Design and Construction of a Novel Tactile Sensor for Measuring Contact-Force, Based on Piezoelectric Effect

N. Nasseri[i]; S. Najarian[ii *]; A. Tavakoli Golpaygani[iii] and G. Darb Emamieh[iv]

ABSTRACT

In this paper, design and construction of a tactile sensor for measuring contact-force is presented. Mechanism of measuring contact-force in this tactile sensor is based on impedance changing of piezoelectric crystal and voltage of different points in circuit as a result of applying force on the crystal. By considering a specific point in the circuit and recording the changes of its voltage, magnitude of applied force can be estimated. Structure of the sensor consists of a disk-shaped piezoelectric crystal that its diameter is 2 cm, its thickness is 2 mm and its resonance frequency is 135 kHz. This crystal is placed in a metal chamber. A spring is on the crystal on which a moving part is installed for applying force.

One of the characteristics of the sensor is that its size and shape can be easily tailored to the different applications. By miniaturizing this sensor and using biocompatible materials, it is applicable in different fields of medicine such as minimally invasive surgery (MIS).

KEYWORDS

TACTLE SENSOR, CONTACT FORCE, PIEZOELECTRIC

1. INTRODUCTION

Useful information such as contact force, temperature, softness and coarseness is supplied by the sensory interactions between humans and different objects through manipulation. Of all the applications of this information, key is the application to robotics, since it can give an estimation of the optimized force for catching and transmitting the object [1], [2], [3]. For example, if a robot is used for object transmission, this information should be received and processed by the robot. The importance of such a piece of information is more considerable in robotic surgery. During applying force to an object in robotic surgery, lack of information will limit development in robotic handling of soft and fragile objects, especially elastic objects such as body tissues. As a result, in a treatment process, from basic assessments to a complete treatment, tactile sensing is of great importance [4], [5], [6], [7], [8].

Open surgery is a traditional method of surgery. Nowadays, many efforts have been done to reduce traditional open surgery's defects. Endoscopic surgery is now being widely used as one of the most preferred choices for various types of operations. Beside the advantages of Endoscopic surgery, there are several disadvantages. For example, in some operations, there are operation sites, full of blood, in human body that are otherwise difficult or may be impossible to see through a camera. In this regard, the only way of recognition, for the surgeon, is tactile sensing. As a result, there is a serious need of intelligent robotic surgery's instruments [9], [10].

Tactile sensors development is delayed because of the inherent complexity in mechanical properties of the skin. As mentioned above, tactile sensing is solely able to detect the characteristics of an object which is in direct contact with the skin. Fabrication of a tactile sensor which is only able to quantify one of the characteristics of an object is a complex procedure, though. So, fabrication of a tactile sensor which acts in a way that is close to the act of the human skin has its own problems. As a result, scientists have considered some kinds of tactile sensors, each of which simulates one of the characteristics of the human skin. Some recent research activities in this area are mentioned below:

Fabrication of density sensor based on resonance vibration [11], supplying contact force and pressure information by the sensory interactions between sensors and different objects [12], measuring nano-gram masses in a fluid medium [13], determination of the physical properties of biomaterials [14], fabrication of sensors for

i N. Nasseri is with the Department of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran (e-mail: nassim_nasseri@aut.ac.ir).

ii * Corresponding Author, S. Najarian is with the Department of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran (e-mail: najarian @aut.ac.ir).

iii A. Tavakoli Golpaygani is with the Department of Physics and Biomedical Engineering, Shiraz University of Medical Sciences, Shiraz, Iran (e-mail: atavakoli@pearl.sums.ac.ir).

iv G. Darb Emamieh is with the Department of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran (e-mail: goldis_emamieh@aut.ac.ir).

static and dynamic force measurement [15], and considerations in the design and sensitivity optimization of micro tactile sensors [16].

