NOVEL METHOD FOR CONVERTING SRS REQUIREMENTS TO THE TIME DOMAIN AS IT APPLIES TO SHOCK DETECTION USING MECHANICAL UNIDIRECTIONAL ACCELERATION SWITCHES

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Unidirectional acceleration switches were investigated for detecting shock environments specified using shock response spectrums (SRS). The design requirements included an SRS for a lower shock level, at or below which the switch should never close, and an SRS for a higher shock level, at or above which the switch should always close. An analysis was performed to estimate the lower and upper bounds of the half-sine-like content of a suite of acceleration time histories, in order to take into account the inherent variability of the shock environments. The results were then used, in conjunction with an analysis of several candidate switches, to select a switch with the appropriate dynamic characteristics. Subsequent testing using hardware prototypes demonstrated that the selected switch met the design requirements, and provided the data necessary to directly quantify the design margin.

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INTRODUCTION

Design requirements related to mechanical shock environments are often specified using a shock response spectrum (SRS). The SRS of a given shock pulse is the predicted peak response of a single-degree-of-freedom (SDOF) system to the shock pulse as a function the natural frequency of the SDOF system. In the most commonly used variation of the SRS algorithm, known as the maxi-max absolute acceleration (MMAA), the maximum acceleration response over all time is computed at each natural frequency. The SRS of a given shock pulse can thus often be used to obtain an approximate indication of the overall "severity" of the shock environment, assuming that both (1) the occurrence of mechanical failures in a system subjected to the shock pulse correlate with peak acceleration levels reached in the system in response to the shock pulse, and (2) real systems subjected to the shock pulse are well-modeled by a SDOF system [1]. While these characteristics often make the SRS a good means for specifying design requirements, the SRS of a shock pulse does not retain all of the information present in the original acceleration time history.

In the present work, unidirectional acceleration switches were investigated for detecting shock environments that were considered outside (i.e., above) a device's normal range of operation. The maximum shock that the device was expected to encounter routinely in the field was known a priori, and was defined in the form of an SRS. This data formed the basis for the first design requirement, which was to never detect shocks at or below this specified level. The second design requirement was to always detect shocks at or above a second, higher level. Unlike the first requirement, this second requirement was derived, in that it was based largely on the performance of the switch selected to meet the first requirement. Part of the research was to quantify the amount of separation needed between the two SRS requirements (the lower "never detect" level, and the higher "always detect" level), in order to characterize the resolution with which the switch could reliably distinguish between shock levels.

DESIGN REQUIREMENTS

The design requirements are shown in Fig. 1. Requirement no. 1 ("never detect") represents the maximum shock expected to be routinely encountered during normal use, so exposure to this shock should not be detected. A notional depiction of requirement no. 2 ("always detect") is also shown, representing the minimum shock above requirement no. 1 that would reliably be detected by the switch. The amount of separation needed between these two requirements in order to assure reliable detection by the switch was part of the scope of the study. It was a goal to limit this required window of separation between the requirements to 10dB if possible.

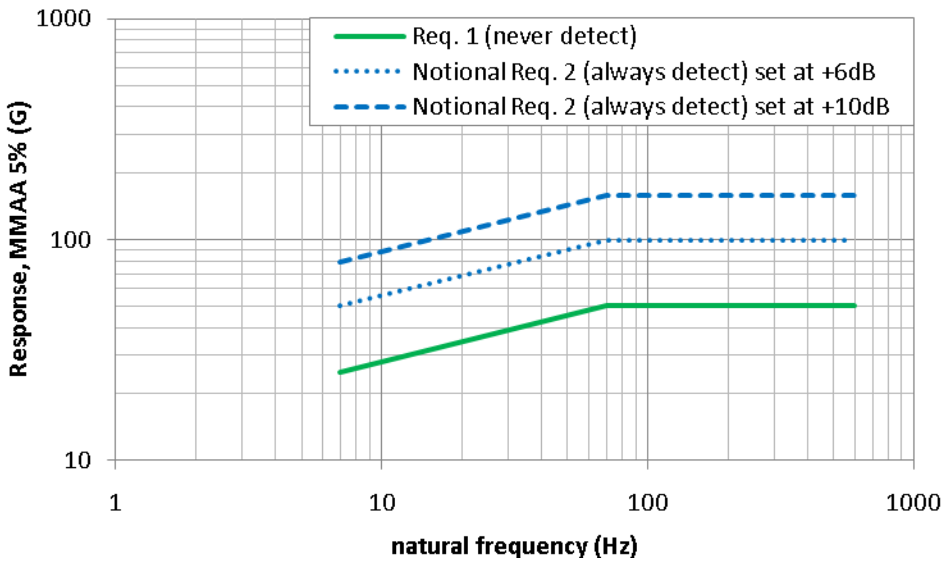

Figure 1: Preliminary design requirements.

