Dynamic Response Assessment and Design Optimization of Aircraft Tyre Pressure Monitoring Unit (TPMU)

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Abstract— Aviation industry demands higher efficiency and reliability of a gas turbine engine and it must provide predictable thrust performance over the tyre operating envelope of the engine, covering altitudes ranging from below sea level to tens of thousands of feet above. These altitude changes, along with differing flight speeds from takeoff to supersonic velocities, result in large variations in engine inlet temperature, inlet pressure, and exhaust pressure. Large variations in engine operating conditions, coupled with the need for precise thrust control and highly reliable operation, create a significant challenge for the design of engine control systems, especially given the complexity of the engine itself. Controlling such complex machinery requires a thorough understanding of the performance of the engine system as a whole. This current research covers the design of aircraft tyre pressure monitoring unit. It focuses on four areas of interest: 1) Modeling of aircraft tyre pressure monitoring unit. 2) Aircraft tyre pressure monitoring unit dynamic response. 3) Design assessment using Steinberg relation.

Key words: Aircraft Tyre Pressure Monitoring Unit, Steinberg Relation

I. INTRODUCTION

Aircraft tyres contain an enormous amount of stored energy which is released quickly, such as in a tyre burst, can cause significant damage to an aircraft and its system. The purpose of the aircraft tyre pressure monitoring unit (TPMU)as shown in figure 1 is to indicate that at least one or more tyres are significantly under-inflated, possibly creating unsafe landing or yawing conditions. A tyre pressure monitoring system (TPMU) is a sensor and monitoring technology that designed to take readings of the air pressure inside aircraft main wheel. TPMU communicate real-time tyre-pressure data to the pilot and provide low pressure alarms.

Direct TPMU employ pressure sensors on each tyre, either internal or external. The sensors physically measure the tyre pressure in each tyre and report it to the vehicle's instrument cluster or a corresponding monitor. Some units also measure and alert temperatures of the tyre as well.

Fig. 1: Direct Tyre Pressure Monitoring Unit.

These systems can identify under-inflation in any combination, be it one tyre or all, simultaneously. Although the systems vary in transmitting options, many TPMU products can display real time tyre pressures at each location monitored whether the vehicle is moving or parked. There are many different solutions but all of them have to face the problems of exposure to tough environments and the majority is powered by batteries which limit their useful life. Some sensors utilize a wireless power system similar to that used in tag reading which solves the problem of limited battery life by electromagnetic induction. This increases the frequency of data transmission up to 40 Hz and reduces the sensor weight which can be important in motorsport applications. when the sensors are mounted on the outside of the wheel, which is the case for some aftermarket systems, they are in danger of mechanical damage, aggressive fluids and other substances as well as theft. If they are mounted on the inside of the rim, they are no longer easily accessible for service like battery change and additionally, the RF communication has to overcome the damping effects of the tyre which additionally increases the need for energy.

II. PROBLEM DEFINITION

The present study emphasizes on the design and optimization of aircraft Tyre Pressure Monitoring unit (TPMU) for acceleration crash safety and vibration load requirements as per RTCA DO160 design guidelines.

III. DESCRIPTION OF THE MODEL

The CAD-2D model of TPMU is as shown in figure 2. The design substantiation has been based on finite element analysis performed on AIRCRAFT TPMU to meet the Steinberg design requirements for better airworthiness. The following analysis has been considered for TPMU design substantiation:

- Acceleration crash safety-20G shock in accordance with RTCA DO-160G.
- Vibration analysis-standard vibration test, category S curve in accordance with RTCA DO-160G.
- Design and optimization of aircraft TPMU to meet the acceleration and vibration design guidelines as per RTCA DO-160G. Design substantiation has also been performed based on Steinberg relation.

IV. MATERIAL-PROPERTIES

The material properties of materials which are used in component is as shown in table 1.

