Analysis of characteristics of piezo-electric material to develop intelligent devices for instrumentation.

B.Girirajan[1], K.C Rajakala[2], J.Tarunkumar[3], N. Shilpa[4] D.Gopinath[5]
[1]SR University, [2]Shanmuga Industries Arts and science college, [3]SR University, [4]SR University [5]Shanmuga Industries Arts and science college
Email:[1]girirajan.b@sru.edu.in, [2]rajakala780@gmail.com, [3]tarun.j@sru.edu.in, [4]shilpa.n@sru.edu.in [5] dgopipec@gmail.com

ABSTRACT

The proposed work gives the details about analysis of properties of piezo electric materials for the selection of material for ultrasonic wave generator. The MATLAB software is used to analyse the characteristics of piezo electric characteristics. The responses are analysed to understand the characteristics and suitability for using the piezoelectric material in ultrasonic wave generator. The responses are obtained by applying impulse input, force and sinusoidal waveform. The quartz crystal is modeled and the inputs, system and outputs are expressed in terms of mathematical equations. The simulation is carried with the help of MATLAB simulink using these mathematical equations related to the piezo electric crystal. The different modes of operations of the crystal are studied to obtain the output. The ultrasonic sensor which uses piezoelectric material to generate ultrasonic waveform is tested and utilized in the distance measuring application. From the analysis of various responses and factors, it is finalized that the quartz crystal is the suitable piezo electric material used in generating the ultrasonic waves. The selection of the material for the ultrasonic wave generator is important to generate ultrasonic wave. The ultrasonic wave generator is initiated by the trigger pulse and generates the ultrasonic wave which is used in various applications and to design intelligent instruments. The proposed work gives an idea about analysis of piezo electric materials for the selection to design intelligent instruments.

Keywords
Piezo electric materials, ultrasonic sensor, intelligent instrumentation

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Introduction

A piezo- electric material is one in which an electric potential emerge across certain surfaces of crystal if the dimensions of crystal are altered by the application of mechanical force[5] .This potential is produced by the displacement of charges . Conversely, if a varying potential is applied to the proper axis of crystal, it will alter the dimensions of the crystal thereby deforming it. This effect is known as piezo –electric effect. Elements exhibiting piezo-electric qualities are sometimes are called as electro-resistive elements.

The quest of piezo electric material came into existence when the “crystal” phonograph microphone came into the market. The advance technologies contributed to create an completely new method of piezoelectric device development-which is designing materials to specific applications. Thereafter the one of the major research areas is the application of piezoelectricity and search for perfect piezo electric products. Health monitoring applications is one of the major application that has received numerous scientists’ attentions around the world[13].

Piezoelectric materials can generate an electric charge with the application of force. They can also change their physical dimensions with the application of electric charge. One of the most important properties of piezoelectric materials is the ability to convert electrical energy into mechanical energy, and vice versa, which is expressed by electromechanical coupling.

The dynamic response[6] of the piezoelectric sensor described by the impedance method is as follows: the dynamic output characteristics of the actuators and the dynamic characteristic of the structure direct the interactions between actuators and structures.

The force relation for the piezoelectric actuators express as:

$F=K_A(X-X_i)$ -------------- (1)

Where F is the force exerted by the actuator, A K is the static stiffness of the piezoelectric transducer, X is the displacement, and i X is the free induced displacement of the actuator.

Materials

Common piezo–electric materials include Rochelle salts, ammonium dihydrogen phosphate[2], lithium Sulphate, dipotassium tartarate, potassium dihydrogen phosphate[11], quartz, and ceramics A and B. Except for quartz and ceramics A and B, the rest are manmade crystal grown from aqueous solutions under carefully controlled conditions. The ceramic materials are polycrystalline in nature[4] .These materials do not have piezo-electric properties in their original state but these properties are produced by the treatment of special polarization.

The materials that exhibit a significant and useful piezo –electric effect are divided into two categories

1. Natural group
2. Synthetic group

Quartz and Rochelle salts belong to Natural group while material like lithium sulphate, ethylene diamine tartarate belongs to Synthetic group.

piezo–electric effect can be made to respond to (or cause) mechanical deformations of the material in many different modes .The modes can be thickness expansion, transverse expansion ,thickness shear ,and face shear .The mode of motion effected depends on the shape of the body relative to the crystal axis and location of electrodes. A piezo –electric element used for converting mechanical motion to electrical signals may be thought as change generator and capacitor. Mechanical deformations generate a charge and this charge appears as a voltage across the electrodes.

The voltage is E=Q/C
----- (2)

Piezo–electric effect is direction sensitive .A tensile force produces a voltage of one polarity while a compressive force produces a voltage of opposite polarity.

A piezo-electric crystal is shown in Fig. 1

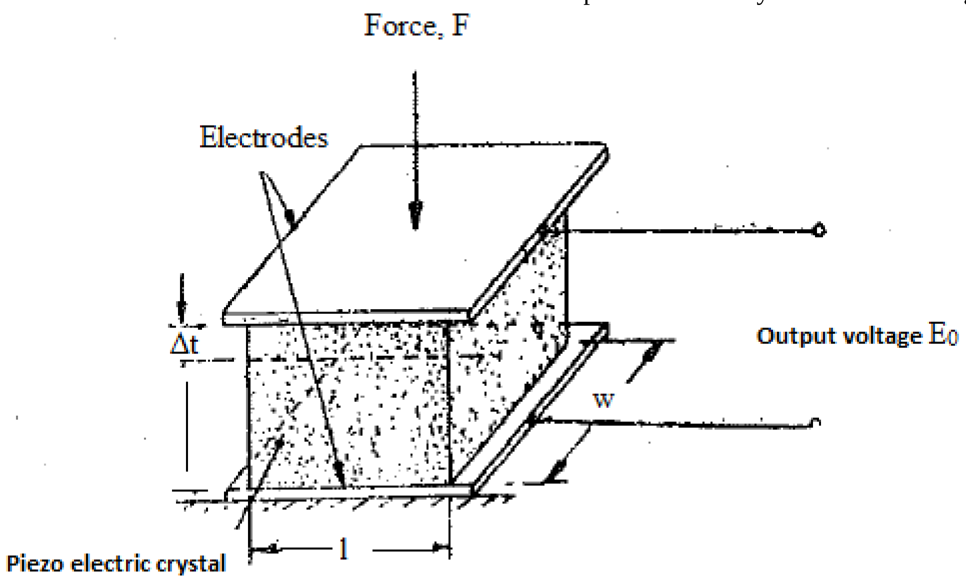


Fig. 1 Piezo electric crystal used for measurement of force.

The magnitude and polarity of the induced surface charges are proportional to the magnitude and direction of the applied force.

Charge Q = dF coulomb
----- (3)

where d=charge sensitivity of crystal .C/N; (It is constant for given crystal) and F=applied force, N

The force F causes in thickness of the crystal.

$F = \frac{AE}{t}$; Newton ----- (4)

where A=area of crystal; m2 t=thickness of crystal; m and E=young's modulus, N/M^2

Young's modulus E=stress /strain
=Ft/At; N/m^2 ----- (5)

Area A=wl where w=width of the crystal; meter & l=length of crystal; m.

Charge is obtained from equations 3 and 4,

Charge:

$Q = d\frac{AE}{t}\Delta t$; Coulomb -----(6)

The charge at the electrodes gives to an output voltage

$E_0 = Q/c_p$; volt ------(7)

c_p = capacitance between electrode; F.

