A PROCESS WITH QUANTIFIED ACCURACY FOR PREDICTING ELECTRONIC EQUIPMENT VIBRATION RESPONSE

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OVERVIEW

Spacecraft electronics are prone to failure due to the severe mechanical environment that is experienced during launch, this necessitates that their reliability be assessed. One possible approach is to create an accurate model of the Printed Circuit Boards (PCBs) dynamic response; subsequently the failure probability can be determined by comparing the response model with corresponding failure criteria for the electronic components. In principle the response model can be achieved by a very detailed Finite Element (FE) model of the PCB which would include the mass and stiffness of all components present on the PCB. Unfortunately the detailed modelling approach requires an excessive effort; therefore it is rarely pursued by the designer. Past research has shown that assumptions can be made about the mass and stiffness of the components that allow simpler models to be created that still achieve appropriate levels of accuracy. However, the accuracy of these simplified models has not yet been quantified over a range of possible design cases. This paper will define a process to quantify how increasing levels of modelling simplifications decrease the accuracy of PCB FE models; this process will also define the limits of applicability.

1. INTRODUCTION

Shock and vibration loads imposed on a PCB cause stresses on the PCB substrate, component packages, leads and solder joints. These stresses are due to a combination of the bending moments in the PCB and the inertia forces due to component mass and acceleration. In a worst case scenario these stresses may cause one of the following failure modes, PCB delamination, solder joint fracture, lead fracture or component package fracture, if any single one of these modes occurred total failure would very probably ensue. The mode of failure experienced in-service depends on the package type, PCB properties, and frequency and amplitude of both bending moments and inertial forces.

It is possible to predict the mechanical failure by a two-stage Physics of Failure (PoF) approach [1]. The first stage calculates the vibration response of the board through a Finite Element (FE) model of the PCB/component system, incorporating some simplification assumptions to simplify the modelling process. The second stage relates this calculated response to some pre-determined component failure criteria, to show whether or not the component can withstand this curvature or acceleration.

Predicting the PCB's response is complicated by the components stiffness and mass affecting the local properties of the PCB vibration response, with particularly heavy or large components significantly altering the local vibration response.

The two most commonly used forms of response prediction are detailed and simplified FE models, detailed models use FE models with very large numbers of elements to model the equipment from PCB to solder leads, sometimes super-element methods are used to reduce the solution time. Simplified models replace complicated 3D models with a very simple 2D model of the PCB, where specific areas of the model have increased mass and stiffness properties to simulate the effect of attaching components. The relative simplicity and speed of simplified methods has led them to be more favourable than detailed methods.

The principal short-coming of the first stage of the PoF process is that the accuracy of the process is unknown, thus the confidence in the failure criteria and consequent reliability estimates can not be assessed. This work will illustrate a process to determine this error dependant on the simplification assumptions used. The process is a Monte Carlo simulation of randomly created PCB's at various levels of simplification, with each run being compared to an unadulterated benchmark case. It will then be possible to calculate the expected maximum error for each level of simplification, permitting accurate factors of safety to be created. In addition to examining how the relative error varies within each level of simplification, the correlation of relative error and input variables (geometry and mechanical properties) can be found. For example, heavily populated PCBs may have larger errors, thus requiring more accurate modelling.

2. CURRENT STATE OF THE ART

The simplified response method (commonly known as the ``smeared'' method) involves creating a 2D FE model with the same geometry as the PCB, it is then possible to locally increase density and Young's modulus to simulate the component effects [2,3]. The density increase can be easily calculated; however the stiffness increase must either be calculated by a FE model or by physically cutting out and bend testing a PCB/component specimen. It is also noted that the torsional stiffness of the combined PCB and component system may be significant for accurate results, requiring torsional testing to be carried out. In Pitarresi's research five different cases were studied, each involving a different PCB and component choices. Each of the boards were modally tested to find the real response, the results were then compared against FE models at different levels of simplification. The levels of simplification were as follows:

1) [Simple method] Completely ignoring the effect of any components, with the FE model reflecting the

underlying PCB. Ignoring the stiffness is assumed to compensate the effect of ignoring the mass.