SL NO	Component	Mass (Grams)	Material	Young's Modulus (MPa)	Poisson ratio	Density (g/cm^{-3})	Adjusted Density (g/cm^{-3})
1	Top cover	100	ABS	1.89E^3	0.4	0.97	1.0408
2	Bottom cover	300	ABS	1.89E^3	0.4	0.97	0.0376
3	PCB board	130	FR-4	1.72E^4	0.12	2.35	4.4
4	Connectors	7	Aluminum	6.82E^4	0.33	2.7	14
5	Capacitors	25	Aluminum	6.82E^4	0.33	2.55	2.55
6	Inductors 1	15	Copper	1.1E^5	0.34	8.25	1.4
7	Inductors 2	12	Aluminum	6.82E^5	0.33	2.7	7
8	Connection board	15	Plastic	1.89E^3	0.4	0.97	0.37
9	DC-Converter	30	Aluminum	6.82E^4	0.33	2.7	1.61

Table 1: Mechanical properties of materials used in component

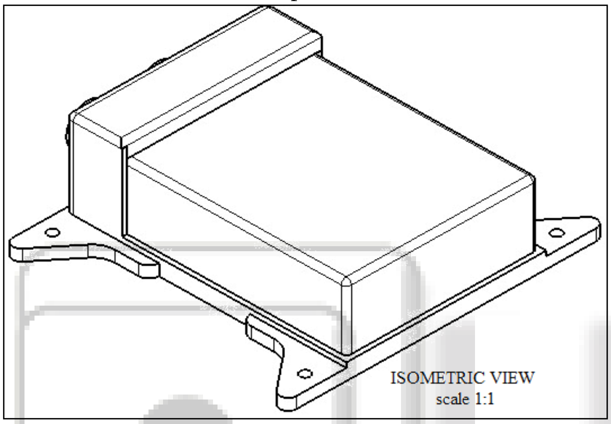

Fig 2: CAD model 2D Isometric view of TPMU.

The CAD model of aircraft TPMU was used to generate the FE model in ANSYS workbench 14.0 as shown in figure 3. Acceleration crash safety analysis model includes all the major components in order to capture the actual centre of gravity under the application of 20G acceleration loading. Total weight of the assembly maintained as pre the component mass details and material density for few of the components (PWB CPU board, PCB I/O board, connector's capacitor, and inductor) has been adjusted to balance the total assembly weight as shown in table 1.

V. ANALYSIS

A. Acceleration Crash Safety Analysis

The crash safety analysis is carried out in accordance with RTCA DO-160G.

B. Finite Element Modeling

The Finite Element model of aircraft TPMU Acceleration model is as shown in figure 3 is generated in ANSYS Workbench V14.0. 3-D 10-Noded tetrahedral structural solid elements are used to generate the FE modeled as shown in figure 3 and number of elements and type of elements is as shown in table 2 for the region of non-linear contact surface for better convergence.

C. Assembly FE Model

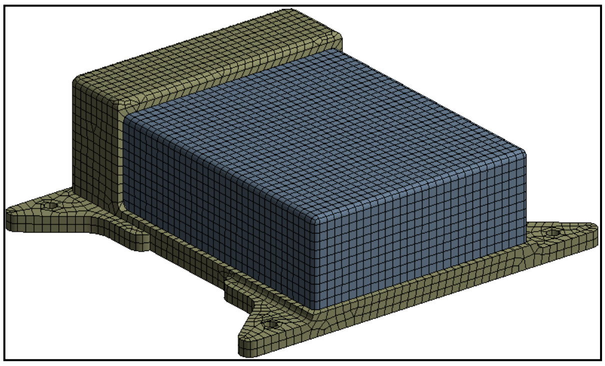

Fig 3: Aircraft TPMU Finite Element Model Assembly.

Sl No	No Of Nodes	No Of Elements	Element Type
1	156420	37183	Quad/Tri

Table 2: Element/Node Table summary

D. Boundary Conditions

Aircraft TPMU is fixed in all degree of freedom at the below highlighted four locations which will be connected to rigid structure as shown in the figure 4 in which front /bottom cover support holes are constrained in all DOF.

