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EMC Testing of Absolute and Differential Pressure Sensors for a Flush Air Data System (FADS)

Vidya SB[1], Finitha KC[2], Shashi Krishna[3], Jayakumar M[4], Abdul Samad AK[5], Vinod P[6], Mookiah T[7], Aisha Sidhick[8], Narasimha Prasad MV[9]

Scientist/Engineers, Vikram Sarabhai Space Centre, Trivandrum, India

Scientist/Engineers, ISRO, Liquid Propulsion Systems Centre, Department of Space, Banglore, India

ABSTRACT: Flush Air Data Sensing System (FADS) form a mission critical sub system in future aerospace vehicles. FADS makes use of surface pressure measurements from the nose cap of the vehicle for deriving the air data parameters of the vehicle such as angle of attack, angle of sideslip, Mach number, etc. These parameters find use in the flight control and guidance systems, and also assist in the overall mission management. The accuracy of the pressure sensors used in the FADS system ultimately decides the accuracy of the estimated air data parameters. Piezoresistive MEMS based pressure sensors are used in the FADS system under consideration. As the FADS system is co-located in the aerospace vehicle along with other Avionics packages it is essential that the pressure sensors meet the EMC standards prescribed for Avionics systems. This paper described the EMC tests carried out on the absolute and differential pressure sensors used in FADS. The tests are carried out as per MIL STD 461 C. Both conducted susceptibility and radiated susceptibility tests were carried out on the sensors as specified in above standard. The experimental result demonstrates that the accuracies demanded by the system are provided by the pressure sensors under the EMI environment.

KEYWORDS: FADS, EMI, EMC, RS03, CS01, CS02, CS06

I. INTRODUCTION

The knowledge of air data parameters like angle of attack, angle of sideslip, dynamic pressure, Mach number, and free stream static pressure with sufficient accuracy in real time is required for flight control of an aerospace vehicle. These parameters are normally obtained from the air data system of the vehicle. These data are suitably interpreted during flight and the flight is manoeuvred in a profile, which limits the vehicle loads and thermal environment and also keeps the vehicle trajectory within the desired envelope.

Traditionally, air data has been measured in aircrafts through the use of intrusive booms or probes which penetrate the flow away from the influence of the vehicle body. These probes have been reliably used for measuring air data in the subsonic and supersonic flight regimes of aircrafts. However, their main disadvantage is the degradation in accuracy while flying at high angles of attack or under dynamic manoeuvring conditions. Accuracy of probe based systems also degrades under conditions of vibration and due to alignment related errors. Probe based systems are not desirable in stealth aircrafts as they increase the radar cross section exposing it to the risk of detection by Radars. Such protruding systems are also not desirable in research aircrafts as they disturb the airflow or boundary layer.

Hypersonic flying vehicles are another area where probe based air data systems cannot be used. The vehicle nose in such vehicles encounter very high temperatures which will result in melting of the protruding boom. Hence, hypersonic flying vehicles essentially adopt the concept of Flush Air Data sensing System (FADS). In FADS, the air

data parameters are estimated using pressure measurements from orifices flushed with the surface of the vehicle [1] – [4]. To perform this estimation, air data states are related to the surface pressure by an aerodynamic model that captures the salient features of the flow, and is valid over a large Mach number range from hypersonic to subsonic [5]-[7]. As FADS relies on the mathematical model that related surface pressure distribution to the air data states, it does not require probing of the local flow field for air data estimation. The FADS system has found application in unmanned aerial vehicles [8] and also in planetary probes [9]. FADS system has been developed for the space shuttle [10], [11], and has also been demonstrated through a number of flight tests. Results of these flight testing has shown that FADS system is unaffected by dynamic flight manoeuvres and high angle of attack flight conditions [12]-[16].

The FADS system mentioned in this paper is configured using nine pressure ports arranged in a crucifix fashion on the nose cone of the vehicle [17]. There are five pressure ports in the vertical meridian and remaining four in the horizontal meridian as shown in Figure 1. Only a minimum of four pressure ports are needed to obtain a complete set of air data parameters. More number of ports is incorporated to increase the accuracy of the estimated parameters and for redundancy purpose. The FADS system comprises of a set of highly accurate pressure sensors along with the pneumatic tubing's to take care of re-entry heating and an electronic module with embedded FADS algorithm [18], [19].

