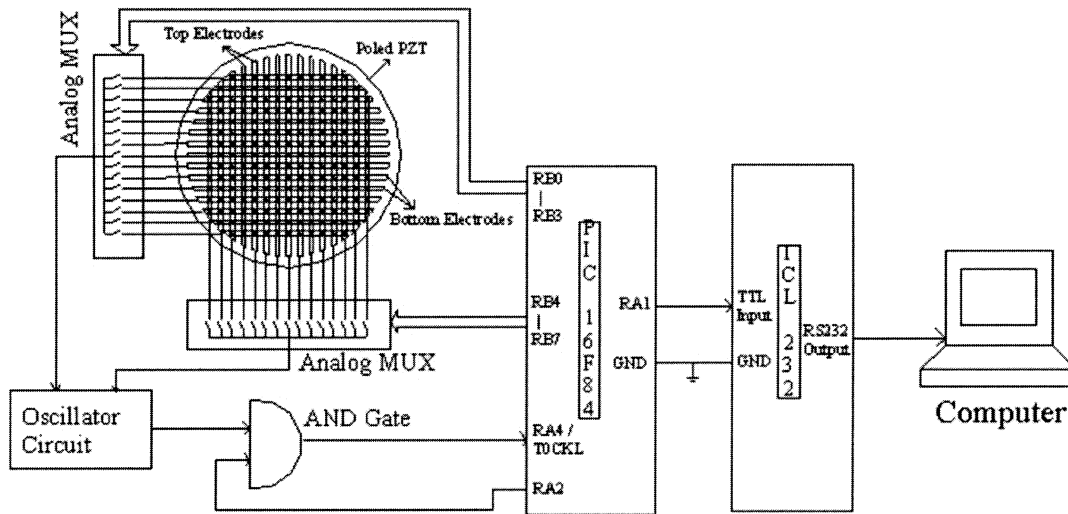
$$f_o \alpha \frac{1}{t}. \qquad (3)$$

Fig. 1.   Block diagram of the experimental arrangement for testing the output response of the tactile sensor.

Hence

$$\frac{\Delta f}{f_o} = -\frac{\Delta t}{t} = AF \qquad (4)$$

where $\Delta t$ is thickness deformation. The negative sign implies that, when force/pressure is applied on the resonating area, thickness decreases, and, hence, the frequency increases. When $\Delta f$ is far less than $f_0$, then [13]

$$\Delta f \alpha F. \qquad (5)$$

The change in frequency is directly proportional to the applied force/pressure. Using this basic principle, an array type tactile sensor is realized in the present work.

### B. Sensor Array Design and Preparation

We have used the commercially available circularly shaped poled PZT material for realizing the tactile sensor. The PZT material used is of thickness 1 mm and diameter 20 mm with a resonance frequency $\sim$1 MHz. Initially, the linear variation of change in resonance frequency with applied pressure/force for the chosen PZT samples was ascertained. Further, rectangular-shaped arrays of electrodes are deposited on either side of the PZT material such that the array of electrodes on one side are perpendicular to the array of electrodes on the other side. DC magnetron sputtering technique has been used for depositing the array of electrodes. Sputtering technique is chosen, as it is known to provide good adhesion of the film on to the substrate. In order to obtain the required array pattern of electrodes, precision mechanical masks were employed during deposition. These masks were designed using AutoCAD and prepared by adopting the chemical milling technique. Double enameled copper wires were attached to the electrodes using temperature-controlled soldering station. The common areas of PZT material sandwiched between the intersecting regions of the electrodes form a matrix of independently excitable resonators at the resonance frequency of the material (Fig. 1). By choosing one electrode from the top side and one from the bottom, the common area

between them is excitable at resonance. This procedure can be repeated for all the matrices of common areas between the electrodes. Each time, the matrix location and its corresponding resonance frequency need to be noted. This becomes the reference data of the sensor before detecting any object. In the present work, the tactile sensors with $3 \times 3$, $7 \times 7$, and $15 \times 15$ array of electrodes have been prepared. In each case, the width of array electrodes and the separation between them were suitably chosen [9].

