Journal of Pure Applied and Industrial Physics, *Vol.10(6),7-15, June 2020*
(An International Research Journal), *www.physics-journal.org*

ISSN 2229-7596 (Print)
ISSN 2319-7617 (Online)

Aerospace MEMS Pressure Transducer Packaging Techniques to Withstand Surge Pressure and Radiation

R Narayan[1 *], Karthikeyan L[1], Aisha Sidhick SM[1], M V N Prasad[2] and G L Shekar[3]

[1]Liquid Propulsion Systems Centre, ISRO, 80 Feet Road,
HAL 2nd Stage, Bangalore, Karnataka-560008, INDIA.
[2]Rtd Group Director-SRDG, Liquid Propulsion Systems Centre, ISRO, 80 Feet Road,
HAL 2nd stage, Bangalore, Karnataka-560008, INDIA.
3National Institute of engineering, Mysore, Karnataka, INDIA.
email: 1*narkal@gmail.com

(Received on: June 27, 2019)

ABSTRACT

In the field of aerospace engineering pressure measurement is playing a vital role in terms of health monitoring of the system and control application. MEMS technology based pressure sensors are extremely appealing for optimizing the size and mass of aerospace system sensors with improvement in their functional performance. In view of the harsh and remote environment of aerospace application, reliability and repeatability are the crucial issues that are holding back MEMS from playing a larger role in space applications. The presently used sensors for pressure measurement have limitations concerning sensitivity, accuracy and long-term stability. The aerospace application involving MEMS based pressure sensors is of particular interest in this study and analysis. However, it has several challenges namely viz., efficient packaging, interface, immunity to radiation and tolerances on assembly and final testing and evaluation. These sensors have to work under harsh and volatile environments, which demands utmost reliability, and long-term performance stability.

In launch vehicle and ground testing of propulsion systems application, the performance of this pressure sensors is very critical to analyse with respect to performance of the vehicle and its subsystems. Hence, the design and packaging of MEMS transducers have to be done in such a way that it has to withstand all the fight against the environmental conditions. In this article, the impact of surge pressure and radiation effects on MEMS pressure transducer along with the design improvement techniques are presented.

Keywords: *MEMS, Pressure sensing, Harsh environment, Surge pressure*.

1. INTRODUCTION

MEMS based pressure sensors are proposed to be used in place of bonded foil strain gauge-based pressure sensors for pressure measurement in launch vehicle, ground testing of engines and spacecraft applications. The sensors are expected to function under harsh and volatile environments there by demanding utmost reliability and long term performance stability (as high as12-15 years in orbit for satellite application).

MEMS based piezo resistive pressure sensors have the sensing element (Piezo resistors implanted on silicon) filled with silicone oil and isolated with Stainless steel metal diaphragm and are packaged in a stainless-steel housing[1-2]. To determine the reliability of MEMS sensors, a rigorous physics-based approach must be followed. Root cause for all failure modes must be understood. The test plan to reveal those failure modes either by applying dynamic conditions or environmental conditions that could accelerate failures to be prepared. Failure modes of MEMS based pressure sensors with built in electronic devices can be categorized in to Mechanical Failure Modes and Electrical Failure Modes.

During inflight operation of propulsion systems, the system is subjected to pressure surge due to actuation of pyro valve, which leads to water hammer effect in the feed systems. Further during ground testing of engines and simultaneous operation of valves pressure surge will occur due to instability during engine operation or during opening of valves in the ground test console[3-4]. Water hammer is a phenomenon leading to sudden increase in fluid pressure, which results in pressure waves which travels along the pipe at sonic velocities. In the presence of pressure waves, it causes dynamic stresses in feed lines and in pressure transducers, which may lead to failure of feedlines or components (valves, pressure transducers). The phenomena of water hammer and its impact on the systems has been understood using references[4-10]. Water hammer pressure transient produces large dynamic forces in the feed system which can damage diaphragms of the pressure transducers.

Therefore, it has to be considered while designing and analyzing a propulsion system. The surge pressure can occur on actuation of normally closed pyro valves as shown in Fig.1.0. which is a generalized schematic of one type of liquid Bi-Propellant propulsion /reaction control system (RCS) for satellite and launch vehicle application.