The FADS system considered in this paper makes use of absolute pressure sensors for air data estimation. In addition, differential pressure sensors are also used for angle of attack estimation [20]. Split range calibration scheme with hysteresis is employed to achieve the required accuracy in pressure measurement [21]. For this purpose, the total range of the sensor is divided into four ranges and different scale factors are used for each range.Typical results from the Electromagnetic Compatibility (EMC) tests conducted on both absolute and differential sensors are discussed in this paper.

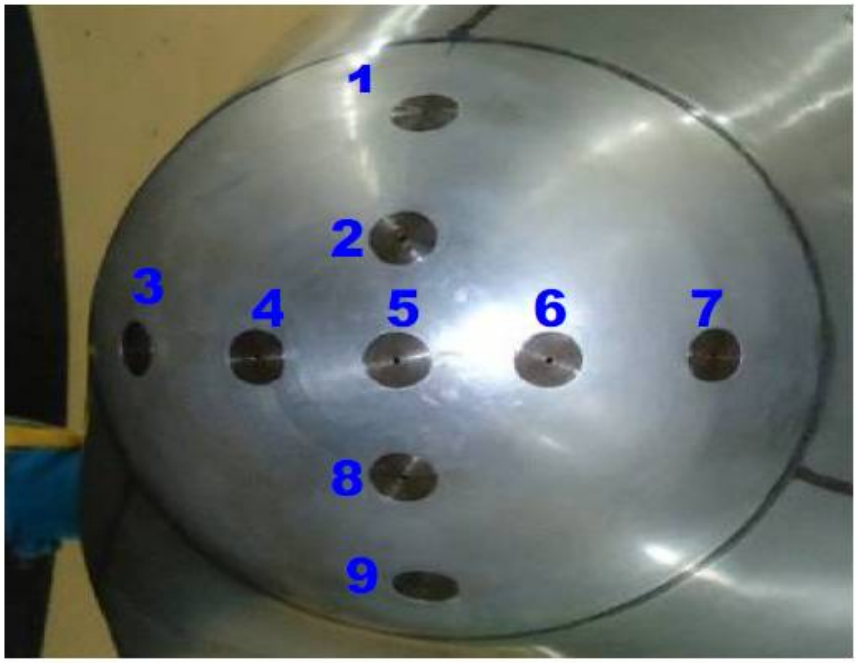

Fig 1: Pressure ports on nose cap

II. FADS System Concept and Estimation Algorithm

FADS Aerodynamic model

To perform air data estimation, the air data states must be related to the surface pressures by an aerodynamic model that captures the salient features of the flow, and is valid over a large Mach number range. A simple aerodynamic model is derived as a splice of the closed form potential flow solution for a blunt body, applicable at low subsonic speeds; and the modified Newtonian flow model, applicable at hypersonic speeds [1]-[3]. This model is based on potential flow and modified Newtonian flow and it describes the measured pressure coefficient in terms of the local surface incidence angle. To blend the two solutions over a large range of Mach numbers, a calibration parameter (ε) is devised,

$$P_i = q_c[\cos^2\theta_i + \varepsilon \sin^2\theta_i] + P_\infty \quad (1)$$

where, P_i is the incident port pressure. In (1), θ_i is the flow incidence angle between the surface normal at the *i*'th port and the velocity vector.

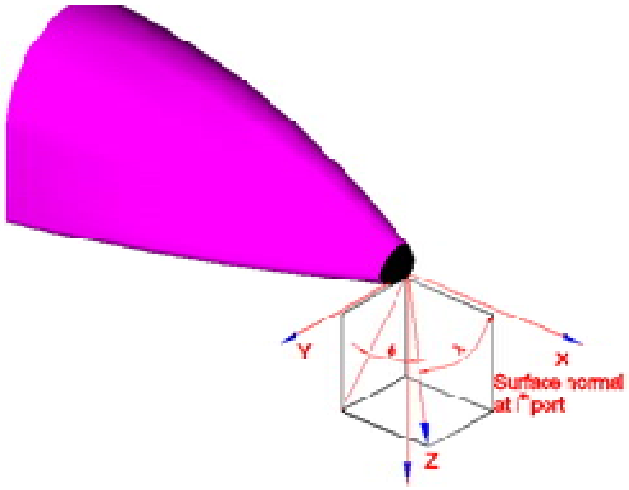

Fig 2: Definition of cone angle and clock angle

The incidence angle is related to the local (or effective) angle of attack, (α_e) and angle of sideslip, (β_e) by