Capacitance between electrode $c_p = \varepsilon_r \varepsilon_0$ A/t

From equation 3&7 :

$E_o = \frac{dF}{\varepsilon_r \varepsilon_0 A/t}$ ------- (8)

$E_o = \frac{d}{\varepsilon_r \varepsilon_0}$ ------ (9)

E_0=gtp ------ (10)

Where g=d/ $\varepsilon_r \varepsilon_0$ ------ (11)

g, is the voltage of the crystal .this is the constant for a given crystal cut. Its units is Vm/N

Now g=E_0/tp =E_0/t/p
------ (12)

E_0/t =electric field strength, V/m, Let ε=E_0/t=electric field

g=electric field /stress = ε/p……………………………………..(13)

From eqn .11

Charge sensitivity d= ε $_r\varepsilon_0$ g F/N……………………………(14)

Typical values of g are: barium titanate: $12x10^{-3}$Vm/N .Quartz:$50x10^{-3}$Vm/N.

The permittivity of these materials is:

Barium titanate: $12.5x10^{-9}$F/m, Quartz: $40.6x10^{-12}$F/m

Typical value charge sensitivity, d, for these materials is:

Barium titanate: $12.5x10^{-9}x12x10^{-3}$C/N=150Pcn.

Quartz:$40.6x10^{-12}x50x10^{-3}$C/N=2Pc/N.

Sometimes it is desired to express the output voltage or charge in terms of deflection rather than in terms of either stress or force .this is because it is really the deformation that cause the Charge generation .thus we must know the modulus of elasticity of the material for this purpose. The values of modulus of elasticity are:

Barium titante: $12x10^{10}$ N/m, Quartz: 8.6x1010 N/m^2

The piezo –electric effect is direction sensitive. The main characteristics of piezo –electric motion to voltage transducers can illustrate considering only one common mode of deformation i.e thickness expansion. For this mode the physical arrangement is shown in below figure (a).various double–scripted physical constants are used to describe numerically the phenomena occurring. The convention is that subscript refer to the direction of the electrical effect and the second to that of the mechanical effect .the axis number system is given in fig

The two main families of constants i.e the,"d" constants and "g" " constants are considered .for Barium titanate the commonly used constants are d33 and g33

$$g_{33} = \frac{\text{field produced in direction 3}}{\text{stress applied in direction 3}}$$

$$= \frac{E_0/t}{F/A} \quad \text{-----(15)}$$

Voltage output $E_0 = g_{33}\,\frac{F}{A}\,t = g_{33}\,tP$ ------- (16)

Thus if g is know for a particular material, the voltage output per unit stress can be calculated by knowing the value of t.

In order to relate the applied force to the generated charge the d constants are used. one of the d constants can be defined as:

$$d_{33} = \frac{\text{Charge generated in direction 3}}{\text{force applied in direction 3}}$$

d_{33} =Q/F -------(17)

Actually d33 can be calculated from g33 if the relative permittivity of the material is known.

$d_{33} = = \varepsilon_r \varepsilon_0 g_{33}$-----(18)

When dealing with quartz, subscripts 11 are used because in quartz the thickness –expansion mode is along the crystallographic axis conventionally called axis 1.

The piezo –electric transducer is cut from a larger crystal in the direction of any of the electrical or mechanical axes perpendicular to the optical or crystal axis .the values of d and g are not necessarily the same but are dependent upon the axis of cut.

Modes Of Operation Of Piezo –Electric Crystals And Properties

The piezo –electric crystals are used in many modes. These modes are:

1. Thickness shear
2. Face shear,
3. Thickness expansion and
4. Transverse expansion

These modes are shown in fig. 2

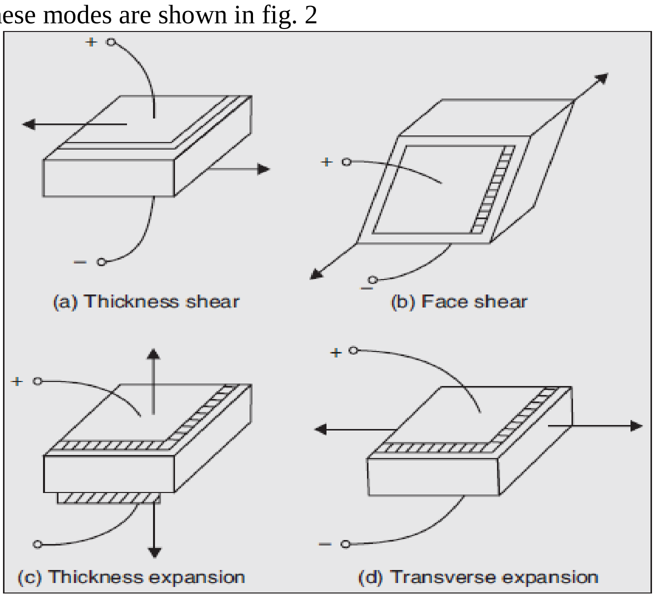


Fig.2 Modes of operation of piezo electric crystals

The piezo-electric effect can be made to react for mechanical deformations of the material in various modes. The mode of motion effected rely on the shape of the body relative to the crystal axis and location of the electrodes. The mechanical deformation generates a charge and this charge appears as a potential across the electrodes.

By cementing two crystals so that their electrical axes are perpendicular, "benders" or twister can be produced (see fig 1.3).A bending motion applied to a bender produces an output voltage. Likewise a twisting motion applied to a twister produces an output.

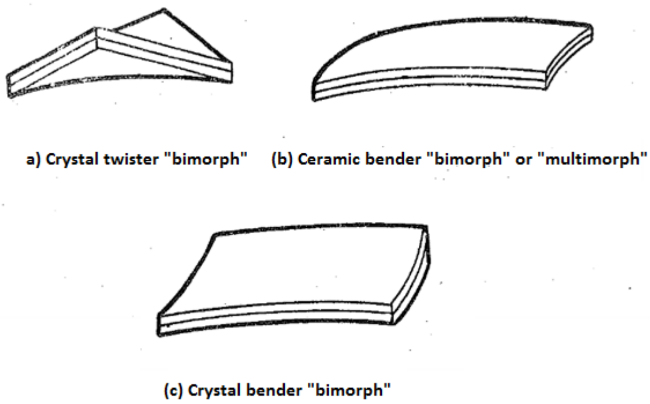


Fig. 3 Curvature of "twister" and "bender" piezo-electric transducers when voltage is applied

The piezo –electric crystals can be used in another mode for force measurement .A crystal controlled electronic oscillator uses a thin plate of quartz .the natural frequency of mechanical oscillation of the plate determines the frequency of electrical oscillation .

Properties Of Piezo –Electric Crystal.

The expected properties of piezo electric materials are good stability, insensitivity to environmental conditions like temperature, humidity and flexibility to be formed in expected shapes.

Quartz is the most stable piezo –electric material .however its output is quite small .on the other hand Rochelle salt provides the highest output but it can be worked over a limited humidity range and has to be protected against moisture. The highest temperature is limited to 45°C.

Barium titanate has the advantage that it can be formed into a variety of shapes and sizes since it is polycrystalline .It has also a higher dielectric constant. Natural crystals[16] possess the advantages that they have higher mechanical and thermal stability, can withstand higher stresses, have low leakage (their volume resistivity is about $10^{10}\Omega$m) and have good frequency response .the synthetic materials in general, have higher voltage sensitivity.

Equivalent Circuit Of Piezo–Electric Transducer.