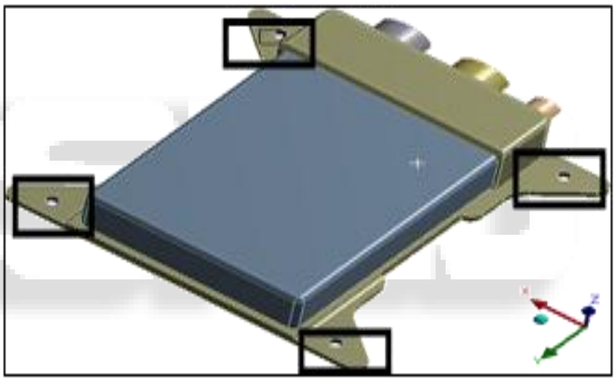

Fig. 4: Front/Bottom Cover support holes are constrained in all DOF.

VI. STRUCTURAL ANALYSIS

Structural analysis is probably the most common application of the finite element method. The term structural implies not only civil engineering structures such as bridges and buildings, but also naval, aeronautical, and mechanical structures such as ship hulls, aircraft bodies, and machine housings, as well as mechanical components such as pistons, machine parts and tools. The types of structural analyses are. Static Linear and Non-Linear Analysis

A. Crash Safety-20g Acceleration Analysis: Load Cases For Acceleration Analysis

Aircraft TPMU assembly is analyzed for 20G acceleration load in each X, Y and Z direction as shown in figure 5. Acceleration load is applied with respect to global Cartesian co-ordinate system and the corresponding loading details in each direction as shown in below Table 3.

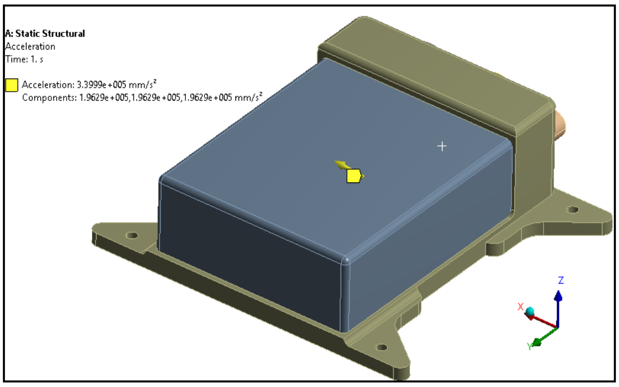

Fig 5: Load- Aircraft TPMU 20G Acceleration.

Sl No	Step	Time(S)	Acceleration X-Direction (mm/s^2)	Acceleration Y-Direction (mm/s^2)	Acceleration Z-Direction (mm/s^2)
1	1	1	1.9629E^5	1.9629E^5	1.9629E^5

Table 3: Shock Loading - Aircraft TPMU 20G Acceleration.

VII. Results and Discussion

A. *PCB Max Von-Mises Stress- Baseline Design*

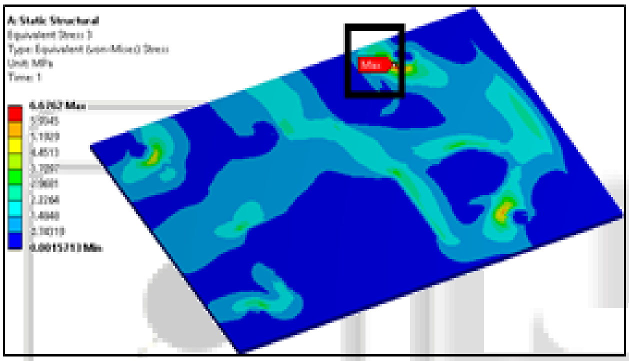

Fig 6: PCB board Maximum Von-Mises Stress plot.

Maximum Von-Mises stress of 6.7 MPa is observed near stand-off location and it is less than the material allowable yield limit of 262 MPa as shown in figure 6.

B. *Proposed Optimized Design*

Based on modal and static behavior of the PCB board, aircraft baseline design has been updated with improved stiffness in order to reduce the out of plane deflection. The proposed design modification is very effective considering high stiffness and lower weight contribution.

C. *Acceleration Analysis Results Summary of Optimized Design*

Optimized Design PCB Max Von-Mises Stress.

