TAMPEREEN TEKNILLINEN YLIOPISTO
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SIMULTANEOUS USE OF PIEZOELECTRIC TRANSDUCER AS ACTUATOR AND SENSOR IN REALTIME APPLICATIONS

Master of Science Thesis

Examiner: Prof. Pasi Kallio
Examiner and topic approved by the Faculty Council of the Faculty of Engineering Sciences
on October, 2013

ABSTRACT

MAJID ALI KHAN: Simultaneous Use of Piezoelectric Transducer as Actuator and Sensor in Real-time Applications
Tampere University of technology
Master of Science Thesis, 60 pages
May 2016
Master's Degree Programme in Machine Automation
Major: Mechatronic and Micro-machines
Examiner: Professor Pasi Kallio

Keywords: Piezoelectric actuator and sensor, self-sensing, precision engineering, Microsystems, real time application, xPC, Matlab.

The role of piezoelectric actuators in application at micro and nano scale has been growing over the past three decades. Piezoelectric actuators have high displacement resolution and large bandwidth, therefore they are used in micro and nano scale control applications. Despite enormous research and development, there are challenges in the control of piezoelectric actuators - mainly due to the intrinsic non-linear properties of hysteresis, creep and external conditions dependant complex dielectric properties of piezoelectric material. A more recent development in the control of piezoelectric actuators is simultaneous actuation and sensing of piezoelectric actuators - also called as self-sensing.

In this thesis the challenge of simultaneous use of piezoelectric material as actuator and sensor is addressed. A novel method for determining the actuator strain is proposed and experimentally tested. The thesis proposal is to assume a piezoelectric stack actuator as a parallel plate capacitor and to estimate the strain/displacement of the actuator from its capacitance. The capacitance signal is intended to be used as a feedback signal for displacement control purpose.

The thesis work started from the scratch - where the proposal was very unclear and needed to be studied and tested experimentally. For experiments a test setup was needed which was designed and built in a clean room environment. In the test setup capacitance of the actuator was measured. A relationship between strain and capacitance was studied from the experimental data. For capacitance measurement a simple low-noise electric circuit based on Op-Amps was designed and built. Whereas strain of the actuator was measured using an interferometer (laser sensor). Charge amplifier was used to give the control signal to the actuator. The capacitance and strain data were acquired using Speedgoat hardware and analyzed in xPC target environment of Matlab.

Results show that there exists hysteresis in the capacitance-strain graph, even when the control signal is provided from a charge amplifier. Piezoelectric actuator cannot

be modelled as a parallel plate capacitor, due to the fact that piezoelectric material has complex dielectric properties which are control signal's amplitude and frequency dependant and that the resistance of the actuator changes with the strain as well.

PREFACE

This thesis has been done for the Optical Column Mechatronic group of the Development and Engineering department (OCM, D&E) of ASML. The work is done as mandatory graduation thesis part of the Master's degree program in Machine Automation at Tampere University of Technology, Finland. The work was done under the supervision of ASML design engineer Arie Scheiberlich.

ASML encourages interns and graduation students to take a full self-reliant approach in the graduation thesis projects. In this way, most of the work in this thesis was done independently - under the supervision of the mentor in the form of weekly meetings.

I am thankful to my colleagues of the OCM group for providing an inspiring working atmosphere. In particular, I would like to thank my mentor Arie Scheiberlich and the team leader Roan Westerhof for providing me with this learning opportunity. I am thankful to design engineer Bas Jansen for his help and allocating time for me in his busy schedule. I have learnt a lot during my work at ASML and improved myself both personally and technically. I am also thankful to my university supervisor Pasi Kallio for his support and guidance in the writing of the thesis.

Last but not the least, I would like to thank my dearest parents, loving siblings and wonderful friends for their moral support during this challenging time.

Tampere, May 24, 2016

Majid Ali Khan

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LIST OF SYMBOLS AND ABBREVIATIONS

ASML	Advanced Semiconductor Materials Lithography
TSMC	Taiwan Semiconductor Manufacturing Company
DUV	Deep Ultra Violet
PEA	Piezo-Electric Actuator
PZT	Lead Zirconate Titanate
FIR	Finite Impulse Response
IIR	Infinite Impulse Response
PIPA	Piezoelectric actuator Power Amplifier
Op-amp	Operational amplifier
In-amp	Instrumentation amplifier
RMS	Root Mean Square
SNR	Signal to Noise Ratio
MCS	Motion Control System
KSPS	Kilo Samples per Second
AC	Alternating Current
PID	Proportional Integral Derivative
db	decibel
IC	Integrated circuit

C	Capacitance
Q	Charge
V	Voltage
i	Current
K	Boltzmann’s constant
T	Temperature
R	Resistance
x	Strain
E	Electric Field
d	Piezoelectric charge constant
P	Polarization
X	Stress
ε	Dielectric constant
s	Elastic compliance
D	Electric displacement

1. INTRODUCTION

Computer chips - also called as integrated circuits (ICs) are used in almost all electronic devices of daily use like cell phones, tablets, laptops etc. These chips are manufactured through a multistage process which involves photolithographic and chemical processing steps. The photolithographic part of the process is carried out in a machine called as photolithography machine or simply a scanner.

Advanced semiconductor materials lithography (ASML) designs, manufactures and sells these photolithography scanners to its customers. Currently it is worldwide the largest supplier of photolithography scanners. World leading chip and communication products manufacturers like Intel, Samsung and Taiwan semiconductor manufacturing company (TSMC) are ASML's main customers. [1]

In ASML scanners piezoelectric actuators are used for some particular purpose, which will be explained in next sections.

1.1 Photolithography process

As mentioned earlier one of the steps in the manufacturing of computer chips is the photolithography process. In the photolithography process, deep ultra violet (DUV) light is used to print nano scale electric circuits on a silicon wafer. The circuit pattern is first drawn on photo mask. And then with the help of lenses it is etched on photosensitive silicon wafer. The etched wafer is finally cut into small pieces and is covered properly to make the final product of ready to use computer chip.

Figure 1- 1 shows, in a simple way, how the photolithography process is carried out.

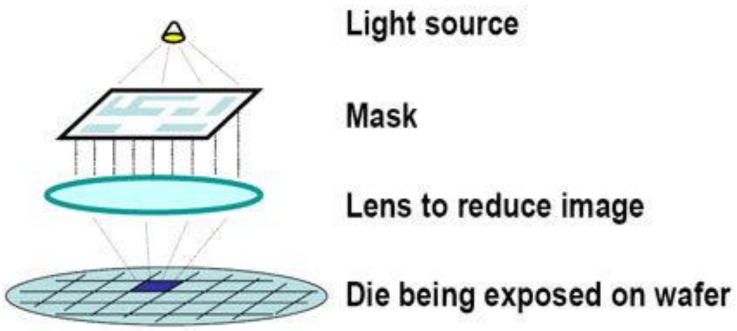

Figure 1- 1 Lithography Process

1.2 Photolithography machine

Figure 1- 2 shows a picture of ASML scanner - so called TWINSCAN NXT machine. During printing of the circuit pattern on a silicon wafer, light delivered by the light source is manipulated at various stages in the machines - from light source to the wafer.

Figure 1- 2 TWIN SCAN NXT Machine produced by ASML

In this process of scanning, the DUV light passes through 'the optical column' of the lithography machine. The optical column has many optical lens elements which focus light on the wafer. When light is focused on the lens elements for a long time, their temperature rises. The high temperature causes change in some properties of the lens material and the sharp focus on the wafer is disturbed. In order to counter this non ideal behavior, some of the lens elements in the optical column are designed in a way that their position can be changed.

In the TWINSCAN NXT machine the movement of the lens elements is done with the help of Piezoelectric motors. Very small adjustments are required on micrometer scale with nanometer scale accuracy.

1.3 Piezoelectric actuator

The design and application of piezoelectric motor, used in the TWINSCAN machine is described in this section.

1.3.1 Actuator structure

The piezoelectric motor used in the optical column of the lithography machine has three main components, namely; external housing, legs/stacks made of piezoelectric material and a driving rod in the centre.

The legs again have two components, so called shear piezo and clamp piezo. Clamp piezos are made of d33 piezoelectric material whereas the shear piezo are made of d15 material. When an electric signal is applied to a d33 piezoelectric material, it performs motion in direction perpendicular to the rod, so that it contracts and expands along its height. Because of different polarity, d15 material expand and contract in slanted position when electric signal is applied to them.

As shown in Figure 1- 3, the central rod is moved due to the action of piezoelectric stacks. The rod is moved in the ±Z direction.

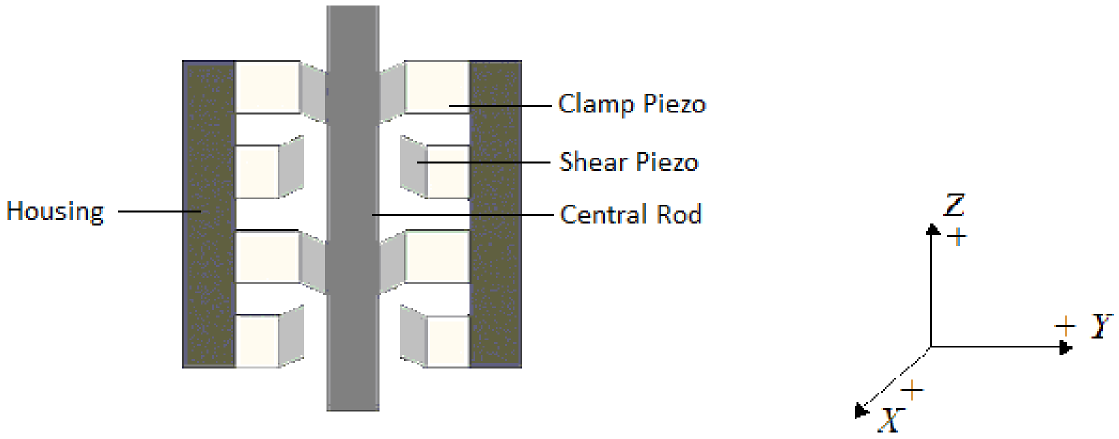

Figure 1- 3 Piezoelectric Motor

1.3.2 Analog and step motion of the legs

There are two modes of motion performed by the piezoelectric actuator.

1) Analog motion: in this step the shear piezos move the attached rod up or down (in ± Z direction).

2) Step motion: this motion is performed in a series of steps of clamp piezo and shear piezo. The clamp piezo legs contract and extend along with a sequenced motion of the shear piezo.

The walking action (combination of step and analog motion) of the piezo legs in effect moves the central rod, which in turn moves the lens elements of the TWINSCAN NXT machine. Figure 1- **4** illustrates the steps of the motion of the rod.

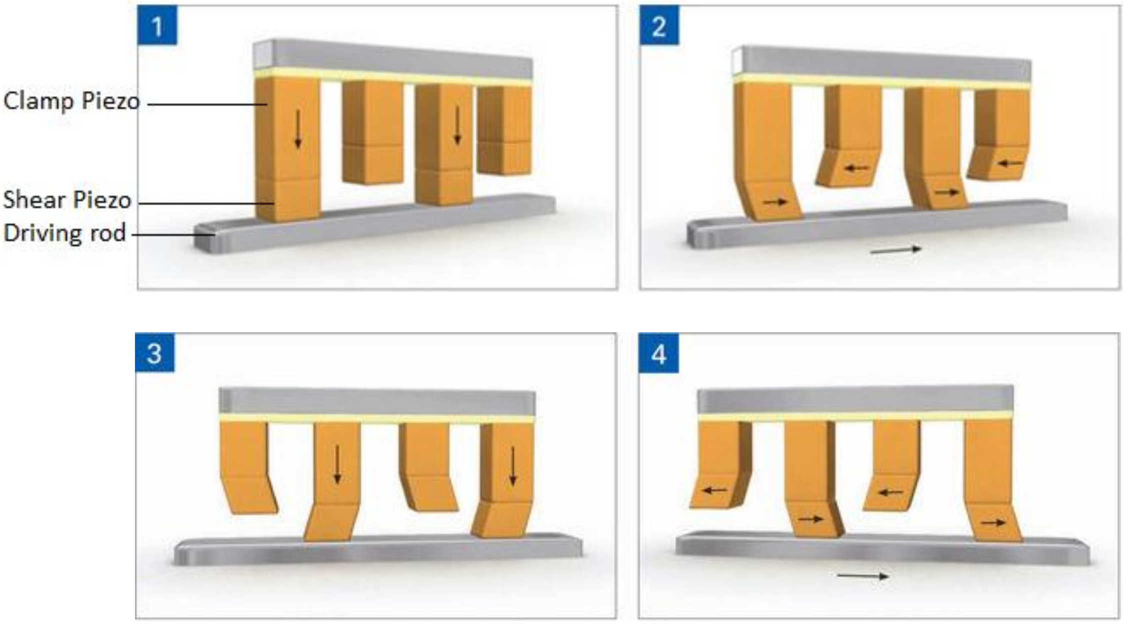

Figure 1- 4 Walking action of the actuator legs [2]

1.3.3 Design problem

The piezo legs (both clamp and shear) are driven in open loop - a control signal is applied to them to perform required motion however there is no feedback signal. The design of the actuator is such that it is not possible to place a position sensor for each leg. Even if the control signal is applied from a charge amplifier, open loop driving generates a position error.

Fundamental challenge in using Piezoelectric motors is to overcome the inherent non-linearity (hysteresis, drift) of piezoelectric material. For this purpose in most cases feedback control method is used, in which feedback signal from a position sensor and a control strategy (e.g. PID control) are used for control purpose. As mentioned earlier, feedback from external sensor is not possible in our system.

An alternate solution to feedback control is feed-forward control in which the actuator's electro-mechanical model is used and a set control signal is given to the actuator. In this case, even the feed-forward method is not sufficient. In a previous study done at ASML, it has been concluded that actuator model is either too complicated or inaccurate for our application.

1.4 Self-sensing proposal

Since an external position sensor cannot be placed inside the actuator and feed forward is not good enough, therefore, to solve the design problem, self sensing of piezoelectric material is proposed.

Piezoelectric actuators are usually regarded as capacitive load for many applications. The proposal of this project is to measure the change in capacitance of the piezoelectric material and to calculate its position from the capacitance.

The clamp piezo leg is considered as a ideal parallel plate capacitor. It is known that the capacitance of a parallel plate capacitor depends on its physical dimensions and the dielectric material properties, given by equation 1-1.

$$C = \frac{\varepsilon A}{d} \quad (1.1)$$

Where C is the capacitance of the capacitor, ε is the dielectric constant of the dielectric material, A is area of the electrodes, and d is the separation between the electrodes.

Capacitance is also equal to the ratio of current to differential voltage (or charge to voltage), i.e.

$$C = \frac{i(t)}{\frac{dv}{dt}} = \frac{Q}{V} \quad (1.2)$$

Where i(t) is the current through the capacitor, dv/dt is the time rate of change of voltage, and Q is the charge on the capacitor.

Equating equation 1-1 to equation 1-2, it is possible to derive displacement "d" from current and voltage information.

This idea has motivated us to study its practical viability, under conditions of external load and different driving frequencies.

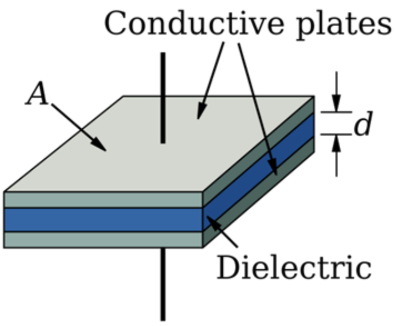

Figure 1- 5 Parallel plate capacitor [3]

1.4.1 Capacitance measurement scheme

For capacitance measurement in real time, a small ac signal (called as test signal) is applied to the actuator, on top of the main driving signal (called as servo signal). The test signal must have very high frequency and small amplitude.

It is assumed that if the frequency of the ac test signal is much higher than the natural frequency (mechanical bandwidth) of the system and if its amplitude is much smaller than that of the servo signal, that the system will reject the ac test signal and no mechanical vibrations/actuations will be introduced because of it.

