Online Model-based Structural Damage Detection in Electronic Assemblies

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ABSTRACT

Electronic assemblies are subjected to damaging impact and shock loadings in various scenarios, including aerospace, automotive, and military applications. In safety-critical situations, the online detection, quantification, and localization of damage within the electronic assembly would enable intelligent systems to take corrective actions to mitigate or circumvent the effects of damage within the electronic assemblies. This preliminary work investigates a reduced-order model-based method for online damage detection, quantification, and localization of printed circuit boards (PCBs). The local eigenvalue modification procedure (LEMP) is used to accelerate the computational processing time of the model, thereby enabling its use in online damage detection during an impact or shock event. The proposed method tracks changes in the model's state using an error minimization technique in the frequency domain. A baseline state is established by creating and simulating a numerical model that accurately represents a healthy PCB response. Potential reduced-order models with varying stiffness matrices are developed online and compared to the system's current state. These reduced-order models introduce a single change in stiffness to the system. LEMP calculates the overall change in the system to obtain the new system-level dynamic response. Incorporating LEMP within the frequency-based analysis demonstrates the potential for effective damage detection on PCBs. This work validates the proposed methodology using a rectangular PCB with induced damage. The PCB is modeled pinned at each corner, and its dynamic response is simulated using ABAQUS and processed with the generalized eigenvalue procedure. LEMP is used to update a single change in the system while obtaining a 587 times speed up when compared to the generalized eigenvalue approach. The LEMP algorithm performance and reliability for updating the model state are discussed in the paper.

Keywords: finite element method, model updating, frequency analysis, damage detection

1. INTRODUCTION

In electronic assemblies utilized across critical sectors such as aerospace, automotive, and military, the integrity of printed circuit boards (PCBs) is paramount. Electronic assemblies, intricate in design and vital in function, are frequently exposed to harsh conditions that may precipitate impact and shock loadings.[1] The consequences of such stressors can be catastrophic, particularly in safety-critical applications where the failure of an electronic component could result in severe outcomes. The ability to detect, quantify, and localize damage within an electronic assembly in real-time could dramatically enhance the resilience and reliability of these systems.[2,3] By facilitating immediate corrective actions, such an online detection system would act as a guardian, mitigating the ramifications of any inflicted damage. This work delves into the preliminary stages of the reduced-order model-based method for online damage detection for PCBs. The research gap identified by this study revolves around the lack of methods that can perform real-time model updating with the requisite speed and accuracy in an online setting, particularly for PCBs subjected to shock and impulse loading.[4]

Tracking a structure's state online and in real-time will be crucial for maintaining safety and stability in next-generation active structures;[5,6] particularly when exposed to changing loads and unpredictable environmental

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factors. Real-time structural tracking can follow a data-driven methodology or rely on model-based strategies. An introductory investigation into real-time high-rate state estimation was demonstrated by Hong et al.[7] In the context of this work, high-rate is defined as a rapid (> 100 ms) change in response behaviors of a system when subjected to events such as blasts or impacts depicted here by a change in mass and stiffness. Similarly, Downey et al[8] applied a model-based technique to update the status of rapid dynamic events observed in the DROPBEAR experimental setup model as a 1D system and achieved a model update every 4.04 ms with an accuracy of 2.9%.

The local eigenvalue modification procedure (LEMP) offers a computationally efficient method to perform Structural Dynamic Modification (SDM).[9] By analyzing its dynamic behavior, SDM has traditionally been used as a tool for engineers and researchers to discern the impact of alterations in a system's physical properties—such as mass, stiffness, or damping. LEMP introduces a more efficient approach by narrowing the focus to the most relevant vibrational modes. One of the compelling advantages of LEMP is its ability to cut down computation times drastically. By circumventing the need to solve the generalized eigenvalue problem, LEMP enables a swift prediction of the structure's dynamic response to modifications.[10] Ogunniyi et al. have proposed the use of LEMP for real-time applications by developing a computing module designed for high-speed model updating on 1D[11] and 2D[12] system, achieving latency requirements—as tight as one millisecond for a Finite Element (FE) derived model with 121 nodes.

The study focuses on a PCB tailored to the recommended standard, without any electronic packages, and subjected to modal analysis through the FE method. In the Finite Element Analysis (FEA), ABAQUS software is used to model the entire PCB, extracting natural frequencies and mode shapes from this model for the PCB's baseline (without damage) model and a second model of the PCB with nodal decreased stiffness to represent damage. For the PCB model, a single alteration stiffness within the system is added, and the resulting change in the system is calculated using generalized eigenvalue (GE) and LEMP. The work showed that LEMP could calculate the overall change and deduce a new system-level dynamic response with a similar level of accuracy as the GE and with faster model updating time. The contributions of this work are 1) FEA of a standard PCB, 2) implementing LEMP to solve for a single change in the system, and 3) evaluation of the performance of LEMP against GE using the error and time as criteria.