While both of these requirements are specified in the form of an SRS, actual shock testing on an electro-dynamic shaker table must be performed using an acceleration time history that is analytically generated to satisfy the SRS. Two methods that are routinely used to generate acceleration time histories to satisfy a given SRS are the method of damped sinusoids [2,3] and the method of wavelets [4]. When an acceleration time history is analytically synthesized to achieve a given SRS, it is but one of an infinite number of unique (although in some way related) acceleration time histories that satisfy the SRS. As such, the intent of these shock requirements is not simply to ensure that a particular acceleration time history is not detected by the switch (in the case of the never-detect requirement) or is detected by the switch (in the case of the always-detect requirement). Rather, the intent is to ensure that *any* acceleration time history satisfying these respective SRS requirements results in the desired behavior of the switch. While this statement is probably also true of most other products that are shock-tested against a requirement specified using an SRS, testing is rarely carried out to prove that this intent is met. In the present application, providing evidence of this was deemed especially critical due to uncertainties associated with field data that relates to these SRS requirements. As such, included in the scope of the study was an attempt to demonstrate that switch performance as a function of variation between acceleration time histories was fully examined.

HARDWARE

Initially, both normally-closed and normally-open unidirectional switches were investigated, but initial testing with normally-closed switches demonstrated that they were not as reliable in shock and vibration environments due to chatter and cross-axis sensitivity. All subsequent work focused on normally-open switches. The particular family of acceleration switches under consideration essentially consisted of a mass and spring housed in a small package, as shown in Fig. 2. The mass is held against the inside of the lid by a preload in the spring. When a sufficient equivalent static acceleration load is applied in a direction opposite of the spring preload, the mass compresses the spring and touches a contact, closing the circuit. If an acceleration load is applied in the negative direction of the switch, the mass bears against the inside of the lid and remains at rest.

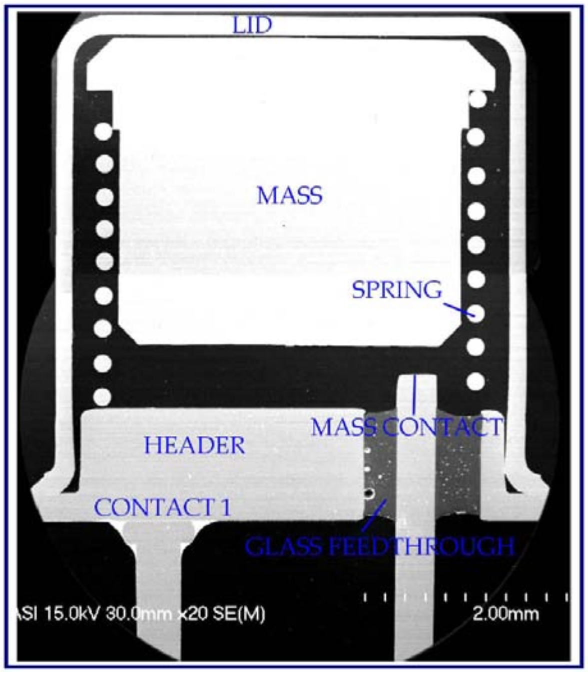

Figure 2: Cross-section of a representative acceleration-sensing switch.

The static acceleration closure level was the primary specification provided by the switch manufacturer. Also available (upon request) was information on the mass, spring constant, and gap distance. This information was used in conjunction with a spreadsheet program provided by the manufacturer to predict the half-sine pulse amplitude required to close the switch as a function of the mass, spring constant, gap distance, actual (as-produced) static acceleration level required for closure, and duration of the applied half-sine pulse. Two early rounds of testing on candidate switches from this family demonstrated that the closure levels predicted by the manufacturer’s spreadsheet for half-since pulses were, in general, fairly accurate. The characteristic curves (predicted closure level as a function of half-sine pulse duration) for a selection of candidate switches are shown for reference in Fig. 3.

ANALYTICAL METHOD

While the behavior of the switches in response to simple, half-sine shock pulses was well-characterized, the behavior in response to more complicated shock pulses, such as the requirements shown in Fig. 1, was not. With strict resource limitations (schedule, funding), a simple means to accurately predict switch behavior in response to arbitrary shock pulses was needed, as opposed to a more rigorous approach, such as that described in Reference [5].

Furthermore, the goal was to implement a method that accounted for the natural variation among the acceleration time histories satisfying the SRS requirements. The intent of this effort was to develop a predictive means of selecting the appropriate switch characteristics (mass, spring constant, and gap distance) from those offered by the manufacturer within this family of switches to meet the intent of the design requirements.

