EPJ Web of Conferences **26**, 05002 (2012)
DOI: 10.1051/epjconf/20122605002

Dynamic response of electronic systems to shocks and vibrations: Application of analytical (mathematical) modeling

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Abstract. Some basic problems of the dynamic response of electronic and photonic (E&P) systems to shocks and vibrations are addressed and discussed. The emphasis is on analytical (mathematical) modeling, the reliability physics behind the addressed phenomena, and design-for-reliability (DfR) issues and challenges. The addressed problems include 1) linear response: effect of viscous damping, shock tests vs. drop tests, role of compliant interfaces, and maximum acceleration and maximum dynamic stress as a suitable reliability criterion; 2) nonlinear response: printed circuit board (PCB) experiencing an impact load applied to its support contour and ball-grid-array (BGA) testing on the board level; 3) shock protection of portable electronics, including the possible use of nano-wires as a suitable protective "cushion". The fruitfulness of the probabilistic DfR (PDfR) concept to quantify and assure the field (operational) reliability of E&P devices and systems is also indicated.

1 Introduction

Dynamic response of materials and structures to shocks and vibrations has always been an important topic of the applied science and engineering, including the electronics and photonics (E&P) field [1–5]. In military, avionic, space, automotive, and maritime E&P, dynamic loading occurs during the normal operation of the system. It is addressed therefore in many MIL-specs and other qualification requirements and standards. In commercial electronics, dynamic loading takes place during mishandling or transportation of electronic equipment and instrumentation. Random vibrations are often applied during qualification testing (QT) as an effective means to detect and weed out infant mortalities, even though a particular product of interest might not be intended for an operation in a dynamic environment. In recent decades, the necessity to protect portable electronics from drop loading triggered an increased interest to the field. The effort is on both modeling, mostly finite element analysis (FEA) based, and accelerated testing, including failure oriented accelerated testing (FOAT).

Modeling is the basic approach of any science. The majority of the today's models in E&P are computer aided. FEA is widely used in the stress-strain evaluations and physical design of E&P systems, including structural dynamics. Broad application of powerful computer programs, however, has by no means made analytical solutions unnecessary or even less important. Simple analytical relationships have invaluable advantages, owing to the clarity and compactness of the obtained information and clear indication on interactions and dependencies of different material and design characteristics. In addition, FEA simulations and analytical solutions are usually based on different assumptions. It is always advisable, of course, to obtain a solution to the given problem using different approaches. But even when application of numerical methods is straightforward and encounters no difficulties, it is certainly useful to investigate the problem analytically first. Such a preliminary step helps to reduce computer time and expense, to develop the most feasible preprocessing FEA model and, in many cases, avoid fundamental errors.

Printed circuit board (PCB) carrying surface mounted devices (SMDs) is the major structure in today's E&P technologies. The board could carry also, in some accelerated test vehicles, heavy concentrated masses to enhance its dynamic response, especially if there is an intent to conduct FOAT to test BGA or land-grid-array (LGA) interconnections. The loading applied to the PCB support contour is transmitted to the SMDs and to the BGA or LGA solder joints through the PCB deformations. In a typical situation, when the PCB contour remains non-deformable during the PCB impact-induced-vibrations, and when the impact is significant, appreciable reactive in-plane (membrane) stresses arise in the board. Because of that, its shock-excited vibrations become nonlinear. It has been determined [4,5] that the PCB response could be described, if the fundamental mode of vibrations only is considered, by the Duffing-type equation for the principal coordinate. It has been found also that this equation lends itself to an exact solution, using elliptic functions, no matter how significant the loading and the resulting nonlinearity level might be, provided, of course, that the elasticity limit of the PCB material is not exceeded

Probabilistic design for reliability (PDfR) is a promising and fruitful technique that has been successfully applied for many years in aerospace, maritime, civil and other areas of engineering, but is new in the E&P field.

Accordingly, this review addresses the recent work on modeling of the dynamic response of E&P systems to shocks and vibrations. The emphasis is on the analytical (mathematical) modeling. We indicate also the fruitfulness of the PDfR approach in structural dynamics of E&P systems.