2) [Global mass smearing] The mass of the components is calculated and ``smeared'' over the entire area of the PCB, any stiffness contributions are ignored.

3) [Global mass/stiffness smearing] Both the mass and stiffness contributions are spread out over the PCB. Where the stiffness is calculated by physical testing a combined component/PCB specimen.

4) [Local Smearing] Instead of smearing the mass and stiffness properties over the entire PCB, the properties are smeared over local regions of the PCB, where the local region can be defined as either areas of similar components or just the individual component region itself.

5) [Detailed FE modelling] Modelling the structure in three dimensions as opposed to two. Substructuring was used to divide the structure into smaller structures to reduce the solution time.

Each level of smearing was compared to the experimentally derived results using the Modal Assurance Criterion (MAC) and also by looking at the natural frequency. The more time-consuming methods generally showed greater correlation with the experimental results, although this is not always the case. It was observed that cases that had a smaller stiffness and mass increase ratio had better correlation with the experiment results, especially if the ratios were similar.

The correlation criteria used (MAC and natural frequency) can not be used to determine the actual error in the local vibration environment. The MAC is only a measure of similarity of shape, which does not consider the scale of the results. The small number of cases studied also limits the applicability of the results.

The boundary rotational stiffness is also known to have a large influence on the vibration response of a PCB [1], significantly altering both natural frequencies and maximum deflection. The amount of boundary rotational stiffness present depends on the method of fixing the PCB to the chassis. Using the percentage fixidity parameter defined by Steinberg [4] the edge stiffness may vary from 0% to 100%, with 0% reflecting a simply supported condition and 100% being fully clamped. In most cases the percentage fixidity will not be greater than 60%, as higher values than this require an excessively overbuilt clamping mechanism. Usually, due to a lack of information, the boundary edge stiffness is modelled as either simply supported or fully clamped, resulting in conservative or underestimated results respectively.

In this work the response variable is defined as some measure of the response model output (usually acceleration in previous research), this measure is used as the input for the failure criteria stage of the PoF process, it may be either acceleration, local curvature or some other variable. The response variable has evolved from using the input acceleration at the chassis, [5,6,7,8], through the actual acceleration experienced by the component to account for the different vibration responses of different PCB layouts [9], and finally to looking at the local deflection [4] or local bending moments [1] experienced by the PCB local to the component. It has been noted that the failure is a function of component location on the PCB as different areas of the board respond with different magnitude [5,11]; therefore the models that consider the local vibration response are more likely to be accurate than those that consider overall vibration input.

3. PROPOSED PROCESS

As stated earlier the process is a Monte Carlo sensitivity analysis, with the aim of creating factors of safety at different combinations of smearing, component choices and board thickness'. These factors of safety can be used to account for any possible underestimate in the calculated response of a proposed PCB. The factors of safety can be made more specific to an individual case by decomposing them into results based on input variables, for example, PCB thickness's, simplification regimes or combinations of components.

3.1. Model properties

To calculate these factors it is necessary to examine the difference between a simplified model and unadulterated model of a hypothetical PCB layout, this difference will be defined as the ratio of the two results (δ). To make the results applicable over a large range of possible design cases, it is necessary to run a large number of test cases, where each run is different from every other. This will be achieved by automatically creating and solving FE models in the MATLAB environment, where the properties of each model depend on randomly created variables. In this study the following variables were used to randomly create each run.

PCB thickness

To reflect standardised industry thickness's, the PCB thickness was given the possibility of two discrete depths of 1.6mm and 2mm. It would be possible to specify a continuous distribution or a larger range of intervals if necessary.

Areal component density

The areal component density were given a uniform distribution between 0 and 0.5 with 0.5 reflecting a board with 50% of it's area covered by components. These values were relevant to this individual case study and the types of board expected to be modelled.

PCB type

the PCB type divides the models into four different categories, to reflect the predominant type of components used in that model. For example, the ''Power`` classification used mainly heavy components and is intended to simulate configurations that incorporate large components such as transformers, large capacitors and heavy power conversion packages. The component types can be divided into the following three categories: Light, Surface Mount Technology (SMT) and heavy components. The *Light component* classification is intended to simulate small discrete components such as resistors or transistors, the length and mass increase of such components is small, the stiffness increase is negligible. The *SMT* category symbolises components such as Quad Flat Pack (QFP), Ball Grid Array (BGA) and Pin Grid Array (PGA), which are generally about 10mm to 30mm square, and have a increased density and stiffness ratios that are in proportion to the length and inversely proportional to the thickness of the PCB to which they are attached. The final *Heavy Components* category is intended to reflect large components such as transformers, large power capacitors and resistors. The density and stiffness ratios were proportional to component length.

With these three component categories defined, four different types of layouts were created (see TAB 1.). In this specific case only four different categories were identified, with the intention of keeping them simple and practicable, more categories could be identified or even a continuous (as opposed to discrete) range could be used if required.

	Component Types		
Equipment Type	Light	SMT	Heavy
Power			1
Power & Processing		0.5	0.5
Processing		1	
Light Processing	0.5	0.5	

TAB 1. Table of relative component distribution for different PCB classifications.

Boundary rotational stiffness

The boundary rotational stiffness was given a value between 0% and 60%, based on Steinbergs percentage fixidity parameter. These values were chosen because a percentage fixidity above 60% is very difficult to achieve in practice (see FIG 1. for boundary condition location).

Component edge length

Finally the component edge length varied for each individual component that was placed, where the lengths were to chosen to make the components more realistic. The component edge length also determined the ratio of stiffness increase, where the relationship was calculated using an FE approach, the calculated ratios. The calculated ratios were in agreement with previously published ratios and included an additional factor of safety [3].

In addition to these variables, the position of each component on each model is randomly chosen, removing any dependence on relative component location and ensuring the results are applicable to a large range of PCB layouts (see FIG 1.] for an example).

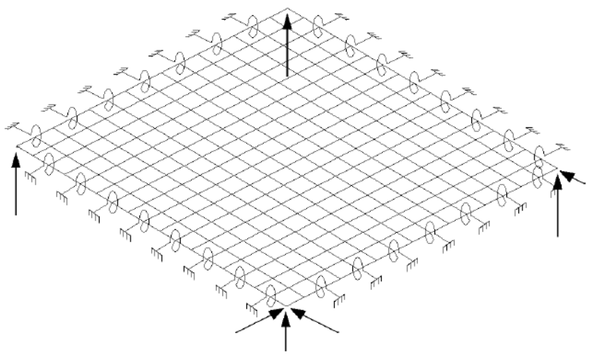

FIG 1. Example of Boundary conditions

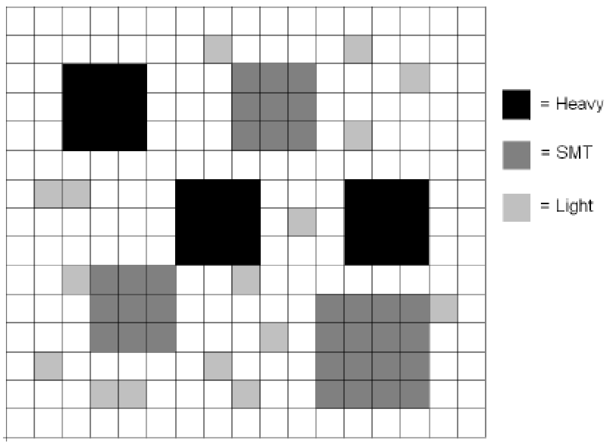

FIG 2. Example of random component placement

3.2 Building and solving FE models

Once the models geometry and layout have been precisely defined it is possible to create the FE model. The FE model is a very simple mesh of 2D shell elements, with component locations represented by areas of higher stiffness and mass. The model was created in the MATLAB environment, using the OpenFEM element library and solver. The nodes of the mesh were at 5mm intervals, as this was shown to give acceptable convergence of results in both MATLAB and NASTRAN.

In terms of boundary conditions, the edge displacements of the model were fixed while the two rotational degrees of freedom were free. The last rotational DOF was constrained by CELAS elements with rotational spring constants, where the constant was calculated from the board percentage fixidity and formula published by Barker [12]. The out-of-plane RMS displacement for a flat acceleration input (0.1g2/Hz) was calculated up to 1000 Hz, because the value of 1000Hz was found to adequately account for the majority of displacement for the cases considered (see FIG 3. for an example deformation).

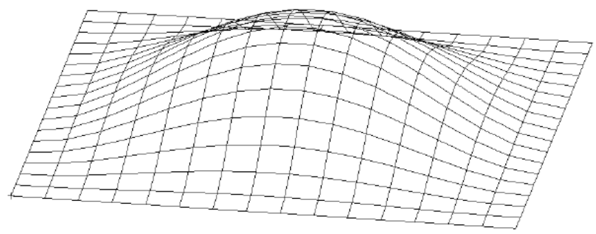

FIG 3. Example PCB deformed shape

3.3 Levels of Simplification

The mass and stiffness were the main variables to be simplified during this study, although useful observations were also gained by examining edge rotational stiffness simplification. Each simplified model was created and solved automatically by altering the properties of the "benchmark`` case in MATLAB. Due to the three different combinations of properties that can be averaged: mass, stiffness and torsional stiffness, and the two different types of simplification: averaging and unpopulated, there are multiple different possible simplification combinations possible. TAB 2. shows the different combinations of simplification types chosen for this study.

id.	Density	Stiffness	Torsional Stiffness
1	Exact	Exact	Exact
2	Averaged	Exact	Exact
3	Exact	Averaged	Averaged
4	Averaged	Averaged	Averaged
5	Exact	Averaged	Unpopulated
6	Exact	Unpopulated	Unpopulated
7	Averaged	Unpopulated	Unpopulated
8	Unpopulated	Unpopulated	Unpopulated

TAB 2. Simplified properties of the different simplification combinations

The averaging was based on the area of the component and the PCB, while the unpopulated simplification completely ignored the effect of components.

Additionally it was possible to simplify the edge rotational stiffness, reducing the edge fixidity to zero and giving a simply supported edge condition. The simply supported edge condition was chosen as it is a commonly used assumption during modelling.

3.4 Calculation of Factors of Safety

Using the calculated deformations it is possible to compare the "benchmark`` and simplified cases. This was achieved on a per node basis, where the curvature in both the x and y directions was calculated. The ratio of the curvatures between the two cases could then be calculated at each node. The resulting set of ratios ($\Delta\theta$), could then be examined to find the maximum curvature underestimate for each level of simplification. The factor of safety is defined as the reciprocal of the maximum curvature underestimate for a specific set of analysis runs. It is also noted that it is possible to choose other response variables to study instead of curvature, it is possible to modify the process obtain maximum bending moment underestimates or acceleration underestimates.

4. RESULTS

The results are shown in table TAB 3. and are decomposed into thickness, equipment type and simplification type. In the cases where no underestimate was seen the factor of safety was set to unity. It is important to note that this data is proprietary and as such the results have been multiplied by an unspecified value.

Thickness	Equipment	Simplification id							
mm	type	1	2	3	4	5	6	7	8
1.6	1	1	1.29	1.1	1.27	1	1	1.14	2.45
	2	1	1.24	1.07	1.25	1	1	1.13	2.84
	3	1	1.06	1.05	1.08	1	1	1	1.2
	4	1	1.08	1.05	1.24	1	1	1.01	1.21
2	1	1	1.26	1.05	1.24	1	1	1.17	3.14
	2	1	1.22	1.04	1.22	1	1	1.15	2.58
	3	1	1.05	1.03	1.05	1	1	1.01	1.17

TAB 3. Factors of safety for different thicknesses, Board types and Smearing regimes (as defined in TAB. 1 and 2 respectively).

The limits of applicability of this case study are shown in TAB 4 to 6.