$$\begin{aligned}\cos\theta_i = {} & \cos\alpha_e \cos\beta_e \cos\lambda_i \\ & + \sin\beta_e \sin\phi_i \sin\lambda_i \\ & + \sin\alpha_e \cos\beta_e \cos\phi_i \sin\lambda_i \end{aligned} \quad (2)$$

In (2), the cone angle (λ) is the total angle the normal to the surface makes with respect to the longitudinal axis of the nose cap and the clock angle (Φ) is the clockwise angle looking aft around the axis of symmetry starting at the bottom of the fuselage. The cone and clock angles are shown in Figure 2. The other parameters in (1) are impact pressure (q_c) and the free stream static pressure ($P\infty$). From these basic equations, the air data parameters of interest are computed using an indigenously developed algorithm.

III. ABSOLUTE AND DIFFRENTIAL PRESSURE SENSORS USED IN THE SYSTEM

In order to keep pace with the technological advancements and simplified assembly procedures with mass production capabilities, higher output, low power, low cost, better accuracy, higher reliability and faster response with low weight, a new class of sensors based on silicon technology i.e. using state of the art MEMS technology is used in FADS.

The sensor configuration consists of three 1.4 bar pressure sensors at each pressure port. A high-sensitivity piezo resistive silicon chip is used for pressure sensing. Compared to the metallic strain gauge based pressure sensor, the semiconductor type pressure sensor are made by single crystal silicon material with diffused piezo resistors, which has more than fifty times higher sensitivity. The piezo resistors normally have a value of approximately 3.5 KΩ. The ΔR resistance change during pressure-induced strain can be as high as 30%. The block diagram of the MEMS pressure transducer is shown in Figure 3. The typical specifications of the absolute and differential pressure transducers are as given in Table 1 and Table 2 respectively:

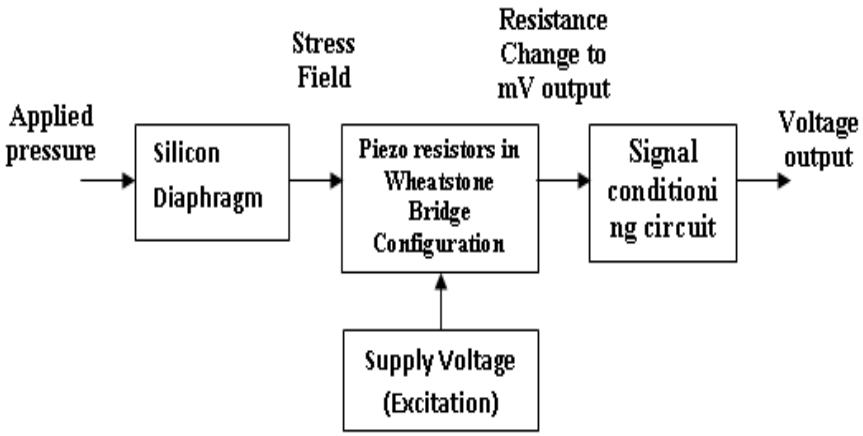

Fig 3: Block diagram of MEMS pressure transducer

The accuracy requirements of air data parameters are 1degree in angle of attach and angle of sideslip and 10% in Mach number and dynamic pressure. These accuracies are mainly dictated by the accuracy of the surface pressure

measurements. Based on simulations it is found that this translates to a requirement of 100 Pascal accuracy for pressure sensor in a full scale of 140000 Pascal (0.07% FS) for absolute pressure sensor. The absolute sensor used in this system is a 3-in-1 pressure sensor, all three sensors measuring the same pressure at a pressure port. The accuracy specification for the pressure difference between the three sensors of a given port shall be less than 350 Pascal taking into consideration the accuracy of the acquisition system also. Since the angle of attack estimation algorithm works on pressure differences between ports, differential pressure transducers are provided for angle of attack estimation. The specification of the sensor is that under ambient conditions, the differential pressure sensed shall be within 250 Pascal.

