Role of Shock Response Spectrum in Electronic Product Suspension Design*

Suresh Goyal  
Lucent Technologies Bell Laboratories  
600 Mountain Avenue, Rm. 1B-212  
Murray Hill, New Jersey 07974  
Phone: 908-582-5959  
Fax: 908-582-6228  
e-mail: goyal@lucent.com

Gary W. Elko  
Lucent Technologies Bell Laboratories  
600 Mountain Avenue, Rm 2D-553  
Murray Hill, New Jersey 07974  
Phone: 908-582-3373  
Fax: 908-582-7308  
e-mail: gwe@lucent.com

Edward K. Buratynski  
Lucent Technologies Bell Laboratories  
P.O. Box 900, Rm. 2-2031  
Princeton, New Jersey 08542  
Phone: 609-639-2313  
Fax: 609-639-3197  
e-mail: buratynski@lucent.com

*Outstanding paper of the International Conference and Exhibition on High Density Interconnect and Systems Packaging

Abstract

The Shock Response Spectrum (SRS) analysis provides general guidelines for the design of suspensions and cushions for shock-protection of fragile components. This paper presents the central results of the SRS approach in the context of designing a compliant suspension for a Printed Circuit Board (PCB) in a wireless telephone handset, for shock amelioration. The dynamic response of the PCB, to a spectrum of shock pulses, is measured for a rigid suspension and for three versions of a grommeted compliant suspension. The resulting SRS plot shows clearly the resonant response of the PCB, and the effectiveness of the compliant suspensions in reducing shock pulse amplification during resonance. The results also illustrate the usefulness of high damping of the suspension material in reducing peak accelerations. The guidelines generated through this study are applicable for packaging design for a wide array of electronic products, especially those pertaining to communications/computing.

Key words:

1. Introduction

Impact-tolerance, or the ability to safely withstand accidental drops and bangs, is becoming an increasingly important aspect of the reliability of telecommunication network components and enablers. This includes, for example, fragile components like ceramic substrates in high-frequency packaged modules, optical sub-systems like Dense-Wave-Division-Multiplexing modules, end-terminals like wireless phones, notebook computers, Personal Digital Assistants, among other products. The shock-tolerance of a product, or electronic equipment, is generally determined by the fragility of its ‘weakest’ components. Invariably, impact-induced forces and deformations are not uniform throughout a product and depend strongly on the location within the object and the ‘connections’ leading to that location. Hence, one of the challenges for the product designer is finding/creating ‘safe’ locations within the object for the placement of fragile components.

The International Journal of Microcircuits and Electronic Packaging, Volume 23, Number2, Second Quarter 2000 (ISSN 1063-1674)
Frequently, during the design of rugged products, a decision has to be made whether a component like a Printed Circuit Board (PCB) or a disk drive be mounted rigidly inside an outer chassis or be connected compliantly through elastomeric-grommets. In this paper, the authors highlight the importance of accounting for the Shock Response Spectrum (SRS) in making the above decision. The work is presented through the example of designing an elastomeric suspension for the PCB inside the housing of a mobile (wireless) telephone.

For completeness, the authors first review the theory underlying the SRS approach, considering the response of suspended fragile systems to uni-modal shock pulses of different shapes and durations, for suspension and cushioning design is first reviewed. The central message of the SRS, that shock pulse duration and the time response of the suspended fragile system be separated to avoid shock-pulse amplification, is highlighted. The design of the PCB suspension tackled in this paper is then presented. The initial experimental results, and the full shock response spectrum evaluation of the PCB that followed using various suspension configurations and a range of elastomeric-grommet materials are presented. The experimental procedure is described in detail along with the results. The results are also verified analytically. The results clearly indicate the resonant response of the PCB, the role played by the grommets in altering this response, and the effect of high damping of the grommet materials in reducing the accelerations on the PCB.

The value of this work lies as an illustration of the tenets of the SRS (based primarily on linear systems theory) in a real-world problem, and the applicability of those results to a wide-array of related products that have similar scale and construction.

The layout of the rest of the paper is as follows. The SRS approach is described and the design problem, suspension design for a PCB, is introduced. The testing scheme is explained including a description of the new test fixture that facilitated it. Results for the shock response of the PCB are shown to be in good agreement with the predictions of the SRS approach and with computational results.

