Leveraging Performance Parameters in Predictive Design Evolution of MEMS

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***Abstract*: - Modern era is witnessing a boom of IT Enabled Services that is converting the world flatter into non-linear functional dimension. Micro-Electro-Mechanical Systems (MEMS), Nano Technology and Genetic Engineering have revolutionised today's industry. MEMS is an integration of mechanical systems, sensors, actuators and electronics all on a common silicon substrate. MEMS development is recursive in nature, which involves various design and testing cycles until design parameters are met. This would prove to be very expensive but for the predictive design techniques that are applied now a days. The paper discusses two design techniques for the prediction of sensor parameters and how they have been leveraged to achieve flexibility in design evolution of MEMS devices. Employment of such techniques will help MEMS designers optimising design parameters.**

***Keywords:* MEMS Accelerometer, Predictive design, Flexible Design, Add-Mass technique, Stress concentration region technique.**

I. INTRODUCTION

This paper gives Techno-Managerial outlook in predictive design evolution of Micro-Electromechanical Systems (MEMS). The predictive design can help development of complex systems at reduced cost and time to- market. MEMS are the systems that having moving parts that are physically small in the dimensions ranging from microns to millimetres. MEMS is one enabling technology that is invading into all the applications right from automobile, medical, consumer products to weapon systems. These are the systems consisting of sensing element,processing block and the actuation mechanism all housed in a single chip. These are constructed on a silicon substrate using one of the batch fabrication technique used for integrated Circuits (IC). Therefore design of a sensor system based on MEMS technology is the matter of complex processing involving a large number of steps and large number of variables. This MEMS development is recursive in nature, which involves design, fabrication, testing and modification of the design so as to ensure that system meets the specified requirements. Simulation techniques when employed during early design phase could be used to predict the sensor behaviour and sensor parameters. This study on prediction would reduce foundry runs and time-consuming test set-ups. Therefore, modelling and simulation techniques are very important in design and development process. Predictive design makes extensive use of mathematical modeling and statistical analysis tools & techniques to introduce variants in the design at key points throughout the process of design and manufacturing. The Figure 1, below shows where predictive design is embedded in a conventional design process.(Willoughby, The Gen, Spring 2008).

Figure 1.Stagesinpredictivedesign

Mathematical modeling & simulation tools are employed as integral part of the predictive design offer. It allows for the design of 'virtual' products, which can then be 'tested' mathematically to determine the nature, predict functional parameters and likelihood of product failure. This paper discusses the prediction techniques and methodology applied to leverage the performance parameters in design evolution of an MEMS Piezoresistive Acceleration sensor. The development of piezoresistive accelerometer for the shock and vibration measurement was first attempted in 1962. MEMS accelerometers began to be commercially available by 1970s. Single chip MEMS accelerometers integrated with electronic circuitry offering full-scale output signal in the range 3 to 5 volts and packaged in a hermetically sealed housing are available since last decade (Patrik 1999). Accelerometer is a type of inertial sensor that finds real-time applications in guidance, navigation, control and actuation. The specific usage is in military and aerospace / aviation systems, direct and indirect fire systems for weapons, missiles, rockets, projectiles, sub-munitions, and smart weapon systems, in commercial systems such as air-bag actuation for sensing impact and in some consumer electronic applications, such as video-camera stabilization, virtual reality, inertial mouse for computers; robotics applications etc. Due to their wide and dominant applications in critical military and commercial systems, the researchers have been consistently striving to achieve improved performance of inertial sensors by exploiting the state of the art technologies since the dawn of inertial sensing in 1979 when Roylance et. al. reported first micromachined acceleration sensor (Roylance & Angell 1979).

II. IMPORTANCE OF PREDICTION USING SIMULATION IN DESIGN OF MEMS

Design of a sensor based on MEMS technology, is the matter of complex processing involving a large number of steps. This development is recursive in nature, which involves design, fabrication, testing and modification of the design so as to ensure that system meets the specified requirements. It could turn out to be very costly as far as fabrication is concerned due to its recursive/ iterative nature. This is where the computer modelling can help us in not only reducing recursive steps but also in reducing the design time. Figure 2 depicts the typical design cycle for MEMS sensors (Fedder 1996). Simulation techniques when employed during early design phase would reduce foundry runs and time-consuming test set-ups. Therefore modelling and simulation techniques are very important in design and development process.