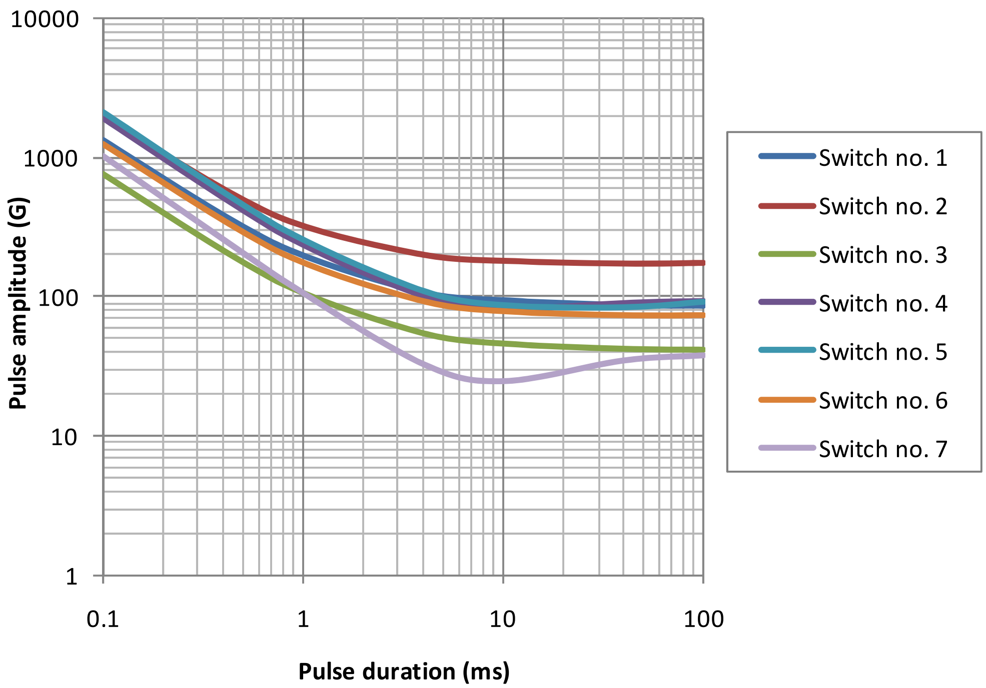

Figure 3: Characteristic curves for several candidate switches.

The first step was to analytically generate 100 unique acceleration time histories satisfying the never-detect requirement, using the method of damped sinusoids [2,3]. This method can be somewhat labor intensive, so in order to make the task more feasible, the realized time histories were allowed to be somewhat less perfect than is typically achieved when only one time history is required. The frequency range of interest (7 to 600 Hz) was discretized into a total of 28 frequencies which were varied to generate the 100 unique time histories. An abbreviated approach was employed in which the frequencies were allowed to vary randomly within a range defined as 40% in the positive and negative direction about the nominal “center” frequency. A representative example of the realized acceleration time histories is shown for reference in Fig. 4. As a result of this semi-automated approach, the resulting SRS profiles of the realized 100 time histories were collectively biased slightly to the low side.

Next, two algorithms were implemented to assess the half-sine-like content of these time histories, since their performance in response to this type of input was well-characterized. The first algorithm was intended to form a high estimate of the half-sine-like content, for use in assessing the performance of candidate switches against the never-detect requirement. In this algorithm, the peak acceleration level achieved between each zero-crossing in the pulse was determined, along with the time between the two zero-crossings on either side of the peak. These pairs of values (a duration and a peak acceleration) were assumed to describe a simple half-sine pulse, as depicted in Fig. 5. The entirety of each acceleration time history was analyzed in this manner, with the results for all 100 time histories compiled together. The acceleration values were plotted against duration, and a maximum bounding curve was drawn around the entire set of points, as shown in Fig. 6.

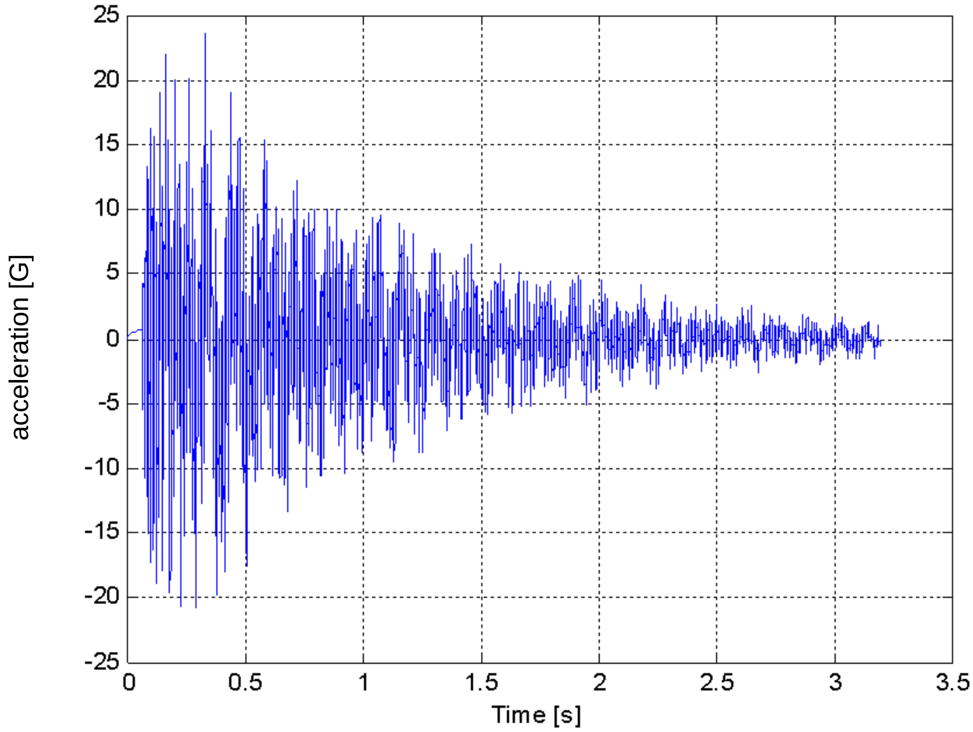

Figure 4: A representative example of the 100 realized acceleration time histories used for the analysis, generated using the method of damped sinusoids [2,3].

