Aeronautics and Astronautics - AIDAA XXVII International Congress Materials Research Forum LLC
Materials Research Proceedings 37 (2023) 601-605 https://doi.org/10.21741/9781644902813-131

The application of modal effective mass for PCB friction lock compliance against spacecraft launch random vibration spectrum

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Keywords: Modal Finite Element Analysis, Electronics, Spacecraft Structures, Friction-Locking Devices, Random Vibration Analysis

Abstract. Modern spacecraft design requires high density, low mass, modular electronic system architectures. This format often utilises a common backplane with Printed Circuit Boards (PCBs) interconnects. Adaptable electronic systems, such as modular Data Acquisition (DAq) systems, allow for configuration via insertion and removal of modules to meet the mission requirements. Common methods to mechanically fix the PCB to the chassis are by using stand-offs, with the primary function to minimise displacement through structural rigidity and to provide strain relief to the electronic connectors. Other methods, such as PCB friction lock allow for strain relief, improved thermal grounding of the PCB to the chassis but also allows for easy insertion and removal of the PCBs. One disadvantage of this system is that the retention force of the PCB is carried by a friction lock device and under acceleration loads, typically experienced in the launch environment, may cause failure. This paper presents a method to establish compliance of PCB friction lock devices using modal Finite Element Analysis (FEA) to predict the resonant frequencies and their Mass Participation Factor (MPF). Using this data, it is proposed that the use of an adaptation of the Miles Equation along with an equivalent g-RMS estimation can be used to determine the Random Vibration Load Factors (RVLF). A comparison of the RVLF with the retention force of the friction lock device can then give insight to the friction joint compliance.

Introduction

Quasi-Static Load (QSL), Shock Response Spectrum (SRS), sine and random vibration Acceleration Spectral Density (ASD) are typical acceleration loads required for qualification of space bound hardware. They represent loads during maneuvers (e.g., roll/tilt and orbital), pyrotechnic events (separation and fairing jettison) and motor induced vibrations. Payload flight equipment is designed against a defined set of these acceleration loads but are often equated to Load Factors (LF) which are equivalent accelerations (expressed in g's) and applied through the Centre of Gravity (CoG) of the structure [1]. This paper considers Random Vibration Load Factor (RVLF) and its equivalent g (force) for verification of PCBs friction lock mechanisms (see Fig 1). This efficient design allows for high density electronic architectures and modularization via insertion/extraction into a chassis by accessing front side only. This verification technique is an effort saving technique for the purposes of Proto Flight development.

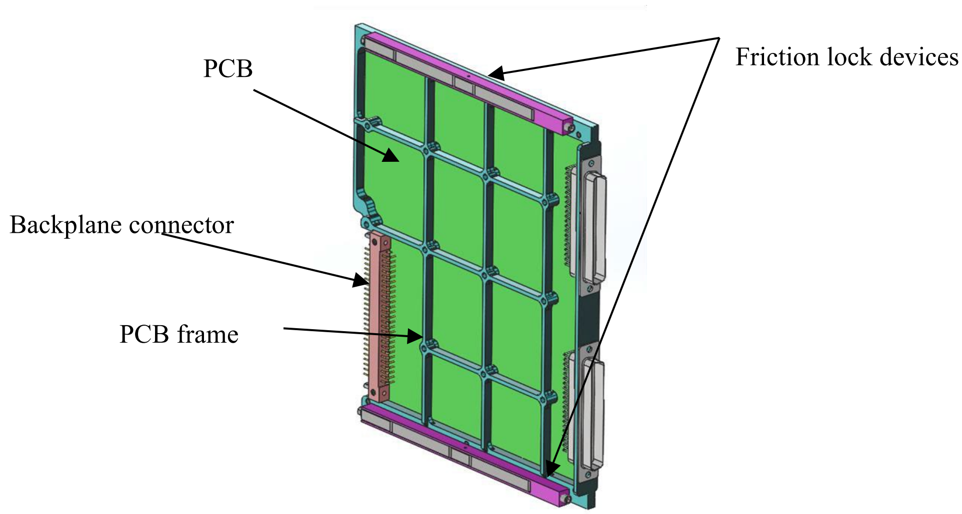

Fig 1: PCB on AA6082-T6 PCB frame with QTY 2 friction locking devices (NVENT).

