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OVERVIEW OF METHODS FOR ANALYZING MECHANICAL VIBRATIONS IN PCBS

BY

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Abstract. Mechanical vibrations play a critical role in the performance and long-term durability of electronic systems, especially printed circuit boards (PCBs) operating in harsh environments. This paper presents an overview of recent research focused on fatigue damage and remaining useful life (RUL) estimation of PCBs exposed to random and sinusoidal vibrations. Emphasis is placed on vibration testing and finite element analysis (FEA) as primary tools for evaluating the dynamic behavior of PCBs. Random vibration tests are examined for identifying natural frequencies and participation factors, while power spectral density (PSD) analysis is used to estimate stress levels and fatigue life of solder joints. Predictive models such as the Oh-Park method, Steinberg’s model, Kirchhoff plate theory, and the modal assurance criterion (MAC) are discussed. Finally, the study highlights the integration of these methods with industry standards like ISO-16750-3 and IPC-2221A to enhance mechanical reliability and guide robust PCB design practices under vibrational loading.

Keywords: Key words: printed circuit board, mechanical vibrations, fatigue life, power spectral density, finite element analysis.

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1. Introduction

Vibration represents one of the most critical mechanical phenomena affecting the performance, reliability, and lifespan of electronic systems, especially printed circuit boards (PCBs) that are widely used in various industrial and aerospace applications. Electronic components mounted on PCBs are continuously exposed to vibratory loads throughout their operational life, which can induce fatigue damage, solder joint failure, and eventual malfunction of the assembly (Kovtun, 2018; Park and Oh, 2021). Understanding the dynamic behavior of PCB assemblies under vibrational excitation is thus essential for designing robust electronic systems capable of withstanding harsh operating environments.

As described in the study by Cao (2023), modal analysis techniques provide valuable insight into the natural frequencies and mode shapes of PCBs, which are fundamental for identifying potential structural weaknesses. This knowledge supports the development of analytical and numerical models that predict the response of PCBs to different vibration spectra. Finite Element Analysis (FEA) has emerged as a reliable tool to simulate these vibrational responses, allowing detailed investigation of stress distribution and deformation patterns within the board and its components (Hegde *et al*., 2008; Kovtun *et al*., 2021). Random vibration testing, commonly employed in industry, simulates operational and environmental vibratory conditions to assess durability and estimate fatigue life. According to Al-Yafawi (2015), such tests combined with power spectral density (PSD) analysis enable evaluation of stress levels in solder joints, which are among the most vibration-sensitive parts of PCB assemblies. The correlation between experimental vibration tests and numerical simulations has been demonstrated to be strong in various studies (Grieu *et al*., 2008; Muhammad, 2020), providing confidence in these methods for reliability prediction.

Theoretical approaches based on Kirchhoff plate theory, as outlined by Steinberg (2000), facilitate rapid modeling of thin-plate vibration behavior typical of PCB substrates. Additionally, predictive models such as the Oh-Park method (Park and Oh, 2021) and Steinberg's vibration fatigue model (García *et al*., 2018) have been applied successfully to quantify damage risks and optimize PCB layouts for enhanced vibration resistance. The Modal Assurance Criterion (MAC) is widely used to validate numerical models by comparing mode shapes obtained from simulations with experimental modal testing data (Ren *et al*., 2014).

Furthermore, the integration of mechanical vibration analysis with industry standards like ISO-16750-3 and IPC-2221A is important for ensuring comprehensive PCB design guidelines are met. These standards specify critical parameters such as creepage distances, clearance, keep-out areas, and manufacturing tolerances, which directly influence vibration tolerance and

electrical performance (IPC-9701A, 2012; Kovtun, 2018). As emphasized by Park and Oh (2021), combining standards compliance with advanced simulation and testing methodologies leads to improved durability and reliability of electronic systems operating in complex vibratory environments.

This paper aims to synthesize the state-of-the-art research on vibration-induced fatigue and remaining useful life (RUL) estimation of PCBs, focusing on the methodologies for dynamic analysis and reliability assessment. By reviewing both simulation techniques and experimental procedures, it highlights the current capabilities and limitations in predicting PCB behavior under vibrational stress. This comprehensive approach intends to identify potential research gaps and provide guidance for future investigations aimed at enhancing the vibration robustness of electronic assemblies.

2. Theoretical Modeling of the PCBs

As mentioned in the introduction, one of the fundamental theories used to describe the vibrational behavior of printed circuit boards (PCBs) is the Kirchhoff Plate Theory (Kovtun, 2018; Suhir, 2000). This classical theory serves as a cornerstone for modeling the mechanical response of thin, elastic structures such as PCBs when subjected to vibrational or dynamic loading conditions. PCBs are typically treated as thin, homogeneous, isotropic rectangular plates–an assumption that significantly simplifies their dynamic analysis while still providing sufficient accuracy for engineering applications (Park and Oh, 2021; Ren *et al*., 2014).