### C. Testing of the Tactile Sensor

In order to study the output response of the tactile sensor, the object to be studied was placed in contact with the sensor and subjected to different extent of pressure/force using an arrangement [9] consisting of a micrometer with digital display and capable of measuring the displacement/deformation up to $\pm 1$ micron accuracy. Small pieces of silicon rubber covering the electrodes region were placed on either side of the sensor. These silicon/rubber pieces ensure smooth transfer of the applied force and avoid the possible shorting, especially in the case of conducting objects between the electrode arrays. In the present study, different sized and shaped objects were used. Keeping the object in contact with the sensor, the entire matrix of elements are excited at resonance one after the other, and their positions with corresponding frequencies are recorded. The matrix of elements subjected to pressure show an increase in frequency proportional to the extent of the pressure applied. The difference in frequency (before keeping the object and after keeping the object) is calculated. It is important to note that, wherever the object is in contact with the sensor, the corresponding elements in the matrix only show an increase in the frequency. In order to obtain a contour of the object that is in contact with the sensitive area of the tactile sensor, a three-dimensional plot was made between the position of the matrix elements in the $X$-$Y$ axes plane and the change in frequency on the $Z$ axis. The process of doing the above operation manually by selecting the individual matrix elements is time consuming and tedious. Therefore, in order to make the whole process automatic and more user interactive, necessary electronic circuits
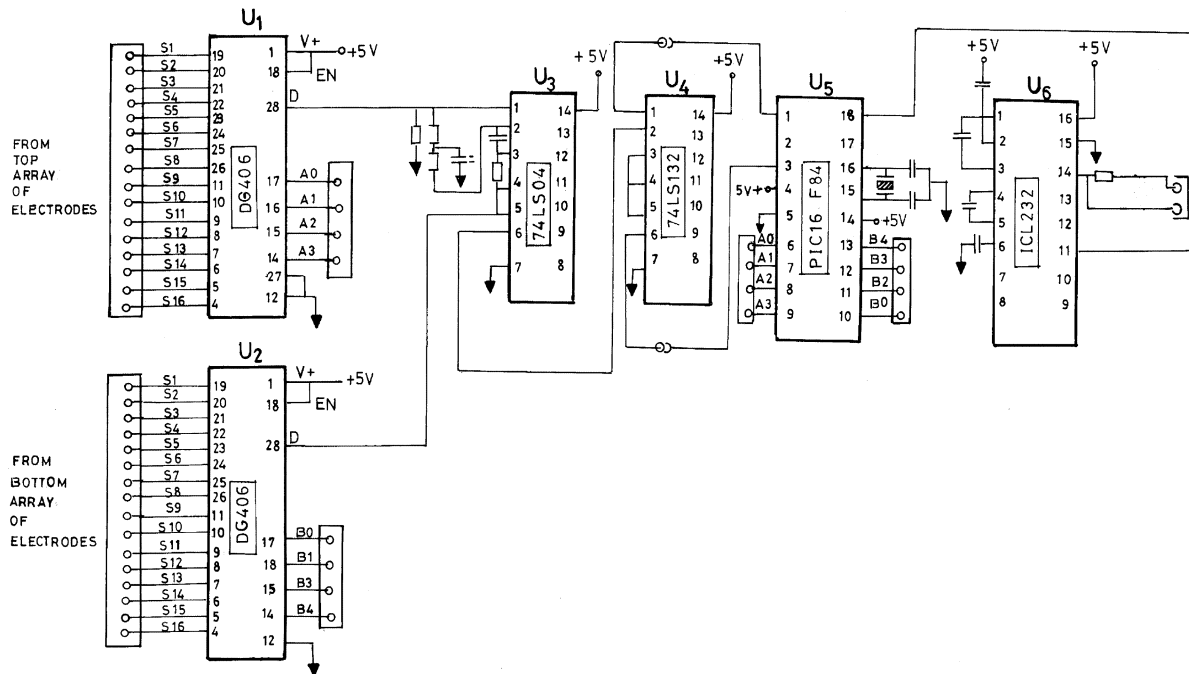
Fig. 2. Schematic diagram of the electronic circuit used for interfacing the tactile sensor to the computer.

and software programs were designed and implemented to interface the sensor with the computer [9]. A block diagram of the complete experimental arrangement along with the tactile sensor is shown in Fig. 1. It consists of analog multiplexers, a series-resonant oscillator circuit, a PIC 16F84 micro-controller, and a level converter for RS 232 interface to the computer. The program written in the microcontroller initially selects a matrix element, and the selected matrix element gets connected to the oscillator circuit. The frequency counter program will measure the oscillator output frequency and it sends the measured frequency to computer through the RS 232 level converter. This procedure gets repeated until the complete scanning of the entire matrix of elements. Hence, the entire operation of scanning the matrix of active elements, measuring the frequency and sending the measured frequency to the computer, is controlled by the microcontroller. The software written for the measurement of the frequency is capable of measuring the frequency with an accuracy of $\pm 1$ Hz at 1 MHz. All the tactile sensors made have been tested for their output response using the above experimental arrangement and procedure.