These specifications shall be met under all EMI environments to which the system is subjected. To ensure the accuracy of pressure data acquisition, proper grounding schemes are implemented in the electronics design and EMI shielding is carried out for sensor cables. The realized absolute and differential pressure sensors are shown in Figure 4 and Figure 5 respectively.

Table 1: Absolute transducer specifications

Parameter	Specification
Sensor Type	MEMS (Absolute)
Absolute Pressure Range	0 to 1.4 bar
Excitation	+5 ± 0.1V DC
Output Voltage	+4.25 ± 0.05V DC
Non-Linearity + Hysteresis	< 0.07 % FSO
Output Impedance	< 10Ω
Bridge configuration	Wheatstone Bridge
Pressure Connection	Swagelok1/8 ″tube socket
Operating Temperature Range	-55 to +150 ° C
Thermal zero & Span drift	< ±0.01%FSO/° C
Compensated Temperature Range	+5 to +75 ° C

Fig 4: Absolute pressure

Table 2: Differential transducer specifications

Parameter	Specification
Sensor Type	MEMS (Differential)
Differential Pressure Range	± 0.5bar
Excitation	+5 ± 0.1V DC
Output Voltage	+2 ± 1.5V DC
Non-Linearity + Hysteresis	< 0.3 % FSO
Output Impedance	< 10Ω
Bridge configuration	Wheatstone Bridge
Pressure Connection	Swagelok 1/8 ″ tube socket
Operating Temperature Range	-55 to +150 ° C
Thermal zero & Span drift	< ±0.02%FSO/° C
Compensated Temperature Range	+5 to +75 ° C

Fig 5: Differential pressure sensor

IV. EMC TESTING

The electromagnetic compatibility test (EMC) is carried out to demonstrate that the electromagnetic interference characteristics (emission and susceptibility) of a component/sub-assembly under normal operating conditions do not result in malfunction of the component/subassembly. It also demonstrates that the component/sub-assembly does not emit, radiate or conduct interference which could result in malfunction of other components/sub-assembly.

The MIL STD 461C and MIL STD 462 are the comprehensive set of military standards for electromagnetic compatibility. MIL STD 461 gives the performance specification limits for the electrical, electronic and electromechanical equipments and sub systems. MIL STD 462 specifies test methodologies and detailed procedures for compliance with MIL STD 461. Normally both emission and susceptibility tests are carried out for Avionics packages. As the emission levels from sensors are very low only susceptibility tests were carried out on the pressure sensors. The following susceptibility tests were carried out as part of qualification of the sensors.

Conducted Susceptibility Test (CS)

The purpose of conducted susceptibility tests is to confirm that EMI emission of specified levels injected on power leads of the sensor would not cause degradation of performance or malfunctioning of the DC-DC converter. It measures the susceptibility of the package to CW emission in the frequency ranges 30Hz-50 kHz on power lines, feeding all DC power leads connected externally to the package. The output ripple at injected frequency at the package power line outputs and analog outputs should be within 50mV.

CS tests also measure the sensor susceptibility to transients or spikes on power lines including all DC power leads connected externally to the sensor. The output spike at injected frequency at the power outputs and analog outputs should be within 200mV. CS01 and CS02 tests and CS06 spike test were carried out as per MIL STD 462.

Radiated Susceptibility Test (RS)

During this test, the sensor is radiated with a prescribed electric field intensity and magnetic flux density over a range of desired frequencies. The performance of the sensor is monitored in the presence of prescribed electric field or magnetic induction field as the case may be and if the deviations of the sensor are within allowable limits, it is said to be compatible to the radiated field. Electric field susceptibility test (RS 03) was carried out to determine whether the sensor exhibits deviations or malfunctions in the presence of electric field of specified intensity.

EMI Test set up

The set up used for carrying out the EMI test is shown in Figure 6. Absolute and Differential pressure transducers are connected to the sensor data acquisition module in the FADS package. The data is acquired through an RS485 data acquisition card to the checkout computer. The tests were carried out in the anechoic chamber in VSSC.