According to Kirchhoff's assumptions, a plate is classified as *thin* if its thickness is small in comparison to its other dimensions (length and width). This allows for the neglect of shear deformation and rotary inertia, enabling a two-dimensional formulation of the bending problem.

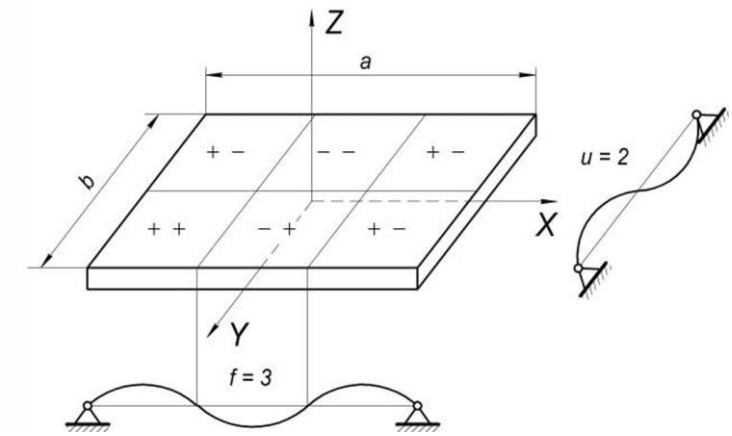


Fig. 1 − Plate deformation and oscillation forms (Kovtun *et al*., 2021).

The central surface (mid-plane) of the PCB is taken as the reference surface, with the X and Y axes lying within the plane and the Z-axis normal to it (see Fig. 1). A key hypothesis–known as the straight normal hypothesis–postulates that cross-sections initially perpendicular to the mid-surface remain so after deformation. This leads to coupled bending in both the XZ and YZ planes, capturing the dynamic flexure experienced by the board under operational stresses (Zhou and Qi, 2011).

The deflection of the mid-plane is represented by a displacement function w(x,y,t), which defines the vertical displacement of the PCB at any point in space and time. This displacement field is used to derive the governing differential equation for the free vibration of thin plates, known as the Kirchhoff–Love plate equation:

$$D\nabla^4 w\,(\mathrm{x,y,t}) + \rho h \frac{\partial^2 w(\mathrm{x,y,t})}{\partial \mathrm{t}^2} = q\,(\mathrm{x,y,t}) \tag{1}$$

where: w(x,y,t) - transverse displacement of the plate at point (x,y) at time t [m], D is the flexural rigidity of the plate [Nm] and is known as:

$$D = \frac{Eh^3}{12\,(1-\nu^2)} \tag{2}$$

where: E is Young's modulus [N/m²], h is plate thickness [m], v- Poisson's ratio, ρ -density of the plate material [kg/m³], $q(x,y,t)$ - external loading (force per unit area) [N/m²], ∇^4 - biharmonic operator defined as:

$$\nabla^4 = \frac{\partial^4}{\partial \mathrm{x}^4} + 2\,\frac{\partial^4}{\partial \mathrm{x}^2\,\partial \mathrm{y}^2} + \frac{\partial^4}{\partial \mathrm{y}^4} \tag{3}$$

The validity and applicability of the Kirchhoff Plate Theory for modeling the dynamic behavior of printed circuit boards (PCBs) have been confirmed through numerous comparative studies involving analytical, numerical, and experimental methods (De Clerck and Epp, 2016; Bao *et al*., 2009). In particular, experimental modal analyses using techniques such as hammer excitation have shown that the natural frequencies and corresponding mode shapes obtained from testing align closely with finite element simulations, with reported frequency discrepancies typically remaining within a 5–6% margin (Karthiheyan *et al*., 2020).

This high level of correlation underscores the theory's ability to accurately predict dynamic responses of PCBs, enabling engineers to identify critical resonant frequencies that may trigger fatigue failure or degradation of solder joints and surface-mounted components (Grieu *et al*., 2008; Kim and Hwang, 2015). By anticipating such vibration-sensitive areas, design

interventions can be implemented early in the product development cycle to mitigate long-term reliability risks.

Furthermore, the integration of Kirchhoff Plate Theory with validation techniques like the Modal Assurance Criterion (MAC) strengthens the reliability of simulation outputs by quantitatively assessing the degree of correlation between measured and computed mode shapes (Yang *et al*., 2000). This provides a structured methodology for verifying simulation accuracy in both academic and industrial applications.

In conclusion, the Kirchhoff Plate Theory, when applied in conjunction with validated simulation and experimental methods, offers a comprehensive analytical platform for investigating the vibrational characteristics of PCB assemblies. Its ability to accurately model plate deformation and resonate behavior underpins its continued relevance in the reliability assessment and mechanical design optimization of electronics used in high-stress environments (Al-Yafawi, 2015; Liu *et al*., 2020).