The schematic diagram of the electronic circuitry used for interfacing the tactile sensor to the computer is shown in Fig. 2. The ICs $U_1$ and $U_2$ are 16-channel CMOS analog multiplexers which receive the inputs from the top and bottom array of sensor electrodes. The outputs of these two multiplexers are connected to the oscillator circuit (with IC $U_3$). The oscillator circuit resonates at the resonance frequency ($\sim$1 MHz) of the poled PZT material used. The resonance frequency is measured at a gate pulse of 1 s using an AND gate (with IC $U_4$) which, in turn, receives the input from microcontroller (with IC $U_5$) for controlling the gate pulse duration of 1 s. The microcontroller (with IC $U_5$) is a flash 8-bit CMOS controller (Microchip Company, USA). The frequency measured by the microcontroller is fed to
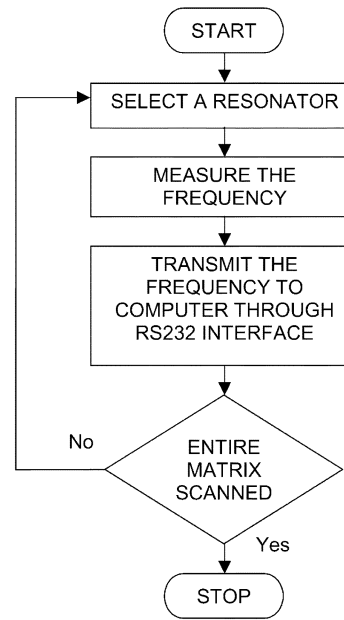


Fig. 3. Flow chart of the entire software implemented.

RS 232 interface (with IC $U_6$). Fig. 3 shows the flow chart of the necessary software implemented.

In order to have a calibration of the sensor output with reference force, a universal testing machine (INSTRON, U.K) along with a load cell has been used. The output of the sensor resonance frequency with applied force was recorded both in ascending and descending order using a dual-beam storage oscilloscope (Hewlett Packard, Model no. 54600, 100 MHz). All the experiments, including the output response study and calibration of the sensor output with reference force, have been carried out at room temperature.
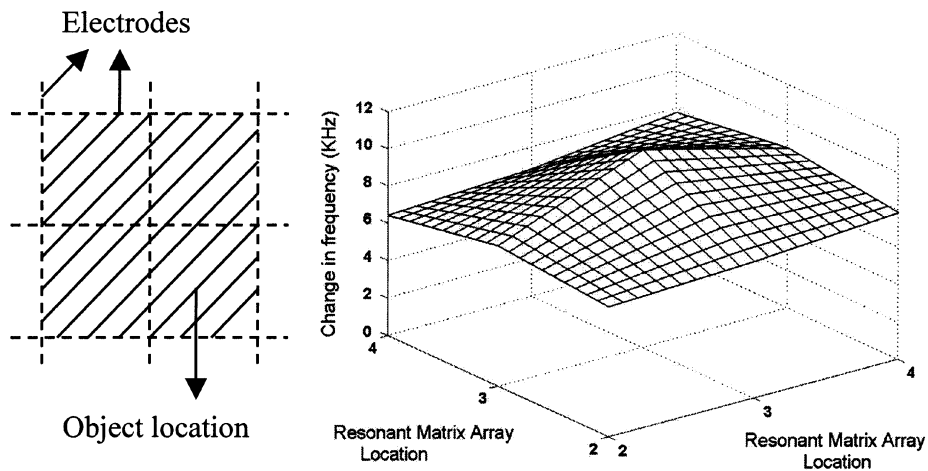
Fig. 4.   Response of $3 \times 3$ array tactile sensor for the object covering the entire active region.
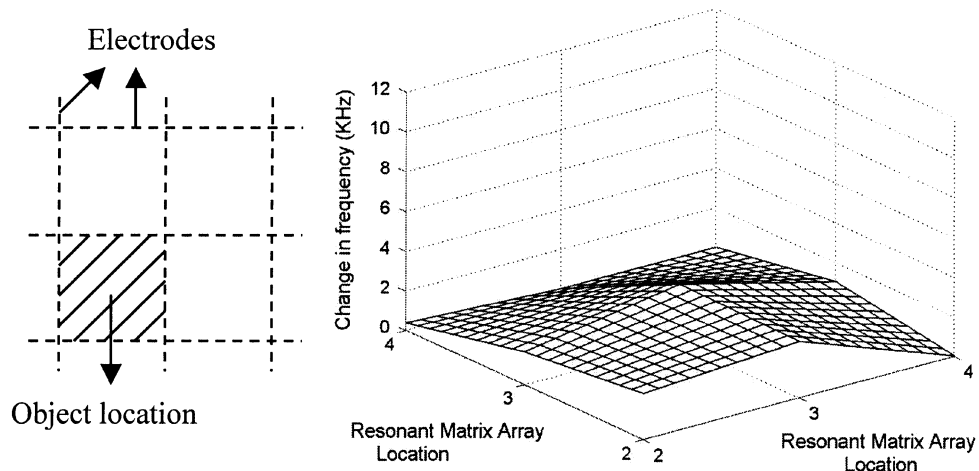