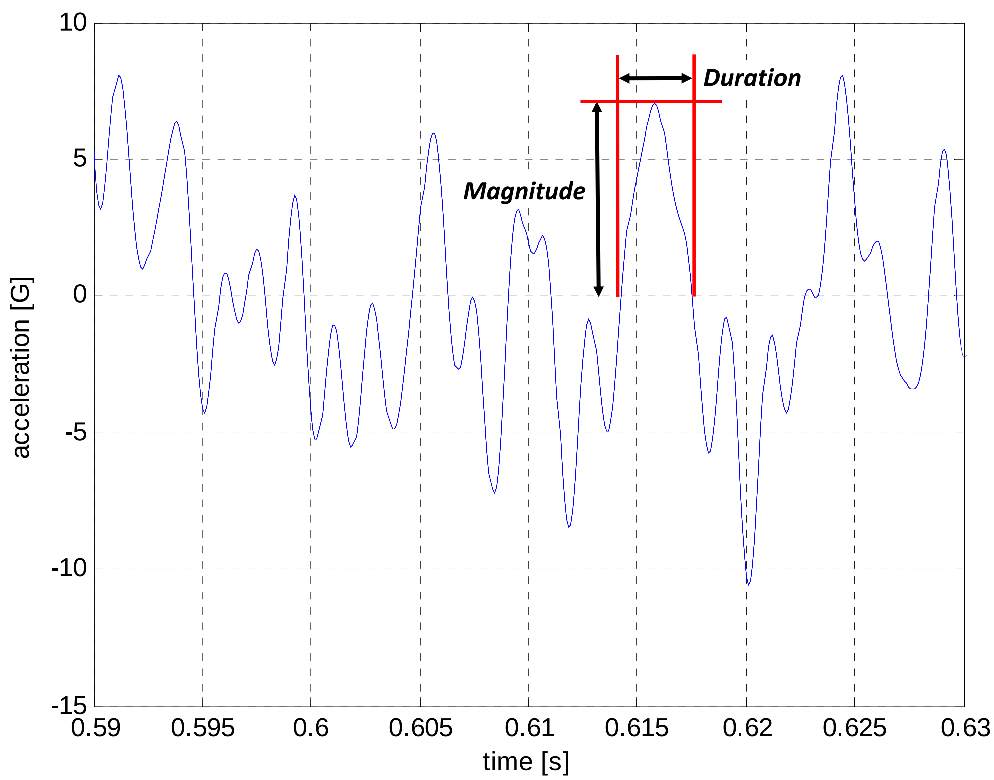

Figure 5: Method for estimating half-sine-like content between each zero-crossing.

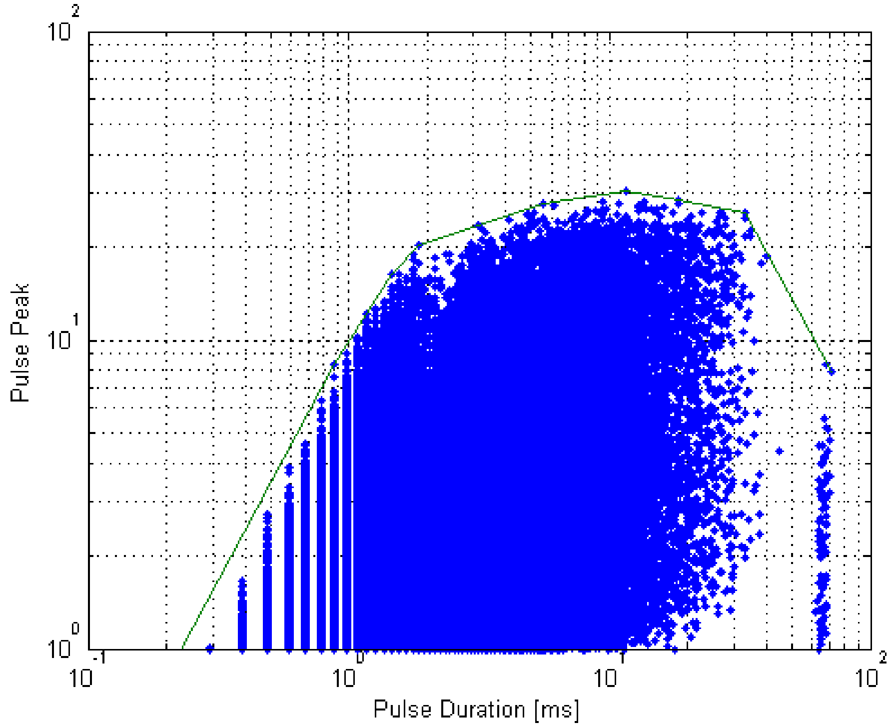

Figure 6: Maximum bounding curve of half-sine-like content of 100 acceleration time histories, computed using the first algorithm.

The second algorithm was a modified version of the first and was intended to form a low estimate of the half-sine-like content, for use in assessing the performance of candidate switches against the always-detect requirement. In this algorithm, the area under the curve was determined between successive zero-crossings, and was used to compute the amplitude of a half-sine pulse with the same duration and area. The entirety of each acceleration time history was analyzed in this manner, and the equivalent peak acceleration values were plotted against duration for each individual time history. Finally, a minimum bounding curve was drawn underneath the set of 100 curves, as shown in Fig. 7.

An illustration of the differences between these two algorithms is warranted. In the limit that the acceleration profile is a perfect half-sine between zero-crossings, the algorithms give identical (and exact) results. However, for non-ideal (i.e., non-half-sine) shapes, the algorithms give different results. Two notional categories of non-ideal, "multiple-peak" shapes are shown in Fig. 8, along with the respective half-sine pulses that are obtained using the two algorithms. As Fig. 8 illustrates, the appropriate pairing of the two algorithms with the two requirements being assessed depends on which of the two types of multiple-peak formations is more likely to occur. A crude inspection of a few example time histories indicated that the first multiple-peak formation was the more prevalent of the two (although this assessment was subjective).