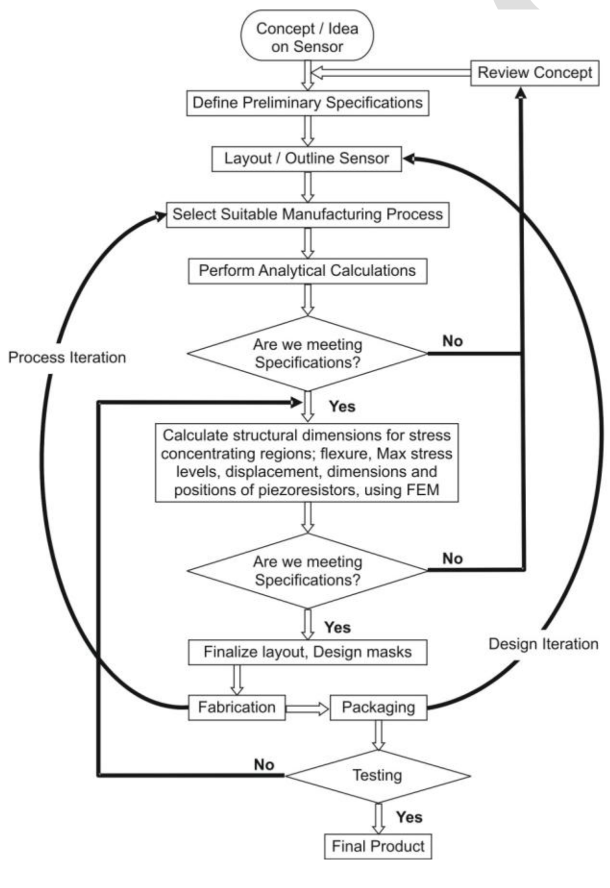

Figure 2. MEMS Design Processes Flowchart

Development of MEMS based products requires simulation of not only multiphysics and device-level behavior but also on fabrication process steps and packaging effects (Joshi 2009). CoventorWare and Intelli-Suit are the fully integrated simulation tools that offer a comprehensive methodology for MEMS design. These software provide MEMS specific material properties, tools for analyzing anisotropic behavior, fabrication residual stresses, temperature dependence, piezo-electric and piezoresistive coefficients etc. In addition, these software have 3-D Finite-element and boundary-element solvers to simulate detailed multi-physics, devicelevel analysis including coupled electromechanics, electro-thermo- mechanics, piezoelectricity, piezo-resistivity, compressible squeeze-film damping effects etc.

III. FLEXIBLE DESIGN-SYNTHESIS OF ACCELERATION SENSOR

Piezorestive acceleration sensor is basically a cantilever structure in micron dimensions. The important aspect of cantilever type of accelerometer is that the measured value of acceleration depends on the deflection and the mechanical resonant frequency but not on the spring constant. This has an implication on the scaling of accelerometers. A cantilever type piezoresistive acceleration sensor is modelled and simulated for structural and geometrical parameters using simulation tool called *Coventorware*. The design concept is realised
using MEMS-CAD, through design of 2D layout masks first and further through 3D model building using the software process akin to fabrication procedure. This is followed by performance analysis using Numerical Analysis (NA) tools for-

- Mechanical stress analysis: for the measurement of solid and surface stresses generated in the flexure.
- Modal analysis: for the measurement of structure's first resonant frequency.
- Piezoresistive analysis: for the conversion of the surface stresses generated on the flexure in terms of electrical output.
- Transient analysis: for studying system response to the excitations of aperiodic nature like shock pulse or a transient excitation.
- Inertia MEMS analysis: for getting structural information such as moment of inertia, centre of gravity, generalized mass etc.
- Simulation manager: for optimizing the structure's dimensions viz. width, thickness and length on the particular created model.

The above NA tools are used to predict the sensor behaviour, performance parameters. The predictions are compared with results also obtained from analytical calculations using theory of mechanics. Prediction of Important design parameters such as sensitivity, natural frequency, range, resolution, fracture strength, deflection, Centre of Gravity (C.G.) and crosssensitivity are carried out using simulation tool and design synthesis. The sensor dimensions are decided based on predictions made for design parameters.

The two most important performance parameters of a sensor are *Sensitivity and Bandwidth*. Sensitivity can be defined as amount of variation in output due change in input. The important concept of sensitivity is that it relates input resolution to output resolution. A sensor with high sensitivity has good input resolution and the one with low sensitivity has poor input resolution. The bandwidth is defined by lower and upper limit of frequency. The mechanical response of a cantilever is attenuated above its resonance; therefore the maximum measurement bandwidth for a cantilever is usually set by its resonant frequency (Chen 2003, Bao 2000).