The basic Equivalent circuit of piezo –electric Transducer is shown in fig.4

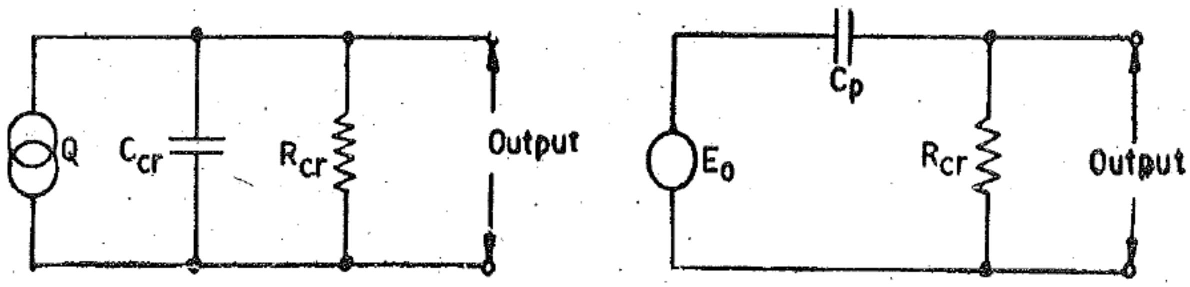


Fig.4 Equivalent circuits of piezo-electric transducers

The source is a charge generator .the value of the charge is Q=dF.
The charge generated is across the capacitance C $_{(r)}$ of the crystal and leakage resistance R_{cr}
The charge generator can be replaced by equivalent voltage source having a voltage of

$$E_0=Q/C_{cr}=dF/C_{cr}$$

In series with a capacitance C_{cr} and resistance, Rcr as shown in fig 4(a).
The value of resistance R_{cr} is very large .it is of the order of 0.1 x$10^{12}\Omega$ and thus the Equivalent circuit Transducer is reduced to the voltage source of voltage E_0 in series capacitance C_{cr} as shown in the figure 1.4(b). Under no load conditions appearing across the terminals of the Transducer is E_0.

Loading Effect And Frequency Response.

Let the transducer is loaded by a capacitance C_r and resistance R_L. The capacitance C_L is the combination of the capacitance of the load, the capacitance of the cable and the stray capacitance. the diagram showing the load connected to a piezo –electric Transducer is given in fig.5 . This diagram is based upon the assumption that the resistance of the load ,R_L is very small as compared with the leakage of resistance of the Transducer R_{cr} i.e $R_L << R_{cr}$

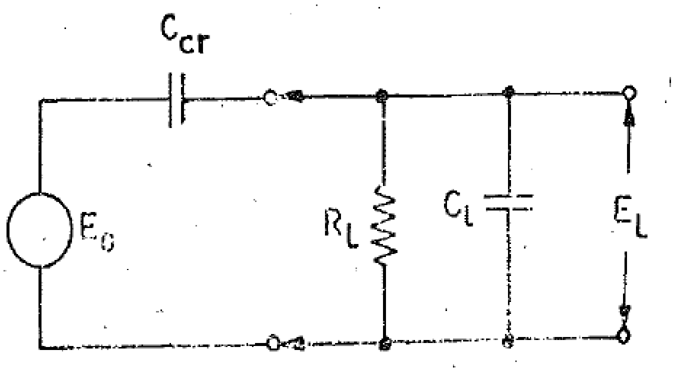


Fig.5. Circuit of piezo-electric transducer under conditions of load

At medium and high frequency $E_L = \frac{E_0}{C_{cr}+C_L}$-------------(19)
This means that at medium and high frequency the output voltage is independent of frequency but dependent upon the load capacitance C_L.
From equation 19 it is clear that under steady state condition i.e when ω=0 the crystal does not provide any output .as far as the maximum frequency limit is concerned ,it is imposed by the mechanical resonance of the piezo–electric crystal and associated mounting.

The piezo–electric Transducers are mainly used for measurement of displacement. They can be used measurement of force pressure or acceleration. These quantities when measured with piezo–electric Transducers are first converted into displacement and the displacement is subsequently applied to these transducers to produce voltage. Hence the conversion of displacement into voltage by piezo–electric crystal is considered here.

Experimental Technique

Experimental Technique To Analyze The Characteristics Of Piezo-Electric Crystal

Through experimental and analytical investigation, the characteristic of a desired piezo electric crystal is analyzed. The differential equation model[1] of the sensor is developed based on the displacement or change of the dimension of the piezo electric crystal and charge generated as shown in Fig. 6.
Figure shows the complete set up for measurement of displacement.
The capacitance connected across the current generator[3] is C where

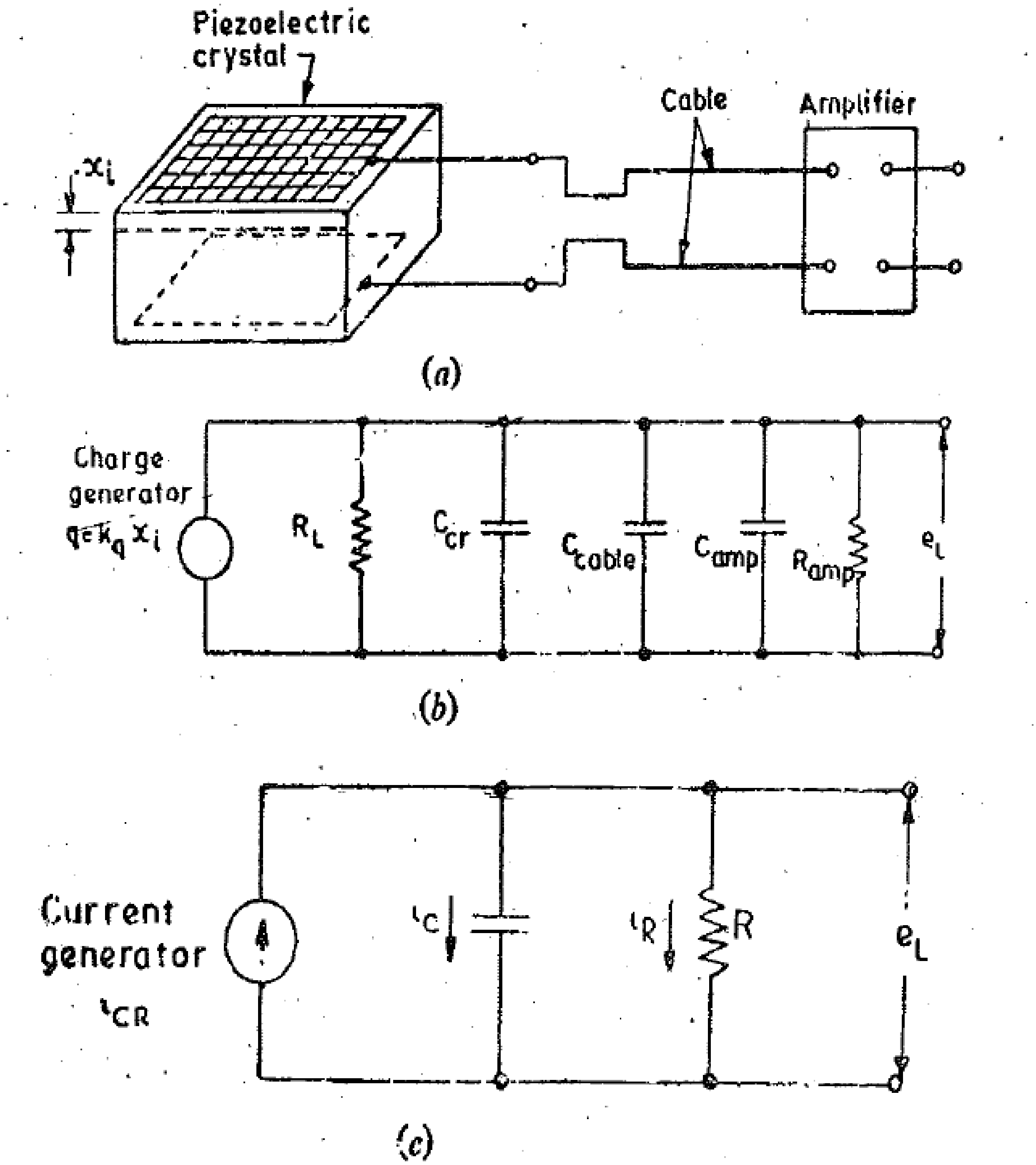


Fig.6 Set up of piezo electric crystal and its equivalent circuit.