Fig. 5.   Response of $3 \times 3$ array tactile sensor for the object located at one corner side of the active area.

## III. DISCUSSION

The tactile sensors with different number of arrays of electrodes namely $3 \times 3$ arrays, $7 \times 7$ arrays, and $15 \times 15$ arrays were studied for their output response by using the aluminum plate (both square and circular shaped) as an object placed over the sensor. In all the figures (Figs. 4–11) which show the tactile sensor response, dashed lines on the left side of the figures signifies the number of electrodes and their location on the PZT material (circular in shape) constituting the sensitive area, with hashed regions indicating the location of the object over this sensitive area and the right side of the figures show the corresponding response. Fig. 4 shows the response for the object covering the entire sensitive area of the $3 \times 3$-array tactile sensor. The response corresponding to regions between the active elements is linearly interpolated from the data obtained from the active elements of the sensor. As can be seen in Fig. 4, the response is higher at the center compared to the regions toward the edges. This is thought to be due to several possible reasons, like nonuniformity of applied pressure, nonuniform poling of the PZT material, or it could be due to nonuniformity in thickness of the PZT ceramic material used. The ambiguity in nonuniformity in applied pressure can be resolved by testing the sensor with higher spatial resolution (more number of matrix elements). The

response of the $3 \times 3$ array sensor for the object located at different regions of the active area are shown in Figs. 5 and 6. As can be seen, it is clearly evident that the response of the sensor is largely confined to the area covered by the object.

The response of the $7 \times 7$ array tactile sensor in case of the square shaped object located toward one corner side of the active area is shown in Fig. 7. The response of the sensor for the same object located at the same position but with the increased extent of pressure is shown in Fig. 8. The change in frequency is more for the higher extent of applied pressure indicating the pressure sensitivity of the sensor. Also, it is clearly evident that, in comparison with the $3 \times 3$ array sensor, the spatial resolution of $7 \times 7$ array tactile sensor has improved significantly as expected.