The test signal is given at the input, and measured at the output. The test signal at the output will change when the capacitance of the actuator changes. So in this way the variations in capacitance (and thus in position) are measured. The aim of this study is to measure the capacitance in run time, when the actuator is driving on high voltage servo signal.

1.4.2 Advantages of self sensing

By having information about the position of the piezo legs in runtime, the stepping motion of the actuator can be performed in a smoother way, with lesser position error. Self-sensing has many other advantages. It allows compact structures to be embedded in the systems as there is no use of external sensor. The limitations of the external position sensor (sensitivity, resolution etc.) can be overcome. In addition to that removing external sensor adds to cost cutting as well.

1.5 Scope of the thesis

The target of the project is to get the function of actuator as well as a displacement sensor from the piezoelectric motor. The end goal of the study is to implement a sensor less feedback motion control system that utilizes the piezoelectric transducer simultaneously as actuator and sensor.

The first step is to experimentally test the proposal of measuring displacement from the capacitance. As we started from very scratch, there was no set up available and therefore a test bench was needed, which can measure and compare the capacitance and position of the piezoelectric actuator in run time. Keeping the targets in view, scope of the thesis broadly includes:

A) Designing and physical implementation of the test setup.

B) Carrying out experiments so as to test and confirm the proposal from experimental data.

C) Study the piezoelectric actuators properties and explanation of the results.

For this purpose the test bench is needed, with proper hardware and software. A front circuit is needed to measure current and voltage of the actuator. Test plans are to be devised and implemented to get the required data.

The scope of this thesis is not to provide the final sensor less feedback positioning system for the piezoelectric actuators. Nevertheless it is valuable first study on the topic. Since piezoelectric actuators have applications in many other areas as well this thesis work is not limited to our application and can be used in other applications as well.

1.6 Thesis outline

The thesis is organized as follows. Chapter 2 gives brief summary of the theoretical back ground of PEA. Chapter 3 describes simultaneous use of piezoelectric transducer as actuator and sensor. Chapter 3 also introduces the theoretical back ground for simultaneous use and the method that is used for capacitance measurement. Chapter 4 is about the test setup and the details of the interface circuit that has been designed, tested and integrated with the hardware. Chapter 5 explains the test plan, experimental results and analysis of the acquired data. Chapter 5 also describes conclusions and future directions for this work.

2. PIEZOELECTRIC TRANSDUCER

This chapter briefly describes the theoretical background about piezoelectric material - its properties and mathematical equations that describe its behavior. Because of their applications in fields like scanning probe microscopy, micromanipulation and micro/nano fabrication, enormous amount of research is being done on the control of piezoelectric actuators. Compared to other actuators, piezoelectric actuators provide a faster response with extremely high force but small displacement.[23][25][30][33]. However their complexity and non linear behavior limit their use[28].

Piezoelectric actuators have applications in industries such as biomedical, automotive, aerospace and robotics. Piezoelectric actuators are widely used in micro mechatronic and micro-robotic applications. An important area of application is nano-positioning where they are employed to perform controlled motion on the scale of micro meters with micro/ nano meter resolution. Because of their fast response, high resolution and compact size, PEA is replacing the traditional drive systems [24]. The limiting factor in the nano positioning system however is the non-linearity of the piezoelectric materials.

Piezoelectric actuators are found in different physical forms like stack actuators, piezoelectric benders, stepping motors etc.

2.1 Piezoelectric effect

The word piezoelectric can be interpreted as "electricity due to force". Piezoelectric effect is the phenomenon of production of electrical charge in a material when a force is applied to it. The materials that exhibit such property are called as piezoelectric materials. The mechanical energy, due to the force, changes polarization of the material and as a result electrical energy/charge is produced.

Piezoelectric effect is reversible in the sense that when electric energy (in the form of voltage or current signal) is applied to these materials a mechanical strain is produced in them, this is called inverse piezoelectric effect.

Certain materials exhibit the direct and converse piezoelectric effect naturally, for example Quartz, Tourmaline etc. While other ceramics are made piezoelectric artificially, for example Lead Zirconate Titanate (PZT). PZT is a commonly used artificial piezoelectric ceramic.

2.2 Properties of Piezoelectric materials

The piezoelectric actuator has a nonlinear behaviour between its strain and voltage. The displacement (strain) is a hysteretic function of the voltage on the actuator. Therefore in case of a voltage amplifier there is hysteresis between the system input and actuator strain. However if a charge signal is given to the actuator instead of a voltage signal, hysteresis is reduced to a larger extent. This indicates that the capacitance of the piezoelectric actuator is not constant. If capacitance was constant, using voltage or charge as input signal would give the same results [6]

Piezoelectric material has electromechanical coupling. It means that by applying mechanical energy (force) to the material, it produces electrical energy in the form of electric charge and inverse is true as well i.e. application of electrical energy to the material produces mechanical energy which causes the material to expand. Because of this property piezoelectric material can be used as actuator as well as a sensor.

The properties of the piezoelectric material is due to its unique polarity. Non-polar materials (in which positive and negative charges are evenly distributed, when there is no external field applied) cannot be piezoelectric. On the other hand piezoelectric materials exhibit spatial shift of electric charges and have dipole moments, even when there is no external field applied.

2.2.1 Actuation properties

Equation (2.1) describes the relation between strain and electric field. It describes the inverse piezoelectric effect and is called as actuation equation.

$$\mathcal{X} = d * E \tag{2.1}$$

Where d is the piezoelectric charge constant, $\mathcal{X}$ is the strain and E is electric field.

Strain is defined as the change in length of a material per unit length.

$$\mathcal{X} = \Delta l / l \tag{2.2}$$

Where *l* is unit length of the actuator.

By definition electric field is given by equation (2.3)

$$E = V/L \tag{2.3}$$

Equating equations (2.1), (2.2) and (2.3) we get,

$$\Delta l = d * V \tag{2.4}$$

Change in length is equal piezoelectric charge constant times the voltage applied. Equation (2.4) is the simplified form of the actuation equation.

2.2.2 Sensing properties

From the direct piezoelectric effect, sensor equation is derived as follows. The basic intrinsic property of the actuator states that polarization is equal to piezoelectric constant times the stress,

$$P = d * X \tag{2.5}$$

Where P is the polarization, d is dielectric constant and X is stress.

Polarization is defined as charge per unit area,

$$P = Q/A \tag{2.6}$$

And Stress is defined as force per unit area,

$$X = F/A \tag{2.7}$$

Putting equations (2.6) and (2.7) in equation (2.5) and multiplying by area (A) we get,

$$Q = d * F \tag{2.8}$$

By definition, polarization is also equal to negative of permittivity multiplied by the electric field,

$$P = -\varepsilon * E \tag{2.9}$$

2.2.3 Elastic properties

Piezoelectric material being an elastic material also hold the following relation between stress and strain,

$$\mathcal{X} = s * X \tag{2.10}$$

Where s is the elastic compliance. $\mathcal{X}$ is strain and X is stress as defined earlier.

2.2.4 Dielectric properties

The following equation defines the dielectric properties of a material.

$$D = \varepsilon * E \tag{2.11}$$

Where D is electric displacement, E the electric field and ε dielectric constant.

2.3 Constitutive equations

Constitutive equations describe the behavior of piezoelectric materials in a mathematical form. The equations are described in terms of electrical and mechanical variables and the relations between them. The electrical, dielectric and elastic properties of the piezoelectric materials are combined into a compact equation - which are called as the constitutive equations.

The constitutive equations are defined in terms of so called actuator and sensor equations. Combing the piezoelectric and elastic property, the following equations are derived,

$$\mathcal{X} = s * X + d * E \tag{2.12}$$

$$D = \varepsilon * E + d * X \tag{2.13}$$

Equation (2.12) is called as the actuator equation. It defines strain as a function of stress and electric field. Equation (2.13) is called as the sensor equation.

Now adding the boundary conditions to equations (2.12) and (2.13),

$$\mathcal{X} = s^{E} * \mathrm{E} + \mathrm{d} * \mathrm{E} \tag{2.14}$$

$$D = \varepsilon^{X} * \mathrm{E} + \mathrm{d} * \mathrm{X} \tag{2.15}$$

Superscript E on compliance means that compliance is measured under constant electric field (E). Superscript X on ε means that the dielectric constant is measured under a constant stress.

(2.14) and (2.15) are called the simplified form of the constitutive equations of piezoelectric materials.

2.4 Electrical model of Piezoelectric actuators

For this study the piezoelectric actuator is considered as an idea parallel plate capacitor. Several studies have been done on the electrical properties of piezoelectric ceramics. Piezoelectric actuators are considered as capacitive loads, if only the electrical domain of the actuators is taken into account. However due to electromechanical coupling, the mechanical boundary conditions greatly affect the electrical properties [4]

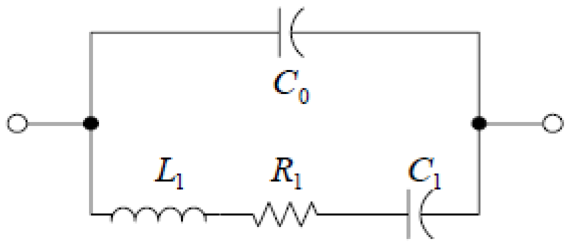

Figure 2- 1 Equivalent circuit of piezoelectric actuator

The above model called as Van dyke model is recommended by the 1987 IEEE standards on Piezoelectricity [5]. Here C_o is the piezo capacitance at non resonant frequencies (usually in the range of 100 to 10 KHz), while the $L_1R_1C_1$ showing the resonant behavior of the PEA becomes active at frequencies around 10 KHZ.

2.5 Non linear properties - Hysteresis and creep

Figure 2- **1** shows a typical displacement-voltage curve of a piezoelectric actuator. As the figure shows the actuator displacement follows a different path when the voltage applied is increasing and then when it is decreasing. In other words, the displacement differs in case of increasing and decreasing input, for the same applied voltage which results in hysteresis

Hysteresis is the most dominant non linearity of piezoelectric material. [29]

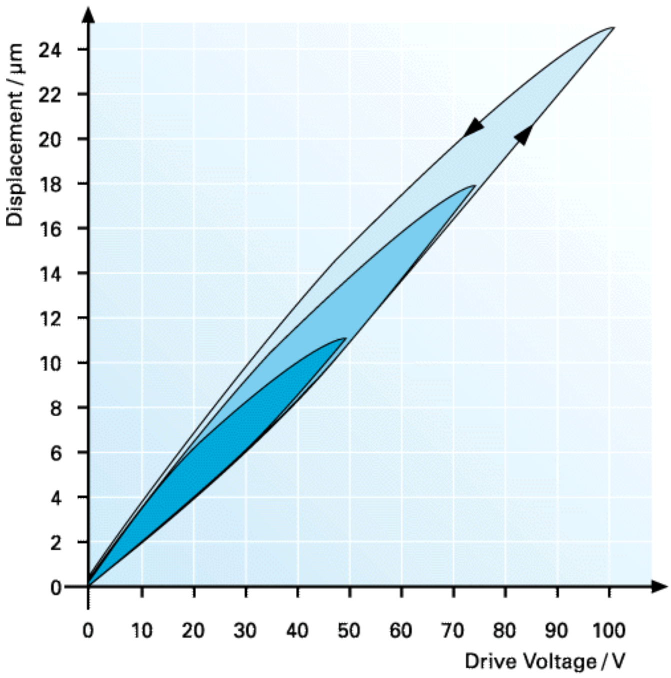

Figure 2- 2 Displacement Voltage Hysteresis Curve [36]

Creep or drift is another non-linear property of Piezoelectric actuators. It causes the actuator displacement to change, even when the input signal is stopped. It is highly undesirable as the displacement is very crucial in Microsystems - it can cause damage to the controlled system. Creep and hysteresis reduce the accuracy of a piezoelectric actuator for positioning. In our application, for example, it causes undesired results in the form of erroneous circuits being printed on the silicon wafers.

Creep is the result of the polarization of the piezoelectric actuator which continues to change after the applied voltage reaches its final voltage. Commonly the creep effect is an issue at low frequencies. [5]

3. SIMULTANEOUS SENSING AND ACTUATION

Mechatronics systems are playing a vital role in the modern hi-tech industry. A Mechatronic system basically consists of three elements: actuator, sensor and control. Actuator is the part of the system that converts the input energy into some form of mechanical energy. Sensors provide feedback about the systems status and thus provide a means for improving the process robustness. Control provides the processing capability of the system. It receives the desired output and sensor feedback signal as inputs and computes the required action to drive the plant according to the reference trajectory.

With time mechatronic systems are becoming more compact and intelligent. A new emerging feature of mechatronic systems is the combination of functions in the same component - called as simultaneous sensing and actuation or self-sensing. In addition to the compactness of the system, simultaneous sensing and actuation has other advantages. It reduces the delays in measurement system and results in smaller tracking errors.[29]

Modern actuators are playing an important role in this regard. Some smart materials have the potential to be used simultaneously as actuator and sensor in mechatronic (motion control) applications.

For this functioning to be possible, there are two fundamental conditions:

1) There exists some property of the actuator that changes proportionally during actuation.
2) The changing property can be measured in a way that it does not affect the normal actuation functioning. This means that a minimum energy interaction with the actuator must be ensured.

The materials that have such properties are called as smart actuators. For example Shape memory alloys are used for simultaneous actuation and sensing. During shape recovery (actuation), several properties of the SMA change, particularly the electrical resistivity of the material. The change in thermal resistivity is used as a gauge to monitor the shape recovery [7].

3.1 Control strategies for piezoelectric actuators

For motion control, there are four main approaches to control the position of the piezoelectric actuators.[10][34]

- Feedback voltage control
- Feed forward voltage control
- Feedback charge control
- Feed forward charge control

Feedback voltage control: In this method voltage signal is used as input to steer the actuator and an external displacement sensor is used in feedback to monitor the displacement output. Proportional , Integral, Derivative (PID) or similar control strategy compensates for the hysteresis and drift of the actuator.

Open loop control/Feed forward voltage control: In this method a model of the actuator is built. The actuator model is made by using the basic physics principles (first principles modeling) or systems identification techniques (data driven modeling). Model of the actuator is used to predict the actuator behavior at different input amplitude and frequencies. And a controlled voltage (as a function of the actuator model parameters) is given to the actuator to achieve the desired trajectory.

Various models of the piezoelectric models are being built. For example in [26] the PI inverse model was used, where the hysteresis is reduced from 20% to less than 2.5%. This model also reduces creep of the actuator from 40% to 2.5%. The creep compensator is implemented in cascade with the hysteresis compensator.

One big challenge in the open loop control is Hysteresis modeling which is simple enough to be implemented in real time. A widely used model is the rate-dependent Prandtl-Ishlinskii model. In [30] this model and its inverse are used to characterize and compensate for the rate-dependent hysteresis nonlinearities of a piezoelectric positioner with cantilever structure.

Feedback charge control: In this method the actuator is steered by a charge signal instead of a voltage signal. The actual charge on the actuator is measured and a desired controlled motion is produced. The advantage of charge steering is that it reduces the hysteresis between input signal and output strain. In [31] charge control method is used. It has been shown that hysteresis between displacement and charge signal is 2 %, although the hysteresis between displacement and voltage is 14%.

Feed forward charge control: In this method a charge amplifier is used to inject a controlled amount of charge in the actuator for a controlled output displacement. For example, in [11] a feed-forward charge control scheme is used to control a piezoelectric actuator displacement. The study suggests a model of the actuator with static part and motion part, which estimates the current required by the actuator for a desired motion. Desired velocity and the actuator voltage are inputs to the model whereas current is the model output.

The voltage control method has advantage of a simpler hardware (voltage amplifier). However there is a large hysteresis between the output displacement and the input voltage. The performance of the voltage control methods is limited by the performance of the sensor in feedback cases or by the model complexities in feed-forward cases [12]. Charge control on the other hand reduces the hysteresis and creep but requires a complex charge amplifier.