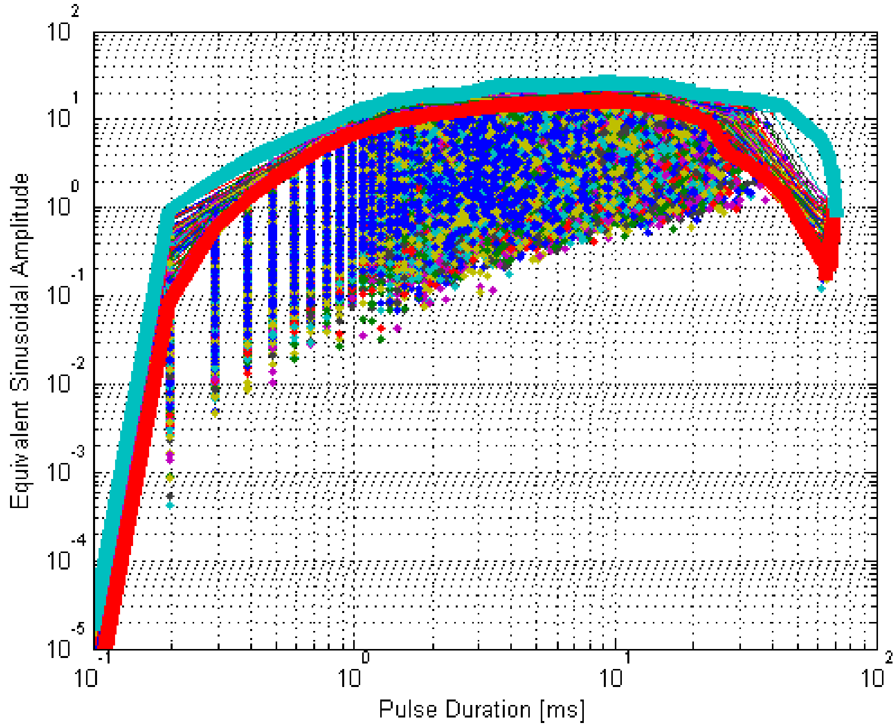

Figure 7: Minimum bounding curve (shown in red) for the 100 individual bounding curves, computed using the second algorithm.

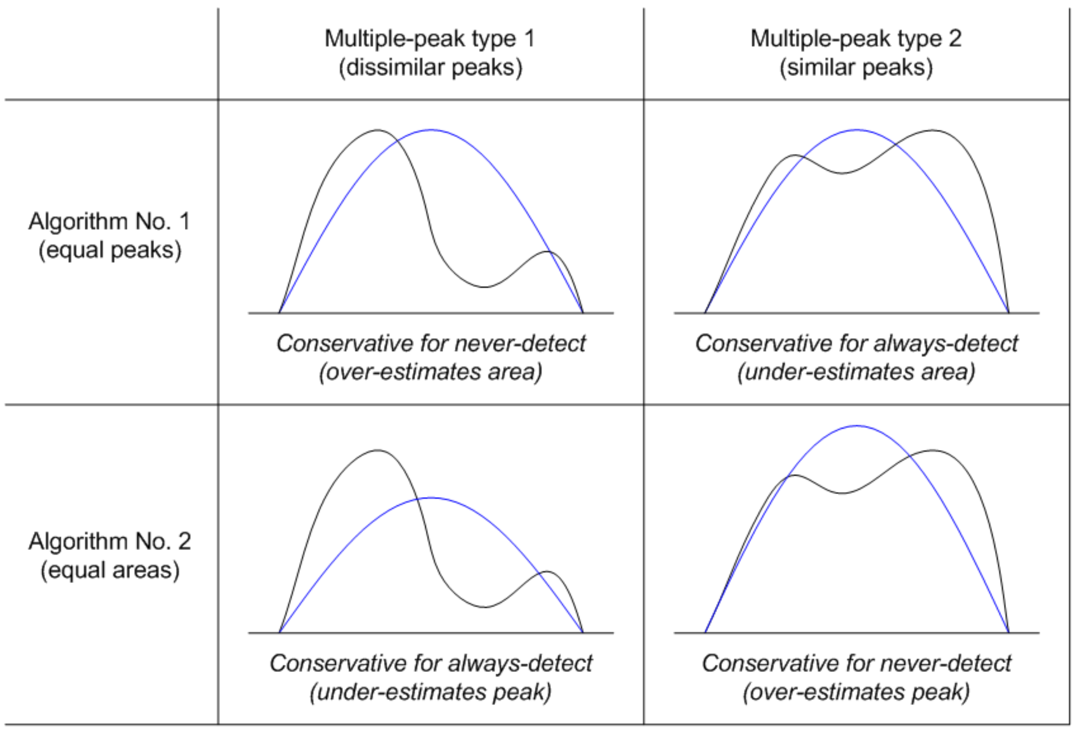

Figure 8: Two notional shapes of non-ideal acceleration profiles between zero-crossings (in black), along with the half-sine pulses (in blue) that are obtained using the two algorithms.