3. Materials and Methods

The vibrational behavior and structural integrity of printed circuit boards (PCBs) subjected to mechanical loads such as shock and random vibration are critical for ensuring system reliability, especially in high-performance electronic equipment. A variety of analytical and experimental methods are employed to evaluate how PCBs respond to these dynamic loads, allowing for prediction of failure zones, validation of structural models, and refinement of design to extend service life. Among the most commonly used techniques are the Modal Assurance Criterion (MAC), Kirchhoff Plate Theory, the Steinberg Method, the Oh-Park Method, Remaining Useful Life (RUL) estimation, gRMS analysis, and the calculation of the Margin of Safety (MoS).

One of the most effective methods for validating the correlation between numerical and experimental modal analyses is the Modal Assurance Criterion (MAC), which quantifies the similarity between mode shapes generated through simulation and those obtained from physical testing. MAC values range between 0 and 1, where values above 0.9 are considered indicative of strong agreement (Yang *et al*., 2000; Bao *et al*., 2009). This makes the MAC a critical metric for ensuring that finite element analysis (FEA) models accurately replicate real-world dynamic behavior.

Modern electronics are increasingly vulnerable to vibration-induced failures due to miniaturization, packaging complexity, and environmental stressors. Studies report that vibration-related factors account for nearly 28% of all electronic product failures (Al-Yafawi, 2015). Therefore, understanding the vibrational characteristics of PCBs is essential for improving operational resilience and extending device longevity.

In a comprehensive study by Cao (2023), the vibration behavior of a servo controller PCB was investigated using a hybrid approach combining finite element modal simulation with experimental testing via the impact hammer method. The objective was to compare natural frequencies and mode shapes between the two methods using MAC values as a validation metric. The results are summarized in Table 1.

Table 1
MAC Results for First Three Vibration Modes

Mode	Simulated Frequency (Hz)	Measured Frequency (Hz)	Frequency Error (%)	MAC Number
1	280	282	-0.71	0.99
2	516	521	-0.96	0.98
3	755	757	-0.26	0.94

The data in Table 1 reveal that the differences between simulated and measured natural frequencies for the first three modes were all under 1%, while the MAC values exceeded 0.94. These results confirm a high level of correlation between experimental and simulated mode shapes, thereby validating the accuracy of the numerical model used. This tight correlation also confirms that the FEA model can reliably capture the real vibrational characteristics of the PCB under test conditions. As highlighted by Cao (2023) and further supported by De Clerck and Epp (2016), such agreement is vital for building trust in simulation tools used in electronic design.

When a PCB is subjected to dynamic excitation near its natural frequency, the amplification of structural response may lead to fatigue damage, solder joint cracks, and component detachment. These effects are particularly severe in regions with concentrated mass or geometric discontinuities, which alter the local stiffness and contribute to non-uniform vibration modes (Karthiheyan *et al*., 2020; Kim and Hwang, 2015). In the studied PCB, the highest modal responses were observed in areas near large components and connector interfaces, aligning with these theoretical expectations.

The study concluded that validated FEA models, corroborated through experimental MAC analysis, provide a dependable basis for assessing PCB vibration behavior. This enables engineers to make informed decisions in the early design phase, reducing the need for costly physical prototypes and minimizing the risk of in-service failures.

The Steinberg Method is a widely adopted approach for assessing the durability of printed circuit boards (PCBs) and electronic components subjected to vibration and shock loads. This method focuses on estimating key mechanical responses of the PCB–such as natural frequencies, deflections, and stresses–to evaluate and enhance the mechanical reliability of the board.

Numerous studies have successfully applied the Steinberg Method to predict the fatigue life of electronic components, particularly within the context of reliability analysis for PCBs under random vibration loading (Steinberg, 2000; Karthiheyan *et al*., 2020).

One notable study combined finite element modeling (FEM) with experimental validation to assess the durability of solder joints under vibration conditions (Al-Yafawi, 2015; Grieu *et al*., 2008). The finite element model of the test vehicle was developed using ANSYS software and validated by correlating the natural frequencies, mode shapes, and transmissibility functions from simulation with experimental data (Ren *et al*., 2014; Cao, 2023). This validation was crucial for ensuring the simulation results accurately reflected real-world behavior. Once validated, the model was used to simulate both sinusoidal and random vibration tests, helping to identify critical stress locations on the PCB, especially at solder interconnects.

The simulation results exhibited a strong correlation with experimental observations, with Modal Assurance Criterion (MAC) values consistently exceeding 0.94, indicating close agreement between simulated and experimental mode shapes (Kim and Hwang, 2015; Zhou and Liu, 2016). These findings demonstrate that finite element modeling combined with the Steinberg Method is a reliable approach for predicting fatigue life and evaluating PCB reliability under vibration.