2. Shock Response Spectrum Approach

Modeling or measuring impact forces, even in the simplest of collisions, is a hard problem due to the multitude of factors involved and the extreme nature (high magnitudes, low durations) of the events. The complicated interactions that occur between (and within) the components of an electronic product during impact make the task of estimating impact loads and deformations even more difficult. Instead of trying to model impact loads in their entirety, the SRS approach, explained in detail in references, focuses on the failure of components suspended internally to the main structure of the product. The dynamics of small internal parts during an impact is known as shock response.

To fall within the scope of the SRS analysis, a fragile component must: a) be considerably smaller in mass than the system to which it is joined; b) not be a load-bearing structural element; c) in combination with its suspension elements, be well approximated by a linear model; d) have its limiting (damaging) conditions defined by its peak acceleration or its peak displacement exceeding some critical value $a_{ex}$ or $x_{ex}$, respectively. Common examples include a PCB suspended inside a product chassis, ceramic substrates or Micro-Electro Mechanical Systems (MEMS) in portable communication/computing terminals, the display or disk drive of a laptop computer, or a product in its shipping container (the classical application). The subject of shock modeling for such systems divides naturally into two parts: impact-induced motion of the ‘suspension point’ that supports the fragile element and the consequent dynamic response of the element. For each of these parts, the SRS approach is to classify typical behaviors; the resulting potential for damage is then either intuitively clear or can be assessed easily.

The general shock problem arises from the impact of a moving (falling) object with a floor, desk, or a fixture, generally something more massive by far. The magnitude of the collision is defined by the velocity of impact (or the drop height). The first step in shock analysis is to recognize that the suspension point of a fragile component undergoes a sudden variation in velocity due to a collision-induced acceleration, or shock pulse $a_s(t)$. Although the exact nature of $a_s(t)$ may be very hard to predict, just a few characteristics are important. First, there is a net change of mean velocity $\Delta v$ of the suspension point, given as follows,

$$\Delta v = \int_0^\infty a_s(t) \, dt$$

where $\tau$ is the duration of the shock pulse.

The essence of $a_s(t)$, frequently a unimodal pulse, can be characterized simply by its magnitude and duration. A particularly useful measure of pulse duration is its effective duration, $\tau_{eff}$, defined as follows,

$$\tau_{eff} = \frac{\text{pulse area}}{\text{pulse magnitude}} = \frac{\int_0^\infty a_s(t) \, dt}{a_{max}}$$

A more complete pulse specification must include its shape, but it has been found that a broad range of pulse shapes is more or less similar. The key information relates to spectral content: does the pulse rise and fall relatively gently? Or do level changes occur extremely rapidly, and thus contain significant high frequency components. Finally, the shock pulse need not be unimodal and the suspension point may continue to oscillate or ‘ring’ after the change in mean velocity $\Delta v$.

The consequences of concern to this forcing input at the suspension point are the fragile-body peak acceleration and displacement. Hence, the most common shock response calculations are those evaluating peak fragile-element acceleration due to a range of acceleration pulse inputs. It turns out that the relationship of...
The most useful facts for shock-protection that emerge from the above calculations are the limiting behaviors, that is, fragile-component response to short duration and long duration shock pulses11.

If \( \tau_{\text{eff}} \) is considerably shorter than \( T_n \), the peak fragile-element acceleration will depend only on the velocity change of the base and not on the time period over which it occurs. This gives rise to the very important notion of ‘velocity shock’ (applicable generally to all well-behaved systems): a base acceleration for a sufficiently short time period whose effects depend only on the net velocity imparted, not on the pulse’s shape, peak magnitude, or precise duration. A velocity shock just great enough to cause damage defines a critical velocity, \( v_{\text{cr}} \).

Since the system of Figure 1 is linear its dynamic response, when subjected to various shock pulses, is represented through a so-called ‘base pulse response ratio R’, given as follows,

\[
R = \frac{\text{peak accel of fragile - part}}{\text{peak accel of shock - pulse}} = \frac{a_f^{\text{max}}}{a_b^{\text{max}}} \tag{3}
\]

To characterize this response ratio analytically for a large variety of shock pulses (differing in shape, spectral content, and duration), simple, analytic, unimodal acceleration pulses of various shapes (like rectangular, sinusoidal, versed sine, or triangular) are applied to the suspension point.