The next part of the analysis was to plot the maximum and minimum bounding curves (shown in Fig. 6 and Fig. 7, respectively) along with the characteristic curves of the candidate switches, as shown in Fig. 9. The minimum bounding curve was scaled up until a reasonable window of separation existed between it and the maximum bounding curve (with the scaled-up minimum bounding curve being higher than the maximum bounding curve). The goal was to identify a switch with a characteristic curve that passed through this region of separation. In other words, the characteristic curve for the switch must remain above the maximum bounding curve at all pulse durations, in order to ensure that the never-detect requirement is met. In addition, the characteristic curve must pass below the scaled-up minimum bounding curve (at least at some pulse durations), in order to ensure that the always-detect requirement is met.

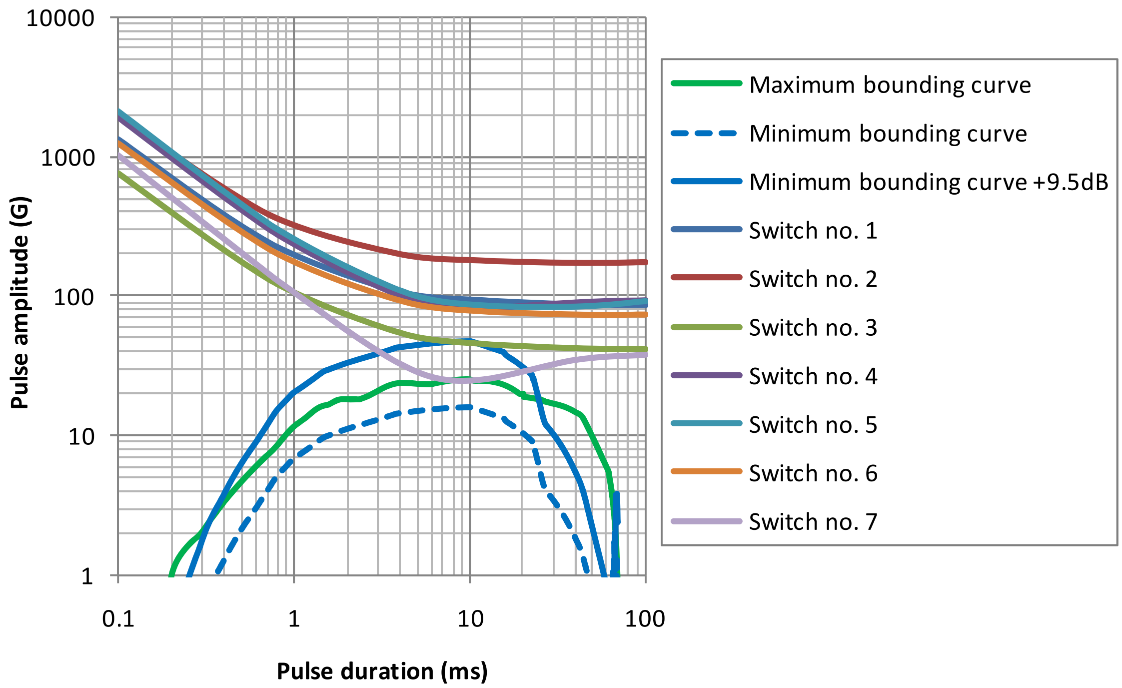

Figure 9: Comparison of characteristic curves of several candidate switches to maximum and minimum bounding curves.

These two requirements are, of course, most easily met as the window of separation (i.e., the scaling factor) between them is increased. On the other hand, it is desirable to minimize the window, since it represents a space of shocks where the behavior of the switch (i.e., closure or no closure) will not be known. Based on the data shown in Fig. 9, switch no. 3 and switch no. 7 emerged as the leading contenders. However, it was unclear whether the dip present in the curve for switch no. 7 at around 10 ms was real or an artifact of the spreadsheet being used to generate these curves, so several of these switches were purchased for testing, and their actual closure levels were measured as a function of pulse duration. The results of this testing are shown in Fig. 10, which shows that the computed closure levels (at least for this particular switch) were not as accurate as had been observed in earlier testing with other switches. On the other hand, the comparison of the measured closure levels for switch no. 7 to the bounding curves clearly predicted that this switch would meet the shock detection requirements with a scaling factor of +9.5dB used to establish the always-detect requirement.