Another study applied Steinberg's three-band method to predict the fatigue life of SAC305 solder material under random vibration (Bao *et al*., 2009; Xia *et al*., 2017). Using the 1-σ stress values extracted from the ANSYS post-processor, the fatigue life of the solder joint was calculated. The predicted fatigue life values closely matched experimental results, with a coefficient of determination R^2 of 0.97, confirming an excellent fit between model predictions and observed data (Muhammad, 2020; Park, 2021).

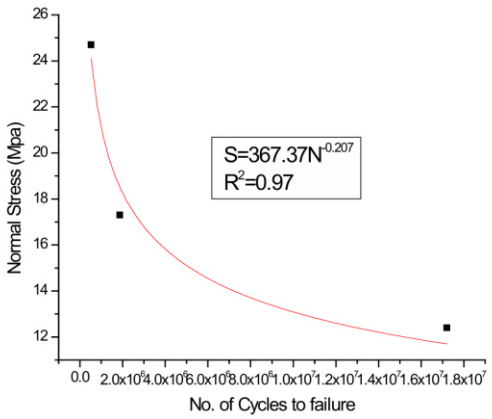


Fig. 2 − Plate deformation and oscillation forms (Steinberg, 2000; Suhir, 2000).

In Fig. 2, the graph of normal stress versus frequency bands is presented, showing the plate deformation and oscillation forms that characterize the PCB's dynamic response under vibration loading.

This figure highlights how stress varies across frequency bands and identifies critical areas prone to fatigue damage. The study showed that the first natural frequency caused the highest stress, resulting in the most significant fatigue damage. This emphasizes the importance of avoiding resonance frequencies during PCB design to improve component longevity (Steinberg, 2000; Suhir, 2000). Higher frequency bands led to reduced fatigue life due to increased stress concentration.

The results show that the first natural frequency induces the highest stress, leading to the most significant fatigue damage. Additionally, higher frequency bands cause increased stress concentration, which corresponds to a reduced fatigue life. These findings are quantitatively summarized in Table 2, which presents the predicted and observed fatigue life values across different frequency bands along with the percentage error between them. The close agreement between predicted and observed fatigue life, with errors all below 5%, further validates the accuracy and reliability of the Steinberg Method for fatigue life estimation under random vibration loading.

Table 2
The fatigue life calculations for different frequency

Frequency Band	Predicted Fatigue Life (hrs)	Observed Fatigue Life (hrs)	Error (%)
Low	4.5	4.7	-4.2
Medium	2.1	2.2	-4.5
High	0.8	0.82	-2.4

Overall, these studies confirm that the Steinberg Method, when integrated with finite element modeling and experimental validation, offers a robust and reliable framework for understanding the dynamic response and predicting the fatigue life of PCBs under random vibration loading. By identifying critical stress concentration areas, such as corner solder balls, designers can target these regions for durability improvements. Moreover, these studies highlight the critical role of resonance avoidance and suggest that adjusting PCB design to shift natural frequencies can substantially enhance the overall reliability and lifespan of electronic components (Xu, 2010).

The Oh-Park Method represents an advanced analytical approach that integrates vibration response analysis with probabilistic fatigue life modeling to evaluate the structural integrity and reliability of printed circuit boards (PCBs) and electronic assemblies (Yunxia *et al*., 2019). Unlike traditional deterministic methods, this approach enables a more accurate prediction of fatigue damage

under random vibration environments, particularly in high-reliability sectors such as aerospace and defense electronics (Park and Oh, 2021).

The methodology comprises several key computational components. First, Power Spectral Density (PSD) is used to quantify the distribution of vibrational energy across frequency bands, enabling a realistic characterization of the excitation input. Next, the vibrational response of the PCB is analyzed to identify critical resonance frequencies where amplification effects can endanger solder joint reliability. This is followed by detailed stress and deflection analysis, where mechanical responses such as strain, displacement, and Von Mises stress are calculated based on material properties and the structural configuration of the board. Based on this, fatigue life estimation is carried out using cumulative damage models that incorporate the actual vibration duration and stress amplitude. Finally, the reliability assessment is completed by calculating the probability of failure and defining a suitable margin of safety (MoS) with respect to observed strain levels (Park and Oh, 2021).

The study employing the Oh-Park methodology developed a novel strain-based structural design technique to improve upon the limitations of conventional vibration assessment models such as Steinberg's theory (Steinberg, 2000). One of the key limitations of Steinberg's approach is its assumption of a high-cycle fatigue threshold (e.g., 2 × 10^7 cycles), which often introduces excessive conservatism, especially in short-duration environments like rocket launch vibrations (Karthiheyan *et al*., 2020). In contrast, the Oh-Park method allows for realistic vibration exposure durations, improving both the accuracy and efficiency of the design process.