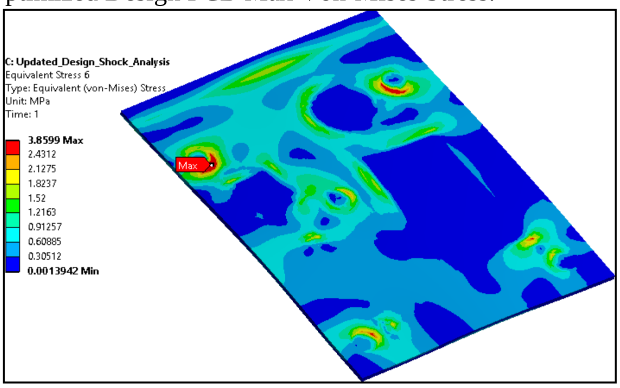

Fig 7: PCB board Maximum Von-Mises Stress plot.

Proposed optimized PCB design as shown in figure 7 shows significant improvement in stress reduction by approximately 50%.

1) Takeaway:

Addition of stand-off in the optimized model shown in figure 7 helps in significantly reducing the PCB board out-offs plane displacement and it meets the crash safety requirements**.**

D. *TPMU Vibrations Analysis*

As per RTCA DO-160G, all aviation electronic equipment's will be subjected to vibration loads. Hence, this section details the vibration analysis performed on AIRCRAFT TPMU assembly in order to meet the RTCA design requirements.

Modal Analysis: Same finite element model from crash safety analysis shown in figure 3 is used in modal analysis. Modal analysis is performed for a frequency range 0 to 2000 Hz and total 6 modes are observed in the specified frequency range as shown in figure from 8 to 13.

E. *Mode Shapes*

Mode-1 Top Cover Bending.

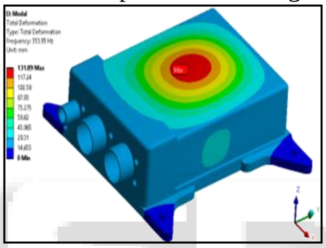

Fig 8: Mode shape at centre.

Mode-3 PCB board twisting.

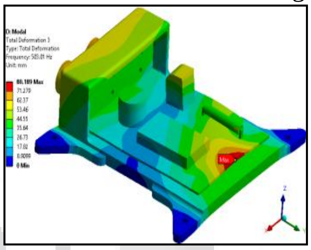

Fig 9: Mode shape at edge.

Mode-6 Top Cover Bending.

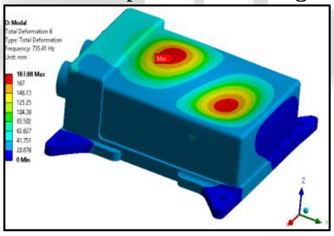

Fig 10: Top Cover Mode shape.

Mode-8 Top Cover Bending.

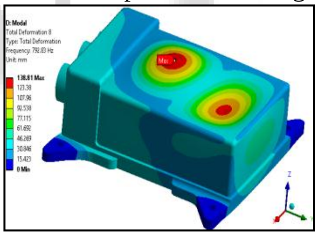

Fig 11: Top Cover Bending.

Mode-9 Top Cover Bending.

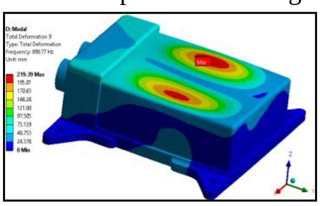

Fig 12: Top Cover Bending.

Mode-12 PCB Board Bending.

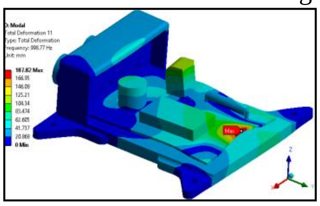

Fig13: PCB Board Bending.

F. *Harmonic Analysis*

The vibration analysis has been carried out in accordance with RTCA DO-160G, high and short level duration vibration test.

Based on the response and mode shapes, initial three modes as shown in figure from 8 to 10 (353.9 Hz, 425.7 Hz and 503.0 Hz) which lie in the range of 10Hz-550 Hz and the same is reported.

1) Harmonic Vibration Result and Discussion

Acceleration response for PCB board is as shown in figure from 14 to 17 and the corresponding output response is as shown in table 4 and 5.