There are several physical effects which result in generation of sensors. All such effects are based on fundamental principles of physics, such as mechanical, capacitance, fiber optics, magnetic, piezo-electric and acoustic wave principals [17], [18], [19], [20]. Piezoelectric crystals are cheap, small, light, and easily available. Besides, hysteresis error can be ignored easily while measuring forces by piezoelectric crystals. So, piezoelectric crystal has been chosen, as the sensing element, because of these advantages. Moreover, piezoelectric crystal can be found in different shapes and sizes. Sensor's availability in different shapes and sizes, gives the opportunity to use it in array elements [21], [22], [23], [24]. These advantages show that using piezoelectric crystals in contact-force sensors has always been of great importance. Using these crystals in on/off sensors has been reflected in previous research works [21], [22], [23], [24], [25]. These crystals are only able to measure dynamic forces and they do not have the ability to measure static forces. Previous research activities show that it is possible to use array piezoelectric elements to detect location and magnitude of applying force and trace 2D schematics for them [26].

Design and construction of a novel tactile sensor, based on piezoelectric effect is being presented in this research work. Of advantages of this sensor comparing to previous ones is that it can measure not only static forces but also a wide and proper range of applied forces. This range covers the range of forces that biological tissues apply to the sensor in a direct contact with it. The designed sensor could be potentially integrated with medical probe if bio-compatible materials were used as its coating. Using this sensor in an array element gives the opportunity to trace a 2D schematic of the location and magnitude of the applied force.

2. Materials and Methods

Using piezoelectric effect in a crystal and tracking its impedance changing is the main idea in designing this sensor.

A. Principles of Design and Sensing

The word piezo comes from the Greek piezen, meaning "to press" [9], [25]. The piezoelectric effect is the generation of electric charge by a crystalline material upon subjecting it to stress. The effect exists in natural crystals, such as quartz (chemical formula SiO_2), and poled (artificially polarized) man-made ceramics and some polymers, such as polyvinylidene fluoride [9], [26]. Figure 1 shows the general structure of a piezoelectric crystal, while it is under force.

When an external force is applied to the crystal, along the z-axis, the mechanical structure of the piezoelectric crystal becomes deformed. As a result, the electrical model of the crystal becomes changed. So, when this crystal is placed in the designed electrical circuit, the current of some branches and the voltage of some nodes will change. The applied force on the crystal can be estimated through tracing the changes in voltage of a node or the current of a branch [18].

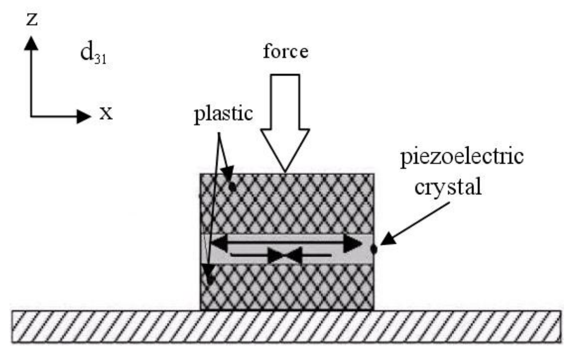

Figure 1. Applying force to piezoelectric crystal.

B. Device Specification

Structure of the sensor consists of a disk-shaped piezoelectric crystal that its diameter is 2 cm, its thickness is 2 mm and its resonance frequency is 135 kHz. This crystal is placed in a metal chamber that its height is 8 cm, and its radius is 3 cm. A spring (k=1800 N/m) is on the crystal on which a moving part is installed for applying force. The output is shown on an LCD through AVR microcontroller (output resolution: 0.01 N).

C. Theoretical Aspect and Circuit Analysis

Circuit in Figure 2 is used for tracing piezoelectric impedance changing.

In Figure 2, R_1=100 Ω and R_2=120 Ω. Z_3 is equivalent impedance of piezoelectric crystal. R_3 and C_3 should be estimated according to the mechanical properties of the crystal.

Since piezoelectric crystal is inherently an oscillator, it can be modeled as a serial RLC. This circuit should work in its resonance frequency. In this work, the resonance frequency of the crystal is 130 kHz. So R_3 and C_3 are calculated as in (1).

$$f_{resonance} = \frac{1}{\sqrt{L_3 C_3}} \qquad (1)$$

In (1), $f_{resonance}$, is the piezoelectric crystal resonance frequency, in Hz, L_3, is the equivalent self in the crystal model, in H, and C_3, is the equivalent capacitor in crystal model, in F.

Since the circuit should work in its resonance frequency (130 kHz), the frequency of the input signal should be equal to 130 kHz. In the resonance frequency, the capacitor neutralizes the effect of the self and they act as a short circuit together. As a result, changing in R_3 determines the output voltage in the circuit.

