Nonlinear Characterization of Microcantilever based Force Sensor using Nanomanipulator System

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***Abstract*—In this paper authors present development of a characterization process for Microcantilever based piezo-resistive force-sensor wherein fusion of real-time vision and force feedback has been used with a nanomanipulator (MM3A®) system. The system works with MM3A nanomanipulator, it applies definite forces in range of 10-80 μN on the force sensor and resulting deflection produces voltage which is directly measured on oscilloscope. Deflection values have been recorded using images captured by CCD camera mounted on a light microscope. The sensor characterization is carried out which considers third order nonlinear behavior in cantilever based piezo resistive force sensor output. The sensor behavior has been studied using both linear assumption and third order nonlinear system, which shows upto 20% of output is produced by nonlinearity term. Therefore it is significant contribution in the sensor, which cannot be treated negligible. The sensitivity of force sensor found out 18.79mV/μN with linear model whereas with nonlinear model, Linear and Cubic coefficients are 14.75 mV/μN and 0.681 μV/μN^3 respectively.**

***Index Terms*—Microcantilever; Nonlinear Sensor Characterization; Nanomanipulator;**

I. Introduction

Cantilever is very widely used device structure in Microsystems; its simplicity, compactness, low cost and ability to operate in different conditions such as liquids, gases, and vacuum, makes it a versatile sensor and actuator platform. It can be used as microsensor as well as actuator in variety of applications. A cantilever deflection is influenced by ambient conditions such as relative humidity, chemical vapour absorption and temperature. It possesses extremely high force sensitivity, in the piconewton (pN) range[1].

Most micro-electro-mechanical systems (MEMS) are inherently nonlinear, and the micro-scale effects and the coupled fields give rise to the complete nonlinearities in MEMS [2-4]. There exist nonlinearities arising from coupling of different domains, large deformations, surface contact, creep phenomena, time dependent masses and nonlinear damping effects[5-6].

Several approaches have been proposed to model microcantilever, most effective modeling methods includes distributed parameter and finite element modeling [7, 8]. When a sensor is being characterized its mathematical parameters are evaluated that fit a particular modeling scheme. Cantilever system can be represented by linear equation or by nonlinear relationships. Considering a system, its linear behavior remains linear only in very limited range of operations [9] with assumptions that it is operated near equilibrium point with small range of input. However, there are exceptions to it and system shows nonlinear dynamic behavior which can lead to chaotic behavior as well.

Chaotic behavior has been reported in many physical systems including MEMS cantilevers. A classical example of a chaotic system is the Lorenz equations [10]. Chaos due to various mechanisms has also been reported for nonlinear MEMS oscillators [11, 12, 13], microcantilevers for atomic force microscopy [14]-[18], an electrostatically actuated MEMS cantilever control system.

Cantilever characterization process reveals parameters that govern its behavior under different input conditions. Considering that in a working system which has cantilever as a component - sensor or actuator, its overall dynamic behavior would be affected by nonlinearities present in it. To create a predictable and safe system design using cantilever as a component one has to find parameters which govern its nonlinear dynamic behavior in the system. Therefore, sensor characterization revealing nonlinear parameters is important first step before one can use it safely with predictable behavior as a part of the system.

In this paper, nonlinear characterization process is presented which uses nanomanipulators to apply small force, a CCD camera mounted on a light microscope to get high resolution images, and force feedback information on oscilloscope to characterize a cantilever based piezo resistive force sensor. The deflection of a standard micro spring provides applied force data, sensor output is measured on oscilloscope as voltage signal, and experimental data is fitted using MATLAB to find nonlinear parameters of cantilever. Section-II describes mathematical model of the sensor system, Section -III experimental setup and characterization process steps, section-IV for experiments carried out, section-V results and discussion, and section-VI conclusion.