Charge produced $q = K_q x_i$; Coulomb
Where k_q= sensitivity; C/m and x_i =displacement; m
R_L= leakage resistance of transducer; Ω, C_{cr}=capacitance of transducer; F.
C_{cable}=capacitance of cable; F, C_{amp}=capacitance of amplifier; F
R_{amp}= resistance of the amplifier; Ω
$C = C_{cr} + C_{cable} + C_{amp}$
Resistance $R = R_{amp} R_L / R R_{amp} + R_L$
With the above mentioned variables the transfer function[10] is derived from the differential equation governing the operation[8] and taking the Laplace transform.
The transfer function[2] is given as

$$\frac{E_L(s)}{X_i(s)} = \frac{K\tau_s}{1+\tau_s}$$

Analysis Of The Characteristics Of Piezoelectric Materials

Impulse Response

Let a displacement x_i be applied to the quartz crystal, where $x_i = 0.1$ for $0 \le t < T$; and $x_i = 0$ for $T < t < \infty$;
Here T=0.85 sampling instants and this function is one of the standard test signal known as impulse input shown in Fig.7

Therefore the charge is suddenly increased to KqA and the crystal voltage rises to $e_L = \frac{K_q 0.1}{c}$.Thus the initial condition is $e_L = \frac{K_q 0.1}{c}\ at\ t = 0^+$.

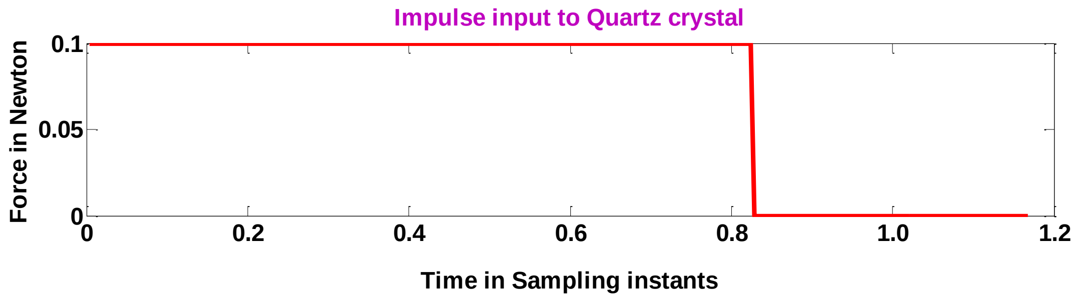


Fig.7 Impulse input

Applying this initial condition and solving the differential equation governing this function we get,

$$e_L = \frac{K_q 0.1}{C} e^{-\frac{t}{\tau}}\ for\ 0 < t < T$$

For T<t<∞, the value of x_i=0, and the solution of the differential equation is

$e_L = \frac{K_q 0.1}{c} e^{-\frac{T}{\tau}}$; at condition t=T^-.

However at t=T, x_i suddenly decreases by a value 0.1. This causes a sudden decrease in charge by an amount K_q0.1 resulting in a sudden change of e_L by an amount k_q0.1/C from its value at t=T^-. Hence at t=T^+, the value of e_L is:

$$e_L = \frac{K_q 0.1}{C}(e^{-\frac{t}{\tau}} - 1)$$

This variation of output voltage is shown in the Fig.8 as impulse response of the quartz crystal and sudden decreasing curve of the output voltage varies with varying the time constant .

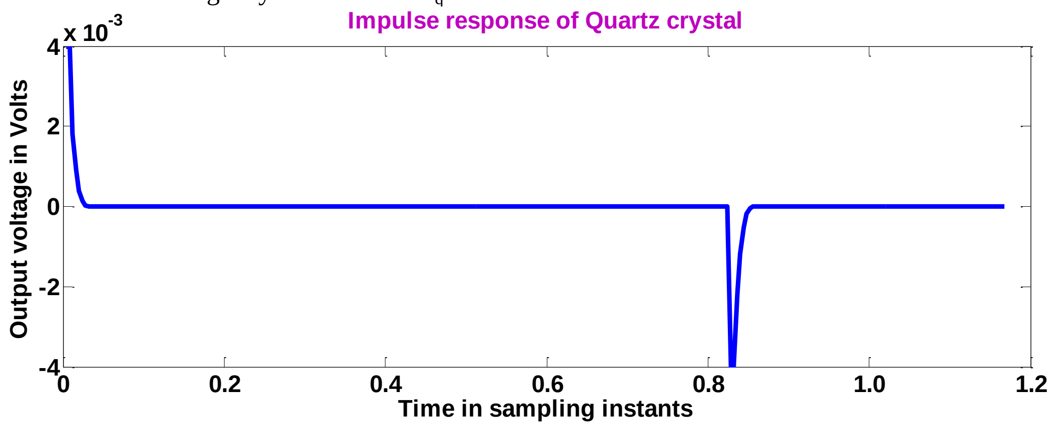
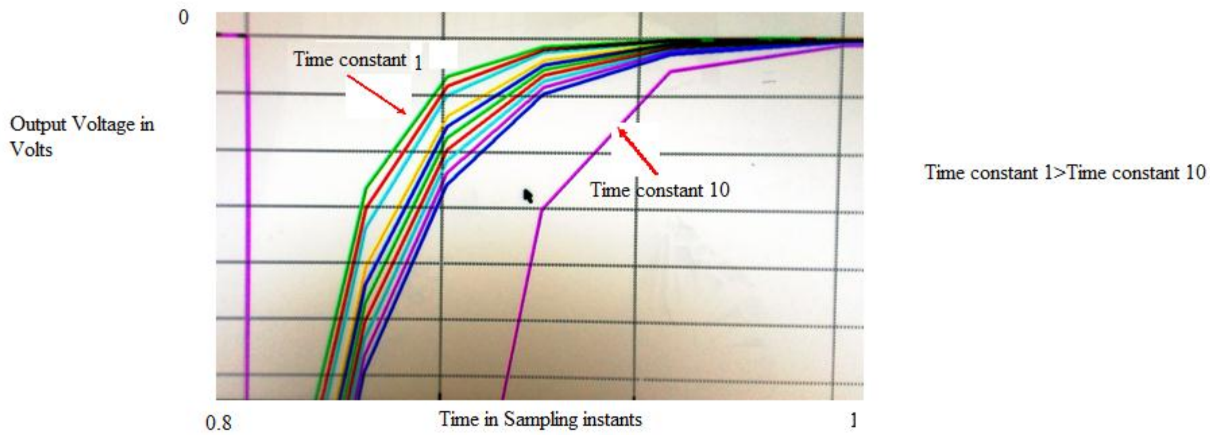


Fig.8 a) Impulse response of Quartz crystal for one



τ

Fig.8 b) Impulse response of Quartz crystal for various values

Response Of The Quartz Crystal For The Applied Force

The force F_t=0.2sin10t Newton is applied to the quartz crystal as shown in Fig.4.4. The peak to peak voltage swings across the electrodes under open circuit and under load conditions and the crystal thickness changes as shown in Fig.4.4.

The resistance of the crystal is very large as compared with resistance of the load i.e R_{cr}>> R_L. The output voltage is attenuated to a great extent due to loading.