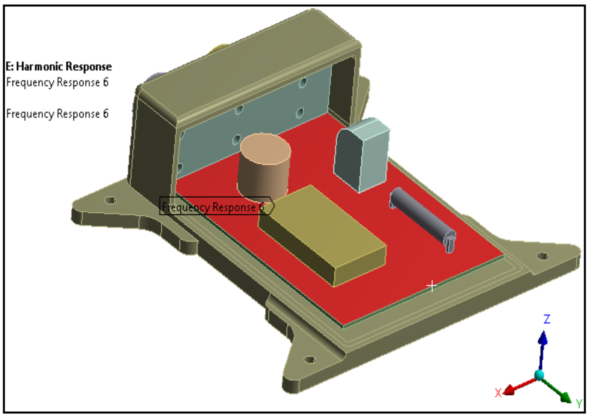

Fig14: Displacement on PCB board in Z-direction.

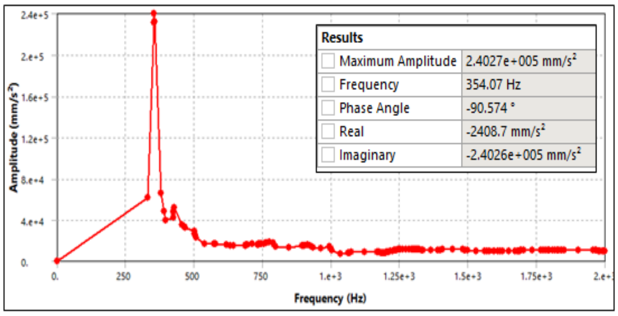

Fig 15: Response curve of PCB board at frequency 355Hz.

	PCB Board Acceleration response (mm/s²)
Output Response for 1G	2.40E^05
Output Response for 2.5 G	6.00E^05
Amplification Factor (Output/Input) G	2.5

Table 4: Frequency response of PCB Board

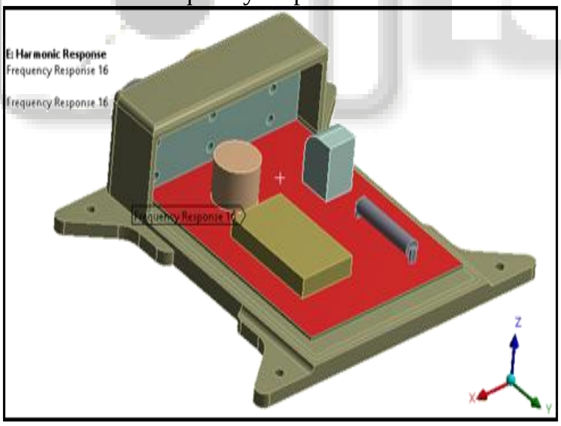

Fig 16: Displacement on the PCB board in Z-direction

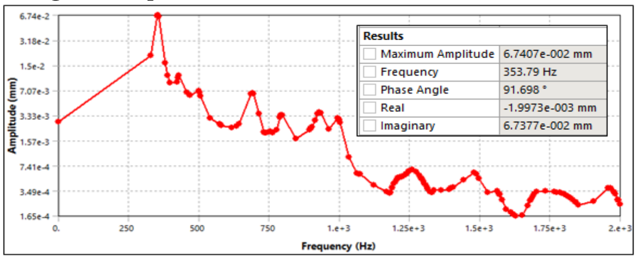

Fig 17: Response curve of PCB board at frequency 353Hz.

	PCB Board Total Deformation (mm)
Output Response for 1G	0.0674
Output Response for 2.5 G	0.169

Table 5: PCB Board Total Deformation.

PCB board total deformation at frequency range 353.8 Hz that is mode 1 as shown in figure 9.

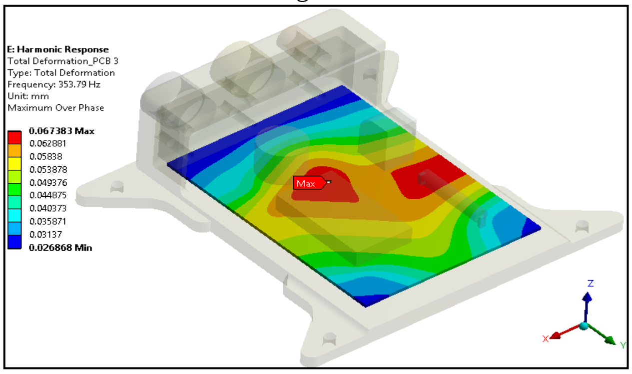

Fig 18: PCB board Total Deformation plot.