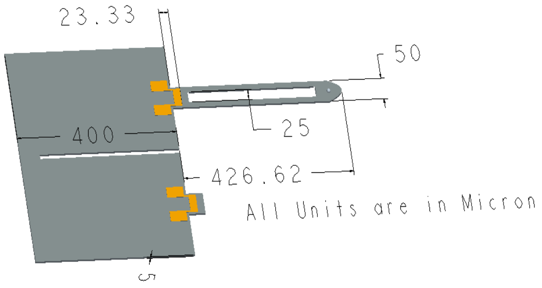


Fig. 1. Cantilever Drawing

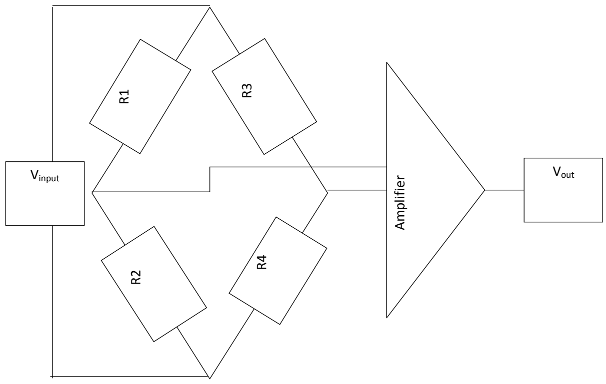


Fig. 2. Sensing Bridge Circuit

II. Mathematical Model of Cantilever based Piezo Resistive Force Sensor

Microcantilever based piezo resistive force sensor is a device which produces sensed value output following static and dynamic deflection properties of a MEMS cantilever. It has been additionally put with a layer of piezo material which converts mechanical parameter e.g. stress into electrical signal (Figure 1). Through standard signal processing techniques, e.g. unbalanced Wheatstone bridge, followed by amplifier and general signal processing, a desired sensor output is obtained. Mathematical relationship, to study a cantilever system, can be obtained by using a spring-mass-damper system model. A cantilever system's equations of motion is given below

$$\mathrm{m}\ddot{x} + \mathrm{b}\dot{x} + \kappa_1 \mathrm{x} + \kappa_2 \mathrm{x}^3 = \mathrm{F}_{external}$$

Where 'm' is mass and 'b' is damping present in the system; κ_1 and κ_2 represents linear and cubic nonlinear stiffness terms, respectively.

The sensor output is obtained by unbalanced Wheatstone bridge method which produces output due to change in resistance in one of the arm (Figure 2). As shown in figure below R_3 and R_4 are piezo resistance of which R_3 changes when there is applied force on sensor this creates unbalance condition and bridge output is amplified to get final reading from the sensor. The output sensitivity of bridge with respect to change in resistance is given in equation below.

$$\mathrm{dV}_o/\mathrm{dR}_3 = -\mathrm{V}_{in}\mathrm{R}_4/(1+\mathrm{R}_3/\mathrm{R}_4)^2$$

It is to be noted that nonlinearity in sensed output not only arises due to mechanical cubic stiffness coefficient of the cantilever structure but also due to bridge and amplifier stages, additionally noise is ever present.

III. Experimental Set up and Characterization Procedure

The Nanomanipulator system used herein is MM3A based Kleindiek micro/nano assembly and characterization set up. The setup consists of nano robots with nanoelectronic controls which can operate under a light microscope or a SEM (Scanning Electron Microscope). These manipulators have joint configuration as RRP (revolute-revolute-prismatic), these utilizes two rotational joints with 0.1 μrad resolution and one prismatic joint with 0.25 nm resolution. These Nanomanipulators have well-behaved kinematic and backlash-free characteristics besides having nano scale precision to guarantee accurate manipulation. The accuracy of manipulator's tip control under a light microscope is in fraction of μm whereas under a SEM, it is in nm.

The experimental set up has been described below; it is shown in block diagram form in Figure 3. It consists of a MM3A Manipulator which has been attached with a Microcantilever based force sensor at its gripper/tip position. To create experimental values of force-deflection interaction, there is a micro spring placed next to it. Using MM3A controls the manipulator can interact with objects in its work space at micro and nano scale. Once its tip comes in contact with object it produces a feedback signal response proportional to force exerted, this is due to piezo resistive layer on force sensor's surface. The force feedback signal is amplified and converted as audio output to sharply notice the first contact between the object and manipulator tip. The manipulator tip and cantilever spring interaction is viewed on a computer screen in high resolution using a light microscope and CCD camera; these images show deflections in micron/submicron.