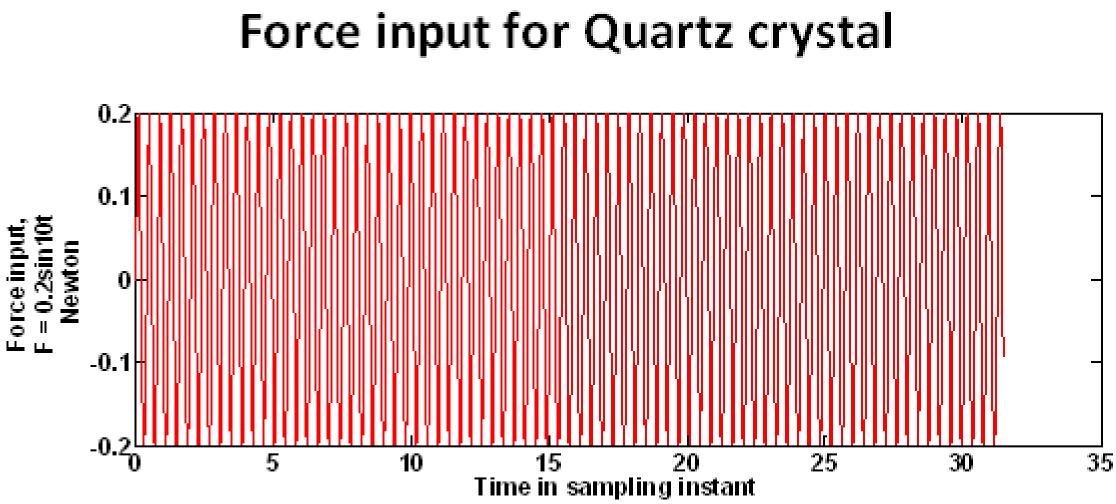


Fig.9 Force input for Quartz crystal

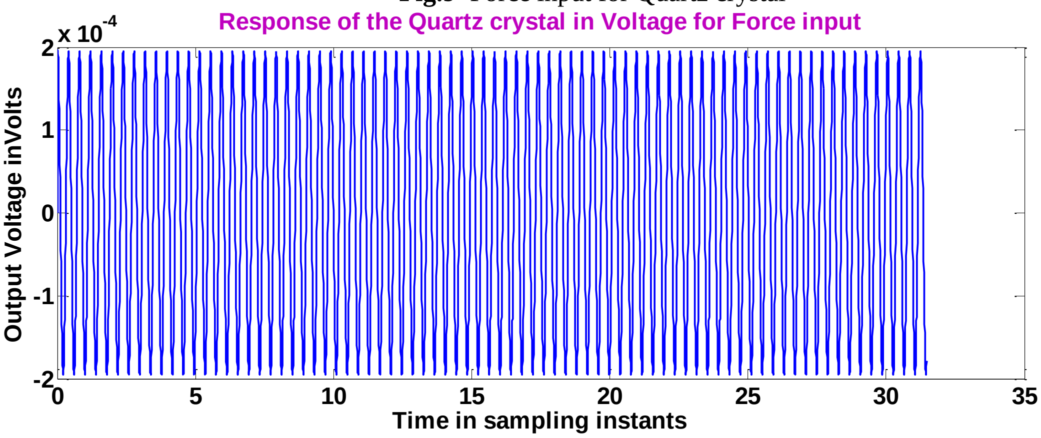


Fig.10. Response of the Quartz crystal for input Force

The comparative graph for various value of force applied to the crystal output voltage under load condition is given. As the force is increased the peak to peak output voltage is increased. The sample input varies from 0.01sin10t to sin10t Newton with the increase of 0.01 Newton as shown in Fig.11.

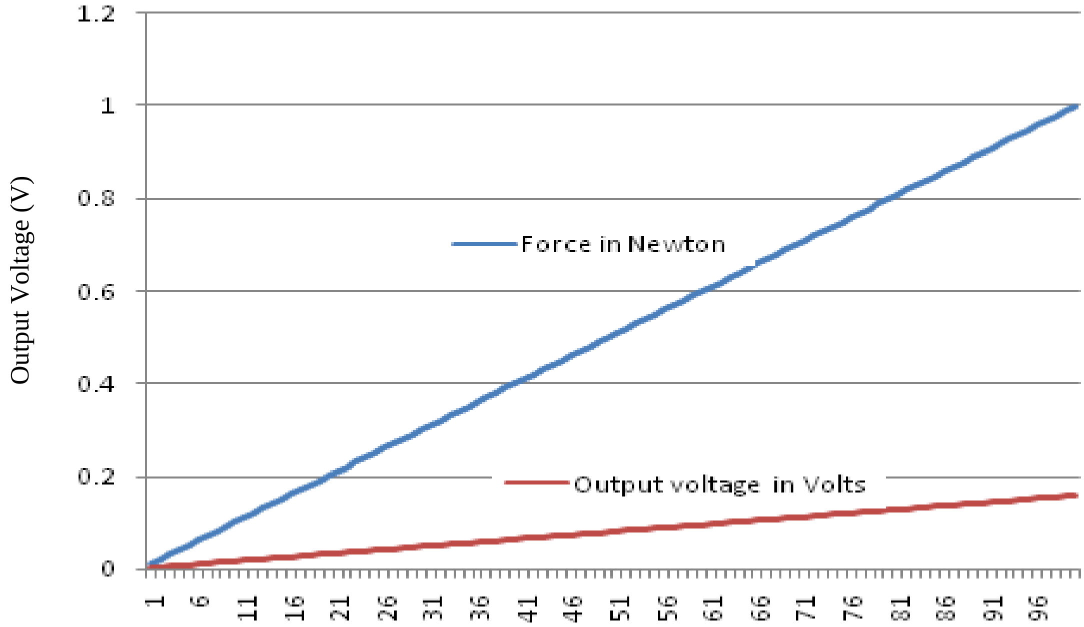


Fig. 11. Comparative graph of Output voltage for the applied Force

Frequency Response Of Quartz Crystal

The voltage across the electrode under load condition varies with increasing the frequency. However at medium and high frequencies $E_L = \frac{E_0}{C_{cr}+C_L}$. This shows that at medium and high frequencies the output voltage is independent of frequency but is dependent upon the load capacitance C_{CL}. Under steady state condition i.e ω=0, the crystal does not provide any output. As far as the maximum frequency limit is concerned, it is imposed by the mechanical resonance of the piezo–electric crystal and associated mounting.

The piezo–electric Transducers[14] are mainly used for measurement of displacement. They can be used measurement of force pressure or acceleration. These quantities when measured with piezo –electric Transducers are first converted into displacement and the displacement is subsequently applied to these transducers to produce voltage. Hence the conversion of displacement into voltage by piezo –electric crystal[15] is considered here.

The frequency response may be plot by Bode plot using MATLAB or by applying manually, the frequencies in the Magnitude ratio expression and phase shift expression