The open loop charge driving method is limited by the functioning of the charge amplifier. The accuracy of the system is as good as the amplifier itself.

Leakage current of the actuator is also an important limiting factor in open loop method. The factors that limit the performance of the charge steering include [12]:

- Temperature drift of the actuator
- Leakage current (Power losses) of the actuator
- Humidity dependant properties
- Non ideal behavior of the charge amplifier

3.2 Self sensing in Piezoelectric actuators

For piezoelectric actuators, there is possibility of self-sensing as the capacitance of a PEA changes during actuation. And capacitance can be measured from the electrical domain (from voltage and current information).

Previously work has been done on the simultaneous sensing and actuation of piezoelectric actuators using different concepts. For example, in [8] it is suggested that the charge drawn by the actuator causes electrical current and mechanical actuation or $Q_{mech} = Q_{total} - Q_{electrical}$. In this way a signal proportional to the mechanical strain is obtained by subtracting the total current drawn by a PEA from the electrical current passing through it.

In [9] simultaneous sensing and actuation is achieved by splitting the actuator electrodes - a small part of the electrode is used as a sensing element. Voltage is developed on the sensing electrode proportional to strain. The strain induced voltage is used as a feedback signal for strain control.

In this thesis work, capacitance is measured by injecting a small ac signal (test signal) on top of the servo signal. Actuation action is achieved by the servo signal which produces the desired motion and sensing is done via the small signal.

This method can be regarded as novel, as it has not been tested before. The basic idea is to use capacitance of the actuator as a feedback signal for position control. Considering the PEA as an ideal parallel plate capacitor, it is know that capacitance is determined by its physical dimensions and dielectric properties. If the dielectric properties are constant, capacitance depends on the physical dimensions only. During motion, the actuator's strain changes so its capacitance will change as well. In this way strain can be calculated from the capacitance.

3.3 Capacitance measurement method

A high frequency small signal injection method is used for real time capacitance measurement. High frequency injection method is commonly used in sensor less feedback control of electric motors. This method has also been used for measurement of clamped capacitance of PEA [13]. Clamped capacitance is the capacitance value of the actuator when it is restrained from movement. In [13] the high frequency injection method is used with voltage control scheme of piezoelectric actuator. Clamped capacitance is used for characterization of piezoelectric actuators and better modeling. In this thesis, the method of high frequency injection is used in charge control scheme. The small signal is added to the large signal at the input of the charge amplifier.

In the experimental setup, current and voltage are measured with a simple electronic circuit, based on Operational Amplifiers (Op-Amp). It will be explained in detail in section 4.5. Data is read in the xPC target environment of Matlab.

In the xPC tagert, the small signal information is extracted from the large signal by using band pass FIR (finite impulse response) filters, whose central frequency is equal to the frequency of the small signal and attenuation in the stop band is 100 dB. Same FIR filters are used for both channels. The current signal is time integrated to get the charge signal. Capacitance is calculated in real time. Figure 3- 1 shows block diagram of xPC target - Matlab, for capacitance measurement.

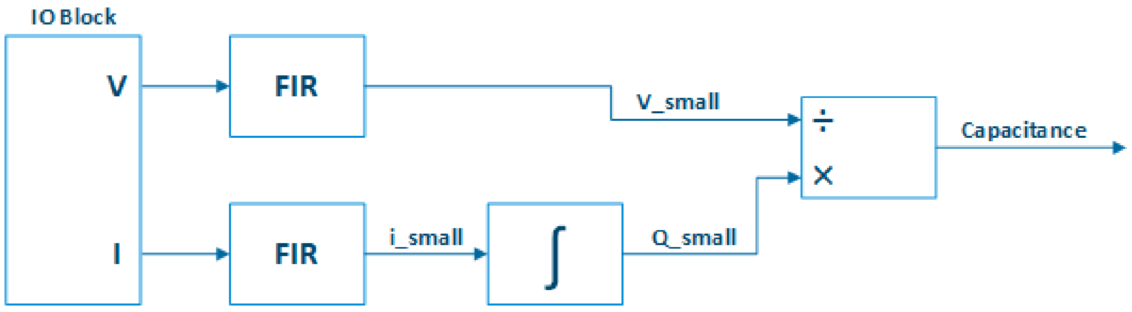

Figure 3- 1 Block diagram for capacitance measurement

It is suggested that high frequency ac signal has very small amplitude, so it does not cause heating of the actuator and it has very high frequency than the natural frequency of the actuator, therefore the system will not respond to it and it does not cause unwanted displacement in the actuator.

4. EXPERIMENTAL SETUP

Since the capacitance is intended to be used as feedback signal for position (displacement) control of the actuator, therefore the first goal is to find the relationship between capacitance and displacement of the actuator.

Change in capacitance of the actuator is caused by several factors like external load, temperature of the piezoelectric actuator, humidity etc [13] [14]. However for this particular case of the piezo legs, our interest lies in finding the capacitance dependence on the physical dimensions (particularly the displacement) of the actuator, only.

In the test setup, an interferometer is used to measure the actuator position. Current and voltage information of the actuator are recorded through a measurement circuit, from which capacitance is calculated. And position and capacitance are compared to each other. Speedgoat hardware (IO cards and target machine) is used for data acquisition. For the software, xPC target of Matlab is used for data acquisition and data processing in real time.

4.1 Charge amplifier

In the test setup a charge amplifier is used to give the input signal. Charge amplifier is preferred over voltage amplifier, as it improves the actuator performance, by reducing the hysteresis[17][35][25]. Charge amplifier produces a charge signal that is proportional to the input voltage signal, thus a controlled amount of charge is input to the actuator.

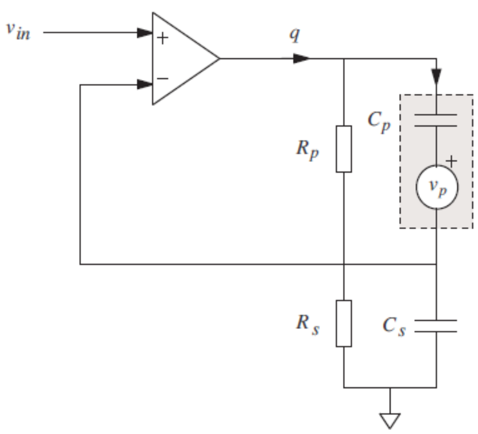

Figure 4 - 1 Simplified Schematic Diagram of a Charge Drive [18]

The high gain feedback loop works to equate the applied reference voltage V_{in}, to the voltage across a sensing capacitor Cs. At high frequencies the resistances Rp and Rs values can be neglected. The charge q is,

$$q = V_{in}C_s \tag{4.1}$$

Ideal charge steering cannot be achieved in reality [25]. In effect charge amplifier only compensates for non-linearity at higher frequencies. At very low frequencies the amplifier functions like a voltage amplifier.

4.2 Optical sensor - Interferometer

In the test setup, micro head Keyence interferometer is used to measure actuator actual displacement. It is compared it to the estimated displacement.

Figure 4 - 2 shows blocks of the measurement setup. In Figure 4 - 2 the interferometer is not shown, however for experiments Keyence interferometer (laser sensor) was positioned at the center of the actuator to measure its displacement.

The interferometer was set up in our test system, according to its user manual. The interferometer's analog out was read in the data acquisition. The analog out of the interferometer gives an analog voltage signal proportional to the measured displacement. [37] shows the product details.

4.3 Data acquisition hardware

IO modules and real time target machine of Speedgoat [38] are used in our test setup, because of its fast speed and compatibility with Matlab and xPC target.

4.4 Software - xPC Target

xPC target (now called as Simulink Real-Time) is used in the test setup for data acquisition. This environment uses a target PC and a host PC, for running real-time applications. The Simulink model is built in the host PC to which I/O blocks are added. xPC then converts the Simulink model into an executable code, which is downloaded from the host PC to the target PC running the xPC Target real-time kernel. [39]

4.5 Measurement circuit

The current and voltage of the actuator need to measured. For this purpose an electronic circuit is needed. The circuit design has many challenges such as high voltage level of the actuator, electrical noise, bandwidth etc. Most importantly it is required that the measurement circuit must not interrupt the normal actuation of the actuator.

For voltage and current measurement, basic electronics concepts are made use of. Voltage across a component in a circuit is the difference of the potentials on its positive and negative sides. Voltages of the positive and negative sides of the actuator are therefore measured via operational amplifiers and their difference is calculated to find the voltage across the actuator. Operational amplifiers buffer the two sides of the circuit, thus the current and voltage of the actuator are not disturbed by the measurement circuit and as usual actuation should be possible.

For current measurement a sense resistor (10 Ω) is placed in series with the actuator. The current through the actuator is same as the current through the sense resistor. An instrumentation amplifier measures the voltage across the sense resistor, which is converted to current.

Starting from very general idea, voltage and current measurement schematic were simulated using NI Multisim. Appropriate Op-amp, In-Amp and other passive components were selected and their performance evaluated.

Multisim is a SPICE (Simulation program with Integrated Circuit Emphasis) simulation platform. There are built-in models for most of the Op-amps available in the market. It gives a good idea about the performance of the amplifiers before the actual soldering. Different Op-amps were tested in NI Multisim, keeping in view the gain bandwidth product, noise performance, supply voltage, and corner frequency.

The measurement circuit was soldered on a breadboard according to the schematic shown in Figure 4 - 2

Detailed functioning of the measurement circuit is explained in section 4.5.

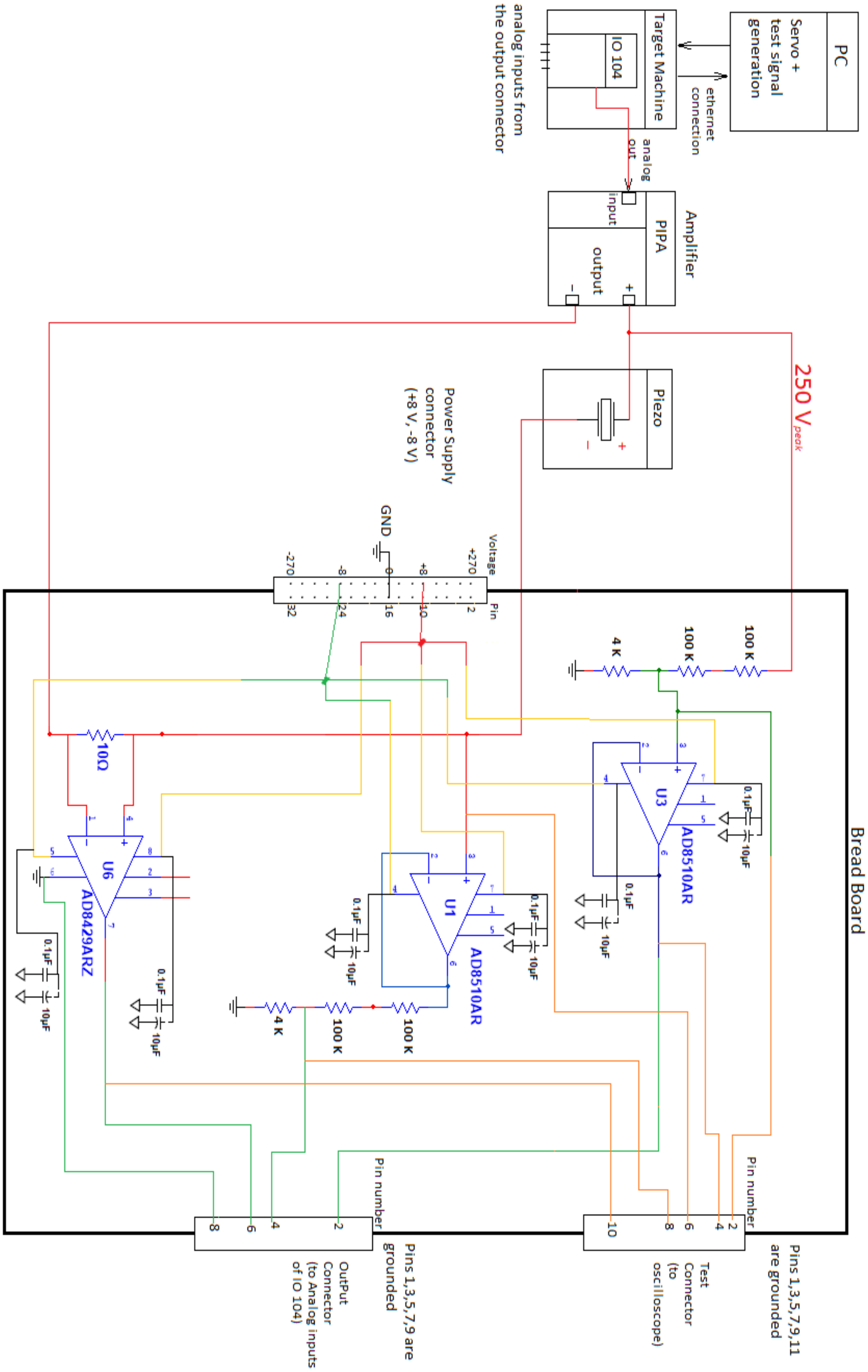

Figure 4 - 2 Experimental Setup

The voltage across the piezoelectric actuator can go up to 250 V peak. A voltage divider is used to reduce the voltage to an acceptable level to be read by the data acquisition IO card.

The proposed circuit is more generic in the sense that it is high bandwidth. It can measure both the servo signal (large signal) and the high frequency ac test signal (small signal). The small signal is used for capacitance measurement whereas the large signal can be used to get insight into other properties of the actuator for control and characterization purposes.

Since a charge amplifier is used for experimentation, one may argue that the current information can be derived from the amplifier transfer function and there is no need of current measurement on the board. However current measurement is needed as the bandwidth of the charge amplifier is 5 KHz, it is not known for sure how the amplifier will process the high frequency small signal. Secondly if there is current variation due to environmental change (such as the actuator temperature, humidity etc.) even then we will have a good measure of the actual charge on the actuator.

4.5.1 Voltage and current measurement

Voltage is measured at the positive and negative side of the actuator, the difference of the two values is the voltage across the actuator. U3 in Figure 4 - 2 is used for the positive side voltage measurement. U3 and the voltage divider resistors are zoomed in Figure 4 - 3.

Since the voltage of the actuator can go as high as 250 V peak, it cannot be input directly to the IO card. To make the voltage levels appropriate for the IO card, a voltage divider is used in parallel with the charge amplifier. The voltage divider steps down the voltage of the actuator by a factor of 51. This brings the voltage level (app. 5 V) in the suitable range of the data acquisition card. High power (and high voltage) resistors are used in the voltage divider.

The voltage divider gives information about the voltage on the positive side of the actuator. The voltage divider will not disturb the PEA actuation functioning, as it is applied in parallel to the PIPA in a separate loop. The PIPA (charge amplifier) can provide enough current for the actuator and the voltage divider resistors. From the technical documentation of the PIPA, the current rating of the amplifier is 75mA. At maximum voltage of 250 V, the voltage divider will draw a current of less than 1.5 mili-amps ($\frac{250\text{v}}{204\text{K}}$).

The voltage level of the actuator is stepped down by a factor of 51, using resistors of 200 KΩ and 4 KΩ in series with each other. Most of the voltage drop occurs across the 200 KΩ resistors. Voltage across the 4 KΩ resistor is buffered via an operational amplifier, and is given to the analog input of the IO card. The Op-amp is used in voltage follower configuration, with a unity gain.

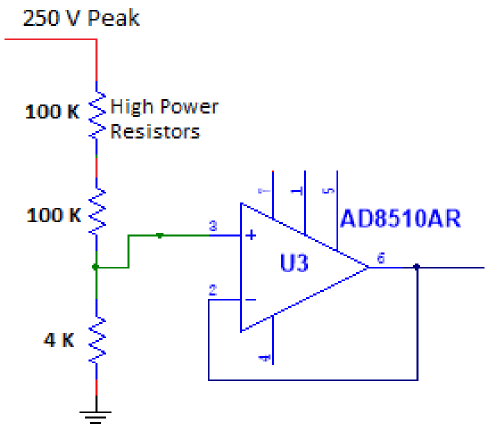

Figure 4 - 3 Positive end voltage measurement

According to the specification document of PIPA, voltage at the negative side of the actuator varies between 0 to 5 volts. U1 in Figure 4 - 2 is used to measure the voltage at the negative side of the actuator. The voltage divider at the negative side is applied at the output side of U1, so that the electrical resistance of the actuator is not disturbed.