Performance Improvement is a topic of research for inertial sensors such as accelerometers because of their wide and dominant applications in the critical military and commercial systems. In military applications, higher performance is needed for accelerometers because of limited number of measurements, single shot operability, strap down or permanent integration in the system and the high cost of the system under tests. In view of the above, design and process development for realization of high sensitivity, high bandwidth, low cost and batch producible bulk micromachined inertial sensors has been an interesting and challenging research problem which has merited focused attention for the investigation under the present study. The objective to optimize the sensitivity and mechanical bandwidth of the sensor in tandem had been a challenging task due to contradictory phasing of both these parameters. The optimization of these two parameters is achieved by way of maximizing their product, which we termed as Performance factor (or *P-Factor*). Leveraging the performance factors for MEMS accelerometers was possible only through predictive design evolution. MEMS-CAD from Coventorware is used to model and simulate the cantilever type of piezoresistive acceleration sensor. In the present work, Finite Element Analysis (FEA) of the sensor models are carried out using *Mem-Mech* and *Mem-Pzr* solvers in Coventorware. This is followed by performance analysis of the model using numerical analysis tools. Mechanical stress analysis is carried out for the measurement of solid and surface stresses generated in the flexure. Modal analysis is carried out for the measurement of structure's first resonant frequency.

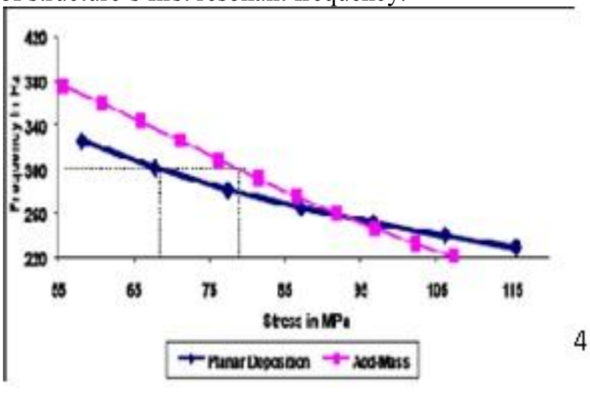

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Figure 3: Performance comparison between Planar deposition and Add-Mass Structure

Piezoresistive analysis is carried out for the conversion of the surface stresses on the flexure in terms of electrical output. Transient analysis is carried out for studying system response to the excitations of aperiodic nature like shock pulse or a transient excitation. Simulations were carried out by varying dimensional parameters of Flexure (cantilever) and *Proof-Mass* to predict sensitivity, Bandwidth, cross-sensitivity etc of the sensor. In order to enhance sensitivity of the sensor with due consideration to its mechanical bandwidth, two new techniques are developed. The first technique involves placement of *Add-Mass* (a high-density concentrated mass) at a particular location on the *Proof-Mass* to decide the C.G. of the structure and in turn choose sensitivity and bandwidth of the sensor in a controlled manner. It is observed from the Figure. 3 that we get better sensitivity for a chosen bandwidth above 250 Hz in case of structure with *Add-Mass*. For example, if a sensor is to be designed for a particular bandwidth say, 300 Hz, the stress value that we get for planar deposition of 10µm, is 67 Mpa. Whereas, in the case of *Add-Mass* placed at about 1500µm from fixed end for the same bandwidth we get a much higher stress value of the order of 79 Mpa. This indicates that we get better sensitivity-bandwidth product for the structure with *Add-Mass* compared to the structure with planar deposition (Joshi 2007). The second technique that was evolved entails judicious introduction of discontinuities to form Stress Concentration Regions (SCR) on the flexure which enhances sensitivity of the sensor by many folds. SCR is with partial etching up to half the thickness of the flexure.

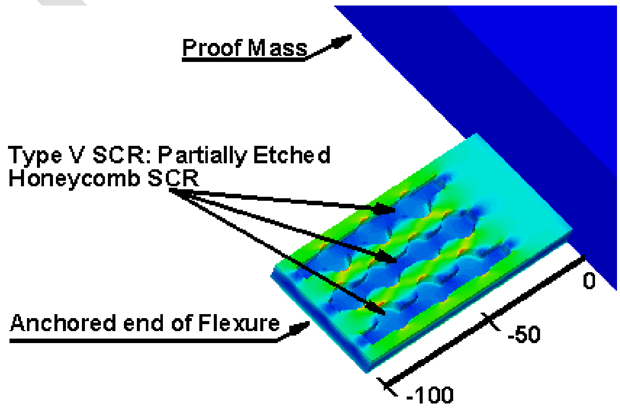

Fig4(a)