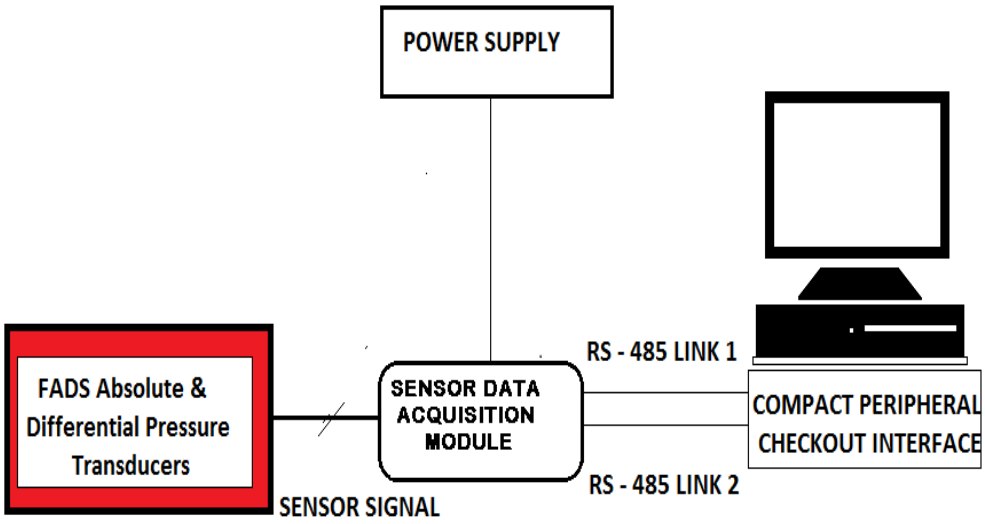

Fig 6: EMI test set up

V. TEST RESULTS & DISCUSSION

The EMI tests carried out as per MIL STD 461C on the sensor under ambient conditions using the above mentioned set up and the results obtained are as follows.

CS01 Test

A continuous AC signal was injected on the power input line of the DC-DC Converter from 30 Hz to 50 KHz at 8 Vpp. The voltage output from data acquisition module was taken for each of the spot frequencies 30Hz, 50Hz, 100Hz, 200Hz, 400Hz, 800Hz, 1kHz, 1.5kHz, 3kHz, 5kHz, 10kHz, 15kHz, 30kHz and 50kHz. The differences between the sensed pressures for the three sensors in a single pressure transducer are shown in Fig 7 to Fig 9. The pressure sensed by the differential transducer is shown in Fig 10.

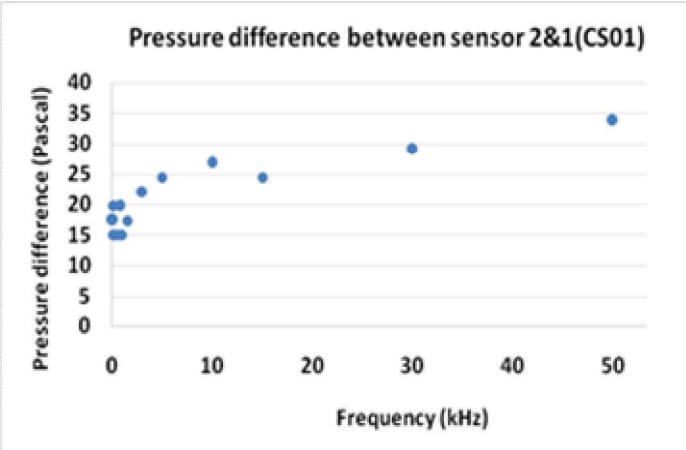

Fig 7. Pressure difference between sensor 2 & 1 in CS01

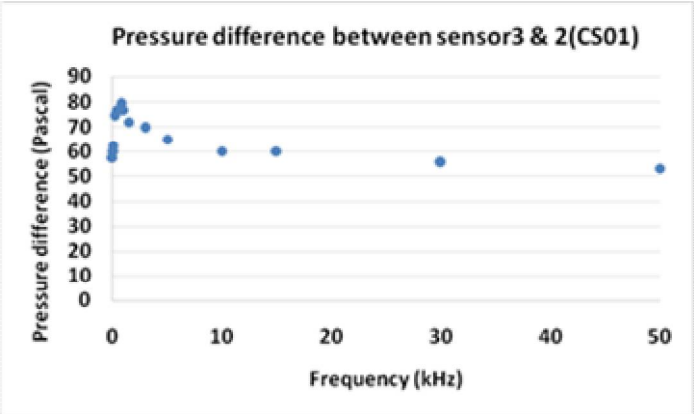

Fig 8. Pressure difference between sensor 3 & 2 (CS01)