The successful deployment of microelectronics into space systems requires the microelectronic components to remain functional over the mission lifetime (12 to 15 years) in the harsh environment of space.

Microelectronic devices are susceptible to radiation damage. Most MEMS devices are radiation hard by default. Failure may occur at a very high dose due to the accumulation of charges in dielectric layers. The resistance value of the piezo resistive sensors tends to increase[11-12]. The electronic ICs, which are of concern, need to be shielded by effective packaging techniques or built in with radiation hardened design and components.

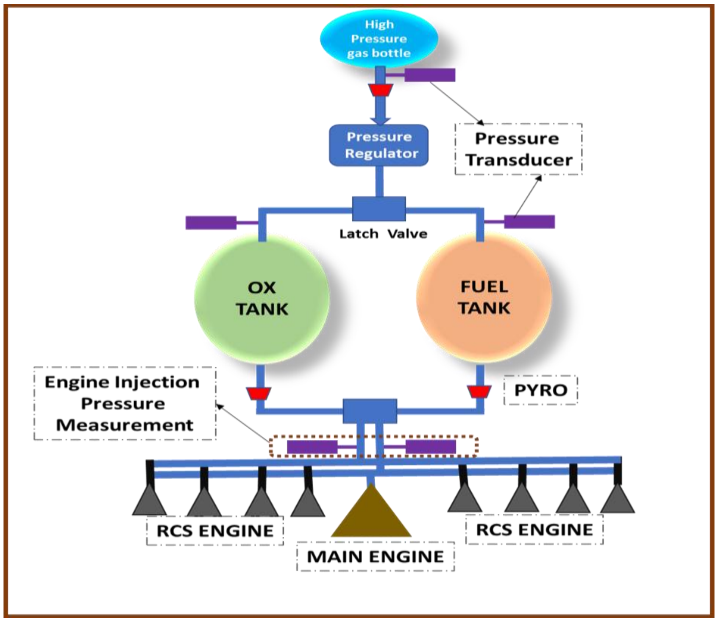

Figure 1.0 Typical Propulsion systems

In the present work MEMS based pressure transducers with inbuilt signal conditioning circuit was successfully packaged and studies were carried out about the surge pressure (water hammer effect) using shock tube techniques for the throttling engine ground testing application, the transducers developed for satellite application was subjected to gamma radiation test. The transducer performance was characterized before and after the test and design modifications were also carried out.

2. EXPERIMENTAL EVALUATION

2.1 Realization of Mems Pressure Transducer

Realization of MEMS based sensor involves both mechanical and electrical design as shown in fig 2.0. Electrical design requirements is to amplify the differential output from the sensor, compensating for temperature effect and to protect the signal conditioner from Electromagnetic interferences & radiation[11].

In this work two versions of 20 Bar MEMS based pressure transducers were developed for engine injection pressure measurement application. A highly sensitive piezoresistive silicon chip is used for pressure sensing. The first configuration has pressure port design with mounting port of 14 mm outer and 8 mm inner dimensions named as Version-I. The second configuration has modified pressure port design with 14 mm outer and 3 mm inner dimensions, named as Version-II shown in figure 4.0. The semiconductor based pressure sensors are made of single crystal silicon material with diffused piezo-resistors, which have very high sensitivity. The Silicon chip as such is protected against ambient influence by a stainless-steel housing sealed with a corrugated diaphragm with a thickness of 50 µm and the effective pressure transmission is by means of a silicone oil transmission medium. The pressure sensor chip is made using IC technology and chemical bulk micromachining technique. Every MEMS application usually requires a new package design to either optimize its performance or to meet the needs of the system. The packaging methods can be categorized into four types: 1) all metal packages, 2) ceramic, 3) plastic packages, and 4) thin-film multilayer. The packaging of a pressure sensor must ensure that the sensing device is in intimate contact with the pressurized medium, yet protected from harsh environments. All metal packaging techniques are adapted for the aerospace grade pressure transducers. The MEMS cell is joined with pressure port by electron beam welding technique, the weld joint configuration is optimized in such a way that silicon Pressure sensing chip experiences very less heat in order to avoid debonding of sensor die adhesive from header. Then the sensor pins are connected to signal conditioning PCB for amplification and temperature compensation. The amplified signal from the sensor is then connected to the external measurement systems by means of MIL standard electrical connector. To avoid short circuit failure and Insulation resistance degradation of signal conditioning in ASIC (Application Specific Integrated Circuit) circuits & connectors due to moisture absorption during assembly process, a silicone rubber based conformal coating is applied on the PCB and connector solder joint. The pressure port assembly and electrical connector assembly are joined with upper cover by Electron beam welding process to provide hermetic sealing construction and environmental protection to the entire assembly. Stainless Steel (SS304L) was selected as the material for construction and sharp corners are avoided in order to withstand the possible shock and vibration anticipated during the launching phase. The assembled sensors is subjected to non- destructive testing during sub-assembly stages. The packaging of MEMS pressure transducer is shown in Figure 2.0.