The concepts of the SRS approach can be reinforced through the example of the system illustrated schematically in Figure 1.

The resulting peak fragile component acceleration \( a_f^{\text{max}} \) due to the above shock pulses, either during or after the pulse, can be determined analytically solving the equation of motion for a forced spring-mass-damper system12,13. For instance, it can be shown that in response to a velocity shock of magnitude \( \Delta v \),

\[
a_f^{\text{max}} = -\Delta v \omega_0 e^{-\xi \zeta} \sqrt{1 - \xi^2} \left( \frac{\xi (\xi^2 - 1)}{\zeta (\xi^2 - \zeta^2)} \right) \text{ for } 0 \leq \xi \leq 0.5
\]

\[
a_f^{\text{max}} = -2 \Delta v \omega_0 \zeta \text{ for } 0.5 \leq \xi \leq 1
\]

where \( \zeta = c_f / \sqrt{k_f m_f} \) is the damping ratio. Similarly, for a step change in acceleration of magnitude \( a_b^{\text{max}} \) applied to the suspension point,

\[
a_f^{\text{max}} = a_b^{\text{max}} \left( 1 + e^{-\xi \zeta} \sqrt{1 - \xi^2} \right) \text{ for } 0 \leq \xi \leq \sqrt{0.5}
\]

\[
a_f^{\text{max}} = a_b^{\text{max}} \left( 1 + e^{-\xi \zeta} \sqrt{1 - \xi^2} \right) \frac{2 \xi (\xi^2 - 1)}{2 \xi^2 - 1} \text{ for } \sqrt{0.5} \leq \xi \leq 1
\]

Collating the response ratios of the fragile component to various shock pulses, the SRS approach plots R as a function of effective shock pulse duration (normalized by the time period \( T_n \) of free vibration of the fragile system). Figure 2 presents the SRS for an...
Role of Shock Response Spectrum in Electronic Product Suspension Design

undamped system, that is, the system of Figure 1 with \( c_f = 0 \). Figure 3 presents a close-up of the SRS plots of Figure 2, around the region of resonant response. Although Figure 2 plots the SRS for a few, but representative, pulse shapes, plots for other well-behaved pulse are not too different and have an upper-bound represented by the response for a rectangular pulse. Observe in Figure 3 that for \( \tau_{\text{eff}} / T_n < 1/6 \), the SRS does not depend on pulse shape and is approximately a straight line through the origin. This means, for example, that for a given pulse shape, halving shock pulse duration and doubling its amplitude, that is applying the same \( \Delta v \), leaves the internal peak accelerations unchanged. This is the short-pulse response discussed earlier.

The highest R for any pulse shape occurs for a pulse duration \( \tau_{\text{eff}} = T_n / 2 \), which is similar to the phenomenon of resonance experienced with sustained-periodic excitation (vibration). The value of R at resonance depends on the pulse shape, being highest for a rectangular pulse. At long pulse lengths, the SRS approaches a horizontal line, of a level depending only on pulse rise time. This is the long-term response discussed earlier and it clarifies the role of cushioning: to transform a given velocity change into an acceleration pulse of longer duration and lower magnitude.

The addition of damping to the suspension, although not illustrated in Figures 2 and 3, tends to reduce R for a given pulse shape and amplitude, particularly around resonance. For velocity shocks, moderate damping (that is \( \zeta < 0.5 \)) is beneficial. For reducing the peak fragile component acceleration to long duration pulses, the more the damping, the lower the R.

The behaviors outlined above and in Figure 2 are applicable to far more general systems than those of Figure 1. One such system, a PCB suspended compliantly inside a wireless handset, is described next section.

4. Suspension Design: Printed Circuit Board

Figure 4 shows a PCB suspended inside a wireless telephone using six screws and six half-grommets around the screws. The handset was expected to be able to safely withstand 20-30 drops from 1.5m onto vinyl tile and 250 drops from 1m onto vinyl tile. Based on drop testing of a wide range of wireless handsets from similar heights, it was estimated that the telephone chassis would be subjected to shock pulses of durations \( \tau \) ranging from 0.3 – 2.0ms (milliseconds).

![Figure 4. Schematic of the suspended Printed Circuit Board (PCB) and an elastomeric grommet to illustrate suspension configuration, approximate shape, and dimensions.](image-url)

The aim was to design a suspension for the PCB that would
minimize the resulting peak accelerations on the PCB. The choices for the suspension were either to connect the PCB rigidly to the outer chassis using the six screws, or to connect it compliantly with elastomeric grommets made from commercially available damped elastomers. The additional design challenge, common in all portable products where small size and low weight are highly desirable, arose from the fact that the space to accommodate the grommets was quite limited, as shown in Figure 4.

Initial impact testing with shock pulses of a fixed duration showed that parts of the PCB experienced acceleration peaks that were considerably higher than the applied pulses and no clear resolution was available for the design choices. It was recognized, then, that these amplifications were a result of the shock response of the dynamic system formed by the compliant PCB, and its suspension had to be tested using a spectrum of shock pulses as detailed in next section.

5. Experimental Procedure

SRS testing was performed using a Dynatup® Impact Testing Machine, Model 8250, equipped with a specially designed fixture that allowed it to be used as a drop-table, as shown in Figures 5 and 6. The fixture, allowing rigid and easy attachment of the suspended PCB, replaced the webs in the dropping cross-head of the machine. The shock pulses were generated through impacts between the falling tup (directly beneath the fixture) and various elastomeric pads placed on a fixed steel plate, that resulted in dead (non-bouncy) impacts. The drop height was set to be 1m and essentially-unimodal shock pulses of durations ranging from 1.5-16ms were obtained. (Finding the right combination of material and size of rubbery pads, to yield a desired pulse duration, is a non-trivial task.) Due to limitations of available materials, it was found difficult to get non-noisy unimodal shock pulses of less than 1.5ms duration.

Figure 5. Photograph of the designed test fixture that is attached to the falling cross-head of the Dynatup Impact Testing machine model 8250. The PCB is mounted with six screws onto a plate that can be attached easily to the fixture. The dark cylindrical tup, whose impact with elastomeric pads produces the shock pulse, is clearly visible under the test fixture.

Figure 6. Close-up of the area where the PCB is suspended, in the test fixture, to show the locations where the accelerometers were attached.
The PCB was tested in four configurations: attached rigidly to the test fixture, and attached compliantly with grommets made from three different versions of the elastomer VersaDamp™, supplied by E-A-R Speciality Composities® (of Indianapolis, IN). The VersaDamp™ family of elastomers is thermoplastic, with a proprietary formulation. The chosen grades of VersaDamp™ represented a wide range of stiffnesses and damping. They were, V2590 (highly damped, Shore A durometer 57), V2750 (moderately damped, Shore A durometer 70), V2325 (lower damping, Shore A durometer 40).

Accelerations were measured at four locations (as shown in Figure 6):
1) At the site where impact first occurs between the tup and the elastomeric pads (using the load cell inside the tup).
2) At the base of the suspended PCB (using an accelerometer), to measure the forcing input, \( a_b(t) \), on the suspended PCB.
3) At a point on the PCB which is close to a support. As expected, the accelerations recorded at this location were not too different from those recorded at the base of the suspended PCB.
4) In the middle of the lower half of the PCB (that is, the most flexible point on the PCB) to measure maximal PCB response, \( a_f(t) \).

For each pulse duration, and PCB configuration, multiple drops were done to check repeatability.

6. Results and Data Analysis

Since the PCB is flexible, it has natural vibration modes that couple with those introduced from a compliant suspension. The accelerometer results showed a clear resonance of the PCB at around 350 Hz and a resonance of the test fixture itself at around 1400 Hz. Keeping this in mind, the accelerometer data was passed through a low-pass filter, designed using the software MATLAB™, with a high frequency cut-off at 2200 Hz. The filtering only smoothed accelerometer data for the very short duration, 1.5-1.6ms, shock pulses; it left the data for longer duration pulses unaltered. Figures 7 and 8 shows examples of \( a_b(t) \), and the corresponding \( a_f(t) \), respectively, for a shock pulse that excites resonant response and for a much longer shock pulse.

![Figure 7. Accelerometer data for the applied shock pulse (\( a_b(t) \)) and the measured acceleration (\( a_f(t) \)) at the center of the bottom half of the PCB (its most flexible portion), for a pulse duration that excites resonant response with the PCB suspended with V2590 grommets.](image1)

![Figure 8. Accelerometer data (\( a_b(t) \) and \( a_f(t) \)) for a very-long duration shock pulse, for the PCB when suspended with V2325 grommets.](image2)

For each PCB configuration, response ratios \( R = \frac{a_f^{\text{max}}}{a_b^{\text{max}}} \) were calculated for all the pulse durations they were tested in. The results are displayed in Figures 9 and 10 where the ordinate is \( R \) and the abscissa is the actual shock pulse duration, \( \tau \), at the base of the PCB. Figure 10 is a close-up of the SRS plots around the region of resonant response. For a linear, undamped system with a natural frequency of 350 Hz (that is, \( T_n = 2.8\text{ms} \)), the SRS approach predicts that sinusoidal shock pulses will yield peak responses at \( \tau = 2.2\text{ms} \) (\( \tau_{\text{eff}} = 1.4\text{ms} \)). Observe in Figure 6 that for each PCB configuration, the maximum response occurs around \( \tau = 2.2\text{ms} \)!
7. Computational Results

A modal analysis of the PCB, using I-DEAS® software\textsuperscript{17}, computed its first mode at 423 Hz. This compares well with the experimentally determined mode of 350 Hz for the PCB, given that the mass of the accelerometers was not modeled and an approximate shape of the PCB was used during analysis. In order to understand why the elastomeric grommets did not alter the response of the PCB dramatically, as hoped, from the configuration when it was attached rigidly to the test fixture, the following approximate analysis can be done.

The flexibilities of the PCB and the grommets are modeled as linear springs, and the mass of the PCB by a lumped mass, to yield a spring-mass oscillator. Using the natural frequency of the first mode of the PCB $\bar{\omega}_{\text{PCB}} = 350$ Hz, and its mass $m_{\text{PCB}} = 0.02$ kg, the equivalent spring stiffness for the flexible PCB can be estimated as:

$$k_{\text{PCB}} = m_{\text{PCB}} \cdot (\bar{\omega}_{\text{PCB}})^2 = 96.7 \text{ N/mm}$$

Using the area of contact $A_c = 20 \text{ mm}^2$ for each of the six grommets, and $l = 1.34 \text{ mm}$ as maximal allowable deformation, the equivalent spring stiffness for the six grommets together can be estimated as $k_{\text{gr}} = 6 \cdot E \cdot A_c / l = 90 \cdot E \text{ mm}$, where $E$ is the Young’s Modulus for the grommet materials. Using the values of $E_{\text{V2590}} = 4.8 \text{ N/mm}^2$, $E_{\text{V2325}} = 2.48 \text{ N/mm}^2$, $E_{\text{V2750}} = 7.4 \text{ N/mm}^2$ from\textsuperscript{16}, we get:

$$k_{\text{V2590}} = 432.0 \text{ N/mm},$$
$$k_{\text{V2325}} = 223.2 \text{ N/mm},$$
$$k_{\text{V2750}} = 666.0 \text{ N/mm}.$$  

Comparing the stiffness of the PCB and the grommets, it can be seen that all three of the grommet materials are essentially too stiff to have any softening effect on the suspension of the PCB! However, the softest amongst the three, V2325, does decrease the natural frequency of the suspended PCB somewhat, to about 314 Hz, as mentioned earlier.

8. Discussion

The main aim in this paper was to explain the reason for a perplexing situation that electronic packaging engineers encounter, measurement of higher shock pulses on internal components of an electronic product than on its outer shell, by describing the response of compliant dynamic systems to a spectrum of shock pulses (called shock response spectrum, or SRS). The work was presented through the example of a suspension design for the PCB of a wireless handset for shock amelioration.

Through measurement of the peak acceleration of the suspended PCB in response to slow-rising shock pulses of different durations, the central message of the SRS, that shock pulse duration, in comparison with suspended fragile component natural response time, is critical in determining suspended component response, was illustrated. It was shown that parts of the PCB...
experienced peak accelerations that were considerably higher (sometimes almost double) than the magnitude of the applied shock pulse, for pulse durations of around 2.2ms, corresponding to the "resonant response" predicted by the SRS analysis. It was also shown that the resonant response occurred for all configurations of the PCB, whether it was suspended through grommets or connected rigidly to the outer chassis. However, the peak accelerations at resonance were always lower for the PCB with grommets, than with the rigidly connected PCB, being least severe for the grommets made from the highly damped elastomer V2590. The design implications of this are several.

Amongst the available choices, a compliant suspension with grommets made from V2590 is the most effective in reducing peak accelerations on the PCB near resonance. Additionally, the high damping is useful in combating vibratory loads. The effectiveness of the V2590 grommets can be increased further if the PCB was made a little stiffer (for instance, by adding more support points) so more of the deformation occurs in the grommets. For a given drop height, conservation principles imply that a shorter pulse duration results in a higher amplitude. It can be seen from Figure 10 that for pulses with duration less than 1.5ms, the preferred PCB configuration does not show any amplification; the amplification above that duration may not be damaging because of the lower amplitudes of the applied shock pulses associated with them. If further separation is desired between the resonant response and expected shock pulses, the height of the grommets (that is, available sway space) would have to be increased in conjunction with a much softer and damped material for the grommets. This is illustrated, to some extent, by the results for the V2325 grommets. Finally, fragile components that are susceptible to higher accelerations should be located close to a support point, the grommets (see also References18,19).

Then, there are aspects of the PCB suspension design that have not been presented in the paper. This includes double integration of the accelerometer data to estimate peak deflections on the PCB (or estimating deflections from the accelerations using spring-mass system formulae), and testing of the PCB in a vertical orientation resulting in shock pulses being applied in the plane of the PCB. Note that the results presented here only considered the first vibrational mode corresponding to the largest PCB deflection. Depending on the duration of the shock pulse and the location of the fragile component, a higher mode may need to be analyzed to assess damage potential.

The results of the SRS analysis are very versatile and applicable for almost all well-behaved systems11. Even the results described above are fairly general, being directly useful for a wide array of products that have similar scale and construction, for example, most hand-held portable electronic products20,21, and optical network component packages.

Acknowledgments

The authors wish to thank Peter Hewett, Rodger Andrew, and Ian Armstrong for their work on the design of the grommets and with initial experimentation; Jeff Bream and David John-Lugo for fixture design; E-A-R Speciality Composites for supplying the grommets and material data; Jonathan Rush for help with the I-DEAS analysis; and Mike Pye, Lou Manzione, and Urmi Ray for support.

References


About the authors

Suresh Goyal received his B.S. Degree from the Indian Institute of Technology, Kharagpur, his M.S. Degree from the University of Iowa, and his Ph.D. Degree from Cornell University, all in Mechanical Engineering. After a year of postdoctoral work in computer Science at Cornell University, he joined Bell Laboratories at Murray Hill, New Jersey, in 1989. Currently, he is involved in research related to wireless packaging. In particular, his research is focused on developing the science and technology to engineer rugged, reliable network components, and equipment. His research interests are fairly broad, encompassing dynamics, solid mechanics, structural mechanics, modeling and simulation, experimental techniques, software development, wireless communication, and data networking.

Edward K. Buratynski received his B. Math from the University of Waterloo in Ontario, Canada in 1978. He specialized in Applied Mathematics, Computer Science, and Physics. He then proceeded to earn a Ph.D. from Cornell University in Theoretical and Applied Mechanics in 1983. Following his education, he joined the AT&T Engineering Research Center in Princeton, New Jersey which eventually became part of Bell Laboratories, Lucent Technologies. During his 17 year career in AT&T, he has worked in a number of areas related to electronics manufacturing. The responsibilities included the development of scientific computational codes for heat transfer and stress analyses, statistical studies of part tolerances, analytical modeling of thermal stress response of trilayer structures and experimental studies in shock and vibration testing. He is currently working in the area of product reliability.

Gary W. Elko was born in Philadelphia in 1955. He received the B.S.E.E. from Cornell University in 1977, and a M.S. and Ph.D. from Penn State University in 1980, and 1984, respectively. He is presently a Distinguished Member of the Technical Staff at Bell Labs, Lucent Technologies where he is supervising a group working on signal processing and electroacoustics related to the hands-free acoustic telecommunication problem. His current interests are in adaptive beamforming, acoustic echo cancellation, 3D audio, and room acoustics. He is a past Associate Editor of the IEEE Transactions of Acoustics, Speech and Signal processing, a member of the IEEE Audio and Electroacoustics Technical Committee, and a fellow or the Acoustical Society of America.