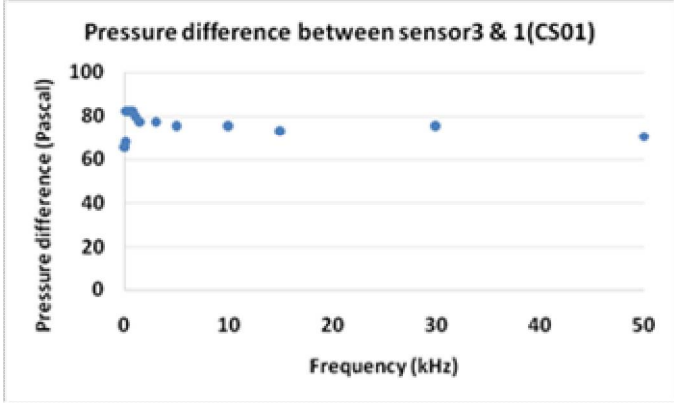

Fig 9. Pressure difference between sensor3 & 1 (CS01)

It is seen that the maximum pressure difference between the absolute pressure sensors is 82.17 Pascals (for 800 Hz between sensor 3 and sensor 1) which is under the maximum specification of 350 Pascals. For the differential pressure sensor the maximum pressure difference is 214.33 Pascals (for 50 Hz) which is within the maximum specification of 250 Pascals.

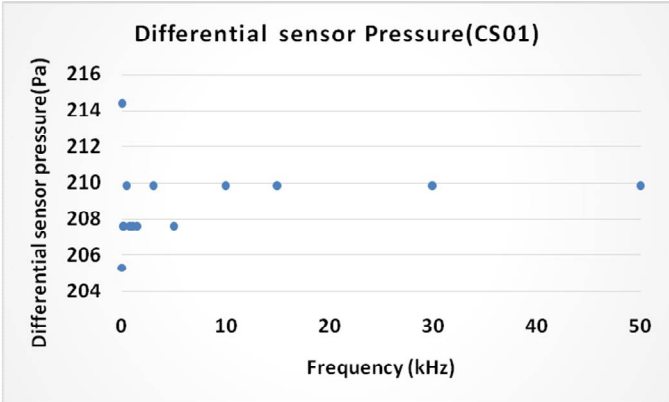

Fig 10. Differential pressure (CS01)

CS02 Test

An AC signal of 1 Vrms was applied across 28 V input of the DC-DC Converter from 100 KHz to 400 MHz. The voltage output from each FSIM was taken for each of the above spot frequencies. The differences between the sensed pressures for the three sensors in a single pressure transducer during CS02 are shown in Fig 11 to Fig 13. The differential sensor pressure plot is shown in Fig 14.