2 Linear response

Linear approach should be applied, whenever possible, first, even when it is clear that nonlinear effects might play an important role. In many cases such an approach is sufficient. Here are several practical problems, in which the application of the linear approach enabled one to obtain practically important solutions for various E&P dynamic response related problems.

1. Application of **viscous damping** has proven to be effective in many engineering systems subjected to vibrations, especially when resonant or close-to-resonant conditions cannot be avoided. It is less obvious to what extent extensive damping could be advantageous in systems experiencing impact (drop) loading. The question is to what extent elevated damping might be able to effectively minimize the deceleration during drop impact and the "breaking distance". It has been shown [6] that while such distance always decreases with an increase in the level of damping, the maximum deceleration first decreases with an increase in damping, but after reaching a minimum rapidly increases and can exceed significantly the low damping decelerations. Because of that viscous damping should be introduced with caution, and its level should be established beforehand, based on the developed model.

2. Shock testers are widely available in E&P engineering practice, and so are drop testers. Shock testers are much cheaper and much simpler to operate than drop testers, and the dynamic response of shock tested specimens is easier to measure and analyze. Could drop test conditions be adequately mimicked by shock conditions? It has been shown [7] that substitution of drop testing with shock testing is indeed possible, provided that the magnitude and the duration of the drop impact is established by modeling, and the shock tester is tuned accordingly. The shock tester should be able to produce very short impacts, shorter than one eighth of the period of linear shock-induced vibrations, in order to adequately mimic the drop test conditions. A shock table has been designed and built [8], based on the developed guidelines, to address actual drop conditions. Detailed analytical and numerical (simulation) analyses of the drop impact response and its sensitivity to the change in the loading pulse parameters was carried out by Luan and Tee [9] and Tee et al [10].

3. The levels of dynamic loading and responses are typically expressed in E&P engineering by the magnitude of the **induced accelerations (decelerations)** [2,3]. Such an approach is widely employed, as far as functional (electrical, optical, thermal) performance is concerned, but might be misleading when the mechanical (structural) reliability is of interest [11]. High accelerations do not always go together with high dynamic stresses and might be considerably higher in systems that experience lower accelerations. Wu et al [12], Tee et al [13] and Syed et al [14] addressed different aspects of the drop performance of electronic devices, including chip scale packages and telecommunication products.

4. Analysis of the response of a **heavy electronic (power) component** to harmonic oscillations experienced by its external electric leads (because of the lateral vibrations of the PCB support contour) has indicated [15] that 1) the natural frequencies of vibration of actual, elongated-and-heavy, components can be significantly lower than in a system idealized as a cantilever beam with a lump mass at the end; 2) if the ratio of the frequency of the external excitations to the natural fundamental frequency of vibrations exceeds a certain threshold, no induced PCB vibrations could possibly occur; 3) if the ratio of the excitation frequency to the natural frequency is small, the amplitudes of the induced vibrations increase rapidly with an increase in this ratio; and that 4)a dynamically stable system can be assured in a system with a high ratio of the excitation frequency to the system's natural frequency.

5. **Solder joint interconnections** (SJIs) in flip-chip, ball-grid-array (BGA) and land-grid-array (LGA) designs provide both electrical connections and mechanical support. When the stresses and strains in the solder material exceed, during temperature excursions or during drop tests, the yield point of the material, low cycle fatigue conditions occur. The long-term reliability of the solder material and the device as a whole could be compromised if the inelastic strains are significant and the fatigue damage accumulates with an increase in the number of temperature cycles and/or with the number of drops impacts, to an unacceptable level. The situation has recently become more important and more complicated, because of the introduction of lead-free solders and wide employment of the BGA and LGA systems. The published work that addresses the performance of solder materials and interconnections, when subjected to thermal or dynamic loading, is enormous. Here are some publications that use modeling techniques. Vodzak et al [16], Condra et al [17], Barker et al [18], Qi et al [19], Ghaffarian [20], Sakthievelan et al [21] addressed the effect of the combined action of dynamic and thermal loading on solder joints. Such a combined loading is typical for many automotive, aircraft, aerospace and maritime systems. Zhu [22], Yu et al [23], Mishiro et al [24], Tee et al [25], Luan and Tee [26], Chiu et al [27] addressed various reliability aspects of BGA systems, including modeling of their dynamic response on the board level. The BGA and LGA systems are now commonly viewed both as a manufacturing opportunity and the major bottleneck of the short- and especially long-term reliability of SMT E&P technologies. Characterization of solder materials and reliability of solder joint interconnections with respect to dynamic loading on the board level was addressed by Tan [28], Xu et al [29], Ong et al [30], Date et al [31], and others.