The difference of the positive and negative voltages is the voltage across the actuator. The negative voltage is buffered through U1. On the output of U1, same voltage divider is used (4:200) is used. The purpose of the divider is to scale down the negative side voltage by the same factor as that of the positive side.

The Op-amps are used in unity feedback (gain of 1). They are effectively buffering the high power side of the actuator from the IO card inputs, thus providing safety to the IO card as well.

The voltage divider resistors have high voltage and power ratings of 400 V and 0.5 watt. They will function normally at high voltages of the PIPA. The chosen resistors are high precision resistors with a resistance tolerance of 1%.

Current measurement: For current measurement a sense resistor is used in series with the actuator. So current through the actuator is same as current through the sense resistor. The current sensing is done at the negative side of the actuator. The sense resistor is a shunt resistor of 10 Ω. An instrumentation amplifier (AD8429) measures and outputs the voltage drop across the sense resistor. The output voltage of the in-amp is proportional to the current across the shunt resistor, as given by the following equation:

$$Vout = I * Rsense \tag{4.2}$$

U6 in Figure 4 - 2 is used for the current sensing. It is shown again (zoomed in) in Figure 4 - 4. Pin7 of the in-amp gives a measure of the actuator current. The op-amps have bidirectional ± 8 V supplies.

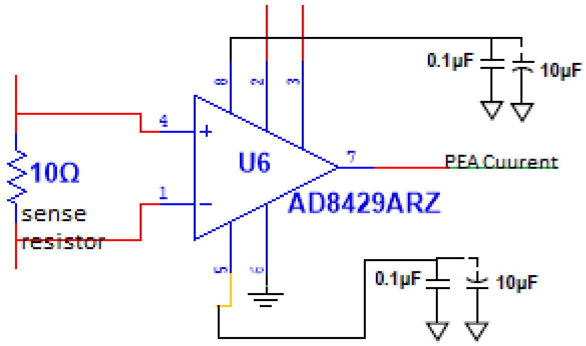

Figure 4 - 4 Current Measurement

Bypass capacitors: A stable power supply is crucial to proper functioning of the op-amps (and in-amps). For this purpose bypass capacitors are used. Bypass capacitors of 0.1µF and 10µF are applied to the positive and negative supplies of the op-amps and in-amps. The bypass capacitors ensure a stable supply to the amplifiers by eliminating voltage drops on the power supply. The bypass capacitors get charged from the power supply and release charge if there is a sudden voltage drop.

4.5.2 Choosing the right amplifiers (op-amp and in-amp)

Noise performance of the op-amp is taken into account when choosing the appropriate Op-amp. Noise sources of an Op-amp can be broadly divided as internal and external noise sources.

External sources: Major external noise source is any resistor in the circuit. There are different types and sources of noise in resistors; the major source being thermal (Johnson) noise. Voltage error produced due to the thermal noise is given by the equation;

$$Vn = \sqrt{4KTBR} \tag{4.3}$$

Where Vn is the voltage noise, K is Boltzmann's constant, T is temperature (in Kelvin), B is the frequency of operation, and R is the resistance. For the Op-amps the resistances in the input and feedback path contribute to the total circuit noise.

Internal sources: Internal noise of an op-amp is specified as:

- Input referred voltage noise
- Input referred current noise

Voltage noise is usually specified for Op-amps in nV/√Hz. It is regarded as most important parameter in the noise calculation. For low source resistances, the noise generated by the source resistance and current noise contribute insignificantly to the total noise. However the source resistance thermal noise may dominate for high values of resistance. Secondly if input impedance levels are high, current noise can be much higher than the voltage noise. Input referred current noise is not always listed on datasheets.

Total input noise: If the noise sources are uncorrelated, then the total input noise source is given by the following expression:

$$V_{ni,TOTAL} = \sqrt{(en)^2 + (Rs * in)^2 + (Vext)^2} \quad (4.4)$$

en is the input referred voltage noise, in is the input referred current noise, Rs is the input impedance of the amplifier, Vext is the noise voltage from external resistors.

To simplify the noise calculations, all the sources are transformed to equivalent at the input of the op-amp, as shown in Figure 4 - 5.

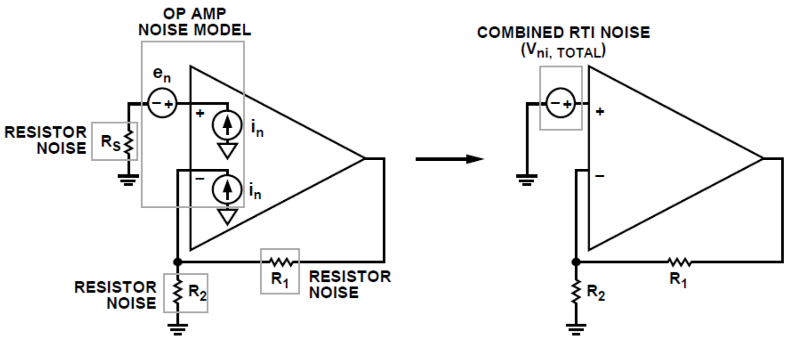

Figure 4 - 5 Noise Sources of an Op-Amp

To calculate the total output noise of the amplifier circuit, the total input noise is multiplied by the gain of the amplifier,

$$Vno = Vni * Gn \quad (4.5)$$

Vno is output voltage noise, Vni is total input voltage noise. The noise gain (Gn) depends on the feedback and inverting input resistor is given by;

$$Gn = 1 + \frac{R1}{R2} \quad (4.6)$$

Low frequency noise: So far we assumed that the noise is random over all frequency range. However at certain low frequencies the noise rises. The voltage noise spectral density is inversely proportional to the square root of the frequency. For this reason, this noise is commonly referred to as 1/f noise. The frequency below which the noise starts to increase is called as corner frequency.

From the above equations one can conclude that noise is the least if the opamp with least En, Rs and in is selected and by reducing the external resistance as much as possible. However, keeping in view other objectives, there is a tradeoff between different factors. For example the external resistors have to be of least value for better noise performance but it is chosen high (200 KΩ and 4 KΩ), as voltage divider is needed and the current through the resistors has to be limited.

The right amplifier: Based on the above criteria AD8510 is chosen for voltage buffering and AD8429 is chosen as instrumentation amplifier for current measurement. AD8510 is a low noise wide band operational amplifier. [15] and [16] are the datasheets of AD8510 and AD8429 respectively. The behavior of different Op-amps was analyzed in NI Multisim SPICE environment.

4.6 Circuit testing

Based on Figure 4 - 2, the circuit was soldered on a bread board. After soldering the circuit was tested to check its functioning. Function generator was used to give input directly to the op-amps and their output was observed via oscilloscope. All the three op-amps were tested for proper functioning at different frequencies from 100 Hz up to 100 KHz. Following are some of the screenshots of the oscilloscope, which are taken during the circuit testing.

Figure 4 - 6 shows the case when a 10 KHz sine wave is given to the op-amp input, with ±8 V supply voltages.

Channel 3 (pink) and channel 4 (green) are, respectively, the positive and negative supplies. Channel 1 (dark blue) is the input and channel 2 (light blue) the output of the Op-amp.

It is obvious from the figure that the Op-amp is functioning properly. The output is perfectly following the input. There is a unity gain of the Op-amp. This specific screenshot is for the negative side voltage channel. Similarly the other two amplifiers were also tested, which were functioning properly at frequencies up to 100 KHz.

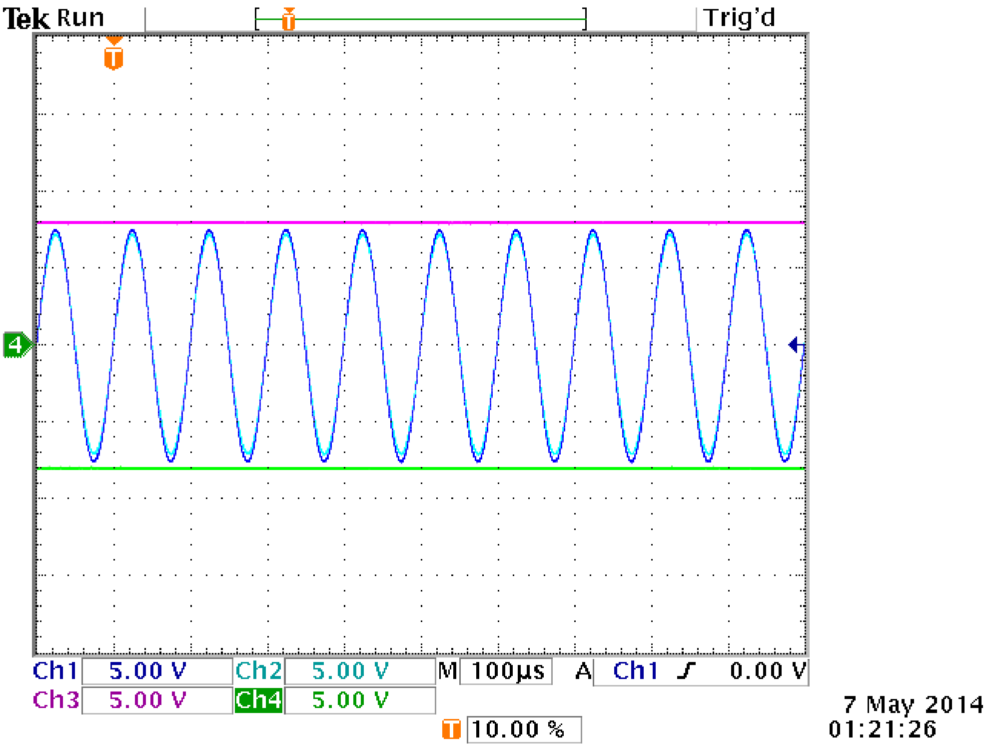

Figure 4 - 6 Circuit Testing - Oscilloscope Screen Shot 1

Figure 4 - 7 shows the op-amp response when input signal amplitude is higher than the supplies. It can be seen from the figure that clipping occurs in the output (channel 2). It indicates that the op-amp is working properly, as the output voltage swing remains within the limits of the amplifier supplies (± 8 V).

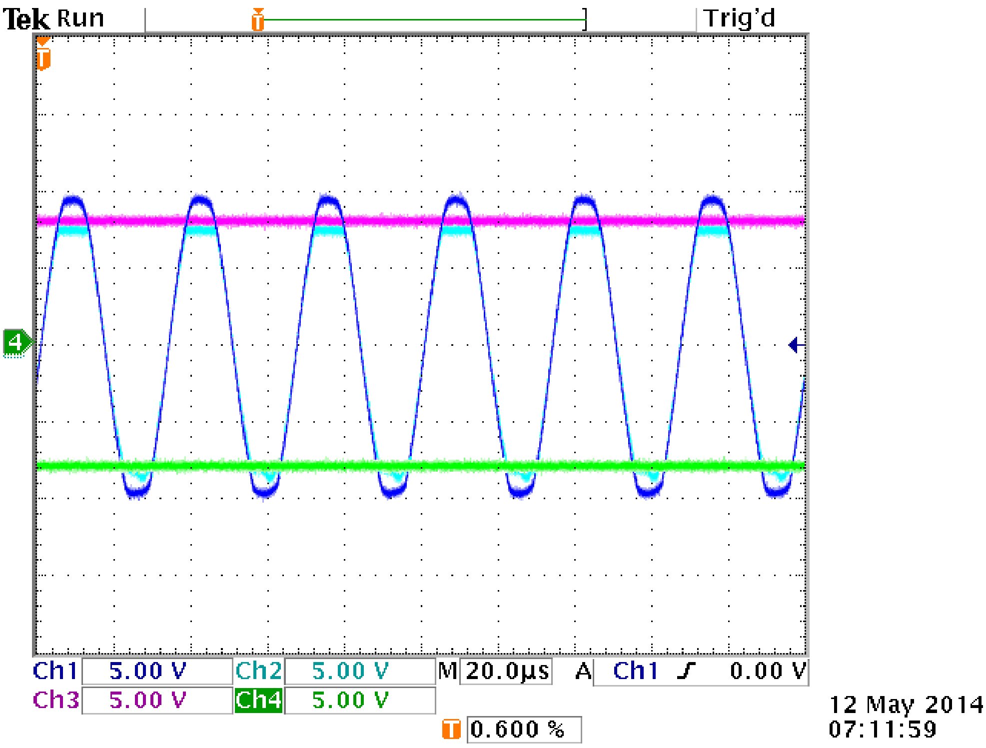

Figure 4 - 7 Circuit Testing Oscilloscope Screen Shot II

4.7 Test system Integration

After the circuit testing and debugging, the actuator and PIPA were integrated according to the format of Figure 4 - 2. The final test setup was made inside a clean-room environment.

Initially function generator was used to give input to the charge amplifier and data of voltage and current was recorded through the USB port of oscilloscope. The function generator and oscilloscope were then replaced by xPC target, so that the data can be further processed in real time, and the small signal information can be extracted.

xPC target is used to give input to the actuator (through the amplifier) and for data logging. xPC a real time operating system developed by Mathworks for optimal performance with Matlab and Simulink. xPC is chosen so as to do the real time calculations and filtering of small signal from the large signal. The environment is usually used for real time testing and control applications.

5. EXPERIMENTAL RESULTS

This chapter summarizes the experimental results and data analysis. The behaviour of the actuator is tested with different inputs of different frequencies. Keyence interferometer is used to record the actuator position. The analog out of the Keyence interferometer gives an analog voltage proportional to the measured displacement. Voltage and current of the actuator are recorded via the measurement circuit. Simultaneous measurements were made for the current, voltage and displacement of the actuator. The IO card has 8 ADC channels and each of the channels is converted from analog to digital at the same rate, simultaneously.

5.1 Tests procedure

Following steps summarize the test plan:

- Voltage and current data is read at no input, this gives approximation of the measurement setup noise.
- A proper small signal is chosen. Sampling rate of the system is 4ksps (40000 samples per second). According to Nyquist criteria, sampling rate of a system must be at least twice the maximum frequency in the system. This means that the small signal can have a maximum frequency of 20 KHZ, at the sampling rate of 40 ksps.
- The small signal is added on top of the large servo signal.
- The output voltage, current and displacement signals are read via the analog inputs of the IO card.
- The current and voltage data is passed through an FIR band pass filter (with central frequency equal to the frequency of the small signal). This filters output is the small signal.
- The current signal is integrated with respect to time, to get charge signal.
- Capacitance is calculated as the ratio of charge and voltage.
- The systems response is observed.
- Capacitance is compared to the actuator's displacement (strain).

FIR filter: As the small signal information is needed to calculate the capacitance, an FIR band pass filter is used to extract the small signal information, from the recorded data.

The recorded data of current and voltage both are passed through similar FIR band pass filter, whose central frequency is equal to 2.5 KHz (frequency of the small signal). The filters have a group delay of 364 samples and has linear phase response in the pass band. The attenuation in the stop band is -120 dB. The FIR filter block is designed using Matlab Signal processing tool box by specifying the filter parameters like stop frequency, pass frequency, stop band attenuation and pass band ripple etc. Figure 5- 1 shows the magnitude response of the band pass FIR filter.