The actual photographs of Manipulator, Complete setup, Cantilever spring, and Force Sensor is shown in Figure 4.

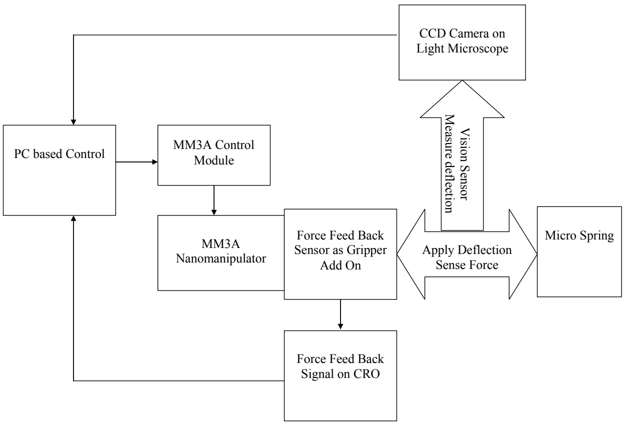


Fig. 3. Block Diagram of Complete Setup

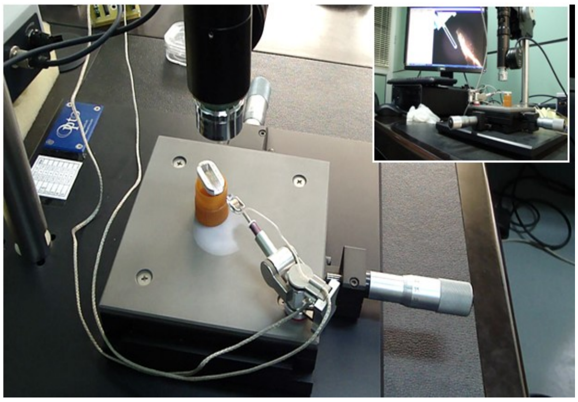


Fig. 4. Experimental Setup Photographs

To characterize a force sensor, the steps are as follows;

- On screen distance calibration
- Contact point detection
- Reference image
- Application of controlled force in steps
- At each step acquire a Deflected image and Voltage value

In reference to above steps the following image in Figure 5 is for on screen distance calibration; Similarly, images have been recorded for contact point detection, reference point and at various deflection points. During the on screen distance calibration 377 pixels are equivalent to 100 μm which corresponds to 0.2652 μm resolution for each image point.The known distance is moved by external micromotion bench on

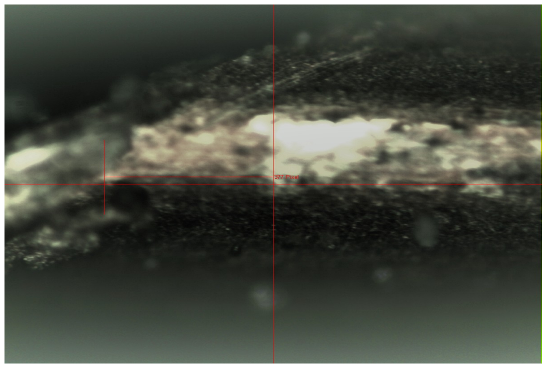


Fig. 5. Calibrating Distance

which the system is placed and pixels value to corresponding movement is measured on image.

IV. Microforce Sensor Characterization Experiments

The following are sample images (Figure 6, 7, 8, and 9) at different deflection values which produce different amount of force that serve input to the sensor for which the output reading of electrical signal have been tabulated below in Table I. Multiple reference points have been marked to suppress measurement errors in computing deflection. Relatively large force and deflection values have been put in experiments to bring out nonlinear effects prominently.Average force data is calculated by finding deflection average, computed from multiple readings on image and multiplying it by known spring constant value 8.75 μN/μm. Initially, when user does not provide deflection force even then there is some voltage signal present, this is due to presence of external acoustic and electrical noise.