In theory, structures may contain millions of Degrees of Freedom (D.O.F), each having a resonant frequency. Of these modes, high resonant frequencies (>2000 Hz or > 10,000 Hz) may be deemed to have low structural impact, one; because it is beyond the typical random vibration spectrum upper frequency limit (2000 Hz) and SRS (10,000 Hz) and two; because displacement is inversely proportional to modal frequency and often do not constitute a ductile failure mode (not withstanding that these modes should still be considered for load spectra for the purposes of fatigue compliance and failure modes for brittle ceramic components).The amount of mass moving in any direction is a function of the mode participation factor and the effective mass at that mode. This is sometimes called Mass Participation Factor (MPF) and it is common, using modal FEA, to evaluate MPF such that the summation accounts for > 90 % of the total structural mass in all orthogonal directions [2]. Significant modes of interest are extracted from this data (typically with MPF > 5 %). The resonant frequency of the structure in each orthogonal axis can also be identified as the first significant mode (i.e., lowest mode frequency typically with > 5 % MPF) in each orthogonal direction. On consideration for structural analysis of the PCB friction lock compliance, the following data is of importance; the mode frequency (Hz), the MPF and the orthogonal direction in which it acts. Mode frequency because it is inversely proportional to displacement and using Steinberg studies can determine electronic component survivability [3], MPF because of the inertia involved with this mode frequency and finally direction (mode shape), because in some cases, the direction in which it acts may coincide with friction locking mechanism or its deformation may cause collision with adjacent structures (i.e., adjacent PCBs components). This analysis considers the modes that are parallel to direction of the friction lock and the MPF at these modes. From this, the force response In-Plane (IP) with the PCB friction lock can be compared to the friction force holding the PCB in-situ. In summary, this method aims to determine if the PCB friction lock will be compromised by random vibration ASD load. Displacement and translation can cause a critical failure, especially for electronic systems that rely on a common backplane for interconnects. In the next section a proposed pass/fail criteria to determine if the friction lock joint will survive the random vibration acceleration load case is presented.

Method

The random vibration spectrum is non-deterministic but when analysed statistically over a period of time the g-RMS is constant and the likelihood of peaks (g) outside of the RMS are given by a Gaussian distribution (3σ). The random vibration spectrum is a base excitation to the hardware and typically ranges from 20-2000 Hz but allows for numerous frequencies to be excited at the same time. A conservative assumption for the analysis of PCBs within an electronic chassis is to assume no attenuation of the base excitation to the PCBs. However, it has been shown for shock inputs that structural discontinuities can significantly attenuate the shock pulse, this is known as the 3-joint rule [4]. For frequencies above 2000 Hz or for systems where the resonant frequencies are unknown, the RVLF can be approximated by multiplying the overall g-RMS by 3 (i.e. 3σ). Standard methods used to formulate the RVLF are based on the Miles Equation [1][5] where the base input amplitude is taken at the resonant frequency and the amplitude (g^2/Hz) is taken as a maximum value from the ASD plateau and considered constant across the entire frequency domain. This is over conservative unless the ASD is flat or within one octave either side of the resonant frequency [7] because typically the ASD plot has a ramp up (+3 dB) to the knee point and decline (-5 dB) after the plateau knee point (e.g. MIL-STL-1540C [6]) where levels are lower in these regions. A more accurate method would be to predict the resonant frequencies and MPF using modal FEA and, using Q (often estimated as Q = 20 or approximated using Q = $\sqrt{Fn_{PCB}}$) [3] calculate the g-RMS ($\ddot{X}_{g-RMS}$) using the following equation Eq 1.

$$\ddot{X}_{g-RMS} = 3\sigma. \sqrt{\sum_{i=1}^{N} \frac{\left[1+(2\xi(\frac{F_i}{Fn})^2\right]}{\left[1-(\frac{F_i}{Fn})^2\right]^2+\left[2\xi(\frac{F_i}{Fn})\right]^2}} \quad (1)$$

The derivation of this method, taken by others [5][7] and adapted for PCB friction lock compliance, is based on the system's response to a typical random vibration ASD. This method allows for the inclusion of the ASD amplitude to vary across the frequency range of interest, i.e. representing the ramp and declines typically found in random vibration ASDs. Once the g-RMS been calculated the total RVLF can be calculated using Eq 2:

$$RVLF = m.\left(MPF.\ddot{X}_{g-RMS,mode\ i} + ((1 - MPF).\ddot{X}_{g-RMS,ASD}\right) \quad (2)$$