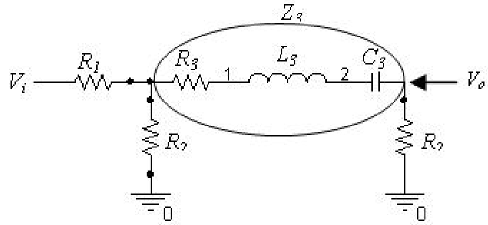

Figure 2. Electrical circuit for measuring force by tracking the output voltage changes.

On the other hand, mechanical structure of the piezoelectric crystal will change if a normal force is applied on the crystal. So, the equivalent impedance of the crystal (Z_3), changes. It has been shown in experimental tests that in our favorite range of forces (0.1-10 N), resonance frequency does not change noticeably. As a result, it can be assumed that it is only R_3 that its magnitude changes with changing in the magnitude of the applying force. Assuming, R_3 and C_3 constant, the output voltage is calculated as in (2).

$$V_o = 0.7 \times \frac{720}{11R_3 + 1920} \tag{2}$$

In (2), V_o, is the output voltage in V, R_3, is the equivalent resistance of the crystal, in Ω, and the input voltage has been fixed on 0.7 V.

D. Modeling

As mentioned before, when the magnitude of R_3 changes, the voltage output of the circuit in Figure 2, will change simultaneously.

Orcade 9.2 is used for modeling the performance of the electrical circuit. Since it is not possible to determine the exact magnitude of R_3, it has been chosen arbitrarily. As it has been clarified before, the magnitude of this resistance is a function of mechanical properties of the crystal and it is only approachable by equalizing the behavior of the crystal in the laboratory and its behavior in a virtual model. Figure 3 shows the changes in output voltage of the circuit in Figure 1 with the changes of the applying force.

E. Calibration

Calibration plays an important role in measuring systems. In this study, the relation between the magnitude of the applying force and the output voltage was obtained through a designed experimental test. Figure 4 shows a basic system for applying force on the crystal. This system consists of a vis with specified steps on it and an elastic spring with specified spring constant. Each time that the vis is twisted a specified force is applied to the crystal. Figure 5 shows how force is applied to the crystal and how the output is obvious on the oscilloscope.

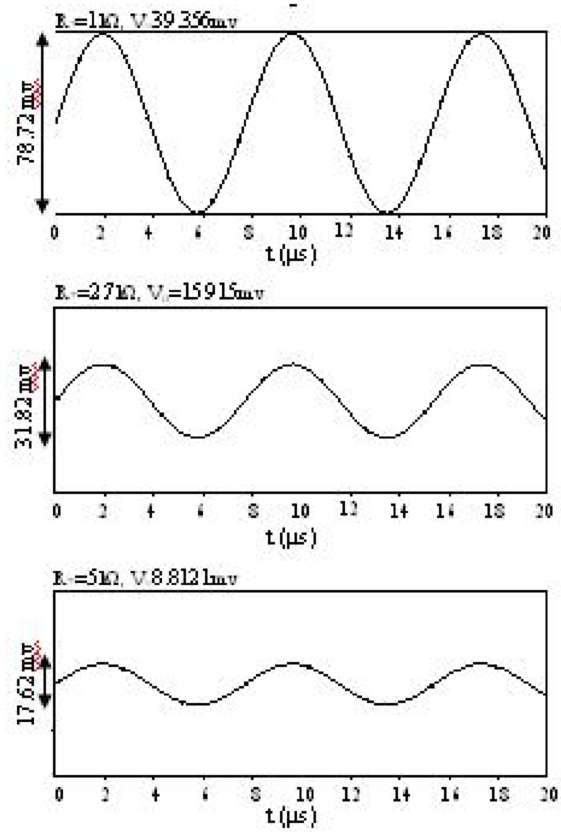

Figure 3. Changes in the output voltage as a result of impedance changing in piezoelectric.

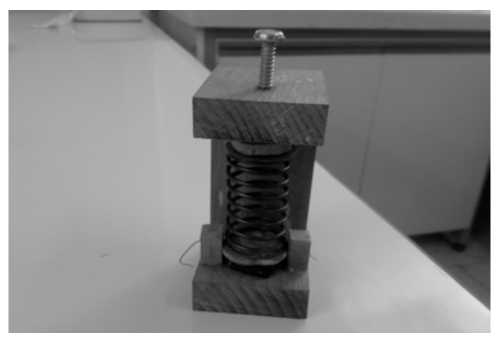

Figure 4. Designed system for sensor calibration.