The response of the $7 \times 7$ array tactile sensor for a circular object located at the center of the active area is shown in Fig. 9. It can be observed that the response of the sensor is not only confined to the actual area of the object which is in contact with the sensor, but also to the closer adjacent regions beyond the edge boundaries of the object. This is attributed to the fact that, when pressure is applied over the object, it is transferred to the active area through the silicon rubber. Since the silicon rubber is elastic, it expands under the application of pressure and covers the adjacent additional regions of the active area of the sensor.
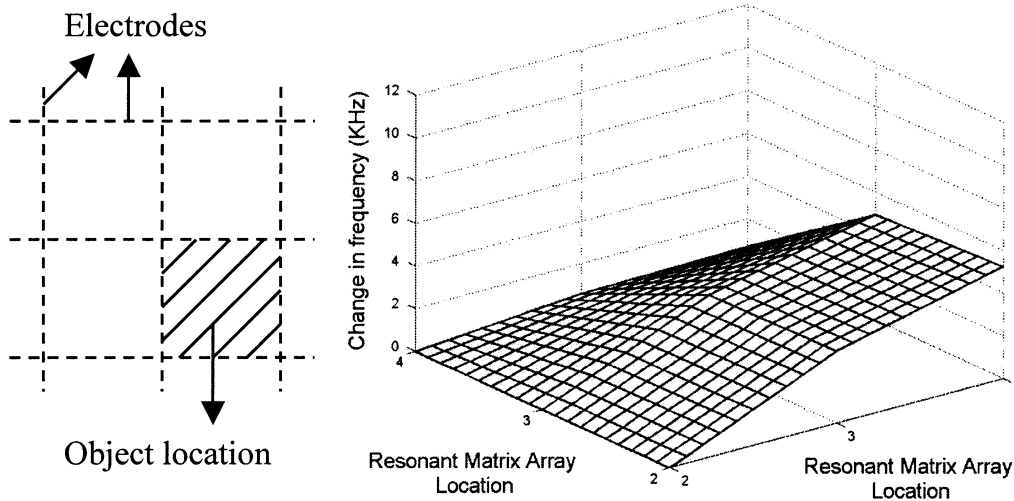
Fig. 6. Response of 3 × 3 array tactile sensor for the object located at another corner side of the active area.

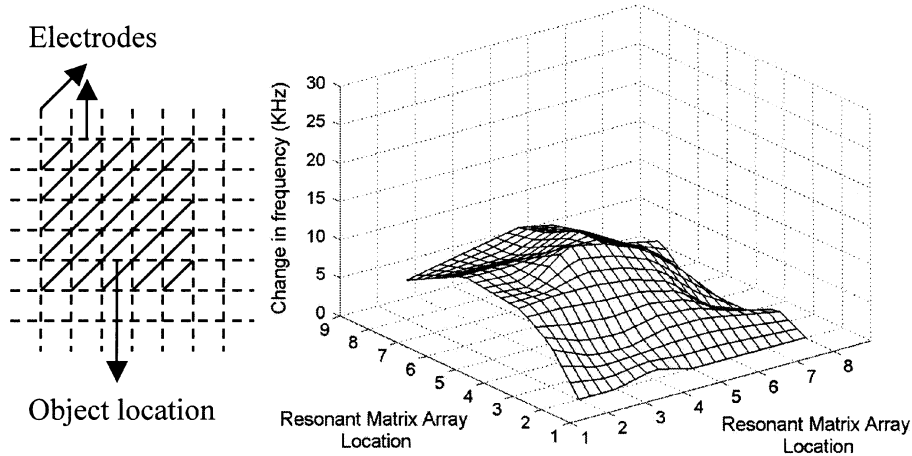Fig. 7. Response of 7 × 7 array tactile sensor for a square shaped object located toward one corner of the active area.

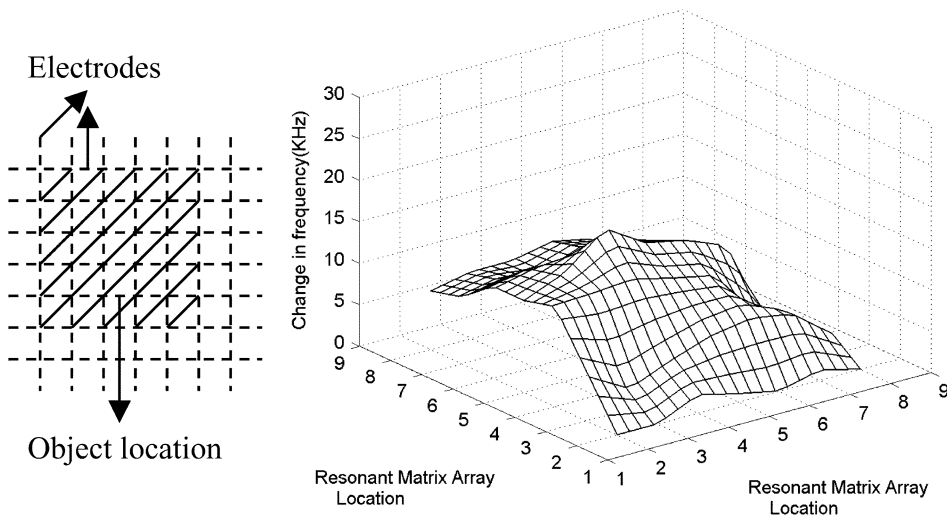Fig. 8. Response of the 7 × 7 array tactile sensor for a square shaped object located toward one corner side of the active area (same as in the case of Fig. 7) and with increased extent of pressure/force.