Where; m = mass of PCB and PCB frame, MPF = MPF at resonant frequency of the system in direction of the friction lock, $X_{g\text{-RMS, mode i}}$ = g-RMS at resonant frequency using Q = 20, ξ=1/2Q, 3σ and $X_{RMS,\ spectrum}$ = g-RMS of overall spectrum multiplied by 3σ. The RVLF is an estimation of the forces acting on the PCB friction lock device in the direction of slippage due to the random vibration load case. The retention force (F_{max}) from a friction lock device (typical values NVENT CardLok systems F_{lock} = 400-3000 N) opposing this is Fmax and is calculated using Eq 3:

$$F_{max} = \mu.F_{lock}.number\ of\ friction\ lock\ devices \quad (3)$$

Friction coefficient (μ) is taken as 0.3 for static aluminum-aluminum interfaces [8]. Failure of the locking device is established when the RVLF exceeds the Fmax. A sample calculation is provided for the PCB and PCB frame in Fig. 1 against the random vibration ASD in Tab. 1. with g-RMS of 14.7 g. A modal FEA study of the assembly predicts an IP resonant frequency of 1318 Hz with an MPF of 0.2 %. This was the only significant mode within an order of magnitude below 2000 Hz.

Tab 1: Random vibration ASD used in study.

Frequency	**$g^{2/}$Hz**
20	0.08
100	0.4
300	0.4
2000	0.017

Results

This paper presents a methodology for the analysis of PCB and PCB frame assemblies that are fixed using friction lock devices against random vibration acceleration load case that are experienced during spacecraft launch. A sample calculation based on the assembly in Fig.1 is presented:

$$RVLF = 0.415 \times [(0.002 \times 120.8) + (0.998 \times 44.1)] = 18.35\,N \quad (4)$$

Where:
$M_{Frame+PCB} = 0.415$ kg
$MPF_1 = 0.002$ @ 1317.8 Hz
$X_{RMS,\ mode\ i} = 120.8$ g (3 σ and Q = 20), see Fig. 2 and Eq. 1, implemented using MS Excel
$X_{RMS,\ spectrum} = =14.7$ g-rms *3 σ = 44.1 g

As per Eq. 3, assuming the use of NVENT Schroff Series 48-5 (1418 N retention force each)

$$F_{max} = 0.3 \times 1481 \times 2 = 888.6\,N \quad (5)$$

Therefore: $M.o.S = \frac{888.6}{18.35} - 1 = 47.4$ (6)

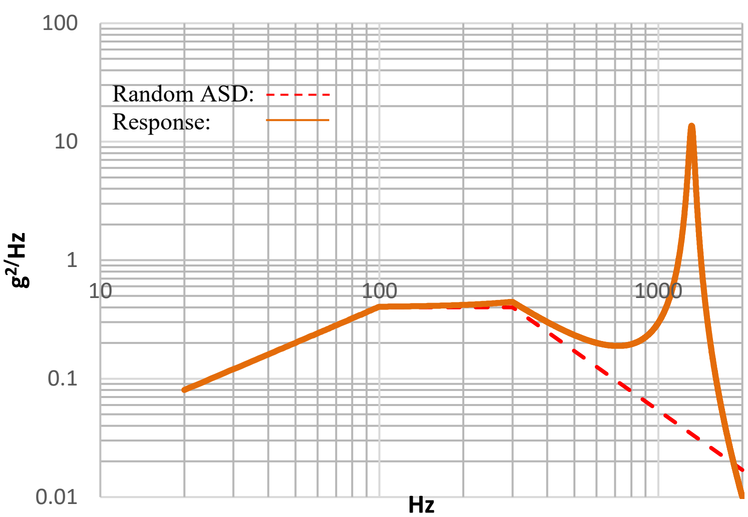

Fig 2: Random vibration ASD response based on Eq. 1 and resonant frequency of PCB assembly.

Conclusion

This research is based on flight hardware destined to be launched on the Ariane 6-2 in 2026 and is currently under development. The hardware has passed system qualification testing for acceleration load cases. The sample calculation shows very low force response acting on the PCB assembly IP (18.35 g) which is primarily due to the low MPF (0.2 %) within the ASD limit range (2000 Hz). It is also due to the vehicle IP random vibration requirements of 14.7 g-rms. The Out-of-Plane (OOP) is greater at 22.7 g-rms. Nevertheless, given the retention force of the NVENT product and excluding any Factors of Safety (FoS), Local Design Factors (LDF), Qualification Loads (QL), Design Loads (DL) etc., the MoS for slip is high at 47.4 and presents a low risk for movement or failure. This study would benefit from a more detailed validation of the PCB assembly modes by locally instrumenting low-mass triaxial accelerometers on PCB locations and spectra analysis of multiple accelerometers across the PCB which can allow for validation of the MPF and mode shapes. It is a laborious technique and one such example of this is presented by Sandia National Laboratories [9]. Furthermore, an experimental apparatus capable of measuring forces on such friction lock devices could be used to establish the random vibration ASD thresholds for slip and failure.

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