The output voltage of the sensor is measured and recorded after applying different magnitude of forces on it and a graph of applied force to voltage is traced. Figure 6 shows the traced graph.

Matlab, according to Figure 6, has calculated the applied force as in (3).

$$F=-29.88V+23 \tag{3}$$

In (3), F is the applied force in N and V is the output voltage in V.

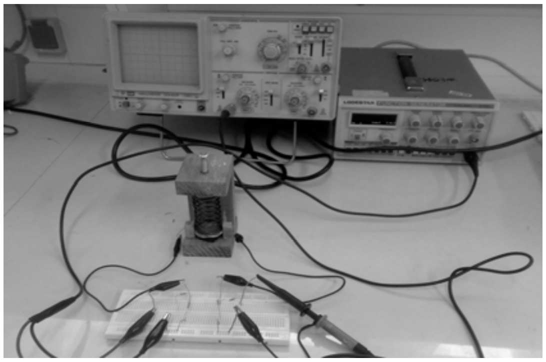

Figure 5. Applying force on the sensor and displaying the output on the oscilloscope.

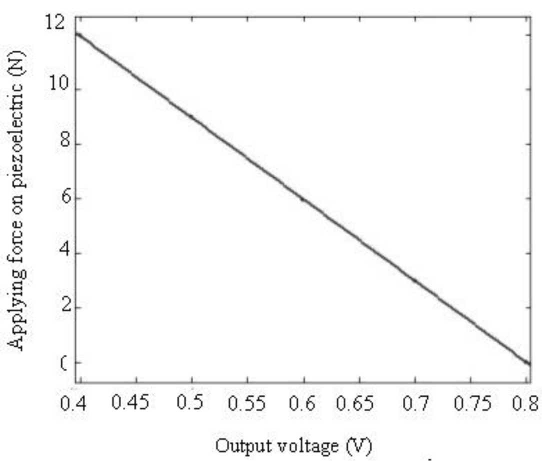

Figure 6. The graph of the magnitude of applying force on the sensor to the output voltage.

3. RESULTS AND DISCUSSION

For evaluation of the efficiency of the sensor, several certain forces were applied on it. Figure 7 shows the results.

As it is obvious in Figure 7, the measured forces coincide effectively to the real magnitudes. Table 1 compares the real magnitude of the forces with the measured ones and clarifies the percentage of the error. As seen in Table 1, in the range of the applied forces, the maximum percentage of measuring error is 3%, and the accuracy of the sensor is 97%.

In this paper, the efficiency of the sensor is evaluated in different experimental tests and one of the results is shown in Table 1. The results of the test clarify the repeatability of the sensor.

As Table 1 shows, it can be claimed that the measurement error is less than 2% in 80% of measurements. If the accepted error goes up to 3%, the sensor will be able to estimate the applied force approximately uncompromisingly.

To evaluate the hysteresis error, the output voltage is measured in direct and opposite directions, as shown in Table 2. When the applied forces increase, a voltage is produced which differs by 0.05 V from that when the forces are decreased. This difference in measurement is obvious only in one point.

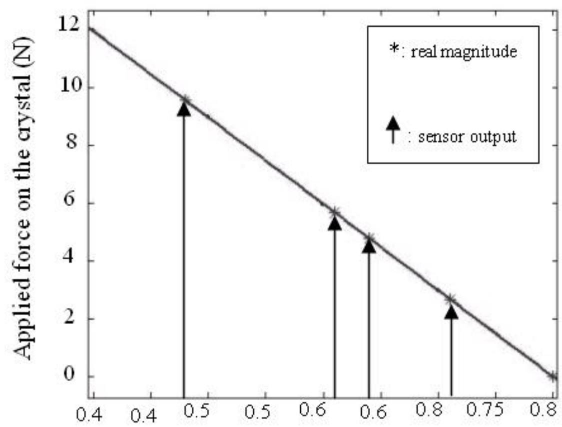

Figure 7. A comparison between calculated forces through the sensor system and the real magnitudes of the applied force.