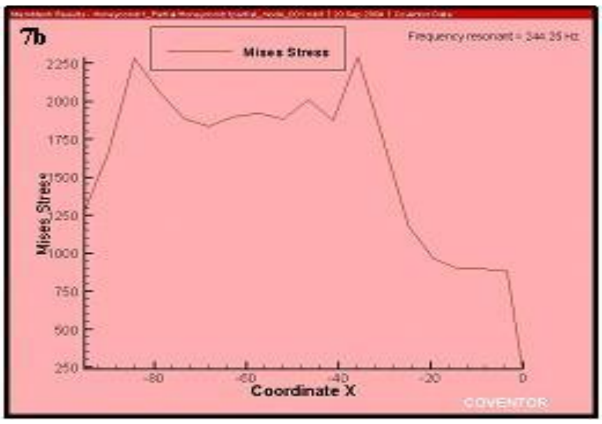

Fig4 (b)

Fig. 4(a) shows the stress concentration regions and the von-mises stress along the flexure length is plotted in *Fig.* 4*(b)*.

In this case stress amplification obtained is better than completely etched SCR while maintaining better mechanical bandwidth. Thus considerable stress amplification with marginal reduction in resonant frequency is achieved by creation of SCR with partially etching up to certain depth on the flexure.

IV. DISCUSSION

The design of MEMS accelerometer using the MEMS-CAD as a tool for prediction of its parameters is discussed above. The CAD/CAE tools are utilised to predict the sensor behaviour and predict the sensor parameters such as sensitivity and bandwidth. Investigations on the design optimization for piezoresistive acceleration sensor in respect of optimization of sensitivity and bandwidth has been used to evolve two novel techniques called *Add-Mass* and *SCR* to improve and optimize sensor performance. The *Add-Mass* technique helps to choose optimum sensitivity for the chosen bandwidth and vice versa. The *SCR* technique enhances sensor sensitivity by a factor 2.6 (Joshi 2007). The advantages of using the prediction techniques, discussed above, give a direct benefit to the MEMS fabricator to reduce the costly foundry runs. In addition it also adds flexibility in MEMS design with benefits such as –

- Enabling technology platform changes with minimal effect on business process.
- Enabling business process changes with minimum effect on technology platforms.
- Enabling modular systems design library for quick system modification

The leveraging achieved here in predicting performance parameters gives flexibility to the fabricator to use the most optimum technology platform to fabricate the device. The achievement of optimum parameter through prediction gives flexibility to the business process with reduced or minimum changes in the technology platform. In both the above discussed optimization techniques, large number of modular designs were created to reach the most optimum parameters. Therefore, one can create a modular design library for quick modification of system. This is the impact of predictive design methodology in obtaining flexibility in design of MEMS devices.

V. CONCLUSIONS

The presented work contributes to the flexibility in design of Micro-accelerometer sensor from engineering point of view. Micro- Electro-Mechanical Systems (MEMS), Nano Technology and Genetic engineering have revolutionised the Multi National Companies and other industries. MEMS is one enabling technology that is invading into all the applications right from automobile, medical, consumer products to weapon systems. These are the systems consisting of sensing element, processing block and the actuation mechanism all housed in a single chip. This MEMS development is recursive in nature, which involves design, fabrication, testing and modification of the design so as to ensure that system meets the specified requirements. The simulation techniques are used to predict various sensor design parameters to help reduce foundry runs. The prediction of sensor behavior is presented in this paper. The prediction technique is used evolve a better design of sensor with improved performance.

The prediction techniques are also used to evolve new sensor structures. The technique was used to device two new techniques of optimizing the two most important sensor parameters. The techniques discussed in this paper would enable the sensor designer community to gather how to leverage these techniques to develop a high performance MEMS sensor. The flexibility in design of MEMS devices is achieved by use of these prediction techniques in choice of technology platforms, minimal changes in business processes and also builds up design libraries to quickly modify the system design.

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BIOGRAPHY

Dr. BP Joshi is a BE (Hons.) in Electrical Electronics Engineering from BITS, Pilani, India, ME (Mech.) in Guided Missiles and Doctorate in MEMS technology from Pune University, India. He also has Diploma in Business Management and Master of Management Sciences degree in Finance. He has 25 years of experience in design and development of critical mechatronics systems for variety of armaments and weapon systems.

He has worked as a Group Director at ARDE, a leading establishment of DRDO, Ministry of Defence; handling variety of projects for defence R&D. He has more than 21 publications. He is life Member of many professional bodies such Fellow IE, Fellow IETE, ISSS, IDST, Vijnan Bharati.