2. METHODOLOGY

The PCB's FE model was developed using the ABAQUS CAE 2021 tool. The design of the PCB for this investigation is based on the standard PCB layout, consisting of a rectangular board with a length and width of 76 mm and 38 mm, respectively, with a thickness of 1.6 mm. For this study, No electronic modules were mounted on the PCB. The mesh PCB profile for the baseline state (healthy PCB) is depicted in Figure 1(a). For this study, the PCB was constrained for displacement and rotation on all four corners. The healthy PCB was meshed with 50 elements, corresponding to 66 nodes and a matrix size of 396 × 396.

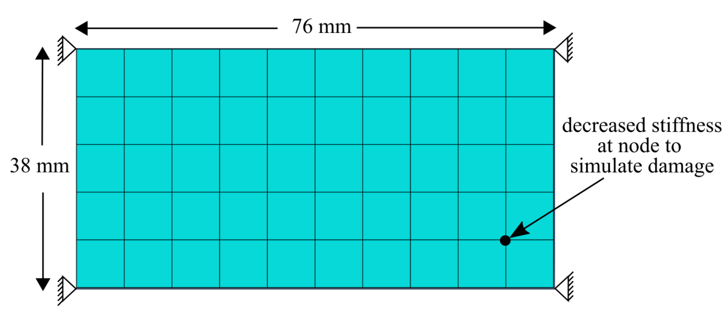


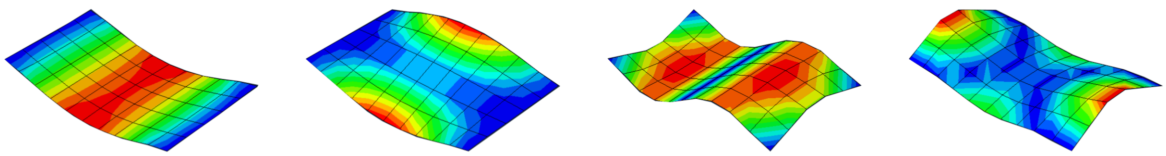
Figure 1. FE mesh profile, showing the baseline state (healthy PCB)

A critical premise for conducting modal analysis using the FE method is the consideration that it exhibits linear isotropic behavior. This assumption is fundamental as it allows for treating the system as linear, a necessary condition for the execution of modal analysis. Table 1 presents the material properties of the PCB used to define the model.

Table 1. Material properties used to model the PCB.

Component	Poisson's ratio, ν	Young's modulus, E (Pa)	density, ρ (kg/m^3)	thickness (m)	length (m)	width (m)
PCB	0.35	1.7 e10	2200	0.00159	0.0762	0.0381

The maximum frequency of analysis was set to 10000 Hz, and the first vibrating frequency was found to be in mode 1 at 484.15 Hz. Mode 1 to 17 fall under the 10000 Hz maximum frequency set in the analysis. Figure 2(a)-(d) shows the vibrating mode 1-14 for the baseline state (without damage) of the PCB while the modal frequencies presented in Table 2 show vibrating frequencies of the first four modes in Figure 2(a)-(d).



(a) (b) (c) (d)

Figure 2. Vibration mode shapes from the finite element analysis of the PCB where (a) is first mode; (b) second mode; (c) third mode, and; (d) fourth mode.

Table 2. Frequency of vibration from FEA of the PCB.

mode	frequency (Hz)
1	484.15
2	1094.7
3	1542.1
4	2396.5

3. RESULTS

From the finite element analysis carried out in section 2 using ABAQUS, the mass (M) and stiffness (K) matrices were extracted from the model results. The extracted M and K matrices were solved using the GE procedure detailed in Downey et al.[8] to obtain the eigenvalues and eigenvectors of the vibrating PCB. The corresponding frequencies for each mode are calculated from the eigenvalues and tabulated in Table 3, representing the frequencies of the initial PCB.

Table 3. Showing frequencies obtained using FEA and GE, and the corresponding single state change frequencies computed using GE and LEMP for the PCB.

mode	PCB					
	initial state		error (Hz)	final state		error(Hz)
	FEA	GE		single change with GE	single change with LEMP	
1	484.15	799.66	315.51	97.333	192.70	95.367
2	1094.7	958.00	136.70	291.45	292.65	1.2000
3	1542.1	2141.1	599.00	1121.4	1625.3	503.87
4	2396.5	2310.9	85.600	2613.4	2675.8	62.400
5	2607.3	3446.0	838.70	2741.6	2756.6	15.000
6	3120.4	3807.8	687.40	3957.3	4059.4	102.10
7	4150.4	4012.9	137.50	4556.6	4351.3	205.30
8	4841.7	4845.8	4.1000	6547.2	6582.4	35.20
9	5125.3	5551.1	425.80	8470.4	8171.5	298.90
10	6113.7	6277.2	163.50	9632.9	9738.6	105.70

Figure 3(a) graphically presents the vibration frequency for modes 1-10 obtained from the FEA and GE methods and the error between the two approaches. The finite element analysis and the generalized eigenvalue procedure produce increasing frequencies for higher modes, typical behavior for structural dynamic analyses. The frequencies obtained from both methods are quite close, as indicated by the proximity of the two lines representing them. However, there are discrepancies, as shown by the error line. The error could be due to the difference between the numerical methods and algorithms used to solve the finite element analysis and generalized eigenvalue problems, which can also introduce errors, especially as the frequency increases and the calculations become more complex.