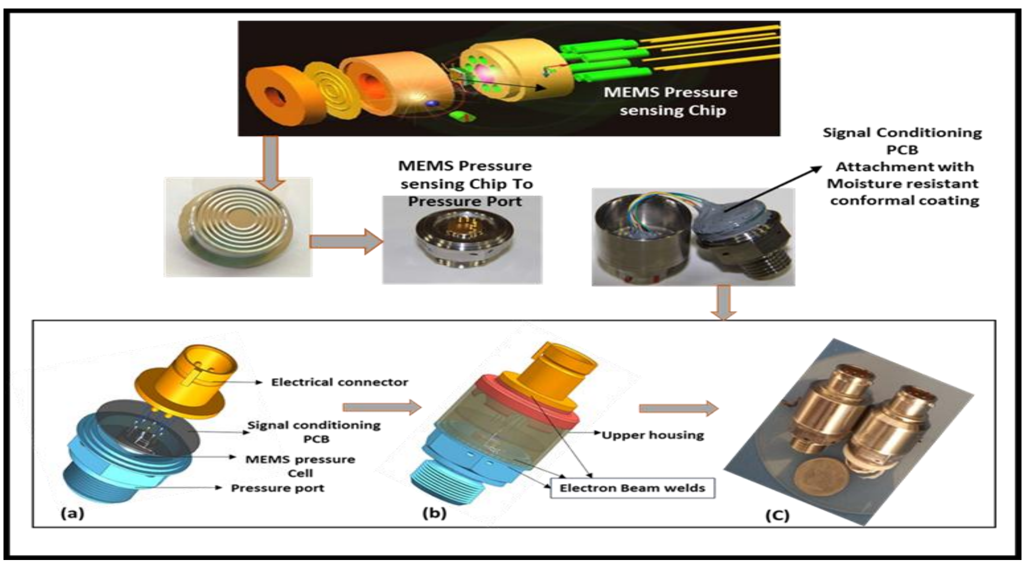

Figure2.0 MEMS pressure transducer assembly and packaging (a). Transducer sub-assemblies (b). Final packaging(c). Realized 20 Bar Transducer

2.2 Surge Pressure and Radiation Effect on Transducer

2.2.1 Test Setup

Many dynamic sensors are made, as there is the need to measure pressures which are rapidly changing. It is necessary that the sensors output provides an accurate representation of the pressure throughout the measurements. At present, many sensors used in such applications are only calibrated using static methods owing to the difficulty in generating known pressure changes of required rate and amplitude. An example is being found in combustion engines where the chamber pressure varies periodically from 0.1 to 10 MPa, at frequencies of up to 30 kHz.

Pressure is measured using electromechanical sensors, which are calibrated statically, and its dynamic characteristics causes their statically determined sensitivity to change as the frequency increases. This may lead to errors in the measured pressures and can cause problems if a sensor has to be replaced. If sensors are calibrated both statically and dynamically, the reliability and uncertainty of measurements can be improved. Combustion pressure is one of the critical parameters usually used in the performance evaluation of launch vehicle. Precise information of the tank and line pressure during firing of rockets can also be used for the health monitoring of satellite propulsion systems.