To validate the methodology, a series of experimental tests were conducted using PCBs mounted with different types of components, including PBGA388 and TSSOP48 packages (Perkins and Sitaraman, 2004; Liu *et al*., 2022.).

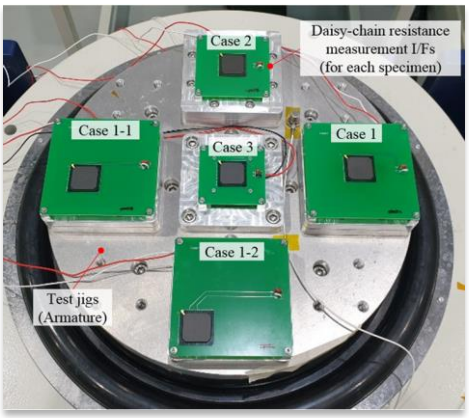


Fig. 3 − Fatigue life test setup for a set of PCBs (Park and Oh, 2021).

These assemblies were subjected to controlled random vibration conditions, and the time to failure (TTF) of the solder joints was monitored. The test setup is illustrated in Fig. 3, showing the mechanical fixture and accelerometer placement used during experimentation (Park and Oh, 2021).

The experimental data were used to calculate the estimated damage factor (DF) for various resonance frequencies, denoted as f_n. The relationship between DF and the estimated TTF for different modal frequencies is presented in Fig. 4, which highlights how changes in natural frequency affect the fatigue performance of solder joints under vibrational loading. The results showed that lower mode frequencies (typically the first mode) result in higher DF values, indicating increased vulnerability to fatigue failure.

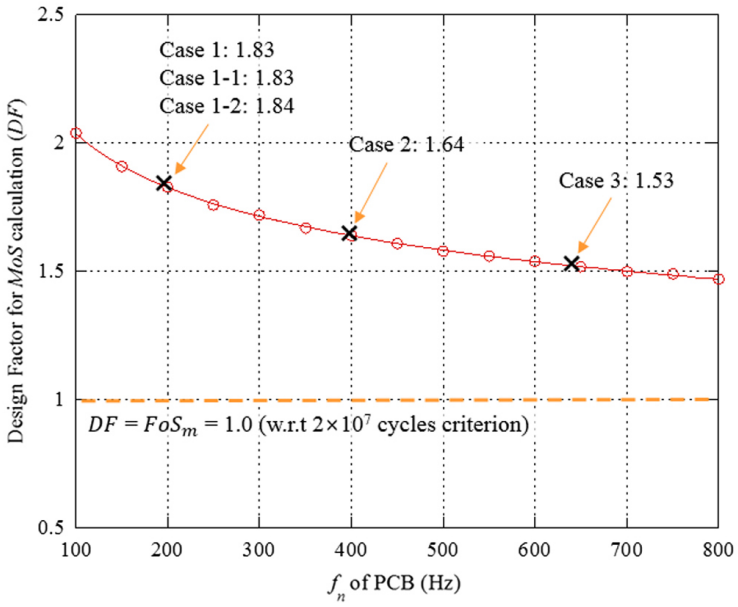


Fig. 4 − Estimated DF for estimated TTFreq as a function of.fn (Park and Oh, 2021).

A comparative analysis was performed between the predicted time to failure (TTF_pred) using both the Oh-Park methodology and Steinberg's model and the actual experimental failure times (TTF_test). As shown in Fig. 5, the Oh-Park predictions closely matched the experimental results, outperforming Steinberg's method in terms of accuracy and consistency across different board configurations.