The magnitude ratio is given by

$$M = \frac{1}{\sqrt{[1 + 1/(\omega\tau)^2]}}$$

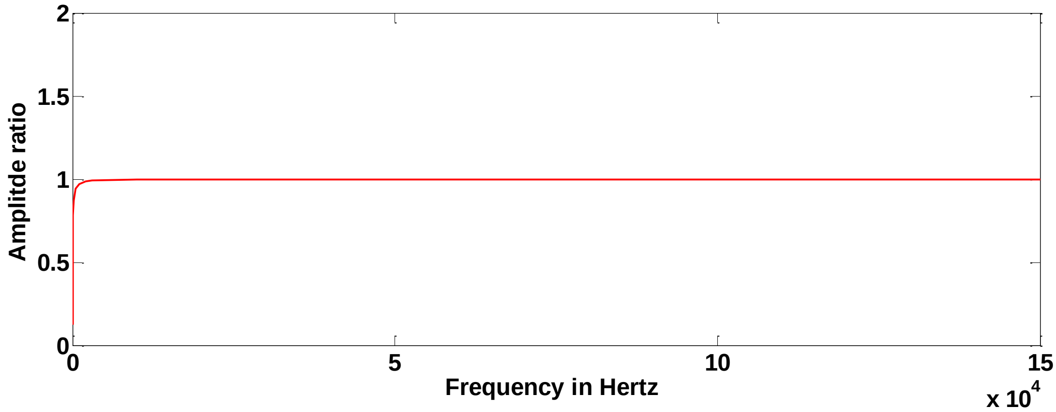


Fig.11. Frequency response of Quartz crystal –Magnitude ratio

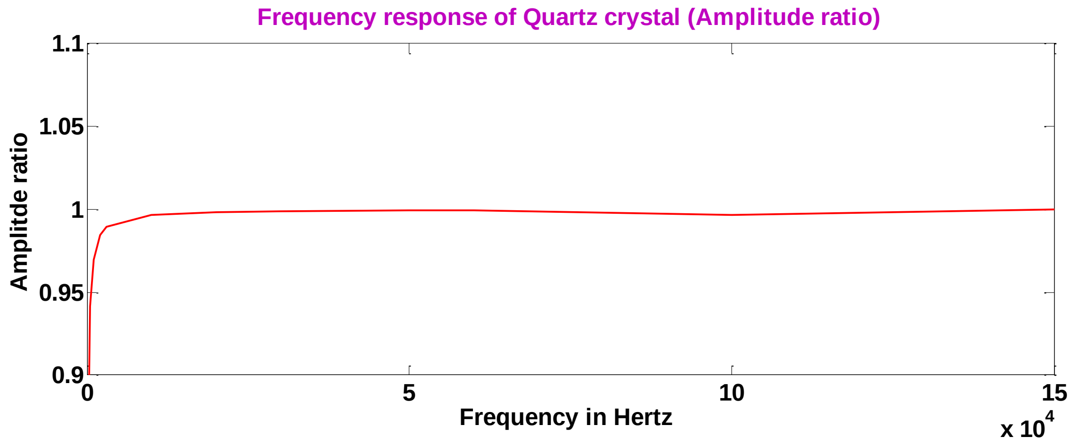


Fig.12. Close view of flat Frequency response of Quartz crystal-Magnitude ratio

The phase shift equation is given by

$$\phi = 90^{o} - \tan^{-1}(\omega\tau)$$

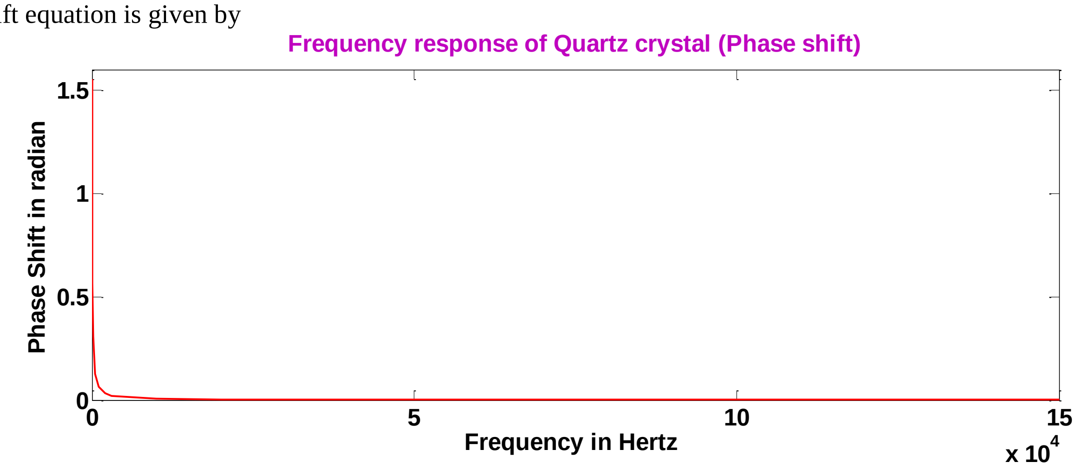


Fig.13. Frequency response of Quartz crystal-Phase shift

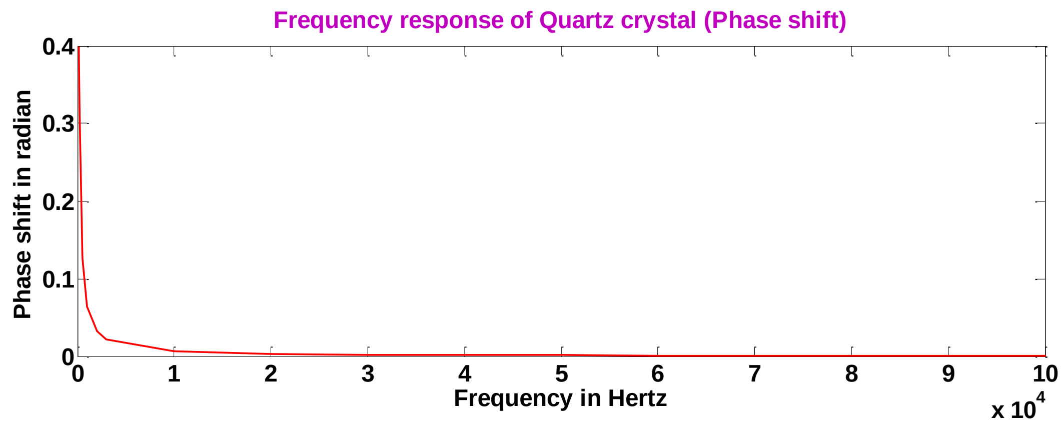
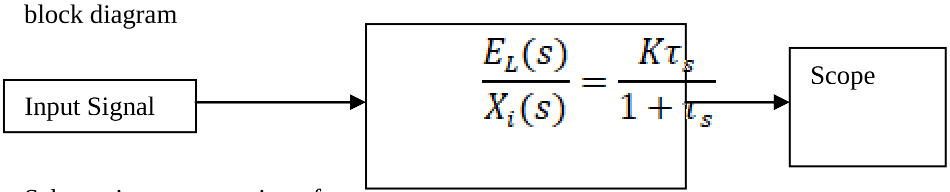


Fig.14. Close view of Frequency response of Quartz crystal- Phase shift.

The Matlab software is used to analyze the Frequency response[9], impulse response and to analyze the value of expected output voltage of piezo electric crystal for various values of force.

a) block diagram



b) Schematic representation of system

Fig 15. Simulink block diagram

Fig.15 shows the block Diagram constructed in Matlab simulink software to perform analysis of Piezoelectric crystal. Using Matlab simulink the above block diagram is constructed. According to our desired response the input signal can be modified. The output is obtained corresponding to the input signal. Some of the inputs used are impulse input for various time constant **τ**, single time constant **τ**, various force F and input voltage as sine wave and corresponding output is obtained.

Procedure To Analyse The Characteristics

i. Install the Matlab software
ii. Matlab simulink block is opened and one new matlab simulink file is created
iii. The input signalblock selecting from the source list in simulink library is constructed and the required quantities in the block are mentioned.
iv. The transfer function block selecting from the General list in simulink library is connected and the required quantities in the block are mentioned.
v. The Scope block selecting from the sink list in simulink library connected.
vi. The file is saved and after running the file the waveforms which gives the details of response are observed.

The Ultrasonic module is connected to the arduino and sketch (program or code) is uploaded in the PC. The arduino is connected to PC using USB cable which is also used as a power source for the Arduino.

Fig.16 is the block diagram that shows the experimental setup to measure the distance using ultrasonic sensor.