Various types of pressure transducers are used for space applications, which are usually selected based on the constraints imposed on the mounting configurations, bandwidth, accuracy, range and environmental operating conditions both during launch as well as in actual flight. Hence, accurate information on various performance characteristics of pressure transducers is very essential for selecting the right kind of sensors in space applications. In most cases, the dynamic performance of pressure transducers is easily characterized by subjecting the sensors to impulsive pressure surge test.

Shock tube is usually regarded as a test tube in gas dynamic studies, which can be used for creating pressure impulses of required strength in the laboratory for dynamic performance evaluation of pressure transducers. It is a device where a planar shock wave of desired amplitude can be generated. A shock tube consists of driver section (High pressure) and driven section (Low pressure) separated by a diaphragm. The test setup for transient surge pressure effect during engine is simulated by using shock tube technique which is shown in Figure 3.0. When sudden rupture of the diaphragm occurs, planar shock wave propagates from driven section to driver section. Shock wave generated in a shock tube has a rise time in the order of few micro seconds. By using thermodynamic equations, the amplitude of the pressure step generated upon reflection of the wave from the end face of the tube can be calculated.

In this work 20 bar pressure range pressure transducer testing was carried out in comparison to an industrial standard, piezoelectric type pressure transducer as a reference sensor having sensitivity of 14.0 mV/bar (Make: PCB Piezotronics, Model No: 113B22). The sensor under test and reference sensor were mounted on the end flange of the shock tube. Output of these sensors were connected to an oscilloscope (Make: Tektronix 1GHz,5G samples/sec). Figure 3.0 shows the schematic test setup and test output waveforms. Pressure waves of required amplitude level was generated using polycarbonate sheet as membrane material separating driver section and driven section of the shock tube. For the engine injection pressure measurement application two types of pressure port designs (Version I&II) were carried out and tested in shock tube setup to evaluate the performance of transducer in surge pressure environment.

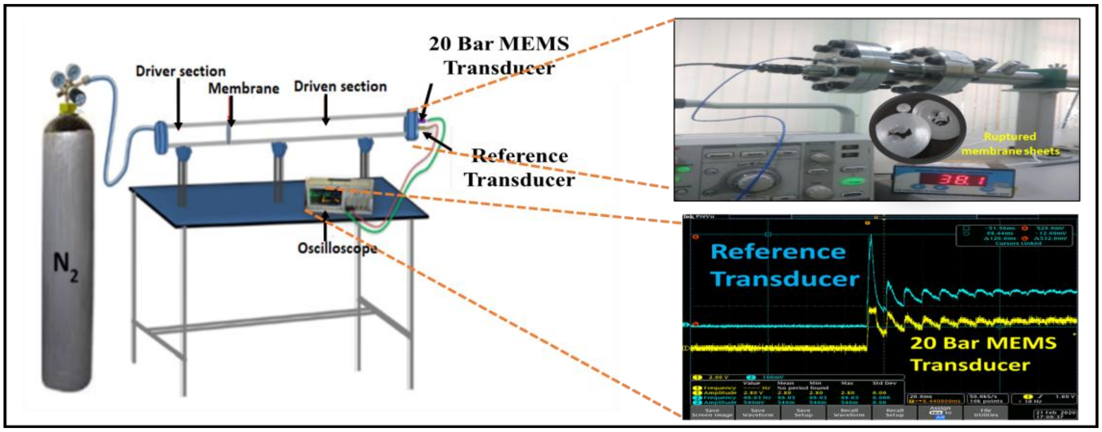

Figure 3.0 Shock tube setup for surge pressure test and test results

3.0 RESULTS AND DISCUSSION

The pressure transducers designed for launch vehicle application Version-I and Version-II are subjected to surge pressure test, pulse peak amplitude of 38 bar similar to pyro opening and throttling effect in engine ground testing by using shock tube test setup. With the pressure port configuration in Version-I, after surge pressure test, degradation of the transducer performance was noticed as shown in figure 4.0 a. Damage was observed in the MEMS cell corrugated diaphragm and transducer accuracy was also degraded. Based on the experiment and analysis, modification in the pressure port was carried out (version-II) with surge protection. The Version-II shows that there is no degradation in the transducer performance and also no damage noticed in the diaphragm which is indicated in figure 4.0 b.