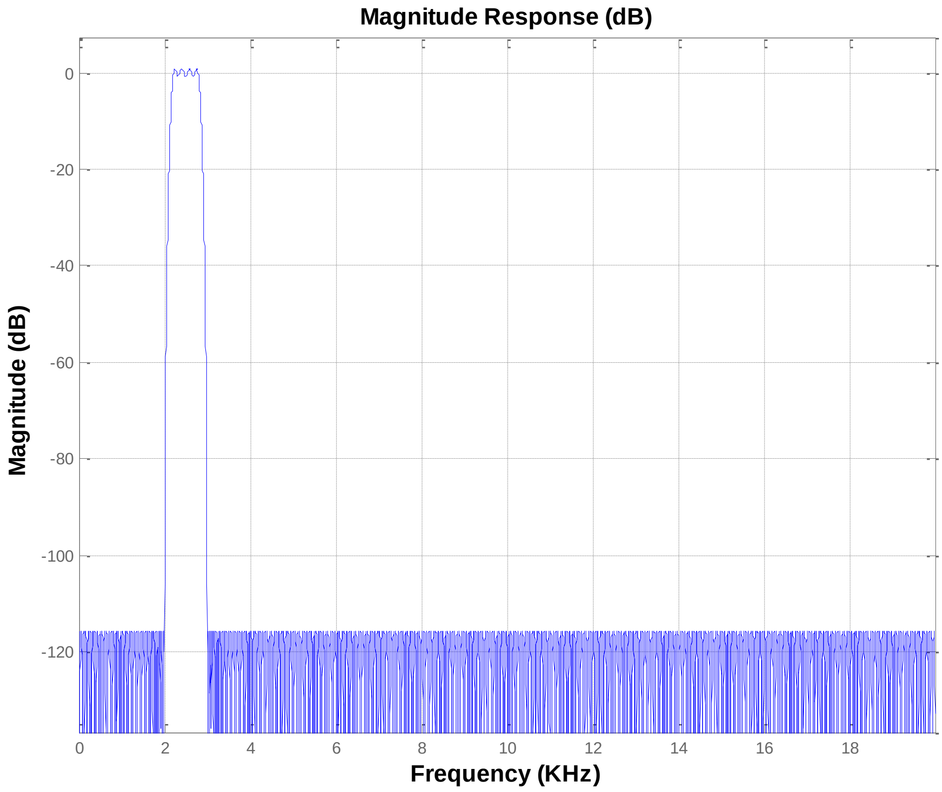

Figure 5- 1 Band pass FIR filter

5.2 Ramp input (1 Hz)

Following figures show the results, when a ramp reference voltage is given to the actuator. Here the Ramp input has frequency of about 1 HZ, whereas the small signal has a frequency of 2.5 KHz.
A maximum sampling frequency of 50 KHz (50000 samples per second) is possible for the experiments. Above 50ksps the target machine CPU gets overloaded and stops functioning. Theoretically the small signal can have a frequency up to 25 KHz, however the frequency of small signal is chosen at 2.5 KHz so as to have many samples per cycle for better calculations of the capacitance. Chosen sampling rate is 40 Kilo samples per second (KSPS).

Figure 5- **2** shows the reference input, given to the PIPA. As can be seen from the figure, the reference voltage has a frequency less than 1 HZ. The small ac signal of 2.5 KHz is added on top of it.

Figure 5- **3** shows the power spectral density estimate of the input signal. The small signal can be seen as a peak at 0.125 of the x-axis, which corresponds to 2.5 KHz at sampling rate of 40KSPS. The x-axis is normalized frequency.

Figure 5- **4** is the resultant output voltage on the actuator.

Figure 5- **5** shows the actuator position (displacement), the reading of the interferometer.

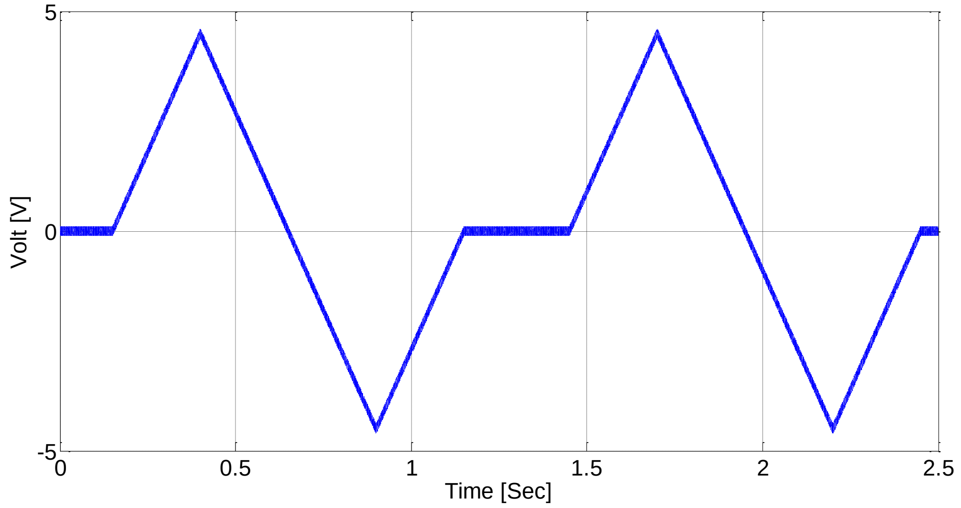

Figure 5- 2 Ramp input

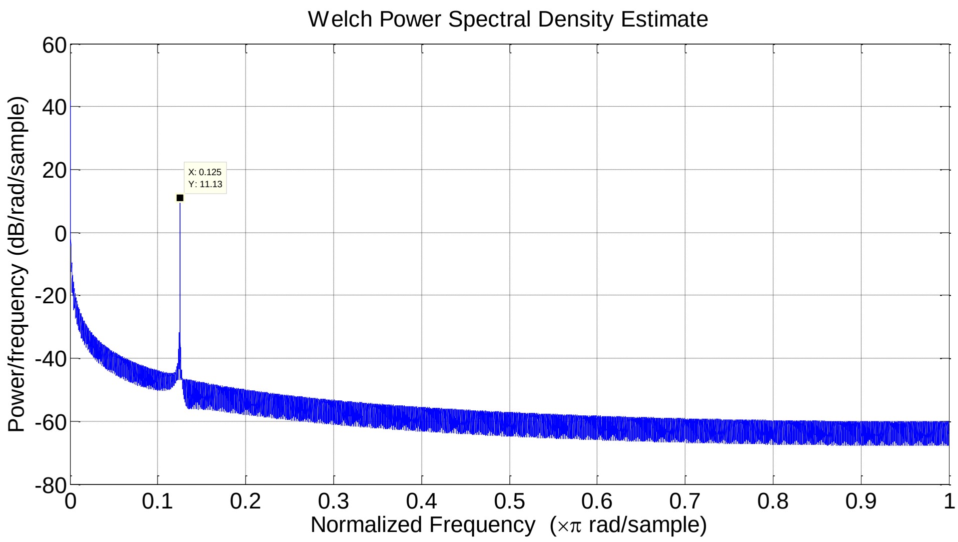

Figure 5- 3 Power spectral density (PSD) of the input signal

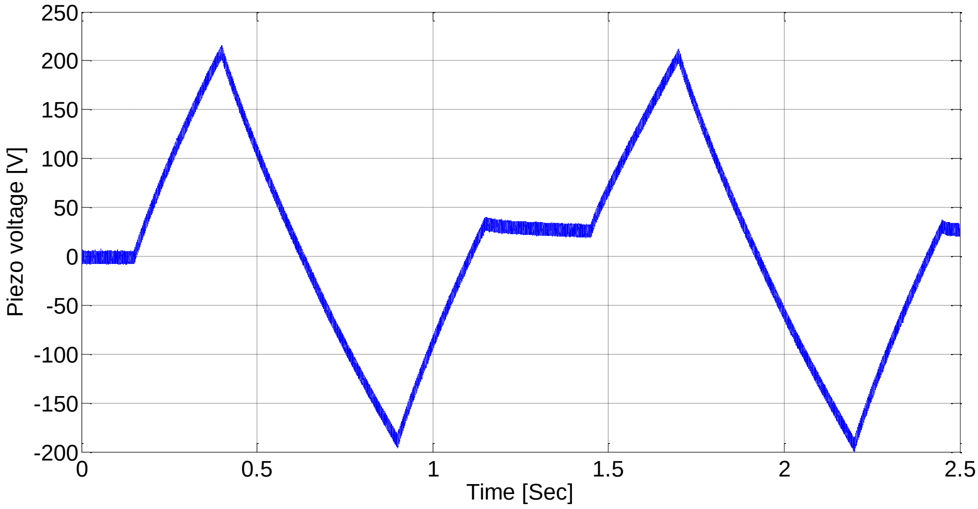

Figure 5- 4 Voltage signal on the actuator

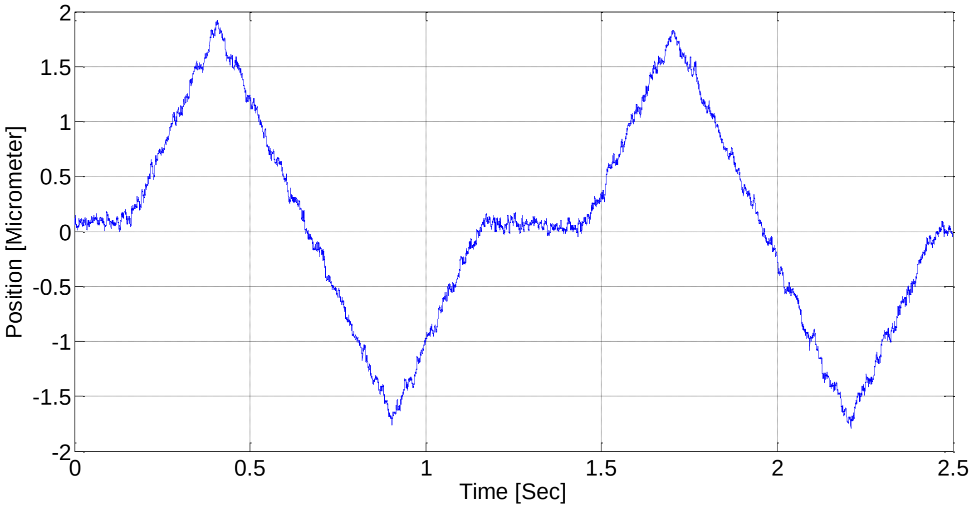

Figure 5- 5 Interferometer reading (position of the actuator)

Figure 5- **6** is the plot of the actuator position against the input reference voltage. The graph shows that the actuator position is almost linear function of the input voltage to the charge amplifier. This is expected in case of charge amplifier, as the charge amplifier converts the input voltage signal into a corresponding charge signal.

From theory it is known that the actuator position is a linear function of the charge on the actuator [17] [18]. In case of a voltage amplifier there is hysteresis between input voltage and the actuator position. This is the main advantage of charge steering.

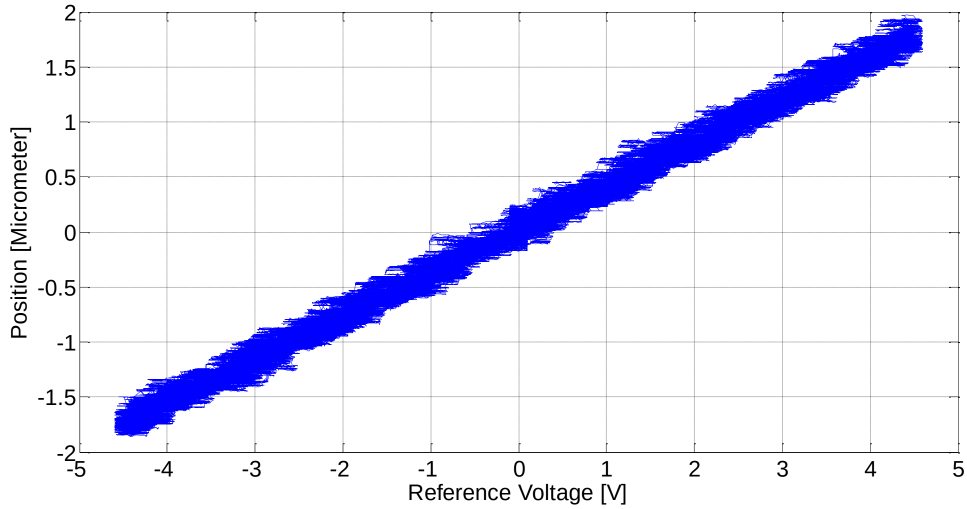

Figure 5- 6 Input voltage VS actuator position

Figure 5- **7** is the plot of the actuator voltage (output voltage of the PIPA) and the input reference voltage. As the graph shows there is hysteresis between the input voltage and the actuator voltage. In case of voltage amplifier, this would be a linear graph.

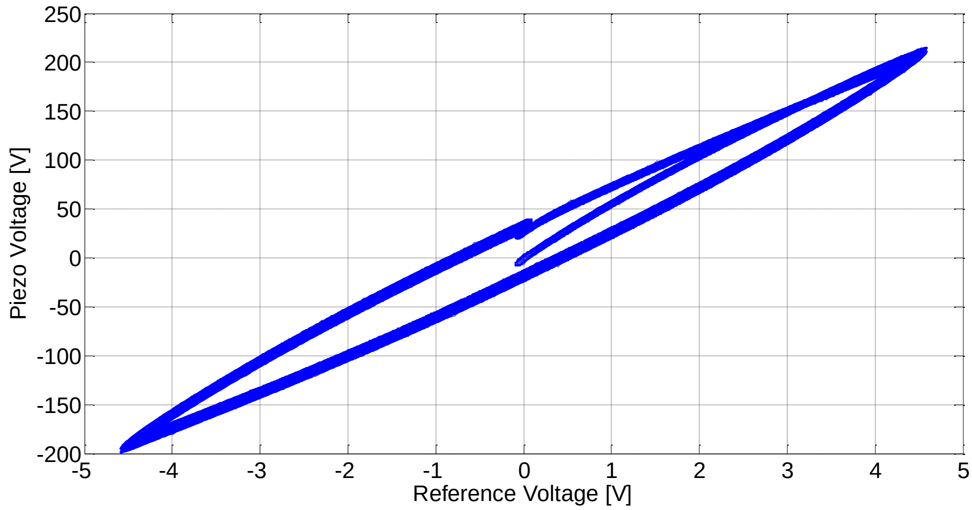

Figure 5- 7 Reference (Input) voltage VS actuator (output) voltage

From Figure 5- **6** and Figure 5- **7** it can be concluded that hysteresis is still there between the actuator position and the actual voltage on the actuator even in case of charge steering. Nevertheless the objective of reducing hysteresis between actuator position and reference input is achieved.

For capacitance measurement the output of the FIR filters, namely v_small and i_small are used. i_small is integrated with respect to time and divided by the voltage to get the capacitance. Figure 5- **8** shows the results when capacitance is calculated with the C=Q/V formula. The figure shows that no useful information can be obtained from it directly. It is because of the "division by zero" conditions in the calculations. At points where V_small is zero, capacitance is undefined and the calculated value of capacitance at these points approaches infinity, as seen by the graph asymptotes.

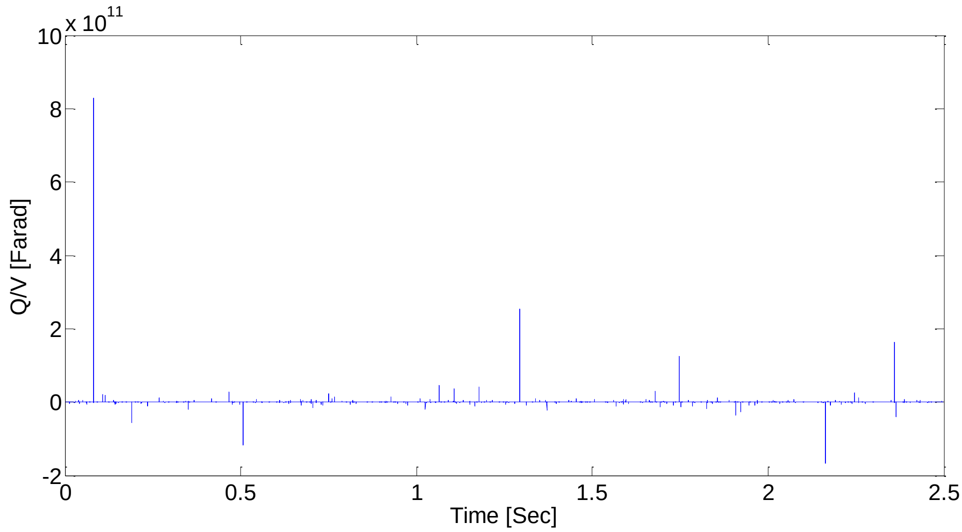

Figure 5- 8 Capacitance of the actuator

To avoid the division by zero condition, RMS value of v_small and Q_small is taken per cycle of the small signal. RMS values are then used for capacitance measurement. At a sampling rate of 40ksps and frequency of 2.5 KHz, there are 16 samples (1/2500*40000) per cycle of the small signal. So RMS value of every 16 samples is taken of V_small and Q_small to calculate one sample of capacitance.