The response of the tactile sensor with 15 × 15 array of electrodes is shown in Fig. 10 for a circular object placed at the center of the active area. Also, the response of the same sensor for an object having a hole at the center is shown in Fig. 11. It is clearly noticeable that, compared to the 7 × 7-array sensor, the spatial resolution has further improved. It is also evident from Figs. 10 and 11 that the sensor can provide information about contour of the object.

Fig. 12 shows the variation of change in resonance frequency of the sensor with applied force (in ascending and descending
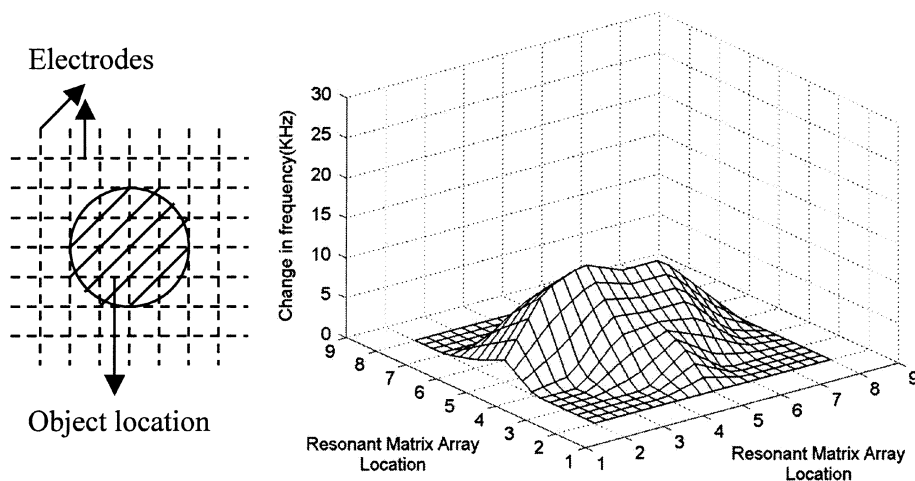
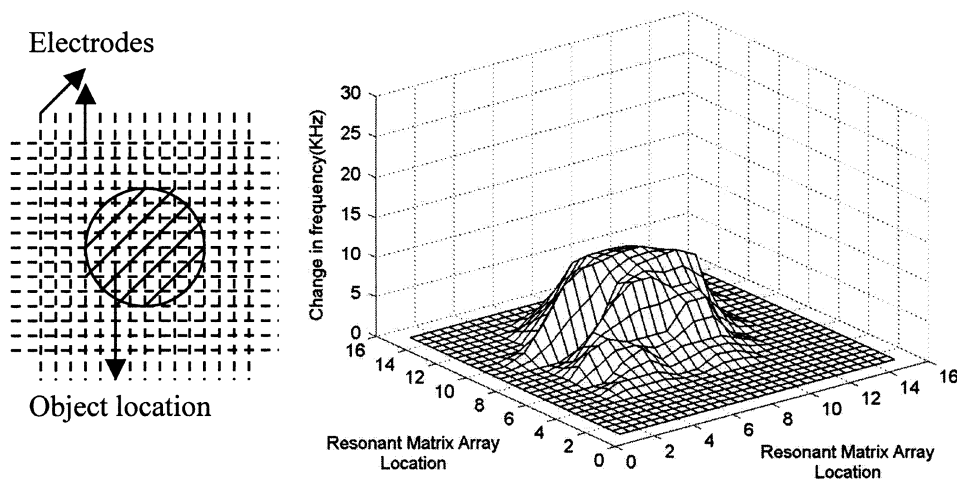Fig. 9.   Response of 7 × 7 array tactile sensor for a circular object located at the center of the active area.