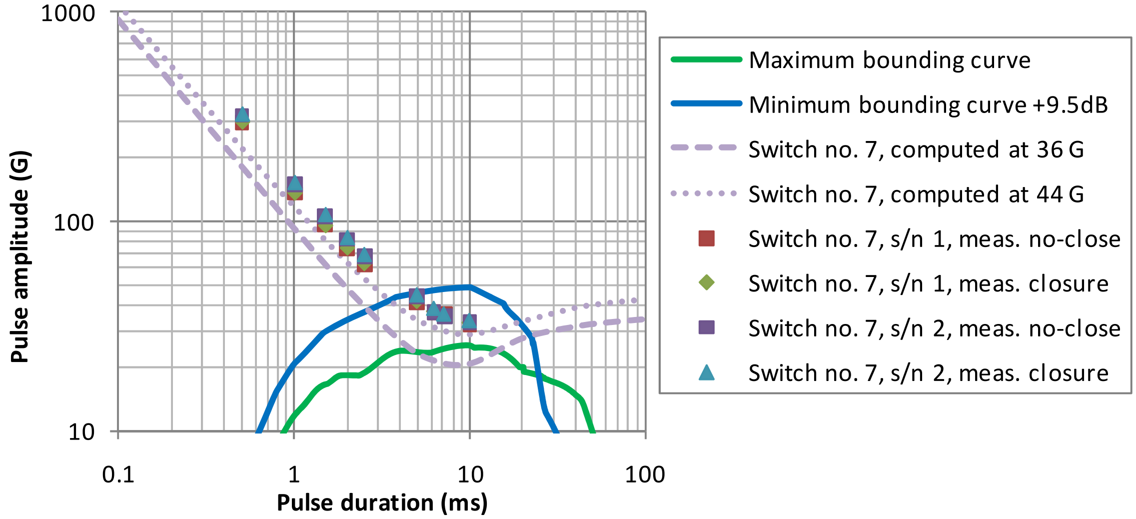

Figure 10: Comparison of calculated and measured performance of switch no. 7 to maximum bounding curve and scaled-up minimum bounding curve.

EXPERIMENTAL RESULTS

Based on the results of the analysis and preliminary testing described above, the always-detect requirement was set at 9.5dB above the never-detect requirement, as shown in Fig. 11. Further testing was carried out to conclusively demonstrate whether or not selected switch would meet these requirements. For this testing, the always-detect SRS requirement shown in Fig. 11 was used to generate 20 unique acceleration time histories using the method of wavelets [4]. The SRS was truncated at 35 Hz to facilitate the limitations of the electro-dynamic shaker table that was used. Because of the different method used to generate them, these 20 time histories were substantially different in form from the 100 used for the analysis, as evidenced by the example shown in Fig. 12.

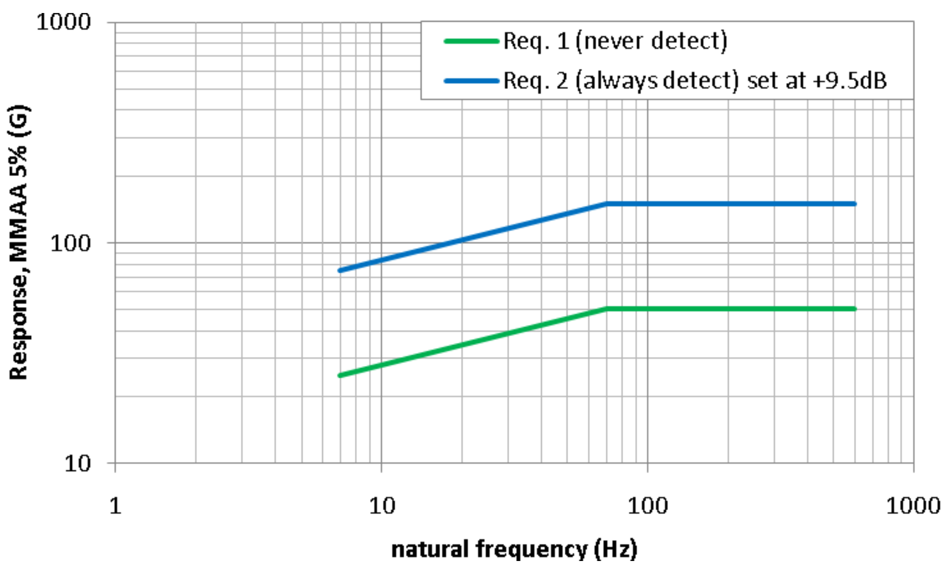

Figure 11: Finalized design requirements.

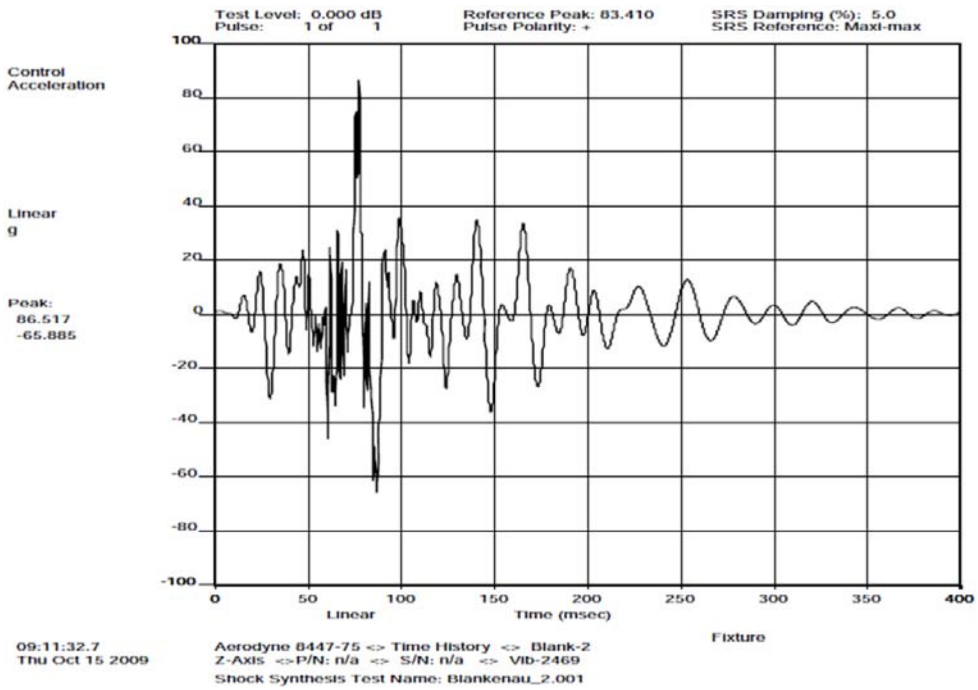

Figure 12: A representative example of the 20 realized acceleration time histories used for testing, generated using the method of wavelets [4].