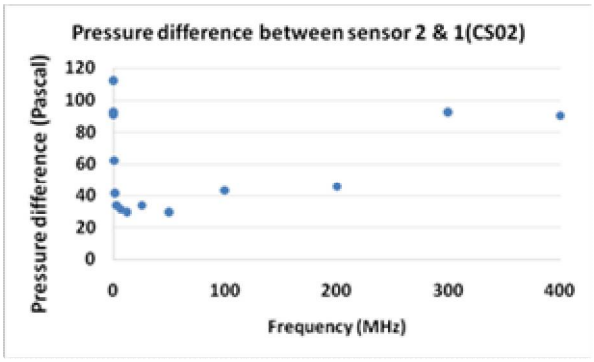

Fig 11. Pressure difference between Sensor2 & 1

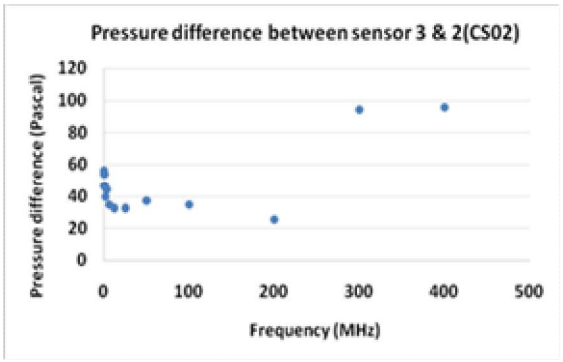

Fig 12. Pressure difference between sensor 3 & 2

It is seen from the figures that the maximum pressure difference between the absolute pressure sensors is 176.76 Pa (for 300 MHz between sensor 3 and sensor 1) which is under the maximum specification of 350 Pascals. For the differential pressure sensor the maximum pressure difference is 243.70 Pascals (for 400 MHz) which is also within the maximum specification of 250 Pascals.

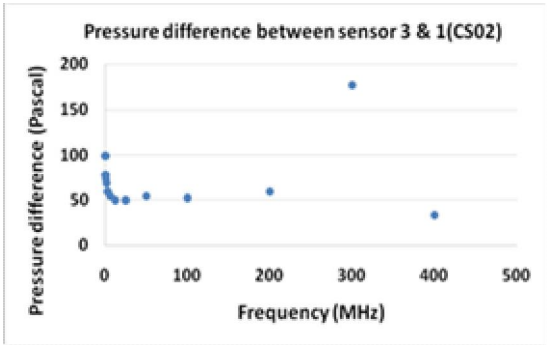

Fig 13. Pressure difference between sensor 3 & 1

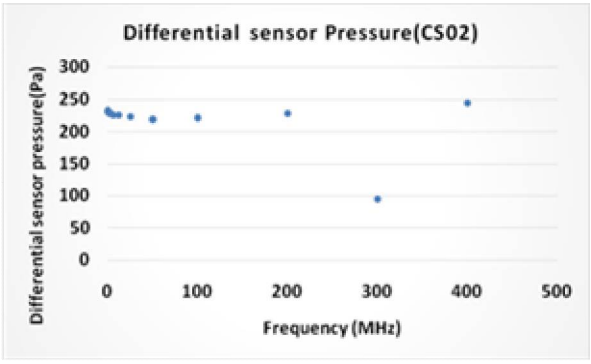

Fig 14. Differential pressure in CS02

CS06

Positive and negative spikes of 56 V peak to peak and width 10µs for duration of 10 minutes were applied to the input supply lines of DC/DC converter. The voltage output from data acquisition module is taken. The differences in the sensed pressures during the application of spikes are given in Table 3.

Table 3: Pressure Sensed by absolute and differential Pressure Sensors during CS 06 test

	Absolute Sensor 1 Pressure (in Pa)	Absolute Sensor 2 Pressure (in Pa)	Absolute Sensor 3 Pressure (in Pa)	Difference 1 (Sensor 2-Sensor 1)	Difference2 (Sensor 3-Sensor 2)	Difference3 (Sensor 3-Sensor 1)	Differential Sensor Pressure (in Pa)
Negative spike	99541.48	99637.64	99775.44	96.15647	137.8046	233.9611	212.0788
Positive spike	99541.48	99609.34	99739.8	67.85708	130.4608	198.3178	214.3377

From the figures it is seen that the maximum pressure difference between the absolute pressure sensors is 233.96 Pa (for negative spike injection between sensor 3 and sensor 1) which is within the maximum specification of 350 Pascals. For differential pressure sensor it is seen that the difference is 214.33Pascals (for positive spike injection) which is within the specification of 250 Pascals.

RS03 Test

The sensors were subjected to the electric field radiations of 5 V/m and 8 V /m at the spot frequencies of 20MHz, 30MHz, 40MHz, 60MHz, 80MHz, 100MHz, 150MHz, 240MHz, 402.663MHz, 402.73MHz, 434MHz, 543MHz, 2211MHz, 2237.5MHz, 2259MHz, 2275MHz, 4GHz, 4.3GHz, 5.6GHz, 7GHz, 8GHz and 10GHz. The corresponding plots are given in Fig 15 to Fig 18.