	X_1 (μm)	X_2 (μm)	F_{mean} (μN)	V_{output} (mV)
1	12.202	24.401	0	5.6
2	14.061	26.26	16.26625	70
3	14.856	26.527	20.9125	140
4	16.446	28.383	35.98875	400
5	17.241	30.24	47.59125	740
6	19.1	31.301	60.36625	1040
7	20.957	33.687	78.92938	1350

TABLE I
X_1 AND X_2:REFERENCE POINT DISTANCES, F_{mean}:AVERAGE FORCE, AND V_{output}:OUTPUT VOLTAGE

V. Results and Discussion

Table I data is fitted with linear as well as nonlinear model of cantilever system. A cantilever is represented by F = k_1X + k_2X^3, Whenever approximation to linear behavior is needed the cubic stiffness term is omitted. The following

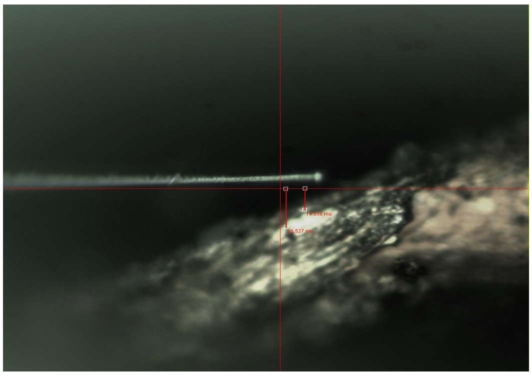


Fig. 6. Measurement Step 1

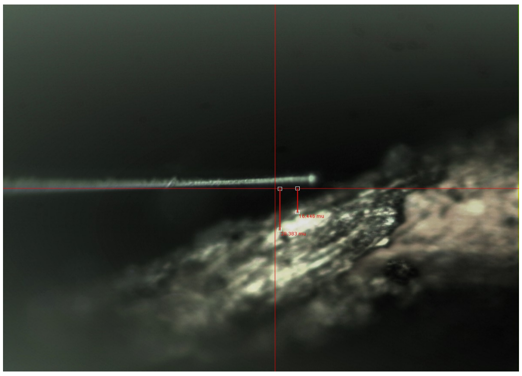


Fig. 7. Measurement Step 2

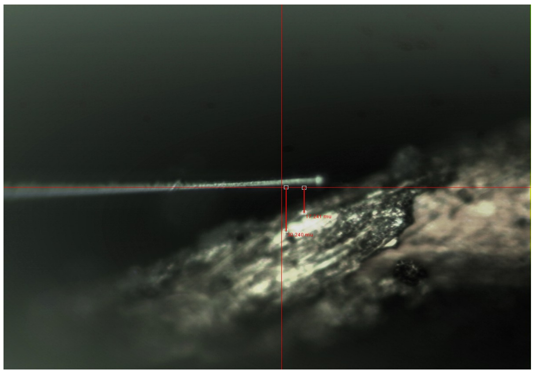


Fig. 8. Measurement Step 3

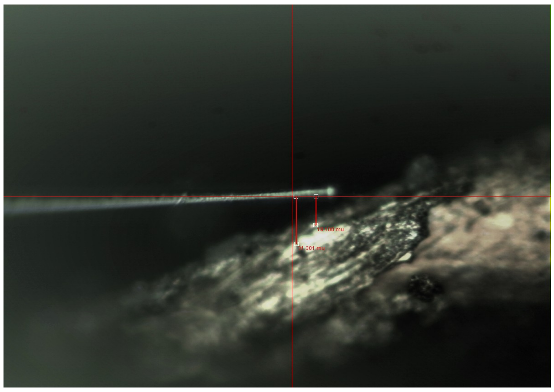


Fig. 9. Measurement Step 4

data fit results equation are found using MATLAB and shown in Figure 10. It is clear that goodness of fit is better in nonlinear model as it brings it close to reality. The actual fitting equation is $F = k_1X + k_2X^3 + k_3$, Where k_3 constant term is kept as there are other sources of noise adding to output and unaccounted nonlinearity due to circuit elements e.g. at zero input force there is output voltage shown by the Sensor. Therefore, the additional constant term is kept to absorb these. More analysis on it shall produce better characterization results.