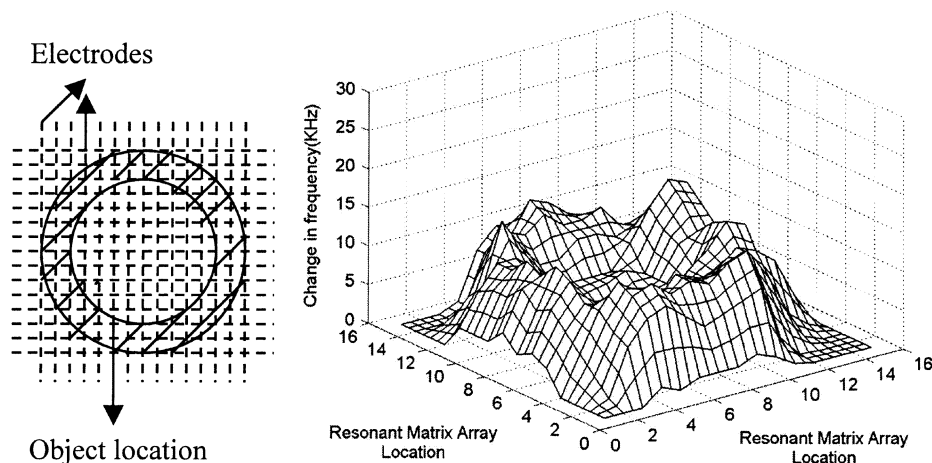Fig. 10.   Response of the 15 × 15 array tactile sensor for a circular object placed at the center of the active area.



Fig. 11.   Response of the 15 × 15 array tactile sensor for an object having a hole at the center.

order) for three consecutive cycles. It can be seen that, in all the three cases, the output is repeatable and the calculated hysteresis is found to be less than 1% full-scale output. It is observed that the initial offset frequency of the sensor reverts to its original value after each calibration cycle. Considering 0.4-N force resolution of universal testing machines used and 0.05% resolution in oscilloscope and related signal conditioner circuitry employed in our experiments, the calculated uncertainty of measurement is below 0.1%. Based on the drop ball method experiment, the dynamic response of the sensor is found to be 0.05 $\mu$s.

## IV. CONCLUSION

We have successfully developed the tactile sensor based on the principle of piezoelectric resonance. An array of electrodes geometry has been employed in the realization of the sensor.
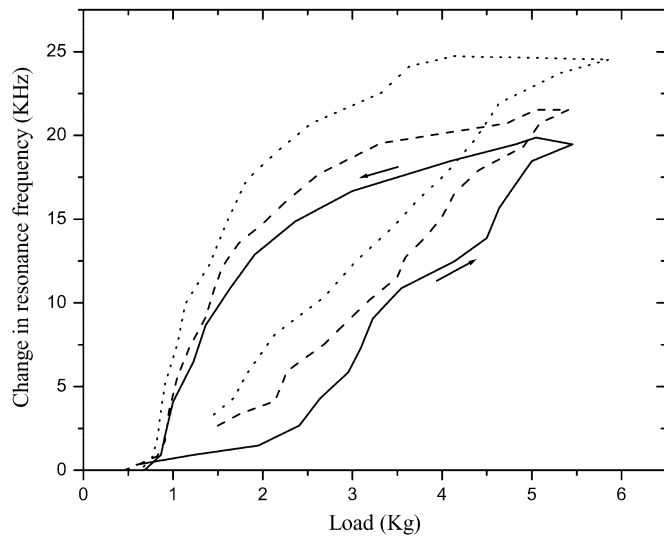
Fig. 12. Variation of change in resonance frequency with applied force for three consecutive cycles.

The necessary electronics (both hardware and software) have been developed and the entire assembly is interfaced suitably with the computer. The output response study carried out on the sensor clearly demonstrate that the sensor can provide information not only about the extent of force/pressure applied on the object, but also the contour of the object which is in contact with the sensor. This scope exists for improving the sensor behavior in terms of its spatial resolution by increasing the number of array electrodes using lithographic techniques. The presently developed tactile sensor has potential application possibilities in the areas of robotics and biomedical engineering.