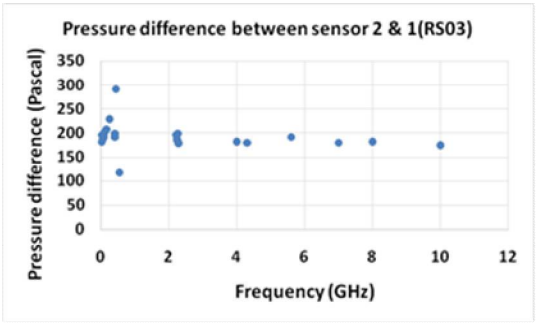

Fig 15. Pressure difference between sensors 2 & 1

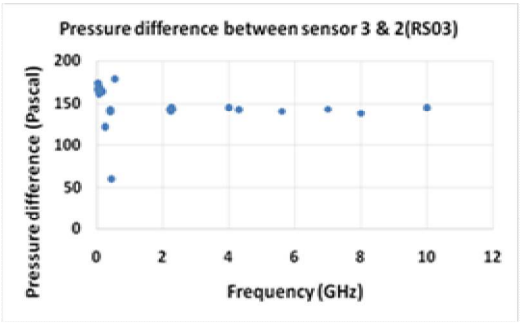

Fig 16. Pressure difference between sensor 3 & 2

From the figures it is seen that the maximum pressure difference between the absolute pressure sensors is 307.51 Pa (for 150 MHz between sensor 3 and sensor 1) which is within the maximum specification of 350 Pascals. For differential pressure sensor the maximum pressure difference is 90.09 Pascals (for 150 MHz) which is within the maximum specification of 250 Pascals.

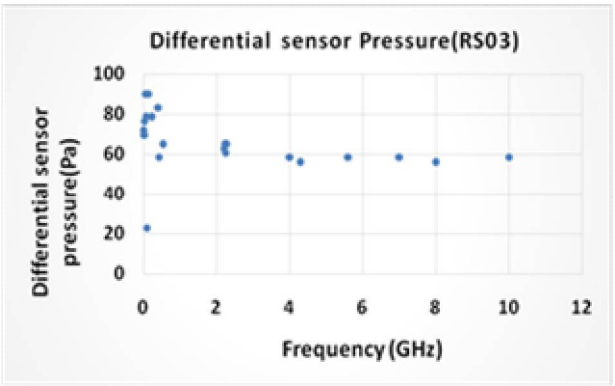

Fig 17. Pressure difference between sensor 3 & 1

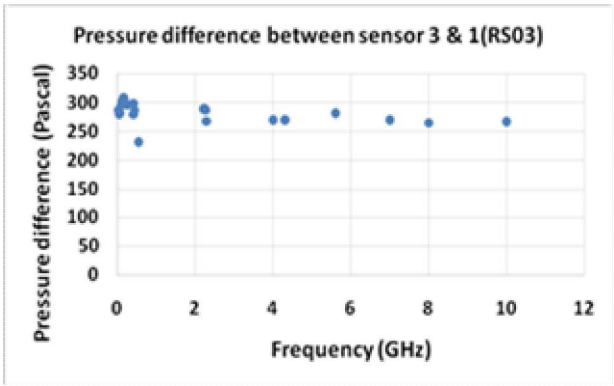

Fig 18. Differential pressure in RS03

VI. CONCLUSION

The EMC tests carried out on absolute and differential pressure sensors in a Flush Air Data System has been highlighted. The tests were carried out with the sensors in ambient condition. Both conducted susceptibility tests and radiated susceptibility tests were carried out on these sensors as per MIL STD 462. The tests carried out are conducted susceptibility tests CS01, CS02 and CS 03 and radiated susceptibility test RS03. For the absolute pressure sensor, it is found that the maximum pressure difference between the two sensors is 307.515 Pascals. This was observed during RS03 test at a frequency of 150 MHz. This value is found to be within the specification of 350 Pascals for the absolute pressure sensor. For the differential pressure sensor, the maximum pressure difference is found to be 243.7037 Pascals. This was observed during CS02 at a frequency of 400 MHz. This value is also within the specification of 250 Pascals for the differential pressure sensor. From these test results it is concluded that the design of both the absolute and differential pressure sensors is in compliance with the EMC requirements of MIL STD 461 C for Avionics systems.

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