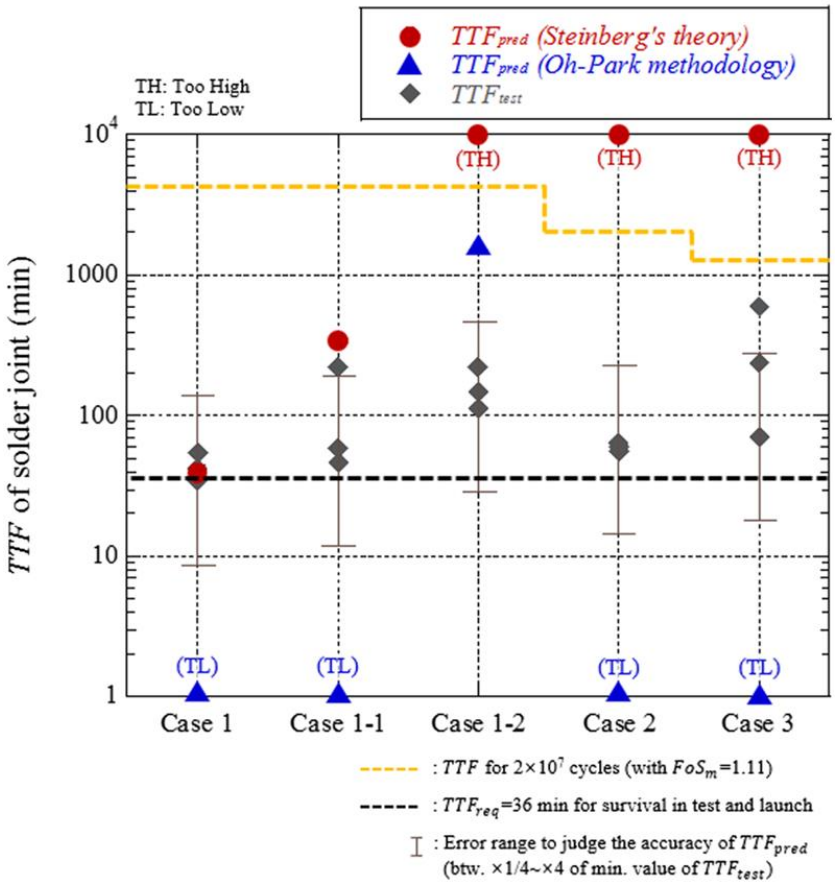


Fig. 5 − Comparison between TTFtest and TTFpred calculated by methodologies (Park and Oh, 2021).

These findings are quantitatively summarized in Table 3, which presents the comparison between Oh-Park and Steinberg's methods based on critical evaluation criteria, including prediction accuracy, strain-based modeling capability, and suitability for short-duration vibration exposures. The Oh-Park methodology demonstrated a significant reduction in design conservatism while maintaining high reliability predictions, thereby offering a practical and more precise tool for spaceborne electronics design.

Additionally, the Oh-Park methodology emphasizes the importance of critical strain theory, which calculates the margin of safety (MoS) using strain amplitude and duration rather than simplified stress limits. This strain-based criterion is more suitable for aerospace applications, where solder joints are subject to short, high-energy vibration events. The study also investigates the impact of boundary conditions–such as mechanical constraints introduced by

screws or connectors–which can significantly influence strain distribution and fatigue behavior (Liu *et al*., 2020).

Overall, the validation experiments and comparative analysis confirmed that the Oh-Park methodology is more reliable than traditional approaches for predicting the mechanical failure of solder joints under realistic random vibration profiles. The method enables rapid simulation using simplified finite element modeling (FEM), reducing computational effort while improving design robustness. As a result, it is considered a viable structural design approach for enhancing the mechanical integrity of spaceborne electronics and other mission-critical systems exposed to dynamic mechanical loads.

Table 3

Comparison between Oh-Park methodology and Steinberg's theory

Case	Method	FoSm (TTFreq)	MoS (TTFreq)	MoS (FoSm = 1.11)
1	Oh-Park	0.542	0.70	0.86
	Steinberg	0.542	0.02	0.50
1–1	Oh-Park	0.543	0.67	0.84
	Steinberg	0.543	0.43	0.30
1–2	Oh-Park	0.545	0.83	0.10
	Steinberg	0.545	7.21	3.03
2	Oh-Park	0.599	0.71	0.84
	Steinberg	0.599	2.44	0.86
3	Oh-Park	0.640	0.67	0.81
	Steinberg	0.640	7.52	3.91

In Table 3, a comparative analysis is presented between the Oh-Park methodology and Steinberg's theory, focusing on the Margin of Safety (MoS) and the Factor of Safety margin (FoSm) for several test cases involving the PBGA388 package, calculated using Type 1 FEM simulations. The table includes values of FoSm (for a fixed vibration time of TTFreq = 35.2 minutes), as well as MoS values corresponding to both this fixed duration and a standardized FoSm value of 1.11.

The Oh-Park method, based on critical strain theory and incorporating real vibrational strain data and boundary constraints, more accurately represents real-world conditions encountered during spaceborne launch events. Its predictions align closely with experimental results from validation tests, confirming its reliability and precision (Park and Oh, 2021). Moreover, this method allows for rapid safety evaluation through simplified FEM analysis, significantly optimizing the structural design process for electronic components subjected to launch vibrations. As such, it provides a better foundation for fatigue life prediction and safety assurance in aerospace electronics, especially

where traditional methods like Steinberg's tend to apply overly conservative or unrealistic margins (Park and Oh, 2021).

4. Reliability Tests for PCBs

Reliability testing of printed circuit boards (PCBs) includes the critical task of estimating the Remaining Useful Life (RUL), which is a key concept in predictive maintenance. RUL represents the estimated duration that a component or system can continue to operate before failure occurs. For PCBs, this estimation specifically concerns the lifespan of electronic solder joints and other critical components, accounting for the cumulative stresses experienced during storage, transport, and operational use. Accurately predicting RUL enables better maintenance planning, reduces unexpected downtime, and improves overall system reliability (Jiao *et al*., 2019).