Max Total Deformation of 0.169 mm is observed at PCB board center as shown in figure 18.

G. *Steinberg Relation*

Vibration and shock cause 20 percent of the mechanical failures in airborne electronics. Proper design procedures for ensuring equipment survival in a shock and vibration environment are therefore essential. Interestingly, the remaining 80 percent of mechanical failures relate to thermal stresses induced by high thermal gradients, high thermal coefficients of expansion and a high modulus of elasticity.

Most modern electronic systems are composed of two major mechanical elements: an equipment chassis and a plug-in printed circuit board (PCB) assembly.

Extensive PCB vibration testing has established that a fatigue life of about 10 million stress reversals under sinusoidal vibration can be achieved for lead wires and solder joints when the dynamic single amplitude displacement at the center of the board is limited to the value in Eq 1. Similarly, about 20 million stress reversals can be achieved under random vibration.

$$Z = \frac{0.00132\, B^2}{C h r \sqrt{L}} \quad \ldots\ldots\ldots\ldots\ldots[1]$$

Where,
Z = single amplitude dynamic displacement
B = length of PCB edge parallel to component located at the center of the board
L = length of component
t = thickness of PCB assembly
c = 1.0 for standard DIP
r = relative position factor

PCB Board Out-Off Plane Displacement At 353.8 Hz.

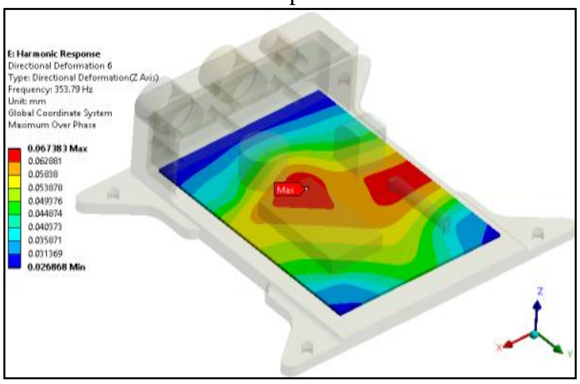

Fig 19: PCB Board Directional Deformation.

	PCB Board Directional Deformation (mm)
Output Response for 1G	0.0674
Output Response for 2.5 G	0.169

Table 6: PCB Board Directional Deformation.

PCB Board Directional Deformation as shown in figure 19 has 0.169mm at frequency range of 353.8 Hz in Z-Direction.

H. Calculation

The validation of the result using the Steinberg relation.

SL NO	Max Allowable Deflection Calculation Of PCB Board-Harmonic Vibration	Dimension (mm)
1	B, Length of PCB edge parallel to component longer edge,mm	141.6
2	L, Length of component,(mm)	57.512
3	h, Thickness of PCB assembly,(mm)	2
4	C, constant related to connection	1
5	r, Relative position factor	0.707
	Z, Maximum Allowable Out of plane Deflection,(mm)	**0.371**

Table 7: Max Allowable Deflection Calculation of PCB Board-Harmonic Vibration using-Dave S. Steinberg relation.

I. Takeaway:

Max allowable PCB board out-off plane displacement of 0.169 is less than the max PCB board directional displacement of 0.371mm at 353.8 Hz as shown in table 7.

VIII. Conclusion

From the study or analysis, came to know that the aircraft tyre pressure monitoring unit designed is not undergo more damage due to inclusion of additional stand-off at the centre of the PCB board.

The following analysis for the aircraft TPMU assembly shows compliance with the RTCA-DO160 design specification.

A. Dynamic Response Assessment

– Optimized TPMU assembly shows acceptable vibration stress and hence meets RTCA-DO160 design requirements.

B. Steinberg Assessment

– Proposed optimized model is validated for the plane displacement and meets the Steinberg requirement which is less than allowable out of plane displacement.

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