To understand the performance of these transducers after the pressure surge test, static calibration was carried out using higher accuracy class (<0.008%FS) Electronic pneumatic pressure controller (Make: Wika). The transducer accuracy is calculated from the static calibration test results by best fit straight-line method (BFSL). Pre and post surge test results are compared as shown in figure 4.0.

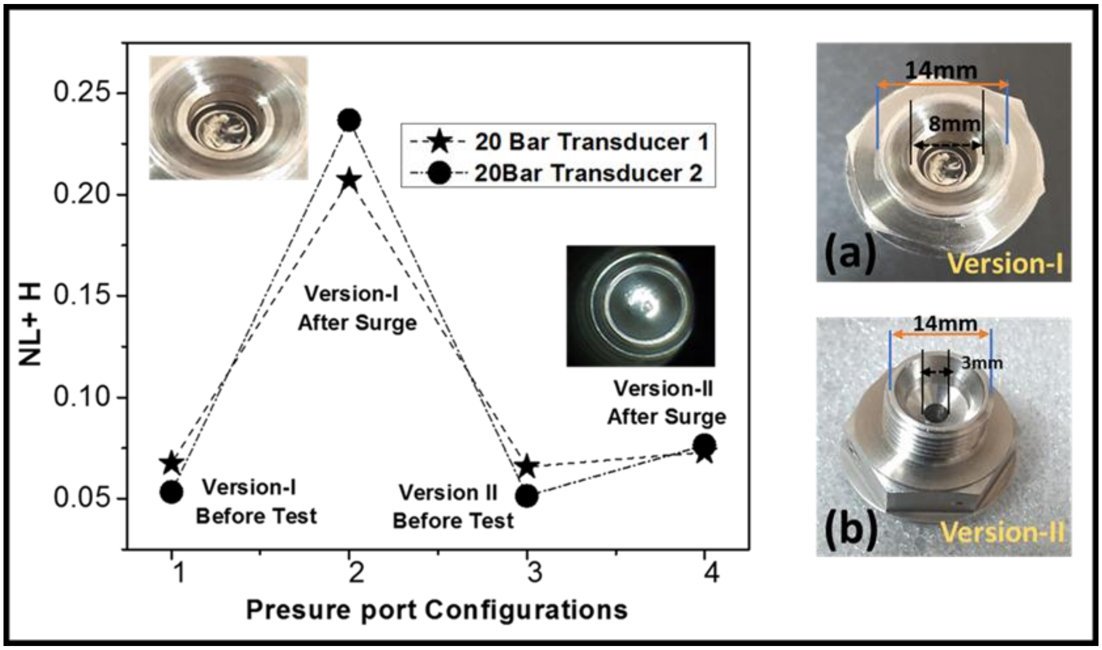

Figure 4.0 Transducer performance in surge pressure test (a). Pressure port design with 8mm internal diameter (b). Pressure port design with 3mm surge protection configuration

Pressure transducers used in satellite propulsion system applications should be able to withstand space radiation environment without degradation in its performance. The accelerating factor for radiation is energy dose ranges.

The satellite transducers are tested for nominal space radiation condition (Maximum dose satellite experiencing in orbit 21 Krad) and very high radiation condition for future interplanetary missions (100 Krad). The different energy doses of radiation field were generated using Co-60,1.2MeV Gamma ray source. The Transducer is subjected to nominal space radiation condition of 21Krad in steps of 3Krad. The performance of the transducer is evaluated and it is observed that maximum changes in output is <0.05% FSO only.

In the second test, the transducer is subjected to 100 Krad radiation source. It is observed that at higher radiation doses the transducer's performance gets degraded. Detailed analysis is carried out to understand the failure mechanism. It is noticed that there is no degradation in the performance of the MEMS cell (silicon Piezo resistive chip). The failure occurred in signal conditioning circuits only. However, from the analysis it is understood that the MEMS pressure cell region has 4mm thickness of stainless-steel housing whereas signal conditioning circuit region has only 1mm thick stainless steel housing. The cut opened view of transducer after the radiation test is shown in figure 5.0.