RMS blocks are added to the initial plan (Figure 3- 1) of capacitance calculation, as shown in the following figure:

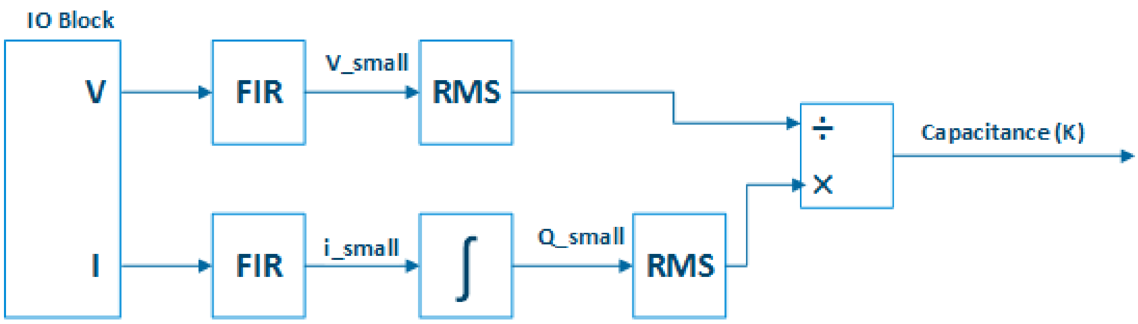

Figure 5- 9 Capacitance measurement algorithm

Accordingly the capacitance becomes as follows:

$$Capcitance(k) = \frac{RMS(Qsmall(i))}{RMS(Vsmall(i))} \tag{5.1}$$

Where k = 1, 2, 3 ... and i is an iteration of 16 samples. i.e. 1 till 16, 17 till 33, … , so on.

Figure 5- 10 shows a graph of the measured capacitance using the RMS values per cycle of charge and voltage, and then using a moving average filter (of length 10), to remove the high frequencies components in the capacitance signal.

The graph shows that the capacitance value varies between approximately 85 nF and 100 nF.

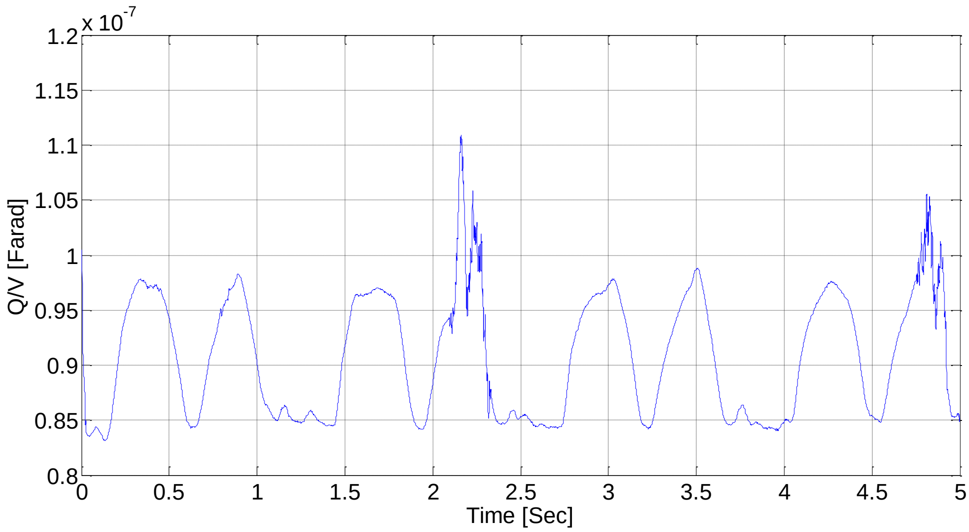

Figure 5- 10 Capacitance signal of the actuator (based on equation 5.1)

Figure 5- **11** shows a comparison of the capacitance to the actuator position. The graph shows that capacitance is a minimum at zero input. It increases to a maximum as the actuator shrinks (moves in the positive direction). Capacitance decreases again to 85 nF as the actuator expands (moves in the negative direction). In effect Capacitance is proportional to the change in displacement in both directions (strain), i.e. the change in capacitance follows similar profile both in the positive and negative direction (expansion and contraction).

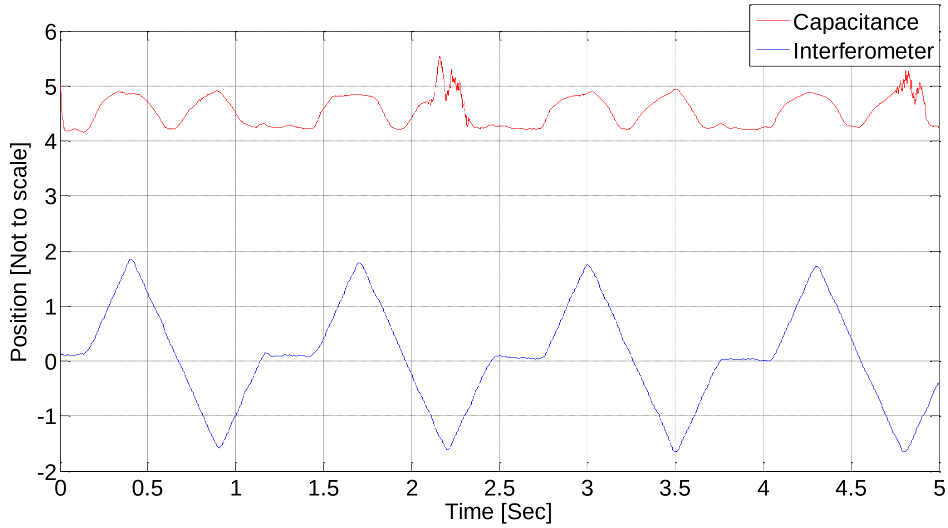

Figure 5- 11 Comparison of the actuator capacitance to its position

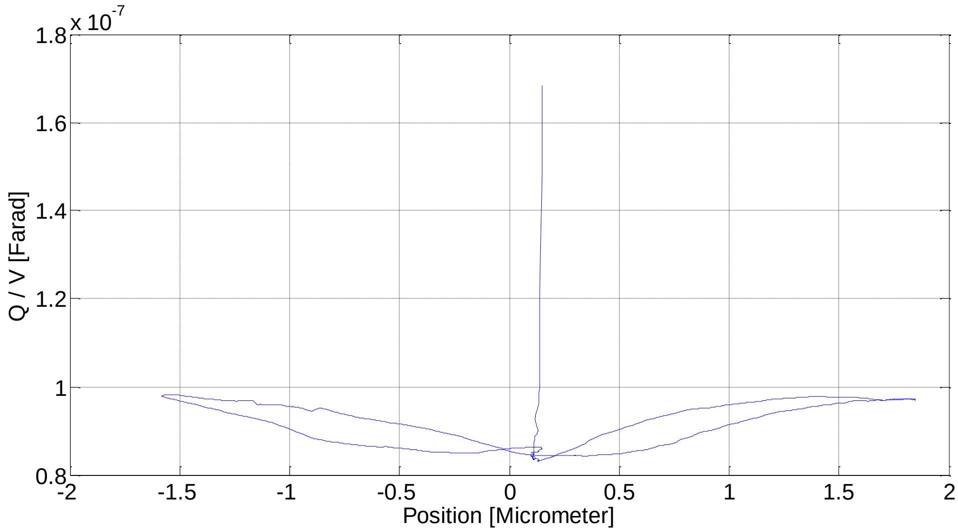

Figure 5- 12 Actuator position VS capacitance

Figure 5- **12** is a plot of the capacitance against the actuator position. This graph shows that there is hysteresis between capacitance and the actuator strain. The capacitance on the positive and negative sides of the strain (expansion and contraction) follow similar pattern. There is not a one to one relation between displacement and capacitance, and the equation for a parallel plate capacitor doesn't fit here.

Two possible reasons are that can explain the above figure are:

- The piezoelectric actuator has non-linear dielectric properties, which changes during the actuation process. [19]
- The area term in the capacitance equation changes. i.e. the area of the electrodes doesn't remain constant.

5.3 Sine input (20 Hz)

In this section the piezoelectric actuator behaviour is observed with a 20 HZ sine input. Again the small signal has a frequency of 2.5 KHz and amplitude of 0.1 V. The response is recorded for a long time; here a small portion of the signal is shown for better visualization.

Figure 5- **13** is the reference voltage, input to the PIPA. Figure 5- **14** is the actual voltage on the actuator. Figure 5- **15** is the actuator position, read via the interferometer.

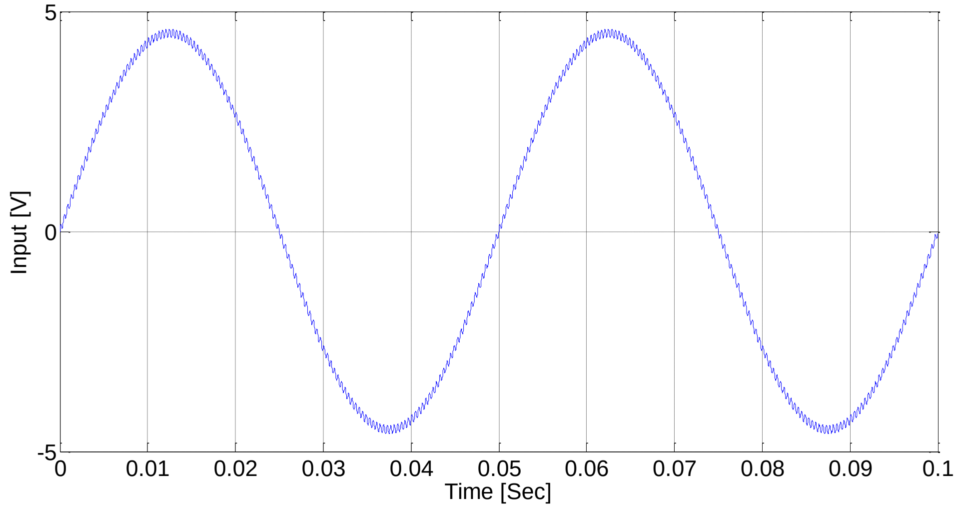

Figure 5- 13 Input signal (20 Hz sine wave)

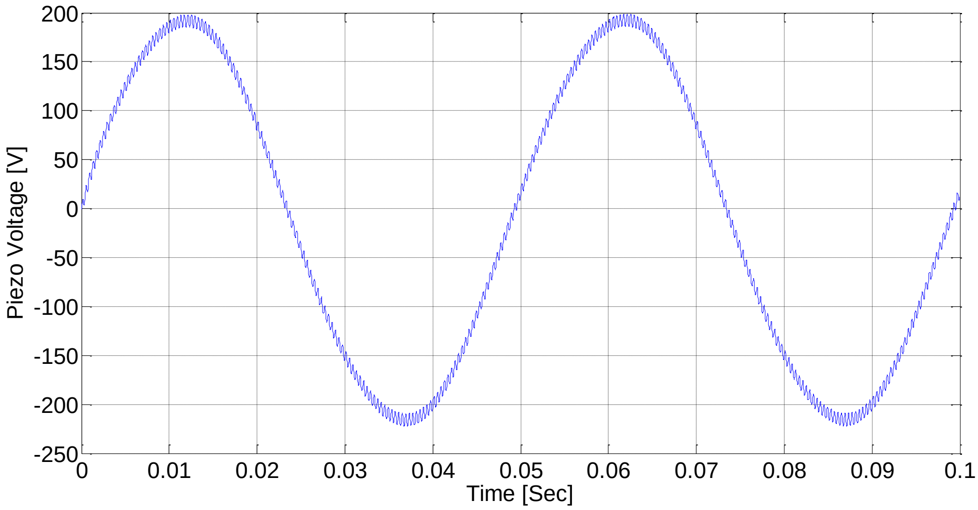

Figure 5- 14 Actuator voltage signal

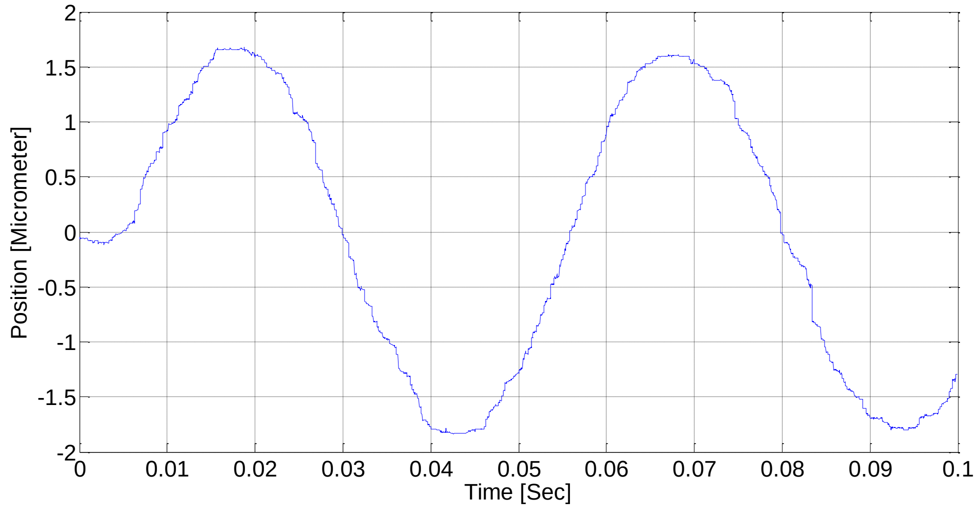

Figure 5- 15 Interferometer reading (position of the actuator)

Figure 5- **16** is the plot of the actuator position against the input voltage. As the graph shows there is a non-liner relation at 20 Hz sine. This is unlike the previous case (1 HZ ramp input), where there was a linear graph between input voltage and actuator position (Figure 5- **6**). The relation looks like a hysteresis graph, but in fact it is not a hysteresis relation. The nonlinear relation is due a phase difference between the actuator position and the input voltage, as shown in Figure 5- **17**.

The phase shift can be due to the transfer function of the PIPA. Figure 5- **18** is same as Figure 5- **16**, after phase correction; meaning that a delayed version of the actuator is plotted against the input voltage, which is quite linear compared to Figure 5- **16**.