The estimation process involves analyzing the equipment's operational history, considering environmental factors such as vibration, temperature, humidity, and mechanical stresses, and applying statistical or machine learning models to assess failure probabilities. In PCB applications, particularly under rugged conditions such as automotive environments, RUL estimation is essential to predict failures caused by solder joint fatigue resulting from random vibrations (Veprik, 2003; Pippola *et al*., 2014).

To simulate the vibrational stresses, PCBs are typically mounted either directly or via vibration fixtures onto shaker tables. These vibration tests can be sinusoidal or random, with the power spectral density (PSD) function used to characterize how vibration energy is distributed across frequency ranges. Time compression techniques using PSD data for both testing and real-world conditions help translate test results into meaningful life predictions. The sine and random vibration tests serve to detect design weaknesses, manufacturing quality issues, and component durability by applying controlled vibration stresses to individual PCB components. Stress and failure analyses conducted during these tests provide valuable insights into improving both component and product reliability, identifying failure mechanisms, and supporting prognostic health monitoring systems (Zhou *et al*., 2011; Pippola *et al*., 2014).

The methodology presented for assessing fatigue damage and estimating RUL in power distribution modules exposed to random vibrations integrates vibration testing with finite element analysis (FEA). Initially, a sine sweep test determines the module's resonant frequencies and transmissibility characteristics. Subsequently, a random vibration test, conducted in compliance with relevant standards, evaluates fatigue-induced failure potential. FEA validates the dynamic behavior of the module by identifying mode shapes, natural frequencies, and participation factors, which align well with experimental data. Additionally, spectrum analysis yields PSD acceleration and stress response values at critical solder joints, confirming the resonant

frequencies and transmissibility findings derived from empirical tests (Zhou *et al*., 2011).

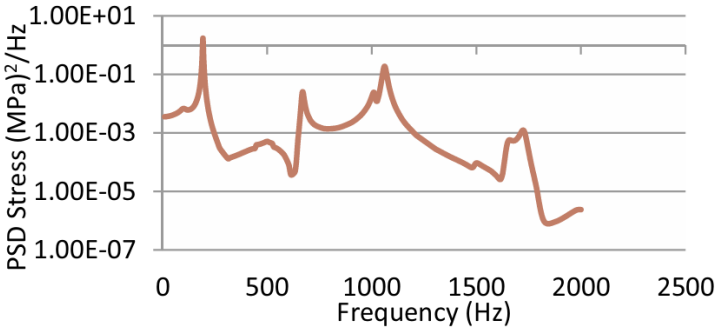


Fig. 6 − Response PSD stress at solder joint node (Muhammad, 2020).

Fig. 6 illustrates the response PSD stress at a solder joint node, highlighting the vibrational stress distribution during testing (Muhammad, 2020). Numerical calculations estimate the fatigue life of solder joints in the capacitor region at approximately 50 minutes, which closely matches the 40-minute failure time observed experimentally. This correlation supports the reliability of RUL predictions for the product. The results further confirm that after five years of operational use, the PCB exhibits no significant damage, thereby validating an estimated remaining life of around 15 years. These findings demonstrate the robustness of both storage and operating conditions as well as the quality of the manufacturing and soldering processes. Consequently, the PCB is expected to reliably meet a total service life of 20 years under typical operational conditions.

This study reinforces the importance of combining experimental vibration testing with numerical analysis to accurately predict PCB durability and improve reliability management in critical electronic systems (Muhammad, 2020).

5. Critical Analysis and Potential Improvements of the Methods

Integrating RUL and PSD analysis with methods like Oh-Park, Steinberg, MAC, and Kirchhoff plate theory can be further enhanced by aligning them with established PCB design and reliability standards such as ISO-16750-3 and IPC-2221A. These standards provide comprehensive guidelines on how to design PCBs for durability and performance under mechanical and environmental stress, including vibration, thermal cycling, and humidity. Combining these theoretical and analytical methods with practical design constraints ensures that the PCB not only performs well under test

conditions but also meets industry best practices for reliability and manufacturability.

ISO-16750-3 focuses on environmental conditions and mechanical testing, including vibration testing, for electronic equipment used in road vehicles. It defines vibration profiles, PSD levels, and test durations for simulating real-world conditions. By correlating PSD data and RUL estimation with the stress levels outlined in ISO-16750-3, designers can ensure that the PCB is capable of withstanding the specific vibration spectra it will encounter in its operational environment. For example, the Oh-Park and Steinberg methods can be used to fine-tune component placement and solder joint design to minimize resonance at the critical frequencies defined by the ISO standard (Park and Oh, 2021; Steinberg, 2000).