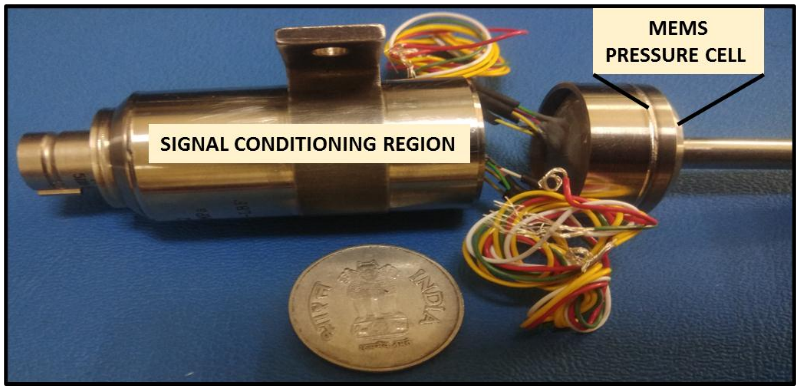

Figure 5.0 Satellite version MEMS pressure transducer cut opened view after radiation test

4. CONCLUSION

In this article the test results of transducers subjected to pressure surge and gamma radiation tests are presented. From the test results it is observed that the design with 3mm surge protection configuration is having adequate safety margin sufficient to withstand surge pressure and the pressure cell housing of 4mm thickness provides shielding from high dose radiation (100K rad). However, the signal conditioning package modification needs to be carried out to avoid failures in extreme radiation environment. With the Version-II configuration pressure transducers realized and used in ground testing of engines, the performance was satisfactory, indicating its capability to withstand water hammer effect. The satellite version pressure transducers are successfully qualified and flown in ISRO's satellite for Electric Propulsion Systems health monitoring and control applications.

REFERENCES

1. K. N. Bhat and M. M. Nayak, "MEMS Pressure Sensors- An Overview of Challenges in Technology and Packaging," *The Journal of ISSS*, vol. 2, p. 3, (2013).
2. Y. Kanda and A.Yasukawa, "Optimum design consideration for silicon piezoresistive pressure sensors" *Sensors and Actuators A: Physical*,vol.62,pp.539-542, (1997).
3. M.A. Chaiko, K.W. Brinckman, Models for Analysis of Water Hammer in Piping with Entrapped Air, 124, PPL Corporation, Nuclear Technology Group, Allentown 124, PA 18101 (2002).
4. R. Lecourt, J. Steelant, Experimental investigation of water hammer in simplified feed lines of satellite propulsion systems, *J. Propuls. Power* 23 (6), (Nov-Dec) (2007).
5. B.E. Larock, R.W. Jeppson, G.Z. Watters, Hydraulics of Pipeline Systems, CRC Press, London, (2000).
6. E.B. Wylie, V.L. Streeter, Fluid Transients, McGraw-Hill, New York, (1978).
7. R.A. Leishear, Dynamic pipe stresses during water hammer: afinite element approach, *J. Pressure Vessel Technol*. 129 (5) (2007).

8. R.P. Prickett, E. Mayer, J. Hermel, Water hammer in a spacecraft propellant feed system, *J. Propuls. Power* 8 (3) (1992).
9. M.S. Ghidaoui, M. Zhao, D.A. Mclnnis, D.A. Axworthy, A review of water hammer theory and practice, *Appl. Mech. Rev*. 58 (2005).
10. G.P. Sutton, O. Biblarz, Rocket Propulsion Elements, Seventh edition, (2001).
11. V. K. Varadan, K. J. Vinoy, and S. Gopalakrishnan, Smart Material Systems and MEMS: Design and Development Methodologies: Wiley Online Library, (2006).
12. Herbert R. Shea Radiation sensitivity of microelectromechanical system devices *Journal of Micro/Nanolithography, MEMS, and MOEMS*, 8(3), 031303 (2009).