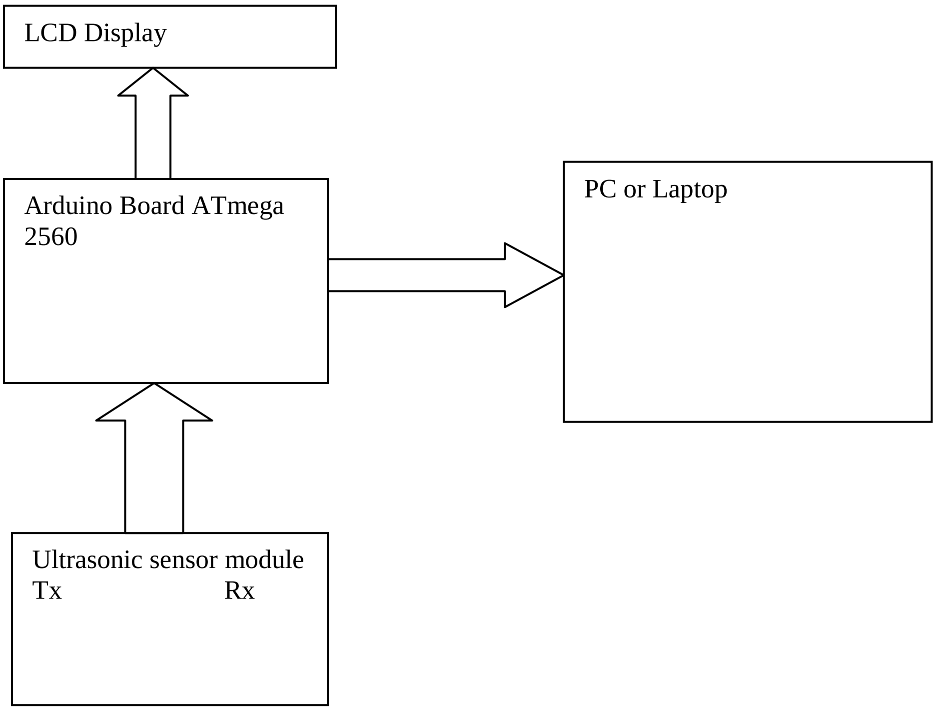


Fig.16 Block Diagram of Distance measurement experimental set up

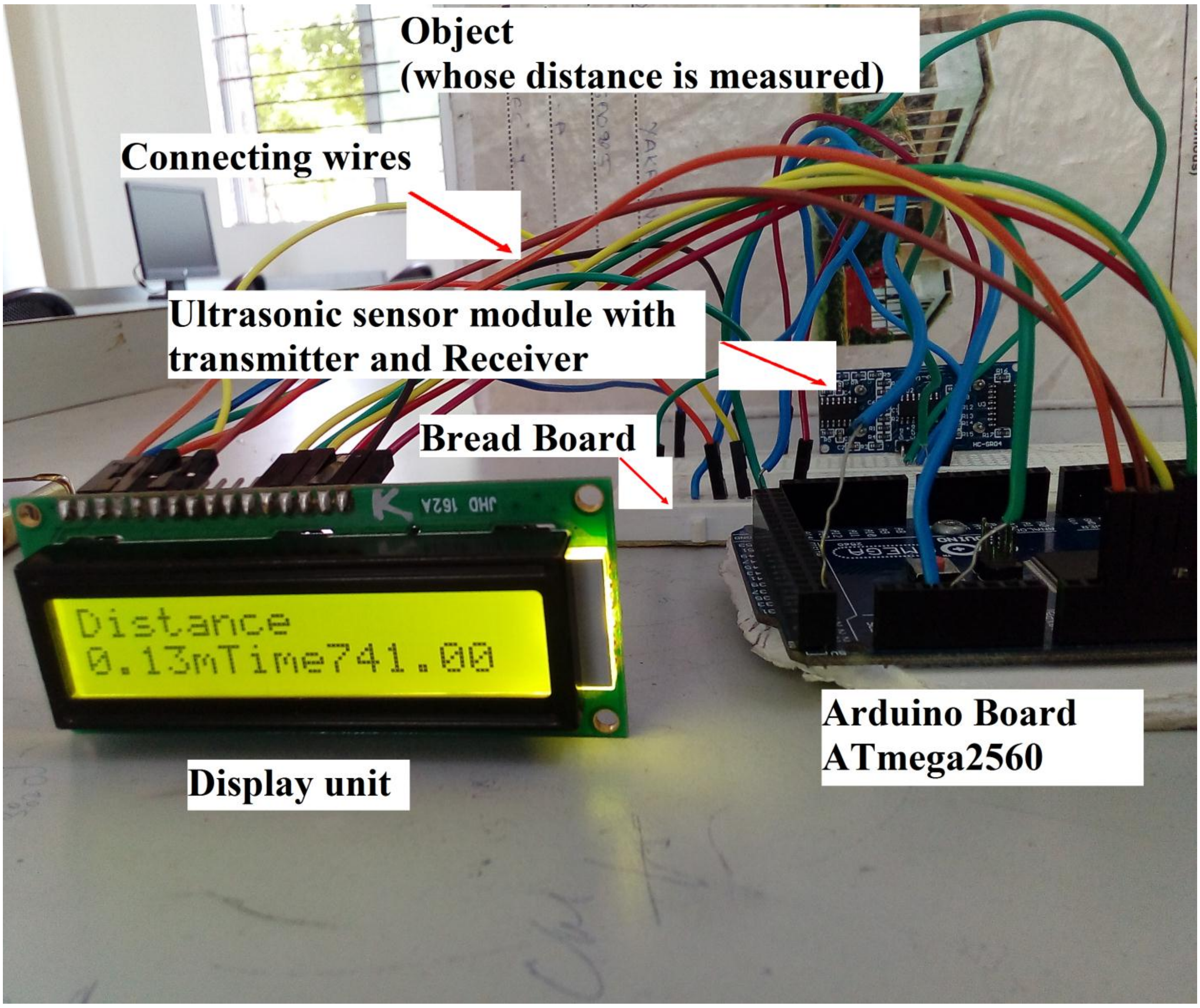


Fig.17. Experimental setup to measure distance of an object using Ultrasonic sensor.

Ultrasonic Sensor And Distance Measurement

The method of distance measurement using ultra sonic distance sensor is illustrated in fig. 18.

Fig 19 and 20 shows the details of typical ultrasonic sensor with the pin diagram and associated waveform.

- Ultrasonic sensors[12] are sometimes used in place of light sensors. Instead of using a light beam, a high frequency [7] sound wave is used.
- Sound wave [13] is above normal hearing frequencies are called ultrasonic. Frequencies around 40KHz are common. Fig 4.10 shows the working principle of ultrasonic sensor.

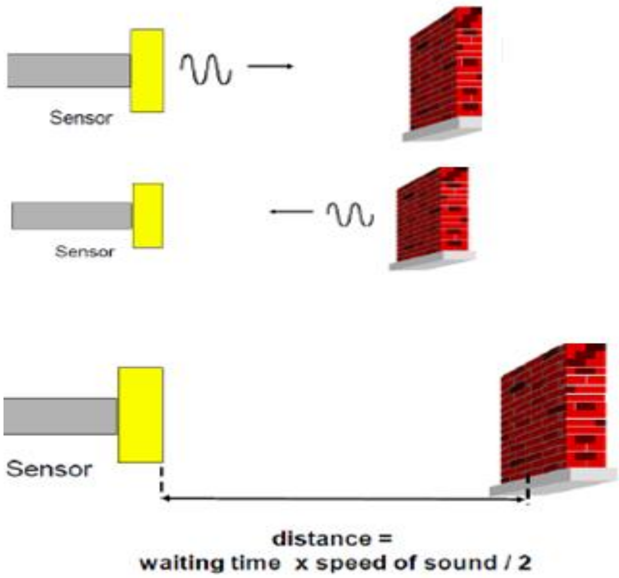


Fig.18. Schematic of ultrasonic sensor working principle

Fig. 19. HC-SR04 Ultrasonic sensor module

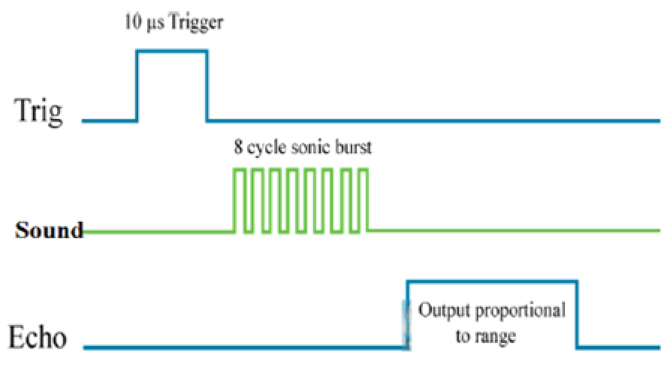


Fig.20. Signals from the ultrasonic sensor

The circuit connections and the readings are tabulated as shown in table 4.2. The readings of the designed instrument are compared with the standard readings.