The IPC-2221A Generic Standard on Printed Board Design provides fundamental guidelines for PCB layout, materials, and design rules to ensure manufacturability and long-term reliability. One critical aspect of IPC-2221A is the specification of creepage and clearance distances to prevent electrical breakdown and arcing under high voltage or humid conditions. When combined with RUL and vibration analysis, these rules help avoid failure caused by electrical discharge or insulation breakdown due to mechanical deformation under vibration (IPC, 2012). For instance, ensuring adequate clearance around high-stress solder joints can prevent micro-cracks and shorts caused by mechanical fatigue. In terms of keep-out areas and component placement, IPC-2221A specifies minimum distances between components to account for thermal expansion and mechanical stress. Vibration testing results from the PSD and Oh-Park methods can help identify areas of high stress or resonance on the PCB. By adjusting keep-out zones and redistributing components based on vibration nodes identified through MAC analysis, designers can reduce mechanical coupling and prevent resonance buildup, thereby increasing PCB resilience to mechanical shock and vibration (Kovtun, 2018; Cao, 2023).

Tolerances specified in IPC-2221A, such as trace width, hole size, and pad alignment, are critical to ensuring consistent manufacturing and long-term mechanical integrity. When combined with Steinberg's and Kirchhoff plate theory, which predict the mechanical response of the PCB under vibration, designers can adjust these tolerances to reduce stress concentration points and enhance fatigue resistance. For example, using tighter tolerances for high-stress solder joints or reinforcing critical vias based on stress analysis results can significantly increase PCB fatigue life (Karthiheyan *et al*., 2020; Park, 2021).

Moreover, PCB designers often face trade-offs between structural integrity and flexibility. Kirchhoff plate theory helps model how the PCB will bend under mechanical stress, while Steinberg's method predicts stress on solder joints. Aligning these predictions with IPC-2221A's rules on PCB thickness, laminate material, and copper weight enables designers to optimize

mechanical properties of the board without compromising electrical performance or manufacturability (García *et al*., 2018; Kovtun, 2018).

By aligning the predictive insights from RUL, PSD, and analytical methods like Oh-Park and Steinberg with design rules from ISO-16750-3 and IPC-2221A, designers can create PCBs structurally optimized for vibration resistance and operational durability. This leads to more robust designs that meet functional and reliability standards while minimizing early failure risk due to mechanical fatigue and environmental stress (Muhammad, 2020; Al-Yafawi, 2015).

6. Conclusions

This study demonstrates that integrating vibration analysis methods–such as Oh-Park, Steinberg, MAC, and Kirchhoff plate theory–with industry standards ISO-16750-3 and IPC-2221A significantly improves the reliability assessment of PCBs under mechanical stress. The combined predictive and experimental approach effectively identifies critical vibration modes and stress points, enabling optimized PCB designs that enhance fatigue life and operational durability. Accurate estimation of the remaining useful life (RUL) using PSD-based fatigue models further supports proactive maintenance and reliability planning. Future research should focus on refining these predictive models by incorporating more complex boundary conditions and material behaviors, expanding experimental validation under diverse environmental conditions, and integrating advanced data-driven methods for improved RUL prediction accuracy. Harmonizing these improvements with evolving industry standards will ensure ongoing relevance and robustness in PCB design for vibration-prone applications.

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PREZENTARE GENERALĂ A METODELOR DE ANALIZĂ A VIBRAȚIILOR MECANICE ÎN PLĂCILE DE CIRCUIT IMPRIMAT (PCB-URI)

(Rezumat)

Vibrațiile mecanice joacă un rol esențial în performanța și durabilitatea pe termen lung a sistemelor electronice, în special a plăcilor de circuit imprimat (PCB-uri) care funcționează în medii dificile. Această lucrare prezintă o privire de ansamblu asupra cercetărilor recente axate pe deteriorarea prin oboseală și estimarea duratei de viață utile rămase (RUL) a PCB-urilor expuse la vibrații aleatorii și sinusoidale.

Se pune accent pe testarea vibrațiilor și analiza cu elemente finite (FEA) ca instrumente principale pentru evaluarea comportamentului dinamic al PCB-urilor. Testele de vibrații aleatorii sunt analizate pentru identificarea frecvențelor naturale și a factorilor de participare, în timp ce analiza densității spectrale de putere (PSD) este utilizată pentru estimarea nivelurilor de tensiune și a duratei de viață prin oboseală a îmbinărilor de lipire.

S-au studiat modele predictive precum metoda Oh-Park, modelul Steinberg, teoria plăcii Kirchhoff și criteriul de asigurare modală (MAC). În final, studiul evidențiază integrarea acestor metode cu standarde industriale precum ISO-16750-3 și IPC-2221A, pentru a îmbunătăți fiabilitatea mecanică și a ghida practicile robuste de proiectare a PCB-urilor supuse solicitărilor vibratoare.