6. In order to understand the reliability physics underlying the performance of BGA, LGA and SMD materials and structures one has to understand, first of all, the behavior of the **PCB** itself, whether "bare" or carrying SMDs. PCBs are usually modeled as thin isotropic plates. The PCB anisotropy, composite structure and possible visco-elastic effects in its material are not considered. When the vibration amplitudes are low and, hence, linear, Goyal et al [32] suggested a shock-protective suspension design. Wang [33] carried out simulation-based investigations of PCB drop tests. Luan et al [34] conducted modal analysis of the PCB response to an impact drop load. In the absence of damping, the higher harmonics are responsible for about 20% of the accommodation of the initial potential energy of the PCB [4]. In the presence of such a damping, the input of higher modes will be even smaller, since higher modes might fade away completely by the time when the displacement of the fundamental mode reaches it maximum value. This circumstance is a justification for considering, in approximate analyses of the PCB dynamic response, the fundamental mode only, despite the fact that, in principle, the spectrum of the generated frequencies might be very broad when a multi-degree-of-freedom system, such as a PCB, is subjected to an impact loading.

7. In the recent years considerable attention has been dedicated to technical **diagnostics, prognostics and health monitoring** (PHM) of electronic systems, including their dynamic response. Although the usefulness of technical diagnostics and the advantages of non-destructive testing have been known in other areas of engineering for many years, it has been only during the last decade that this direction has attracted interest of the E&P community. Gu et al [35] addressed PHM implementations for electronic systems under vibration loading. Mathew et al [36] assessed the virtual remaining life of electronic hardware subjected to shock and random vibrations

8. Linear vibrations of a **fused bi-conical taper (FBT) light-wave coupler** were modeled, with consideration of the high FBT non-prismaticity, the non-linear stress-strain relationship of the silica material and thermally induced tensile loading caused by the thermal contraction mismatch of the coupler (dopped silica) and its substrate (regular silica) [37,38].

3 Nonlinear response

1. Nonlinear dynamic response of flexible structural elements experiencing acoustic (sonic) **periodic shock loads** idealized as a train of instantaneous impacts was addressed, apparently for the first time, in connection with the observed stochastically unstable ("chaotic") motions of such elements [39]. The formalism was extended to shock loads applied to the PCB support contour [40–42]. It has been found that the linear transient response of a SDOF linear system with viscous damping can lead, for particular combinations of the frequency ratio and the level of damping, to higher amplitudes and accelerations than in the subsequent steady-state vibrations; that in linear systems low level damping might be responsible for the very fact that the vibrations eventually stabilize (become steady-state), but might not affect the non-resonant response (this can be found by simply imposing the conditions of periodicity on the system: these conditions state that the sequential impulse does not change the position of the system, but changes its velocity in a step-wise fashion); that the nonlinear response of a PCB can be described, if the fundamental mode of vibrations only is considered, by the Duffing equation (Duffing oscillator) for the principal coordinate. Exact closed form solution to the above equation can be obtained for time-independent practically important types of excitations (instantaneous impulses, or suddenly applied and then remaining constant and then suddenly removed loading), no matter how significant these excitations and the corresponding nonlinear effects might be [43]. The role of the higher modes of PCB vibrations could be accounted for, if necessary, on the basis on the linear theory, by assuming that the response of the fundamental mode is determined beforehand on the basis of the solution to the Duffing equation for a highly nonlinear system, that this solution is not affected by the higher modes of vibrations (at least during the first quarter period of the shock-induced vibrations) and can be used as the excitation force when determining the higher modes of vibrations.