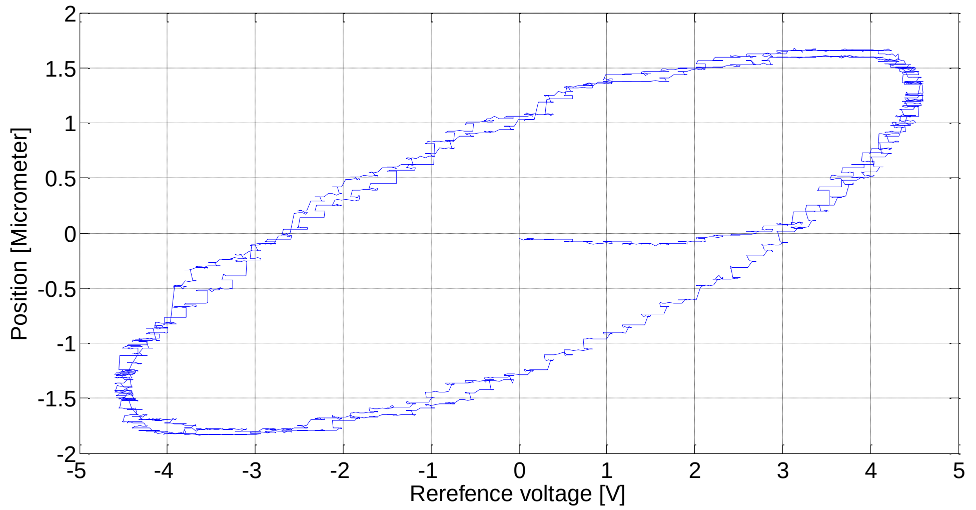

Figure 5- 16 Input (reference) voltage VS the actuator position

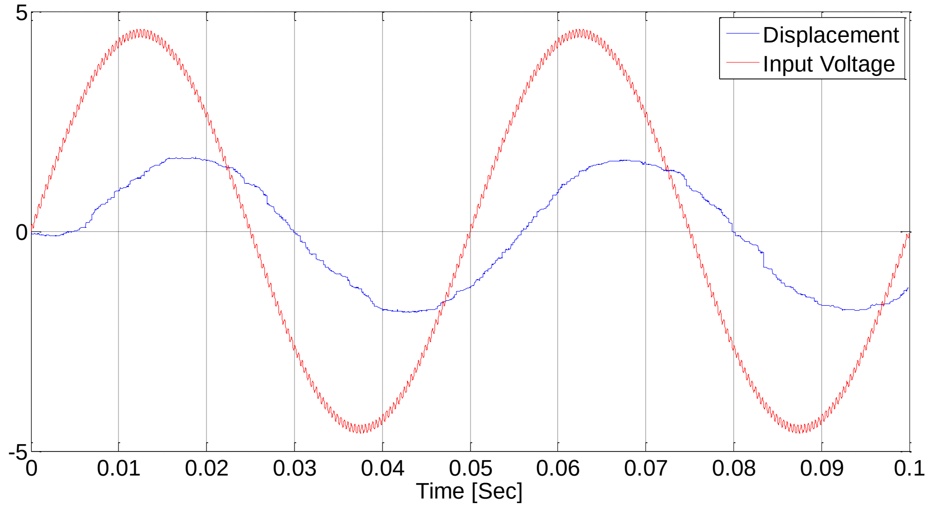

Figure 5- 17 Comparison of actuator position to input voltage

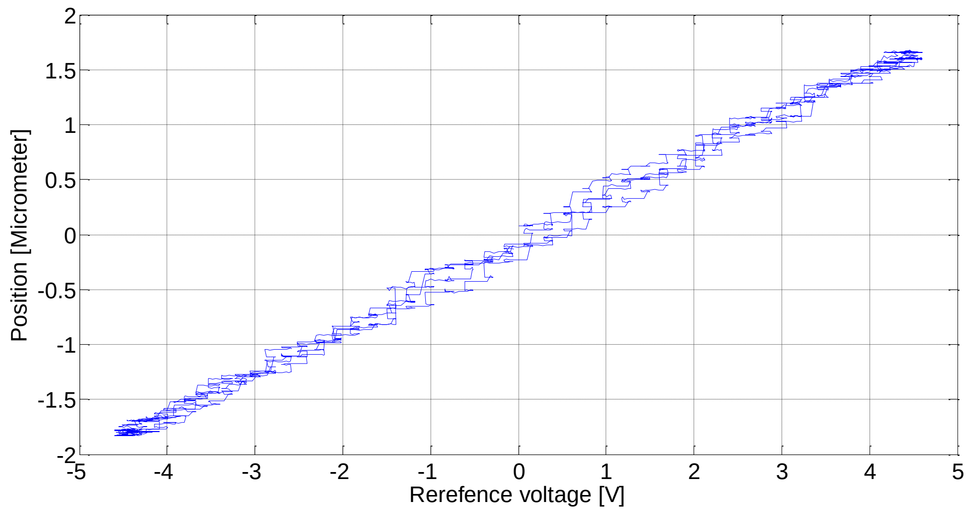

Figure 5- 18 Actuator position against input voltage, after phase correction

Figure 5- **19** is the input voltage plotted against the actuator voltage. Like Figure 5- **7**, hysteresis can be seen here as well.

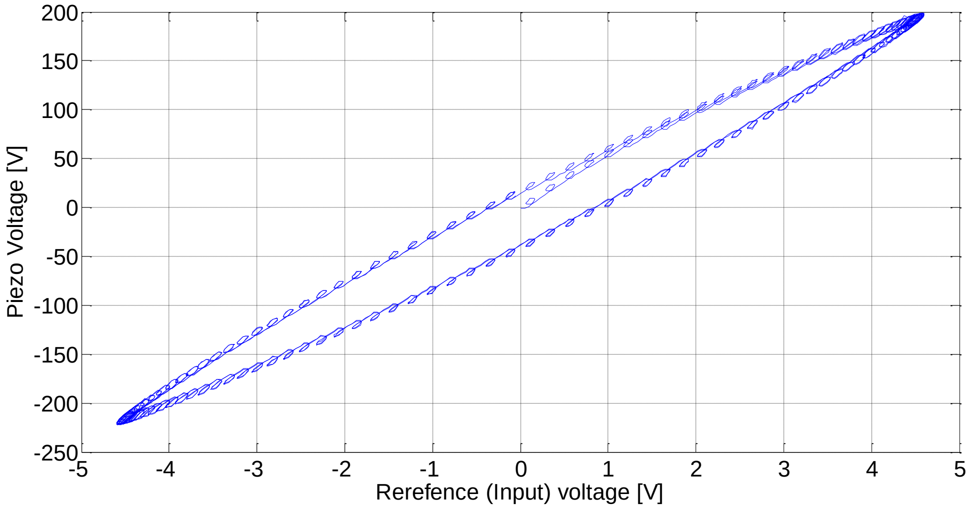

Figure 5- 19 Input (reference) voltage VS actuator (output) voltage

Figure 5- **20** is the graph of capacitance derived using equation 5.1. Here the capacitance value varies between 88 nF and 102 nF.

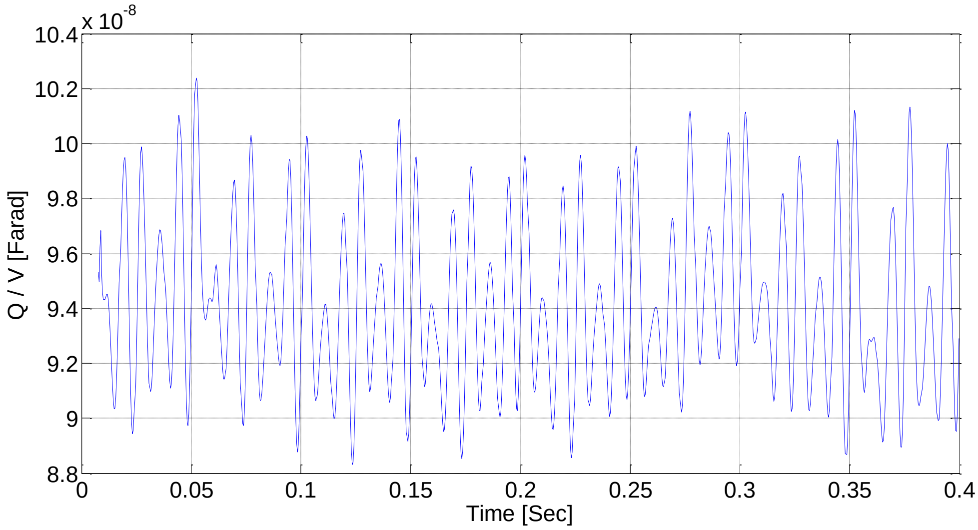

Figure 5- 20 Actuator capacitance signal

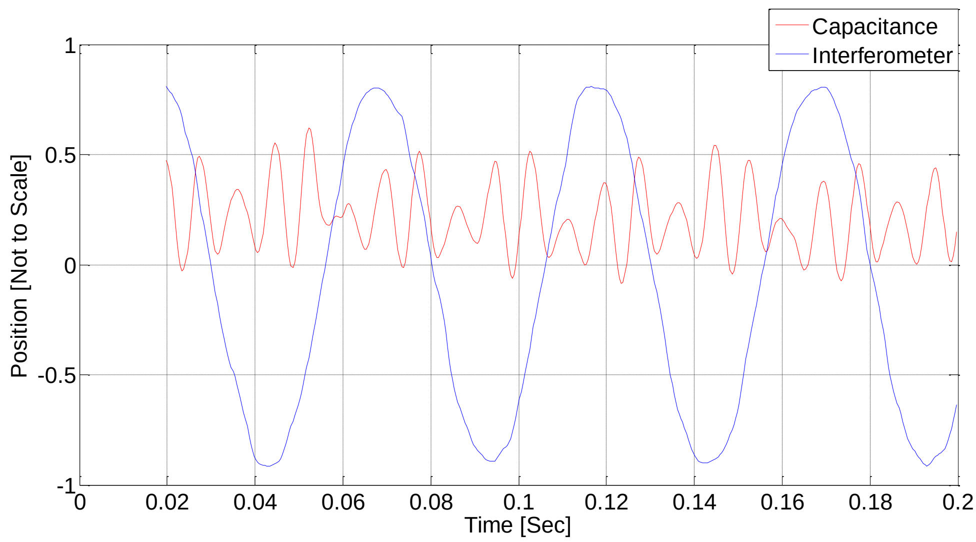

Figure 5- 21 Capacitance comparison with actuator position

Figure 5- **21** shows a comparison of the change in the actuator position and capacitance. Here capacitance is amplified version of the actual value. It shows that:

- Capacitance is changing at a higher frequency than displacement.
- There is more than one sinusoid in the capacitance signal.
- No clear relation can be observed between capacitance and displacement.
- However capacitance is a periodic (repeating) signal.

It can be concluded that:

- There are multiple factors, along with the displacement as well which cause the capacitance variation in a nonlinear fashion.
- Other obvious factors are area of the actuator and the dielectric properties.
- Piezoelectric actuators are nonlinear dielectrics, although the displacement (position) is one factor that determines the change in capacitance, but it is not the single factor which determines the capacitance. The dielectric properties change as well.
- Piezoelectric material is a nonlinear dielectric. The capacitance of nonlinear dielectrics is nonlinear with respect to the operating voltage and is mostly related to changes occurring in the material during operation. So the change in the capacitance is due to the changes in the dielectric. [19]
- Another explanation for the nonlinear capacitance change can be; the PEA is not a pure capacitor but a parallel RC circuit. Like capacitance, resistance of an electrical component also depends on its physical dimensions. So during actuation, as the actuator expands or shrinks the resistance changes as well. The basic relation for resistance of a resistive element is:

$$R = \rho L/A \tag{5.2}$$

Where ρ is the resistivity that depends on the element, L is length and A the cross sectional area of the sensing element.

Figure 5- 22 is a plot of the actuator position versus its capacitance.

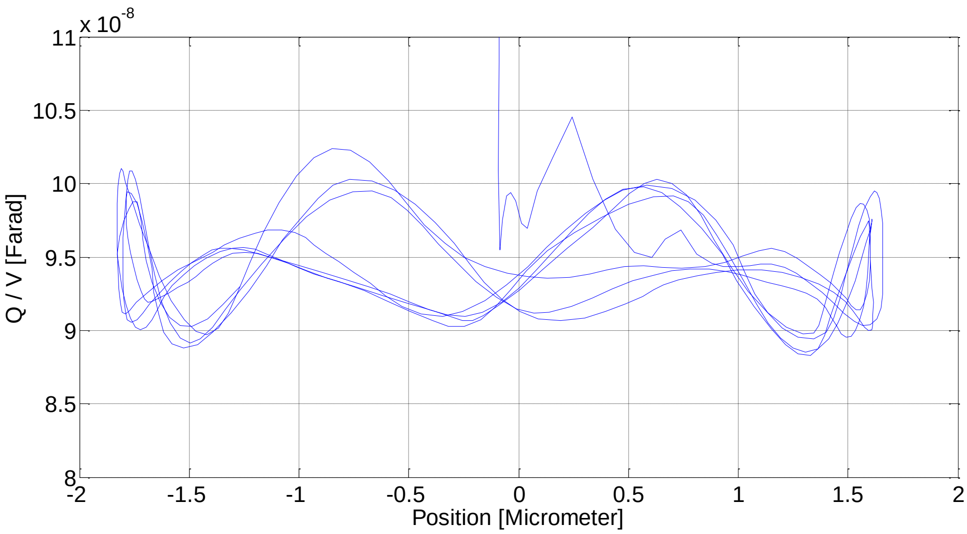

Figure 5- 22 Actuator position VS capacitance

The multiple loops in the figure are due to the fact that capacitance has a higher frequency than strain.

5.4 Sine input (50 Hz)

In this section the actuator displacement is observed at 50 Hz sine input to compare if the actuator has the same behaviour as in the previous section 5.3. Here the small signal has a frequency of 20 KHz and sampling rate is 50ksps.

Figure 5- 23 is the input signal. Figure 5- 24 is the resultant (output) voltage of the actuator. Figure 5- 25 shows the interferometer reading for the actuator position (or displacement).

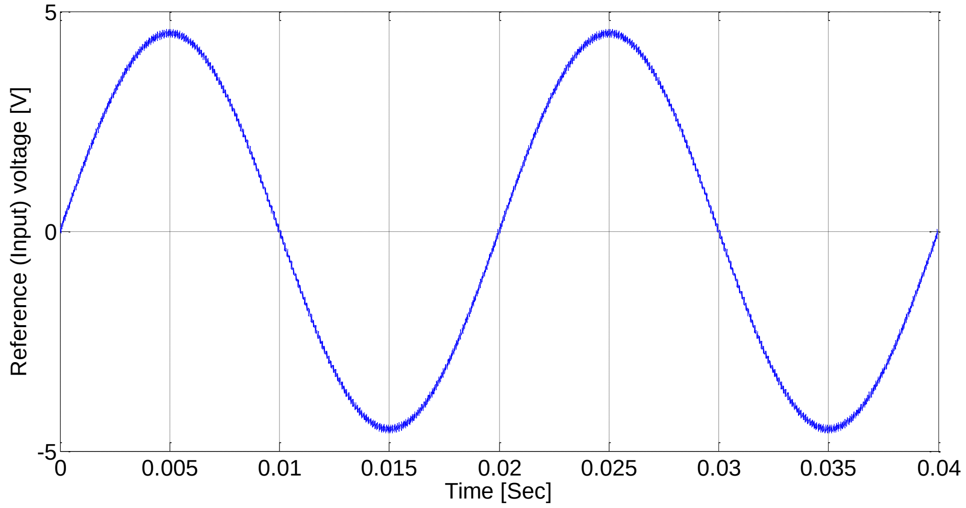

Figure 5- 23 Input signal (50 Hz sine wave)