Table 4.2 Comparison of distance measured by Ultrasonic sensor vs standard scale

Sl.No	Ultrasonic distance meter		Distance measured in Standard meter Scale (m)
	Ultrasonic wave travel Time (µsec)	Distance measured in Ultrasonic distance meter (m)	
1.	1720	0.29	0.29
2.	1746	0.40	0.40
3.	2450	0.40	0.40
4.	2928	0.50	0.50
5.	4546	0.60	0.60
6.	4165	0.70	0.70
7.	4744	0.80	0.80
8.	5249	0.90	0.90
9.	5864	1.00	1.00
10.	6478	1.10	1.10
11.	7044	1.20	1.20
12.	7620	1.40	1.40
13.	8224	1.40	1.40
14.	8786	1.50	1.50
15.	9465	1.60	1.60
16.	9994	1.70	1.70
17.	10678	1.80	1.80
18.	11202	1.90	1.90
19.	11882	2.00	2.00
20.	12449	2.10	2.10
21.	14129	2.20	2.20
22.	14551	2.40	2.40
23.	14098	2.40	2.40
24.	14720	2.50	2.50
25.	15422	2.60	2.60
26.	15821	2.70	2.70
27.	16466	2.80	2.80
28.	17040	2.90	2.90
29.	17618	4.00	4.00

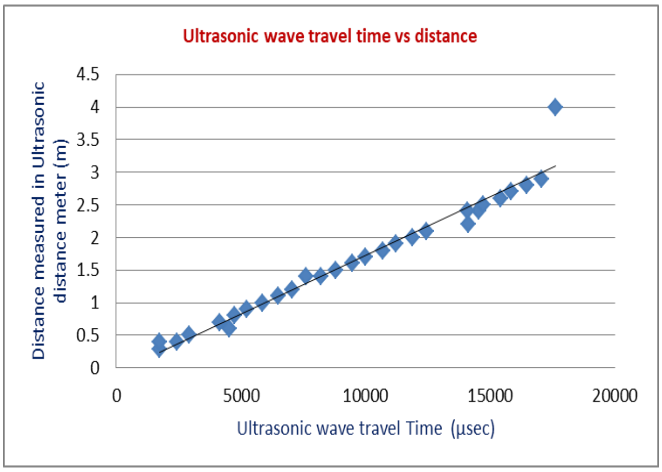


Fig. 21 Graphical representation of Distance Vs Time duration of ultrasonic waves travelled.

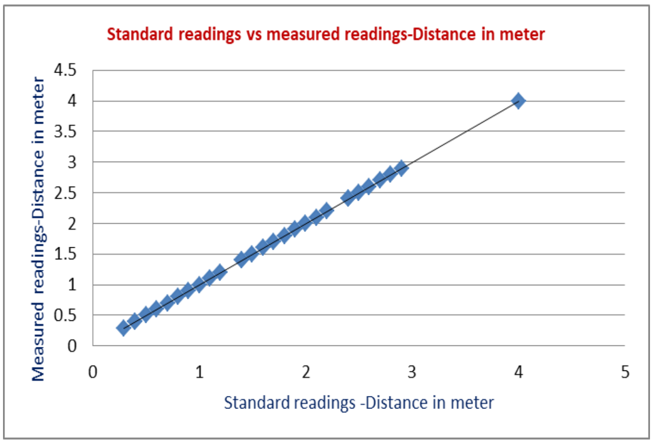


Fig. 22. Graphical representation of Distance displayed in Distance meter Vs Standard readings

Conclusion

The properties of piezo electric materials are analyzed by MATlAB Software for the selection of material for ultrasonic wave generator. The impulse response, response for various force values and sinusoidal input is obtained. From the analysis of various responses and factors, it is finalized that the quartz crystal is the suitable piezo electric material the used in generating the ultrasonic waves.

The impulse response shows that for various time constant **τ** values, the response is changing and for lower time constant the response is good. The force input applied to the quartz crystal gives detectable output which can be further modified or amplified by the signal conditioning circuit. Based on this the ultrasonic sensor module is tested for distance measurement which is using quartz crystal with ultrasonic wave generator. For the various distance values of the object, the LCD display unit interfaced with Ultrasonic sensor through Arduino, displays the distance of the object. As the distance of the object is varied from short distance to long distance the value of the distance is also varying accordingly.

References

[1] “Piezoelectric Transducers Used for Piezoelectric Accelerometers with Integral Electronics,” Published by Springer International Publishing Switzerland 2015 F. Levinzon, Piezoelectric Accelerometers with Integral Electronics.

[2] “Piezoelectric Transducer Modeling: with System Identification (SI) Method” published by World Academy of Science, Engineering and Technology 39 2008

[3] “Analysis of the transfer function for layered piezoelectric ultrasonic sensors”

[4] Published by the American Institute of Physics

[5] (Flynn and Sanders) Flynn, A.M.; Sanders, S.R. 2002." Fundamental limits on energy transfer and circuit considerations for piezoelectric transformers". IEEE Transactions on Power Electronics, vol.17, (no.1), IEEE, Jan. 2002. p.-14.

[6] (Ikeda1990)Ikeda.T "Fundamentals of piezoelectricity", Oxford University Press.

[7] R.L.Lin, F. C. Lee, and E. Baker, " Characterization of piezoelectric transformers" in Proc, IEEE VPEC, 2000, pp. 219-225.

[8] S. Nitin, "Introduction of System Identification",DOI= http://www.Tataelxsi.co.in

[9] Lennart Ljung , "Nonlinear Black-Box Modeling in System Identification". Dept of Electrical Engineering, Linkoping University, Sweden.2001.

[10] R. Haber and L. Keviczky , " Nonlinear system identification – input output modeling approach, Vol 1 and 2. Kluwer Academic Publisher (2004) 901-903.

[11] A. Juditsku, H. Hjalmarsson, A. Benveniste, B. Deylon,L. Ljung, J.Sjoberg, and Q.Zhang." Nonlinear black-box modeling in systemidentification: Mathematical foundations," Automatics, 31, 1995.

[12] Webster JG (1998) The measurement, instrumentation and sensors handbook. CRC,Boca

[13] Raton, FL (2012) Test and measurement product catalog. Meggitt Sensing Systems, Irvine, CA. https:// www.endevco.com/resources/catalog/

[14] K. S. Valluru and J. K. Willmann, “Clinical photoacoustic imaging of cancer,” Ultrasonography **35**, 267–280 (2016).

[15] Shuo Hou,Xing Tan,Jincheng He,Huan He, et.al “Dynamic similarity analysis for a piezo-electromechanical system”, published in International Journal of Applied Electromagnetics and Mechanics, September 2020

[16] Geonwoo Kim,Young-In Hwang,Mu-Kyung Seo,Ki-Bok Kim, Electrical tuning for sensitivity enhancement of a piezo-electric ultrasonic transducer: Simulation and fabrication Journal of Mechanical Science and Technology published in Journal of Mechanical Science and Technology

[17] A.K.Sawhney, A course in Electrical and Electronic measurements and instrumentation, published by Dhanpat rai and sons.