TABLE 1
A COMPARISON BETWEEN CALCULATED FORCES THROUGH THE SENSOR SYSTEM AND THE REAL MAGNITUDES OF THE APPLIED FORCE.

Real magnitude (N)	0	2.94	4.9	5.88	**9.8**
Sensor output	0	2.98	4.78	5.97	**9.86**
Error percentage	0	1.3%	2.4%	1.5%	**0.6%**

TABLE 2
MEASURED VOLTAGE IN DIRECT AND OPPOSITE DIRECTIONS, FOR EVALUATING HYSTERESIS ERROR.

Real magnitude of force (N)	2.94	4.9	5.88	9.8	14.7	9.8	5.88	4.9	2.94
Output voltage (V)	0.7	0.6	0.5	0.4	0.3	0.35	0.5	0.6	0.7

Force changes directly with the output voltage, when the applied forces are between 0.1-10N. So, the sensor acts directly in this range of forces.

Table 3 shows the sensor's output in four experimental tests. As presented in Table 3, only in one test of these four tests the output of the sensors differs from the others. This difference is shown in bold.

The efficiency of the sensor is tested in different times and environmental conditions and the maximum difference in the output of the sensor, for a specific measuring force, was less than 7%.

The output does not differ for forces more than 12 N because the sensor is saturated for forces more than this value. The saturation level could be increased by using a different type of crystal.

Dead band for this sensor was around 0.1 N. It means that the sensor cannot measure forces less than this amount. Since in this paper measuring forces less than 0.1 N is not of great importance, the dead band is acceptable. The measured force can be shown on an LCD with 0.01 N in precision.

The specifications of the designed sensor, such as precision, accuracy, dead band, and linearity are some of the advantages of this sensor over other previous types. These advantages make the designed sensor a good choice for using in robotic surgery.

TABLE 3
SENSOR'S OUTPUT IN FOUR DIFFERENT MEASURING LEVELS, FOR EVALUATING SENSOR'S REPEATABILITY.

First level	**Force (N)**	0	2.94	4.9	5.88	9.8
	Output voltage (V)	0.8	0.7	0.6	0.5	0.4
Second level	**Force (N)**	0	2.94	4.9	5.88	9.8
	Output voltage (V)	0.8	0.7	0.6	0.5	0.4
Third level	**Force (N)**	0	2.94	4.9	5.88	9.8
	Output voltage (V)	0.8	0.7	0.6	0.5	0.4
Forth level	**Force (N)**	0	2.94	4.9	5.88	9.8
	Output voltage (V)	**0.7**	**0.65**	0.6	0.5	0.4

4. CONCLUSION

Although the theory of sensor design and specifically tactile sensor design has been developed recently; for fabricating sensors that can act as the human's tactile sensing, additional efforts are necessary. In this paper, a novel tactile sensor for measuring contact force, based on piezoelectric effect has been designed and fabricated.

First, theoretical approaches were used to evaluate the sensor's work and then the sensor was simulated virtually. The results of theoretical evaluation were matched with the results of modeling. At the end, using the information of previous sections, the sensor was fabricated.

Of the advantages of this sensor are its simplicity, and suitable price. If much smaller crystals were used in the sensor system, and the sensor was covered by bio-compatible polymers, it could be simply used in robotic surgery. Moreover, this sensor is usable in array elements for tracing schemes of location of the applied force.

5. ACKNOWLEDGMENT

The authors gratefully acknowledge the Center of Excellence in Biomedical Engineering of Iran for their support in conducting this project.