$F = 18.79\ X - 163.7$ ($R^2 = 0.9643$)
$F = 14.75\ X + 0.6816 \times 10^{-3} X^3 - 99.47$ ($R^2 = 0.9748$)

The fitting results have been analyzed wherein it is clearly visible in figure 11 that nonlinear term contribution goes as high as 20% when deflections are large. On average it is 10% share in output value, therefore, its significance is high.

VI. Conclusion

The Nanomanipulator system used herein is capable of experimentally characterizing microcantilever based piezoresistive force sensor with accuracy. The sensor has been characterized for nonlinear parameter evalution which is very important for nonlinear dynamic behavior prediction. Nonlinearity plays significant role when larger deflections appear therefore it cannot be ignored in system design. There are other unaccounted sources of nonlinearity and noise in measurement system for which additional constant term appears in the fitting model. The characterization system's accuracy depends on several system parts i.e. vision resolution, accuracy of electrical signal measurement, standardized spring quality, and reduced environment noise and vibration acoustic as well as electrical.

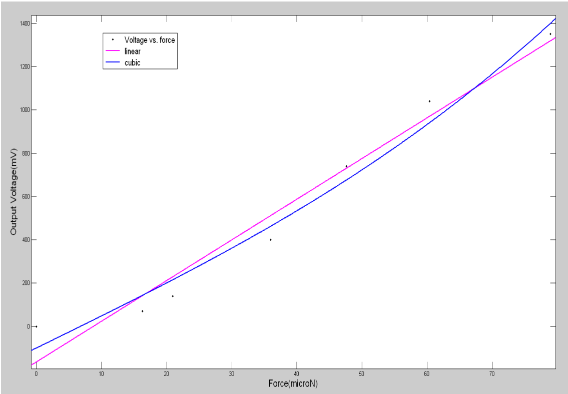
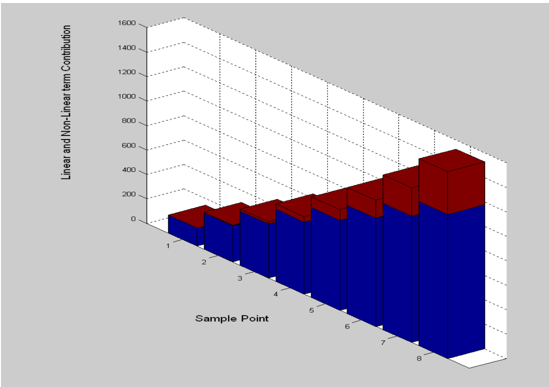
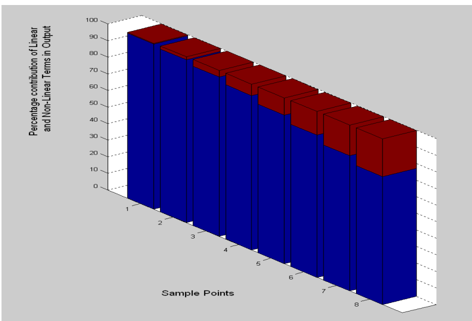


Fig. 10. linear and nonlinear fit on experimental data F_{mean} vs. V_{output}



(a) Absolute Value Share



(b) Percentage Share

Fig. 11. Linear and Nonlinear Term Share in Sensor Output

ACKNOWLEDGMENT

The Authors would like to thank C.S.I.R. for funding the Research Program under Network Project, NWP-30 and C.E.E.R.I.,Pilani for creating supporting facilities for the Project. Authors also wish to thank Dr. P. Bhanu Prasad, Mr. Amit Tholia, Mr. Govindram and Mr. Talebar Singh for their support towards this Project.

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