2. The loading on a PCB in an aircraft, spacecraft or a missile, during the take-off of the flying apparatus, can me idealized as a **suddenly applied (in a "step-wise" fashion) constant load** whose duration exceeds considerably the PCB fundamental period of vibrations. It has been shown [41] that the actual (nonlinear) accelerations in the mid-portion of the PCB can be significantly larger than those predicted on the basis of the linear theory.

3. It has been found [39] that a train of impact loads can lead to **"stochastic instability"** ("chaos") even in the case of a weak nonlinearity and in the simplest case of a SDOF system: the system's response is a quasi-random, although neither the excitation, nor the system itself are characterized by a random loading or by random properties of the system. The random phase approximation and Smoluchowski's equation were used to obtain the condition of the "stochastic instability" and to characterize the behaviour of the "chaotic" vibrations.

4. The **method of principal coordinates** was employed in the above solutions to separate in the equation of motion the (time-dependent) principal coordinate from the (location-dependent) mode (coordinate function). It has been assumed that the nonlinear effects could be accounted for by considering their effect on the principal coordinate only, while the coordinate function was assumed to be the same as in the linear approach. It has been shown [44] that this assumption is valid for a simply supported PCB, but is not valid in the case of other boundary conditions.

5. One way to enhance the dynamic response of the SJIs, when conducting accelerated reliability testing on the board level is to attach **heavy concentrated masses** to the PCB. This measure increases the inertia forces and, hence, the total accumulated strain energy in the board, the induced lateral accelerations and the PCB in-plane deformations. When modelling the response, it has been assumed [43] that the attached concentrated masses are sufficiently small in size, so that their effect on the flexural rigidity of the board may not be considered, while their mass has an appreciable effect on the effective PCB mass. Elliptic functions were used to find the exact solution to the basic equation for the principal coordinate for any level of nonlinearity. Unlike in linear systems, the dynamic factors for different response characteristics (amplitudes, accelerations, frequencies, stresses) are different and are highly dependent on the loading level.

6. It is considerably easier to carry out the dynamic response analysis, when a short-term loading can be approximated by an **instantaneous impulse**. Having in mind a nonlinear system with the rigid cubic characteristic of the restoring force, it has been concluded [45] that, as far as the vibration amplitudes are concerned, the nonlinear system is less sensitive to the dynamic nature (short time) of the applied load than a linear system, but the situation is opposite for nonlinear accelerations. These might be substantially larger than the linear ones. It has been concluded also that thorough predictive modeling based on the developed algorithm should always precede the construction of an experimental setup, the experimental design and the analysis of the obtained data.

4 Shock protection of portable electronics

1. Shock protection of **portable electronics** was addressed during the last decade or so by many investigators: Suhir and Burke [46], Suhir [47,48], Goyal et al [49], Huang et al [50], Seah et al [51], Lim et al [52], Zhu [53], Irving and Liu [54]. It has been determined that significant improvement in shock protection of a vulnerable structural element in an electronic device can be achieved by using a "box-in-a-box" system [46]: the liquid crystal display in the National Cash Register (NCR) device was securely protected by employing a cabinet and a chassis, and by the proper selection of the flexible cushions – the gasket and the grommet considering the masses of the plate element (glass LCD) and the chassis. The computed data indicated that if the ratio of the two natural frequencies in this two-degree-of-freedom system was below 0.25, then no resonant conditions could be possible.

2. **Nano-wire arrays** are promising systems to be used in portable electronics as effective shock-absorbers [4]. When evaluating the feasibility and performance of nanowires for the application in question, both pre-buckling and post-buckling behavior of the wires should be addressed, as well as their dynamic response to impact loading applied to the substrate on which the wires are fabricated.

5 Probabilistic design for reliability (PDfR)

1. Probabilistic DfR (PDfR) approach is based on the probabilistic risk management (PRM) concepts, and, if applied broadly and consistently, brings in the probability measure (dimension) to each of the design characteristics of interest [55–64]. When the PDfR approach is employed, the reliability criteria (specifications) are based on the acceptable (allowable) adequate (not necessarily very low) probability of failure (PoF) for the given product and consequences of its failure. Using accelerated test (AT) data (and particularly FOAT data) and the predictive (PM) techniques, the PDfR approach enables one to establish the PoF of the product under the given operation conditions and for the given moment of time in operation (in the field). After the probabilistic PMs are developed, one should use sensitivity analyses (SA) to determine the most feasible materials and geometric characteristics of the design, so that the adequate PoF is achieved. In other cases, the PDfR approach enables one to find the most feasible compromise between the reliability, cost effectiveness of the product and time-to-market. The role of the human factor can be also accounted for, if necessary.