6. REFERENCES

[1] Najarian, S.; Dargahi, J.; Zheng X.Z.; "A Novel Method in Measuring the Stiffness of Sensed Objects with Applications for Biomedical Robotic Systems", Int J Med Robotics Comput, vol 2, p.p. 84-90, 2006.
[2] Omata, S.; Terunuma, Y.; "New Tactile Sensor Like The Human Hand and Its Applications", Actuat A-Phys, vol. 35, p.p. 9-15, 1992.
[3] Dargahi, J.; Najarian, S.; "An Endoscopic Force Position Grasper with Minimum Sensors", Can J Electr Copmut Eng. , vol. 28, p.p. 155-161, 2004.
[4] Dargahi, J.; Najarian, S.; "Analysis of a Membrane Type Polymeric-Based Tactile Sensor for Biomedical and Medical Robotic Applications", Sensor Mat, vol. 16, p.p. 25-41, 2004.
[5] Dargahi, J.; "An Endoscopic and Robotic Tooth-like Compliance and Roughness Tactile Sensor", J Mech Des, vol. 124, p.p. 576-582, 2002.
[6] Lee, M.H.; Nicholls, H.R.; "Tactile Sensing for Mechatronics, a-State-of-the-Art Survey", Mechatronics, vol. 9, p.p. 1-31, 1999.
[7] Nicholls, H.R.; "Advanced Tactile Sensing for Robotics", World Scientific, Singapore, 1992.
[8] Widmann, G.; "Image-Guided Surgery and Medical Robatics in the Cranial Area", Biomed Imaging Intervention J, vol.3, 2007.
[9] Wilson, J.S., "Sensor Technology Handbook", Elsevier, Newnes, 2005.
[10] Guyton, A.; Hall J.; "Text Book of Medical Physiology", 9th edition, 1996.
[11] Crescini, D.; marioli, D.; Taroni, A.; "Piezoelectric Thick-Film Fluid Density Sensor Based on Resonance Vibration", IEEE Instrumentation and Measurement, Technology Conference, Minnesota: USA, 1998.
[12] Zheyao, W.; Huizhong Z.; Yonggui D.; Jinsong, W.; Guanping, F.; "Force-frequency Coefficiant of Symmetrical Incompelete Circular Quartz Crystal Resonator", IEEE T Ultrason Ferr, vol. 48, No. 5, 2001.
[13] Hyung Joon, K.; Young-Bum, K.; Juebum, P.; Tae Song K.; "Biological Element Detection Sensor Application of Micro Machined PZT Thick Film Cantilever", Proceedings of IEEE, vol.2, p.p. 1054-1058, 2003.
[14] Omata, S.; Murayama, Y.; E.Constatinou, C.; "Real Time Robotic Tactile Sensor System for the Determination of the Physical Properties of Biomaterials", Sensor Actuat A-Phys, vol. 112, p.p. 278-285, 2004.
[15] Ozeri, S.; Shmilovitz, D.; "Static Force Measurement by Piezoelectric Sensors", ISCA, 2006.
[16] Omata, S.; Murayama, Y.; "Considerations in the Design and Sensitivity Optimization of the Micro Tactile Sensor", IEEE T Ultrason Ferr, vol. 52, 2005.
[17] Bentley, J.; "Principles of Measurement Systems", Longman Singapoure, 1988.

[18] Fraden, J.; "Hand Book of Modern Sensors (Physics, Designs, and Applications)", 3rd edition, California: San Diego, 2003.
[19] Dario, P.; "Tactile Sensing-Technology and Applications", Sensor Actuat A-Phys, vol. 26, p.p. 251-261, 1991.
[20] Dargahi, J.; Najarian, S.; "Advances in Tactile Sensors Design/Manufacturing and Its Impact on Robotics Applications-a review", Ind Robot, vol. 32, p.p. 268-281, 2005.
[21] Dargahi, J.; "Piezoelectric And Pyroelectric Transient Signal Aanalysis For Detecting The Temprature Of An Object For Robotic Tactile Sensing", Sensor Actuat A-Phys, vol. 71, p.p. 89-97, 1998.
[22] Ferri, V.; Murioli, D.; Taroni, A.; "Thick-Film Resonant Piezo-Layers as New Gravimetric Sensors", Meas Sci Technol, vol. 8, p.p. 42-48, 1997.
[23] Arnau, A.; "Piezoelectric Transducers and Applications", Springer Verlog, Berlin Heidelberg, 2004.
[24] Reviakin, A.N.; Morozov, F.; Rosseti, F.; "Effects of Finite Crystal Size in the Quartz Crystal Micro Balance with Dissipation Measurement System: Implications for Data Analysis", J Appl Phys, vol. 95, 2004.
[25] Benes, E.; Groschl, M.; Burger, W.; "Sensors Based on Piezoelectric Resonators", Sensors and Actuators–A, vol. 48, p.p. 1-21, 1995.
[26] Murali Krishna, G.; Rajanna, K.; "Tactile Sensor Based On Piezoelectric Resonance", Indian Institute of Science, 2002.