### ACKNOWLEDGMENT

### REFERENCES

[1] M. F. Barsky, D. K. Lindner, and R. O. Claus, "Robot Gripper control system using PVDF piezoelectric sensors," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. UFFC-36, pp. 129–133, Jan. 1989.
[2] E. Benes, M. Groschl, W. Burger, and M. Schmid, "Sensors based on piezoelectric resonators," *Sens. Actuators A*, vol. 48, pp. 1–21, 1995.
[3] C. Gehin, C. Barthod, and Y. Teisseyre, "Design and characterization of new force resonant sensor," *Sens. Actuators A*, vol. 84, pp. 65–69, 2000.
[4] H. Morimura, S. Shigematsu, and K. Machinda, "A novel sensor cell architecture and sensing circuit scheme for capacitive fingerprint sensors," *IEEE J. Solid-State Circuits*, vol. 35, pp. 724–731, May 2000.
[5] [Online]. Available: http://www.soton.ac.uk/~rmc1/robotics/artactile.htm
[6] B. V. Jayawant, M. A. Onorio, and J. D. MacWatson, "Robot tactile sensing: A new array sensor," in *Robot Sensors II Tactile and Non-Vision*, A. Pugh, Ed.   London, U.K.: IFS, 1986, pp. 199–205.
[7] K. Tanie, "Advances in Tactile sensors for robotics," in *Proc. 6th Sensor Symp.*, 1986, pp. 63–68.
[8] L. Liu, X. Zheng, and Z. Li, "An array tactile sensor with piezoresistive single crystal silicon diaphragm," *Sens. Actuators A*, vol. 32, pp. 193–196, 1993.
[9] G. Murali Krishna, "Development of tactile sensors based on piezoelectric resonance and surface acoustic wave techniques," M.Sc. (Engg.) thesis, Indian Inst. Science, Bangalore, India, 2001.
[10] M. R. Neumann, *Medical Progress Through Technology*.   New York: Springer, 1982, vol. 9.
[11] S. Omata and Y. Terunuma, "New tactile sensor like human hand and its applications," *Sens. Actuators A*, vol. 35, pp. 9–15, 1992.
[12] P. Pagh, W. B. Heginbotham, and C. J. Page, "Novel techniques for tactile sensing in a three dimensional environment," *Ind. Robot.*, pp. 35–48, Mar. 1977.
[13] P. Li and Y. Wen, "An arbitrarily distributed tactile piezoelectric sensor array," *Sens. Actuators A*, vol. 65, pp. 141–146, 1998.
[14] J. Rebman and K. A. Morris, "A tactile sensor with electro optic transduction," in *Proc. 3rd Int. Conf. Robot Vision and Sensory Controls*, Cambridge, MA, Nov. 1982, pp. 210–216.
[15] R. Adler and P. J. Desmares, "An economical touch panel using SAW absorption," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. UFFC-34, pp. 195–201, Jan. 1987.
[16] J. Sorab, R. H. Allen, and B. Gonik, "Tactile sensory monitoring of clinician-applied forces during delivery of new borns," *IEEE Trans. Biomed. Eng.*, vol. 35, pp. 1090–1093, Dec. 1998.
[17] S. Sugiyama, K. Kawahata, M. Yonendu, and I. Igarashi, "Tactile image detection using 1 K-element silicon pressure sensor array," *Sens. Actuators A*, vol. 21–23, pp. 397–400, 1990.

**G. Murali Krishna** was born in 1975 in India. He received the M.Sc. degree in electronics from the School of Physics, University of Hyderabad, India, and the M.Sc. (Engg.) degree from the Department of Instrumentation, Indian Institute of Science, Bangalore, where he was involved in the development of tactile sensors. His thesis was titled "Development of tactile sensors based on piezoelectric resonance and surface acoustic waves." He is currently pursuing the Ph.D. degree in nanotechnology-based cantilever sensors at the Institute of Physics, University of Basel, Basel, Switzerland.

**K. Rajanna** was born in Karnataka, India. He received the M.Sc. degree in physics from the University of Mysore, India, in 1976 and the M.Sc.(Engg.) and Ph.D. degrees from the Indian Institute of Science (IISc), Bangalore, in 1988 and 1993, respectively.

At present, he is an Associate Professor at the Department of Instrumentation, IISc. He was a Visiting Fellow of the Japan Society for the Promotion of Science (JSPS) twice from 1997 to 1998 at the Toyohashi University of Technology, Japan. He was also a Visiting Professor at Tohoku University, Japan, during 2000 and 2002. Recently, he was invited to serve on the program committee of the Asia-Pacific Conference of Transducers and Micro-Nano Technology 2004 (APCOT'04) to be held in Sapporo, Japan. His current areas of interest include thin-film sensors and microsensors (including MEMS), vacuum and thin-film technology, and novel materials engineering for sensor applications.

Dr. Rajanna served as a member of the Editorial Review Committee of the IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT.