Micro Electronic Components Vibration Fatigue Damage Evaluation

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ABSTRACT

In the current analysis tools, the outputs of random vibration analysis are limited to spectral densities and root-mean-square values of the strain components with no phase information, which is required to be able to correlate the strains and thus calculate the effective strain using a type of von Mises relationship. In addition, due to the lack of phase information, it is impossible to use a macro/micro (or global/sub) modeling technique, which is based on interpolation of the solution from an initial, relatively coarse, global model on the nodes at the appropriate parts of the boundary of the refined-meshed submodel, to determine the strains in the submodel. The objective of the present study is to develop a methodology to determine strains in electronic components (micro level) resulting from exposure of modules (macro level) to random vibration environments. Specifically, it addresses the problem associated with the analysis of almost microscopic elements attached to larger physical structures, e.g., ball grid array (BGA) solder balls attached to printed wiring board (PWB).

The proposed methodology includes two stages. The cross correlation of output displacement responses versus frequency for each of the degree of freedom of the connection points of the micro model to macro structure is first developed using a MSC/NASTRAN™ frequency response analysis of the macro model. In the second stage, a static analysis is conducted using MSC/NASTRAN™ to generate the transfer functions corresponding to each of the strain components for each of the input source loading conditions. These transfer functions are then statistically correlated with the degree of correlation determined by the cross-spectral density in the first stage to calculate the power spectral for each of the strain components. The effective strains of the micro electronic components can then be derived using a type of von Mises relationship and a volume-weighted average technique. In the methodology development process, several in-house developed Fortran computer programs, in conjunction with the outputs obtained from MSC/NASTRAN™ static and frequency response analyses, are used to perform the required computations. An example of a 600-pin BGA soldered onto the PWB is illustrated in the present study. Developing test modules, on which various sizes of the BGAs will be soldered, is currently under way to validate the proposed methodology.

INTRODUCTION

Many micro electronic components, such as solder joints and connecting leads, are not only very small compared to surrounding components but also usually large in quantity. As a result, it is difficult if not impractical to include their mathematical representations (finite element models (FEMs)) with sufficient degree of complexity to permit accurate determination of the stress or strain state resulting from exposure of a model of the complete package (‘macro model’) to random vibration environments. Instead, it is more practical to include them in the macro model of the complete package by simplistic representations, such as beam elements, which are sufficient so as to provide adequate representation of their effect on package response and to provide output information as to displacements of the connection points which can then be utilized as input source displacements to ‘micro models’ (or submodel).

If current analysis tools provided information which described the frequency dependent correlation of the displacement outputs of the connection points, then a portion of the problem would be solved. However, these analysis tools do not provide that information. In addition, no phase information is available to assist in the determination of how the displacement degrees of freedom act relative to one another. Also, another limitation of the tools is that a very important output response is not generated, i.e., the von Mises equivalent strain (or the effective strain) which is a function of the six components of the strain tensor existing at any point in the model. Instead, the output is limited to spectral densities and root mean square (rms) levels of the strain components with no phase information available to be able to correlate them and thus calculate the effective strain using a type of von Mises relationship. Note that the effective strain is traditionally utilized in component strength durability analyses to predict fatigue damage, as opposed to any single component of strain.

The result is that the analysis tools are deficient in two ways to permit accurate durability analysis: i.e.: 1) correlation of displacements resulting from exposure of the package to random vibration excitation, and 2) calculation of the effective strain at any point in the structure. Thus, the objective of the present study is to develop a methodology to determine strains in electronic components (micro level) resulting from exposure of modules (macro level) to random vibration environments. Specifically, it addresses the problem associated with the analysis of almost microscopic elements attached to larger physical structures, e.g., ball grid array (BGA) solder balls attached to printed wiring board (PWB). Some understanding of solder joint vibration fatigue damage can be obtained from Barker et al. (1990/1991), Jih et al. (1993/1998), Lau and Pao (1997), Liguor and Followell (1995), Pitarresi and Akanda (1993), Yang et al. (1998), and Steinberg (1988). A theoretical background of the random process can be found in Shinozuka and Jan (1972), Meirovitch (1967), Elishakoff (1983), and Lin (1973).

In the present study, an example of a 600-pin BGA with the package size of 1.8 in. square is illustrated. This BGA has perimeter solder balls with 35 balls along each periphery of the package and five rows of balls along each side. The pitch of balls is

0.05 in. The BGA is soldered onto a polyimide printed wiring board (PWB), on which some reinforced stiffeners are mounted. The solder balls are made of 63Sn/37Pb solder. The microsection of the solder joint assembly, whose height is about 0.02 in., is shown in Figure 1 (Darveaux and Mawer, 1995).

METHODOLOGY DEVELOPMENT

The proposed methodology include two stages. First, it is necessary to obtain the cross correlation of output displacement responses versus frequency for each of the degrees of freedom of the connection points of the micro model to the macro structure. It is assumed that five degrees of freedom exist at each end of the micro model (perhaps, a beam), representing the micro model in the macro model (i.e., three displacements and two rotations, as the rotation about the axis normal to the module is negligible). The transfer functions, H_j^{δ}, relating the displacement response of each of these independent degrees of freedom to single or multiple point source excitation of the macro model can be obtained from a MSC/NASTRAN™ frequency response analysis of the macro model. The cross correlation of the degrees of freedom, one to another, can be obtained by permuting the transfer functions. Note that these transfer functions are complex quantities, possessing real and imaginary values, equivalent to magnitude and phase but in the complex plane. Thus, the transfer function relating the correlation of the response of displacement 'j' to displacement 'k' may be expressed as

$$H_{jk}^{\delta}(i\omega) = H_j^{\delta}(i\omega) \bullet H_k^{\delta}(-i\omega) \tag{1}$$

and the output cross-spectral density response is given by

$$S_{jk}(\omega) = S_e(\omega) \bullet \left[H_j^{\delta}(i\omega) \bullet H_k^{\delta}(-i\omega)\right] \tag{2}$$

where S_e (ω) is the input power spectral density of the source excitation. It is to be note that there are ten independent variables (displacements), five at each end of the equivalent beam. The number of combinations of these variables, taken two at a time, is 10^2 or 100. In addition, for the case when j=k in Eq. (2), the output is the usual power spectral density given by

$$S_j(\omega) = \left|H_j^{\delta}(i\omega)\right|^2 \bullet S_e(\omega)\ . \tag{3}$$

Relations of Eqs. (2) and (3) provide the cross and power spectral densities of the connection point displacement inputs to the micro model. These are to be considered as independent source excitation (loading conditions), correlated by the cross-spectral density functions, variant with frequency.

In the second stage, a static analysis is first performed using MSC/NASTRAN™ to generate the transfer functions (H_{lj}^{ε}) corresponding to each of the strain components ‘l’ (l=x, y, z, xy, yz and zx) for each of the input source loading conditions (10 in all). The 10 input sources have been statistically correlated with the degree of correlation determined by the cross-spectral density given by equation (2). Then, the spectral density of the response quantity ($S_l(\omega)$) for each of the strain components over the 10 input case is given by

$$S_l(\omega) = \sum_{j=1}^{10}\sum_{k=1}^{10}\left(H_{lj}^{\varepsilon}(i\omega)\bullet H_{lk}^{\varepsilon}(-i\omega)\right)\bullet S_{jk}(\omega). \tag{4}$$

The power spectral of the response quantity (corresponding to each of the strain components) for each element, $p_{l,e}$, can be calculated as

$$p_{l,e} = \int_0^{\omega} S_l(\omega)d\omega\,. \tag{5}$$

where the subscript l is corresponding to x, y, z, xy, yz and zx. The effective strain of each element, using a type of von Mises relationship, is assumed as

$$\varepsilon_{eff,e} = \left|\frac{\sqrt{2}}{3}\sqrt{\left(p_{x,e}-p_{y,e}\right)^2+\left(p_{y,e}-p_{z,e}\right)^2+\left(p_{z,e}-p_{x,e}\right)^2+\frac{3}{2}\left(p_{xy,e}^2+p_{yz,e}^2+p_{zx,e}^2\right)}\right|^{1/2}. \tag{6}$$

Note that the term under the radical is a complex quantity. Recall from the theory of complex variables that

$$\sqrt{(a+ib)} = \pm\left\{\frac{\sqrt{a+\sqrt{a^2+b^2}}}{2}+i\frac{b}{|b|}\bullet\sqrt{\frac{-a+\sqrt{a^2+b^2}}{2}}\right\}. \tag{7}$$

It is well known that the derived strains are heavily dependent on finite element mesh size. The smaller the element size, the higher the resulting strains. This finite element mesh size dependency is primarily due to the stress/strain singularity at the edge of a bi-material (Kuo, 1990/1997; Yin, 1992/1993). Therefore, to minimize the mesh dependence problem, a volume-weighted average method (Kuo, 1997) was used to compute an average effective strain over all the elements in the cross section, which is expressed as

$$\varepsilon = \frac{\sum \varepsilon_{eff,e}V_e}{\sum V_e} \tag{8}$$

where V_e is the element volume. Thus, the predicted vibration fatigue damage can be obtained.

The procedure described above has been programmed using Fortran77 on the SUN Workstation as a series of MSC/NASTRAN™ run and Fortran executions. Figure 2 is a flow chart, which summarizes the procedure of the proposed methodology.

FINITE ELEMENT ANALYSIS

A macro/micro (or global/sub) modeling technique is utilized to estimate the stress/strain of the BGA solder joint. The FEMs are constructed with a MSC/PATRAN™ code. The linear dynamic and static analyses are performed with a MSC/MSC/NASTRAN™ finite element code on a SUN workstation.

Table 1 lists the material properties of aluminum, polyimide/glass, copper, 63Sn/37Pb solder, dry film solder mask, polyimide tape, silicon, mold compound, and epoxy adhesive (ASM, 1979; IFI/Plenum, 1977; Rohde and Swearengen, 1980; Darveaux and Mawer, 1995).

In the macro level analysis, a 3-D global FEM of the electronic module, shown in Figure 3, is constructed to simulate major structural elements and to determine the module dynamic responses when subjected to an excitation normal to the PWB. Three BGA mounting locations are selected and shown in this figure. However, only one 600-pin BGA (at location #1) is mounted on the PWB in the present study. A 3-D finite element local model (Figure 4) with refined mesh solid elements to simulate the local region is constructed to determine the solder effective stress/strain. The detailed modeling information can be found in Wong, et al. (1999). The average effective strain of the BGA solder joint at the interface of package/solder is then derived using the proposed procedures described in the previous section or Figure 2, and its value is 0.000134.

SUMMARY

A methodology for determining strains in micro electronic components, e.g., BGA solder joints, resulting from the exposure of macro structures, e.g., electronic modules, to the random vibration environments has been developed. This method is implemented by the utilization of the several in-house developed Fortran computer programs, which, in conjunction with the outputs obtained from MSC/NASTRAN™ static and frequency response analyses, perform the required computations. The Fortran computer codes allow the users to obtain the average strains of the micro components. An example of a 600-pin BGA soldered onto the PWB is illustrated and the solder effective strain is calculated to be 0.000134. Currently, test modules, on which various sizes of the BGAs will be soldered, have been developed to validate the proposed methodology.

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Table 1. Material Properties

Material	Tensile Modules, Msi	Shear Modulus, Msi	Poisson’s Ratio
Aluminum	**10.0**	**3.76**	**0.33**
Polyimide/ Glass	**2.46 (X & Y) 1.08 (Z)**	**0.44 (XY) 0.35 (YZ & ZX)**	**0.129 (XY) 0.417 (YZ) 0.183 (ZX)**
Copper	**17.0**	**6.39**	**0.33**
Solder	**4.38**	**1.56**	**0.4**
Solder Mask	**0.71**	**0.25**	**0.4**
Polyimide Tape	**2.1**	**0.91**	**0.16**
Silicon	**19.0**	**7.31**	**0.3**
Mold Compound	**1.81**	**0.7**	**0.3**
Epoxy Adhesive	**0.5**	**0.19**	**0.35**

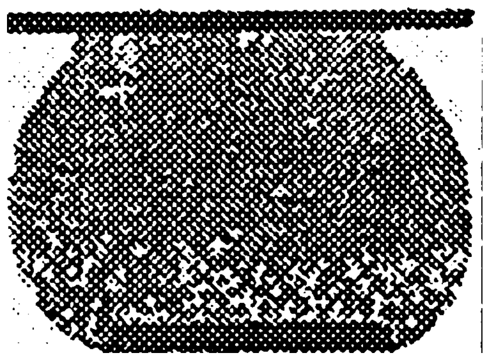


Figure 1. Microsection of BGA Solder Joint Assembly (Darveaux and Mawer, 1995)

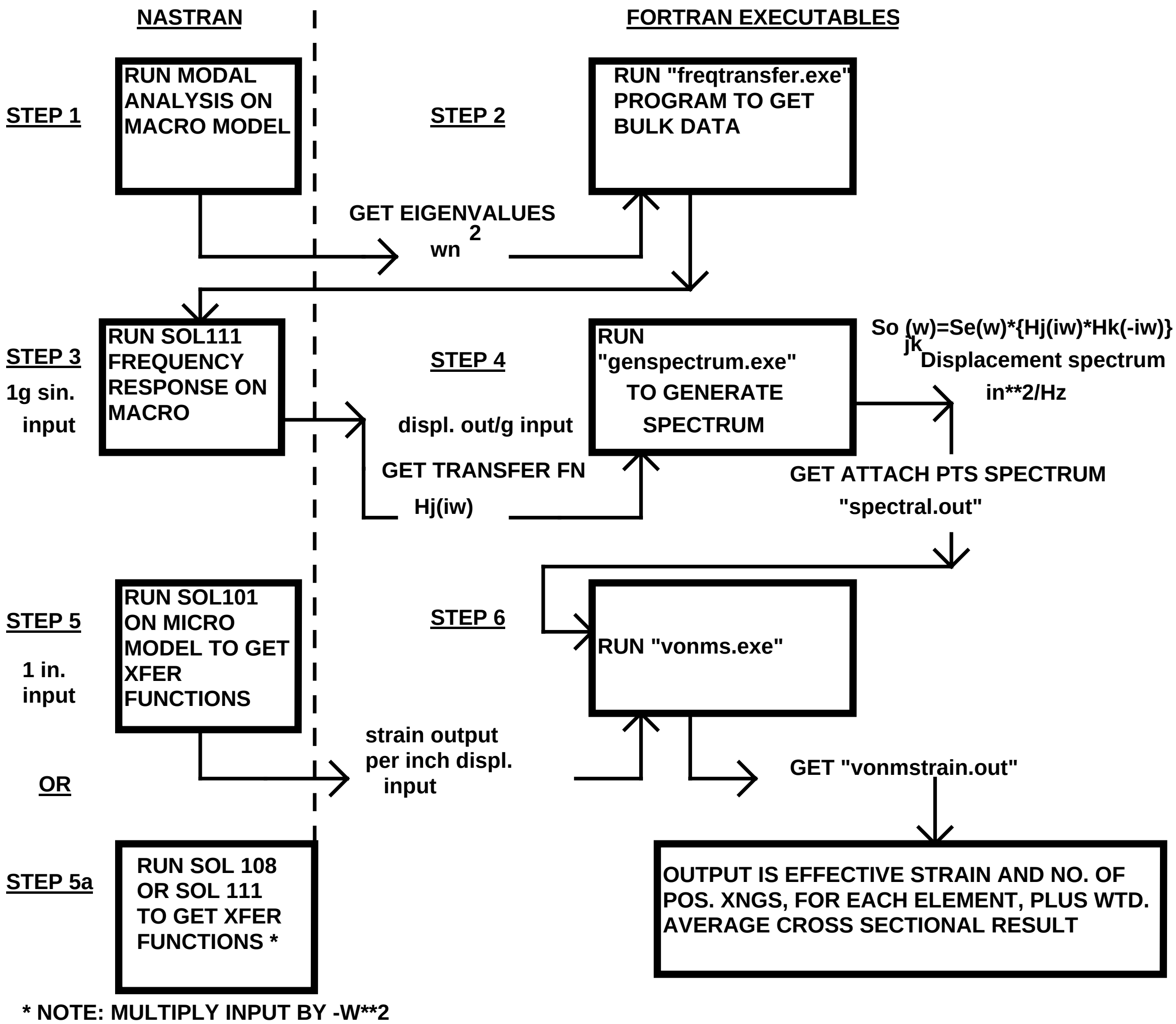
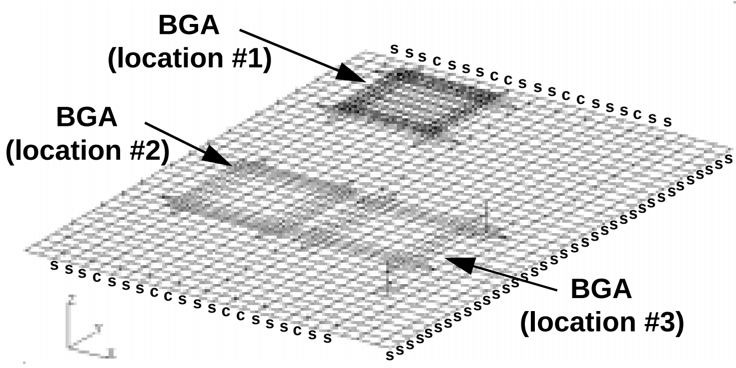


Figure 2. Flow Chart for Evaluating Micro Components Vibration Fatigue Damage



s=simply supported
c=clamped

Figure 3. Global FEM (only main PWB and BGA at location #1 are shown)

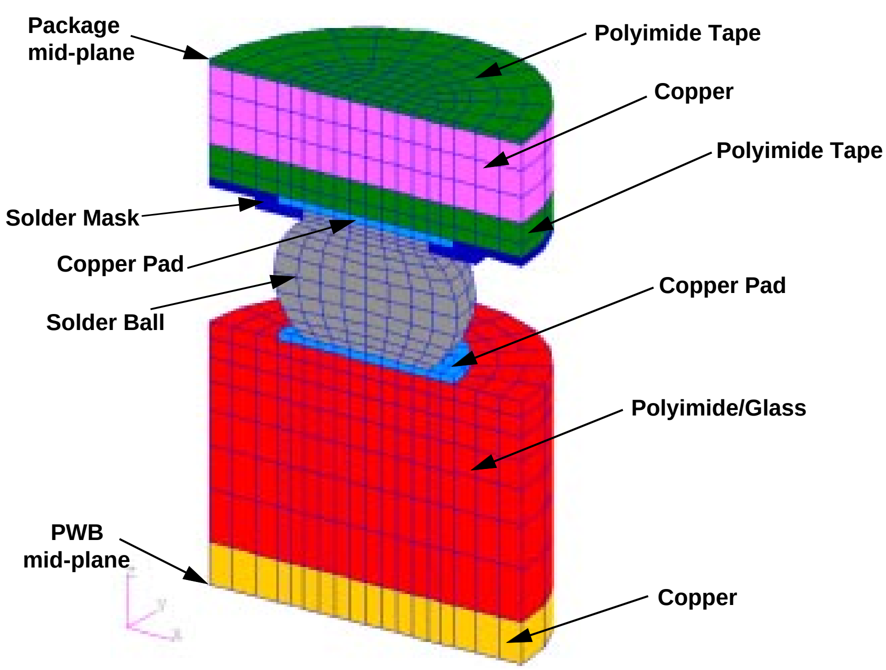


Figure 4. One Half of Solder Joint Submodel