Variable	Range	Distribution
Thickness	1.6 or 2mm	Discrete
Edge Length	75 - 150mm	1mm intervals
Young's modulus	$25.5 * 10^9$	Single value
Edge ratio	1.0 - 0.7	Continuous
Component areal density	0.1 - 0.5	Continuous

TAB 4. PCB properties

Edge Degree of Freedom	Condition
Translational displacement	Fixed
Rotations perpendicular to specific edge	Fixed
Rotation parallel to specific edge	0% - 60% fixidity

TAB 5. Boundary condition limit of applicability

Classification	Edge	Ratio		
	length (mm)	Stiffness	Torsional stiffness	Density
Light	5 - 10mm	1.3 - 1.6	1.6 - 2	1.5 - 2
SMT	10 - 30mm	1.33 - 3.5	1.6 - 7	1.5 - 6
Heavy	20 - 35mm	3 - 4	5 - 6.5	6 - 56

TAB 6. Component properties (all values are from continuous distributions, apart from length which is in 5mm intervals)

5. ACCURACY OF RESULTS

The process described here calculates the ratio of a simplified and non-simplified model, the ability of the non-simplified ``Benchmark" case to realistically represent a real-life case is dependant on the following assumptions. There is assumed to be a **Homogeneous density and stiffness increase under the components**, highly detailed analysis may find that the stiffness and mass are concentrated in small areas, but this is unlikely to greatly affect the accuracy of the results. It was assumed that the boundary conditions exhibit a **Homogeneous edge rotational stiffness**, or more specifically continuous and constant for all edges. Real-life situations are more likely to exhibit discrete locations of stiffness which vary between edges. The homogeneous assumption was used due the excessive amount of runs that would be required to incorporate all different possible combinations of edge stiffness. It could be feasible to model this if really necessary, especially if other input variables could be assumed constant. Finally the components were modelled with **Zero stand-off height**. For small components and those of SMT type, this is a safe assumption, as they have negligible height above the PCB. Equipment with higher percentage of large tall components is more likely to be adversely affected by this assumption, as possible rocking modes associated with tall components may cause stresses that are not modelled. For the case study presented here these assumptions were assumed safe, thus it was assumed that the benchmark models could accurately represent a real-life cases.

In addition to these aforementioned sources of error there are also the following factors which are of practical importance when applying the results of the process. It is assumed that the **Natural frequency percentage error** is low, as otherwise it is possible that the modes with a significant frequency change may actually occur at frequencies with a more intense vibration input spectrum (if the vibration input is assumed to be shaped). For the 7 levels of simplification studied here, the maximum variation in frequency was typically within 5%. Whereas boards modelled as unpopulated varied by as much as 20%, whilst for large amounts of edge stiffening simplification the variation rose to 30%. Ultimately it should be noted that for shaped vibration input, the statistics of frequency change should be taken into account when choosing a simplification regime. [\bf Damping] was assumed constant through all the cases, at 2% critical damping. In real situations the amount of damping may vary from board to board, depending on: the components present, the method of PCB fastening, specific material properties and many other factors. In practice it is not possible to accurately determine damping analytically, and each individual case will require experimental testing of a representative specimen to obtain damping values.

6. OBSERVATIONS

The most important observation that can be made from the results concerns the effect of the simplifying the mass or the stiffness. In the cases where only the mass was simplified it was observed that an underestimate of the response was likely, whereas overestimates occurred where only the stiffness was simplified, as would be expected. As such it is inferred that simplifying the stiffness is a conservative and fairly safe assumption, whilst simplifying the mass leads to non-conservative answers. This is fortunate as it usually much easier to find the component mass increase rather than its stiffness increase.