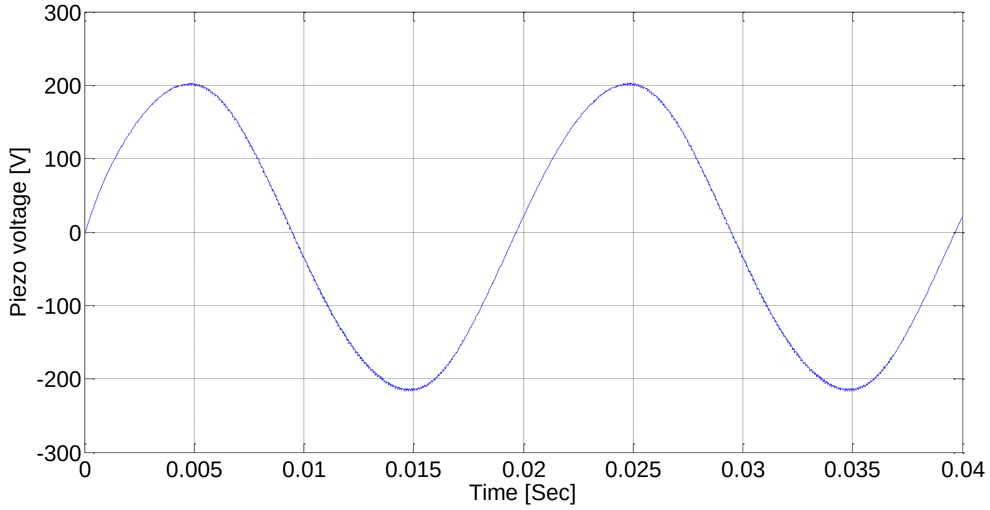

Figure 5- 24 Actuator voltage signal

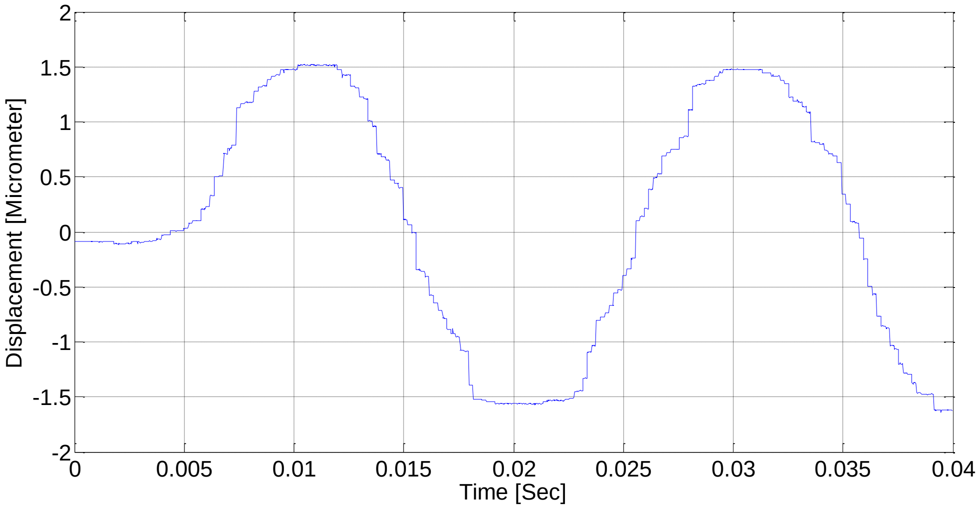

Figure 5- 25 Interferometer reading (position of the actuator)

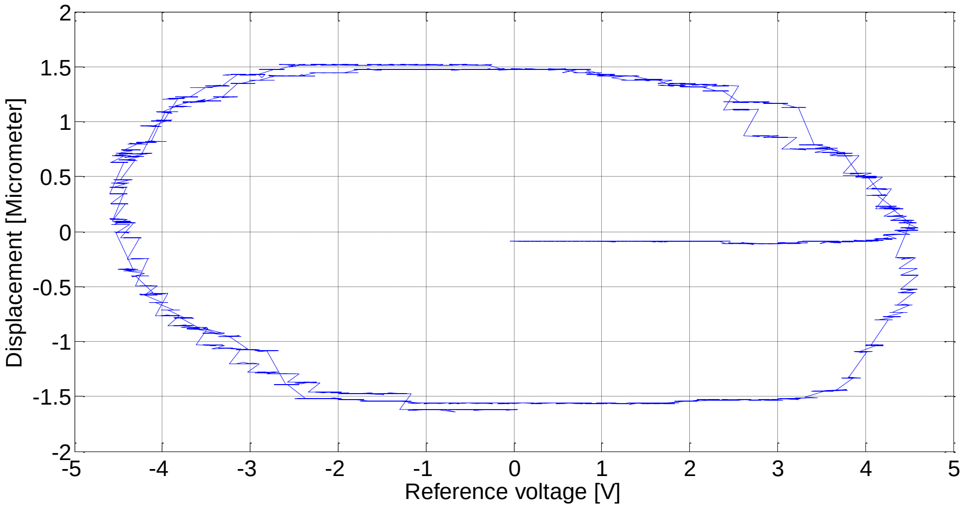

Figure 5- 26 Input (reference) voltage VS the actuator position

Figure 5- 26 is plot for the actuator position plotted against the reference (or input) voltage. Figure 5- 26 is again a nonlinear graph. But the shape is different than Figure 5- 16. This shows that:

- The phase response of the charge amplifier (PIPA) is not the same over all frequencies, which causes a phase shift in the actuator displacement at different frequencies.

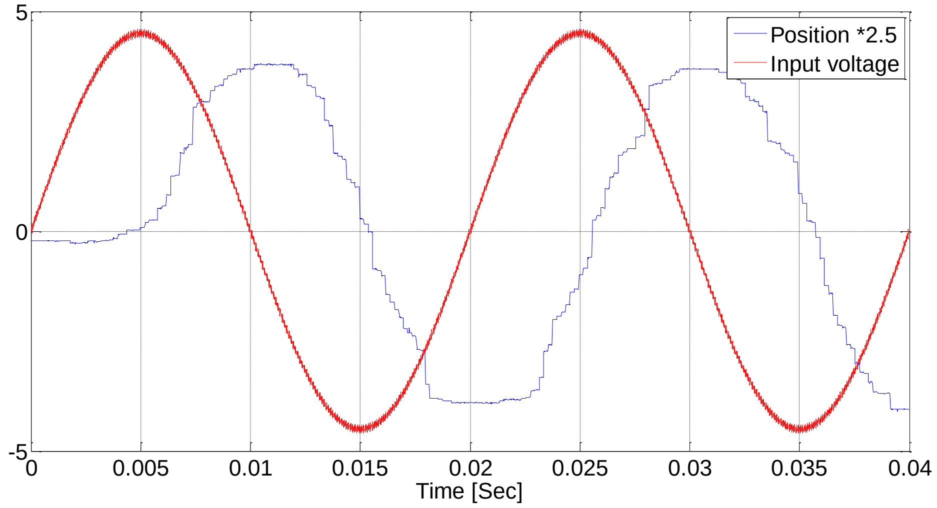

Figure 5- 27 Comparison of actuator position to input voltage

Offline analysis in Matlab shows that there is a phase difference of 275 samples. Removing the phase difference and plotting again is shown in Figure 5- 28.

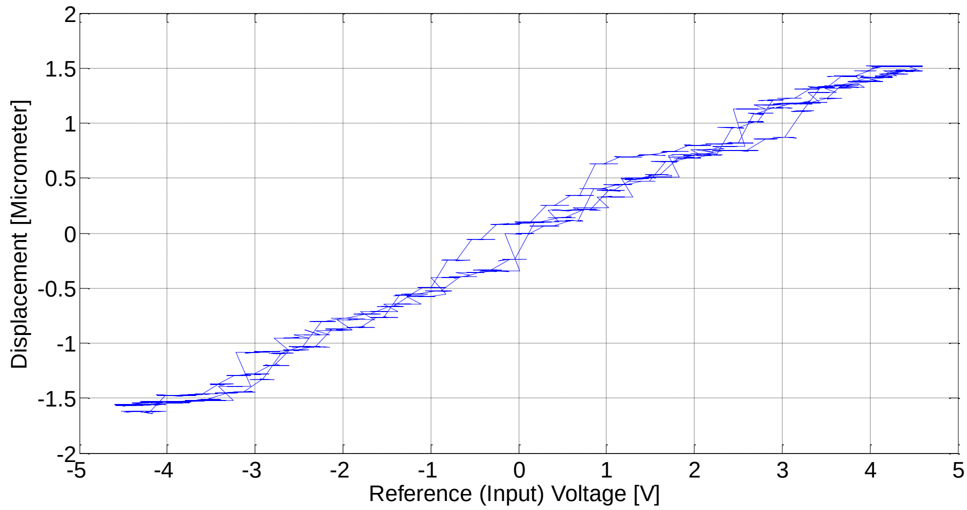

Figure 5- 28 Actuator position against input voltage, after phase correction

Figure 5- 28 shows that:

- The actuator position is a function of the input voltage as well as input frequency. The input frequency factor must be taken into account when driving the actuator legs in open loop during shuffle.

5.5 Piezoelectric actuator impedance analysis

To investigate the electrical properties of the PEA, a measurement device called bode plotter is used. It measures the gain and phase of the impedance of the actuator. Bode plotter sends a small voltage sweep signal and records the resultant current signal. Figure 5- 29 is the impedance graph of the piezo actuator on a large frequency range, obtained from the bode plotter data. The graph shows that till 30 KHz the actuator has a clean response like a capacitor or a parallel RC circuit. Figure 5- 30 shows that the impedance phase is not -90 degrees at all frequencies. For an ideal capacitor the phase is always -90 degrees.

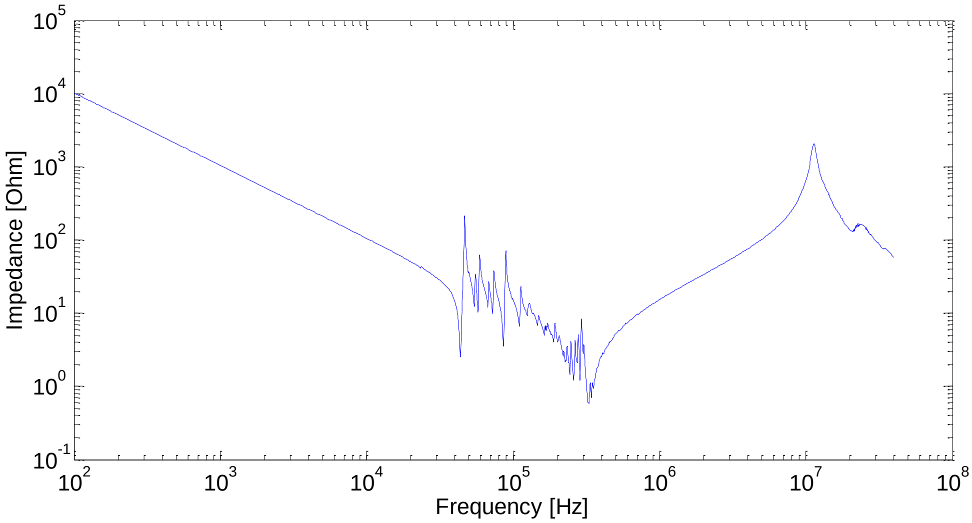

Figure 5- 29 Impedance of piezoelectric actuator

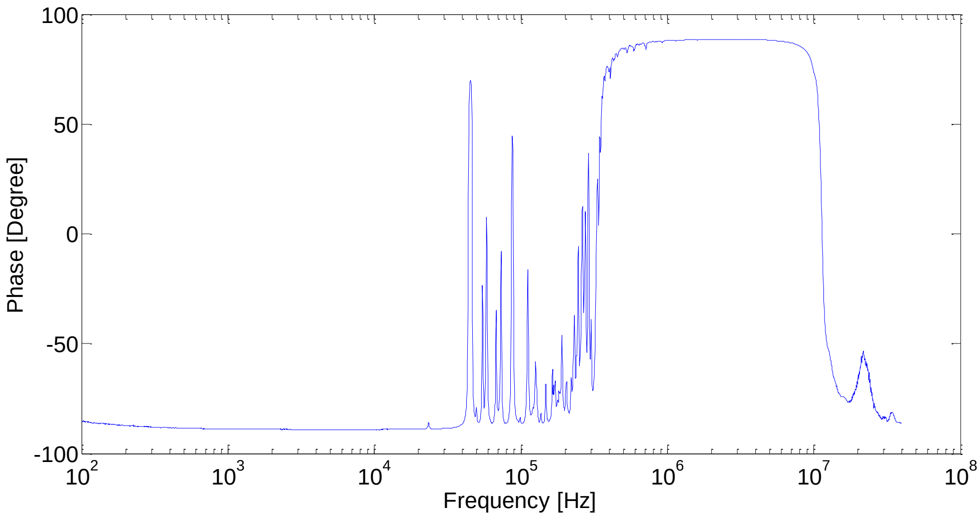

Figure 5- 30 Phase response

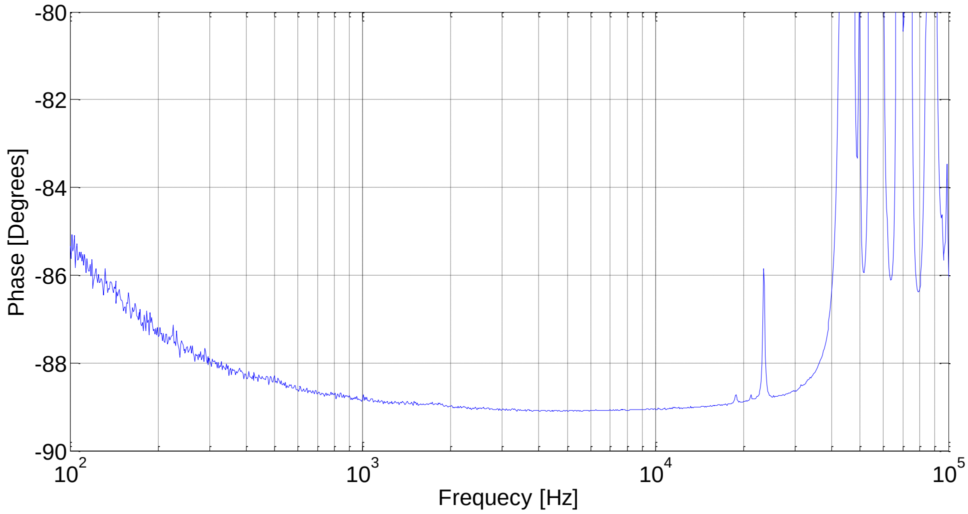

Figure 5- 31 Phase of the impedance

It can be concluded that:

- A parallel RC circuit is a better representation of the piezoelectric actuator than a pure capacitor.
- A parallel RC circuit matches the piezo response till the resonance frequency (up to 20 KHz in this case).
- Above the resonance frequency (30 KHz and above), the piezoelectric actuator has a very complex behaviour. It can be explained with RLC representation, however these frequencies are not of use as far as our application is concerned. Inductance term is ineffective in above the resonance frequencies.

5.6 Improvement suggestions / future directions

Following are some suggestions for improvements:

- Piezoelectric material has a very complex response. The elastic loss factor etc. must be considered for proper use. It was not possible to cover these equations in the given time of the thesis. Main emphasis was on the practical implementation.
- The constitutive equations, derived in chapter 2, are very simplified form of the real performance. In practice properties of the actuator changes with variations in external signal.[19]
- Current signal should be amplified on the circuit. In our measurement circuit (section 4.5.1), the current is a very small signal and the signal to noise ratio (SNR) is relatively low. It can be improved by increasing the gain of the In-amp (U6 in Figure 4 - 2). The SNR can also be improved by using a better sense resistor (with less tolerance, around 1%). In the present circuit a normal resistor is used.

- The phase shifts of the three channels (current, voltage and position) of the measurement system should be investigated further. Although they are sampled at the same time and ideally there will be no phase delay among the channels however for real time applications even a small phase shift between different channels can give erroneous results [20].
- Figure 5- 6, Figure 5- 16, Figure 5- 26 indicate that the system response is different at different frequencies. The difference in response may be due to a mismatch between the reference impedance of the charge amplifier and the actuator impedance. A feed forward block should be used in the control scheme that takes into account the transfer function of the charge amplifier.
- The starting point of this thesis is to consider the piezoelectric actuator as a pure capacitive element, however as explained in section 5.5 a parallel RC is a better representation of the actuator in the non-resonant frequencies. The R term and thus the impedance phase should be considered in calculation of the electrical properties. This should also be considered in the future design of the charge amplifier. The charge amplifier that is used here is designed for pure capacitive loads.
- Thermal expansion of the actuator is another important factor that must be considered. It acts as a disturbance in the system. In high speed applications, the actuator heats up (called as self-heat) which causes expansion and thus changes the actuator displacement. Both operation frequency and amplitude of the applied voltage contribute to the self heat generation [33][34]. Material properties such as dielectric properties, piezoelectric constants etc. are dependent on the actuator temperature.[33]. In [34] it is suggested that the peak to-peak value of the consumed current is a good indication of the temperature rise of the actuator.

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