Figure 3(b) depicts the data from a single state change from the initial state presented in Table 3. The single change in the system is achieved by decreasing a single node stiffness by a large number (10e100) and computing the final state frequencies using GE and LEMP. The updated stiffness on the undamaged PCB by GE and LEMP are significantly similar, with low errors in each vibrating mode. Even though the two methods achieved similar results, the first vibration mode frequency was solved at 270 ms via GE and 0.46 ms through LEMP. The 587X speedup in timing suggests a preference for using LEMP modal updating for more nodes.

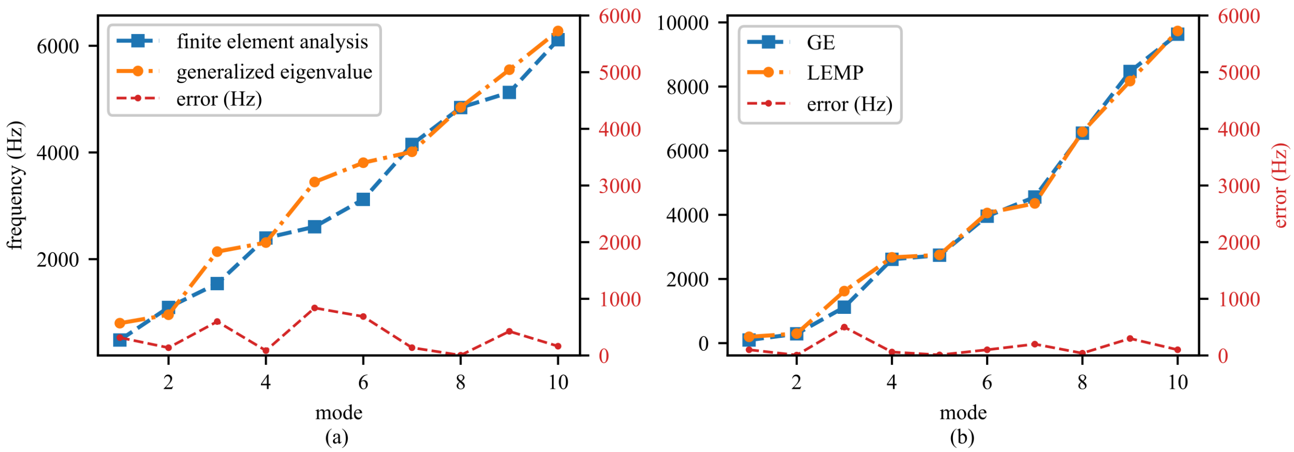


Figure 3. Vibration frequencies of the undamaged PCB for (a) the initial state computed using FEA and GE, and; (b) single state change computed using GE and LEMP.

4. CONCLUSION

The paper uses a reduced-order model-based method to detail a study on online damage detection, quantification, and localization in printed circuit boards (PCBs). The local eigenvalue modification procedure (LEMP) is applied to enable rapid computational processing that is suitable for real-time applications. This study demonstrated the use of LEMP for efficient and accurate model updating in PCBs subject to damage. This was accomplished through comparative analysis against the traditional generalized eigenvalue procedure (GE), showing LEMP's superior speed with comparable accuracy.

A finite element analysis of a standard PCB, both in a baseline healthy state and with simulated damage, was conducted. GE and LEMP were then utilized to detect changes in system dynamics and update the model accordingly. LEMP can achieve model updating with millisecond latency, meeting the tight latency requirements necessary for real-time applications. The time for LEMP to solve for a single change in the system was 0.46 ms, as opposed to 270 ms using GE. The findings suggest that the LEMP method can potentially be employed in a real-time control framework for safety-critical applications where PCBs experience shock and impact events, enhancing system resilience by allowing immediate corrective actions following damage detection.

The potential limitations include the complexity of implementing the method in various real-world scenarios or the challenges in integrating this approach with existing electronic systems for diverse applications. However, the method has potential applications in the aerospace, automotive, and military sectors, where PCBs are integral to system operations, and real-time damage assessment is crucial for maintaining functionality and safety. Future research will focus on scaling the LEMP approach for complex systems with multiple damage sites, enhancing the method's robustness against a variety of real-world variables.

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