In addition to looking at the effect of simplifying the mass and stiffness properties, another simulation was run that looked at the effect of simplifying the boundary conditions. This simulation considered the effect of simplifying the edge rotational stiffness to 0% fixidity, again looking at the error in the curvatures between a simplified and non-simplified case. In agreement with past research [13,12] the results were very sensitive to error in specifying the edge rotational stiffness. The cases where the edge rotational stiffness was originally low (close to 0% fixidity) showed fairly good accuracy, whilst the cases where the edge rotational stiffness was high (up to 60% fixidity) showed poor accuracy. In effect the cases with high percentage fixidity had much more to lose from the simplification process, therefore they showed greater error. It was noted that assuming the PCB to be simply supported is conservative as it only overestimated the results; although in extreme cases this overestimate can approach a factor of three times the actual results (See FIG 4. for an example).

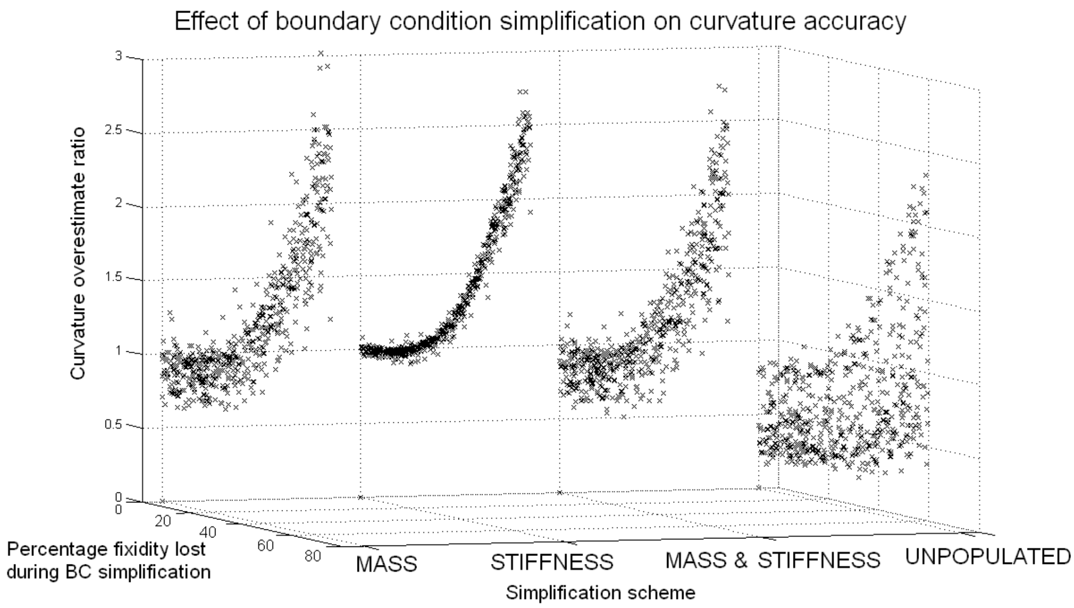

FIG 4. Relationship between amount of boundary condition simplification and curvature overestimate, four different levels of property smearing are considered here.

In addition to the results presented in this study another simulation looked at a much larger range of input variables. This led to choosing the thickness and component type as the variables for partitioning the results, due to their practicality and strong correlation with accuracy. This preliminary study examined the effect of thirty different input variables (as opposed to the three in this study) on accuracy. Some variables (for example, ratio of PCB edge lengths) had very low correlation with error and were removed from further analyses. Other variables were shown to strongly correlate with accuracy, but would be difficult to use in a practical situation. For example, the ratio of unpopulated to populated stiffness (global stiffness ratio) was calculated for each analysis run, showing strong correlation with result accuracy (in agreement with past research [2]); unfortunately the global stiffness ratio is difficult to practically calculate.

7. CONCLUSION

A process has been illustrated that calculates factors of safety for FE models of electronic equipment, using the Monte Carlo approach to ensure that many possible configurations are considered. The resulting factors of safety can be used on a wide range of equipment (As defined in the limits of applicability) and can be decomposed into different variables (in this case thickness, simplification type and equipment type) to increase relevancy. The factors of safety can be used to ensure that any calculated response of a PCB is conservative.

In addition to the process some observations have been made during the analysis process, notably the importance of accurately modelling the mass and boundary conditions if accurate results are required.

8. ACKNOWLEDGEMENTS

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