2. The **most general PDfR** approach is beyond the scope of this review and could be based on the use of probability density distribution functions for 1) the PDfR characteristics of importance: electrical parameters (current, voltage, etc.), light output, heat transfer capability, mechanical ultimate and fatigue strength, fracture toughness, maximum and/or minimum temperatures, maximum accelerations, etc., and for 2) the factors affecting these characteristics: high an/or low temperatures, high electrical current or voltage, electrical and/or optical properties of materials, mechanical and thermal stresses, displacements, maximum temperatures, etc.

6 Do industries need new approaches to qualify their devices into products?

1. The **PDfR approach** can be helpful in answering this question. The short-term and down-to-earth and practical goal of a particular device manufacturer is to conduct and pass the established QTs, without questioning whether they are perfect or not. On the other hand, the ultimate long-term and the broad goal of the E&P industries, regardless of a particular manufacturer or a product, is to make their products reliable in the field, be consistently good in performance, and so to elicit trust of the customer. QTs, such as, e.g., JEDEC, Telcordia, AEC or MIL specs, are the major means that the E&P industries use to make their viable-and-promising devices into reliable-and-marketable products. It is well known, however, that devices that passed the existing QTs often fail in the field. Are the existing QT specifications adequate? Do E&P industries need new approaches to qualify their devices into products? If they do, could the today's QT requirements and procedures be improved to an extent that if the device passed QTs, its performance in the field would be satisfactory and, preferably, could be predicted and assured? Would it be possible to specify, predict and, if necessary, even control the adequate and specified PoF for a system that operates under the given stress (not necessarily mechanical, of course) for the given time?

2. Such QT improvements are indeed possible, provided that the PDfR methodologies are employed. One **effective way** to improve the existing QT and specs is to 1) conduct, on a much wider scale than today, FOAT and, since FOAT cannot do without PM, 2) carry out PM to understand the physics of failure and to accumulate failure statistics; 3) revisit, review and revise the existing QT and specs considering the FOAT data for the most vulnerable elements of the device of interest; 4) develop and widely implement the PDfR methodologies having in mind that nobody and nothing is perfect, that probability of failure is never zero, but could be predicted and, if necessary, controlled and maintained at an acceptable low level. These activities (efforts) should be conducted on the ongoing basis. If the QT specifications have a solid basis in FOAT, PM and PDfR, then there is reason to believe that the product of interest will be sufficiently and adequately robust in the field. The new generation of QT could be viewed as "quasi-FOAT," as a sort-of the initial stage of FOAT that more or less exactly replicates the initial non-destructive, yet full-scale, stage of FOATs. We believe that our new approach to the E&P device qualification will enable industry to specify and the manufacturers to assure a predicted and adequate PoF for a device that passed the QT and will be operated under the given stress conditions for the given time. We expect that the suggested new approaches to the DfR and QT will be accepted by the engineering and manufacturing communities, implemented into the engineering practice and be reflected in the future editions of the QT specifications and methodologies.

7 Conclusion

A number of practically important dynamic problems encountered in electronics engineering have been addressed, with an emphasis on the nonlinear dynamic response of PCBs, with electronic devices mounted onto them, to shock loading applied to the PCB support contour. Simple, easy-to-use and physically meaningful predictive models enable one to determine the role of various structural, materials and loading factors that affect the behaviour of the electronic systems in experimental setups. It is always advisable to carry out both analytical and FEA-based modeling and to make sure that the analytical and simulation data are in good agreement. Predictive modeling, especially analytical (mathematical) one, enables one to better understand the physics of possible failures and to make a viable-and-promising device into a reliable-and-marketable product. Analytical and computer-aided modeling should always be considered and conducted, in addition to accelerated testing, in the analysis, design and manufacturing of E&P systems. We have indicated also the fruitfulness of the PDfR concept in this effort.

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