Two no. 7 switches were mounted together in a test unit, with both switches oriented in the same axis and direction. Each of the 20 acceleration profiles were scaled down in incrememnts of 0.5dB, and were applied in-line with the switches in both the postive and negative directions. The minimum shock amplitude required to register a closure of both switches was recorded in terms of dB below the always-detect level. These results are shown in Table 1 for the two directions of shock application (positive and negative). As shown in the table, an additional acceleration profile (no. 21) was generated and tested because the shaker table could not properly execute the no. 14 profile.

A second, more in-depth round of testing was conducted on switch no. 7 using the same 20 acceleration time histories. In this round of testing, two no. 7 switches were mounted together in each of several test units, with the pair of switches mounted in the same axis but opposite directions. The shock level requried to cause at least one of the two switches to close was measured for each test unit in increments of 1dB below the always-detect level. These tests were performed at three different temperatures (cold, ambient, and hot). A total of 360 measurements of the switch closure level were acquired at the three different temperatures using these test units. A plot of all measured closure levels is shown in Fig. 13, along with a comparison to a normal distribution fit to the data.

The analytical method was applied retrospectively to assess how well it would have predicted the observed results (i.e., closure levels) for the 20 acceleration time histories used for testing. The bounding curve for each of the individual 20 times histories was generated using the second algorithm (equal areas). Next, each of the 20 bounding curves was scaled up by the average closure level measured for that time history, as measured in the second round of testing. The 20 scaled bounding curves are shown in Fig. 14, along with the measured characteristic curve for switch no. 7.

Acceleration profile no.	Direction of shock application		Expected closure level if one switch is mounted in each direction (dB)
	Positive (dB)	Negative (dB)	
1	-4.5	-4.5	-4.5
2	-5.5	-4.5	-5.5
3	-5.5	-4.5	-5.5
4	-4.5	-3.0	-4.5
5	0.0	-6.5	-6.5
6	-2.0	-2.0	-2.0
7	0.0	-1.5	-1.5
8	-0.5	-4.0	-4.0
9	-2.5	-5.5	-5.5
10	-0.5	-5.0	-5.0
11	-2.0	-3.0	-3.0
12	-3.5	-2.0	-3.5
13	-1.0	-3.0	-3.0
14	Aborted (shaker table could not run this profile)		
15	-2.0	-4.5	-4.5
16	-2.5	-2.0	-2.5
17	-3.5	-3.0	-3.5
18	-5.0	-2.0	-5.0
19	-3.5	-4.5	-4.5
20	-4.5	-3.5	-4.5
21	-3.5	-1.5	-3.5

Table 1: Results of the first round of testing: measured minimum closure levels for the 20 accleration time histories, shown in dB below the always-detect requirement.

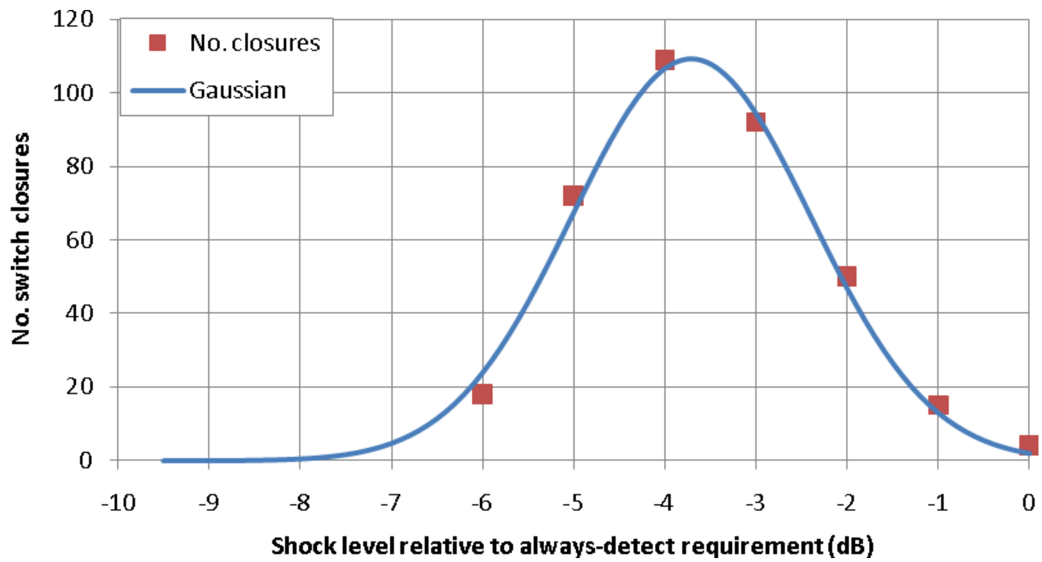

Figure 13: Results of the second round of testing: histogram of measured minimum closure levels for all tested configurations, shown in dB below the always-detect requirement.

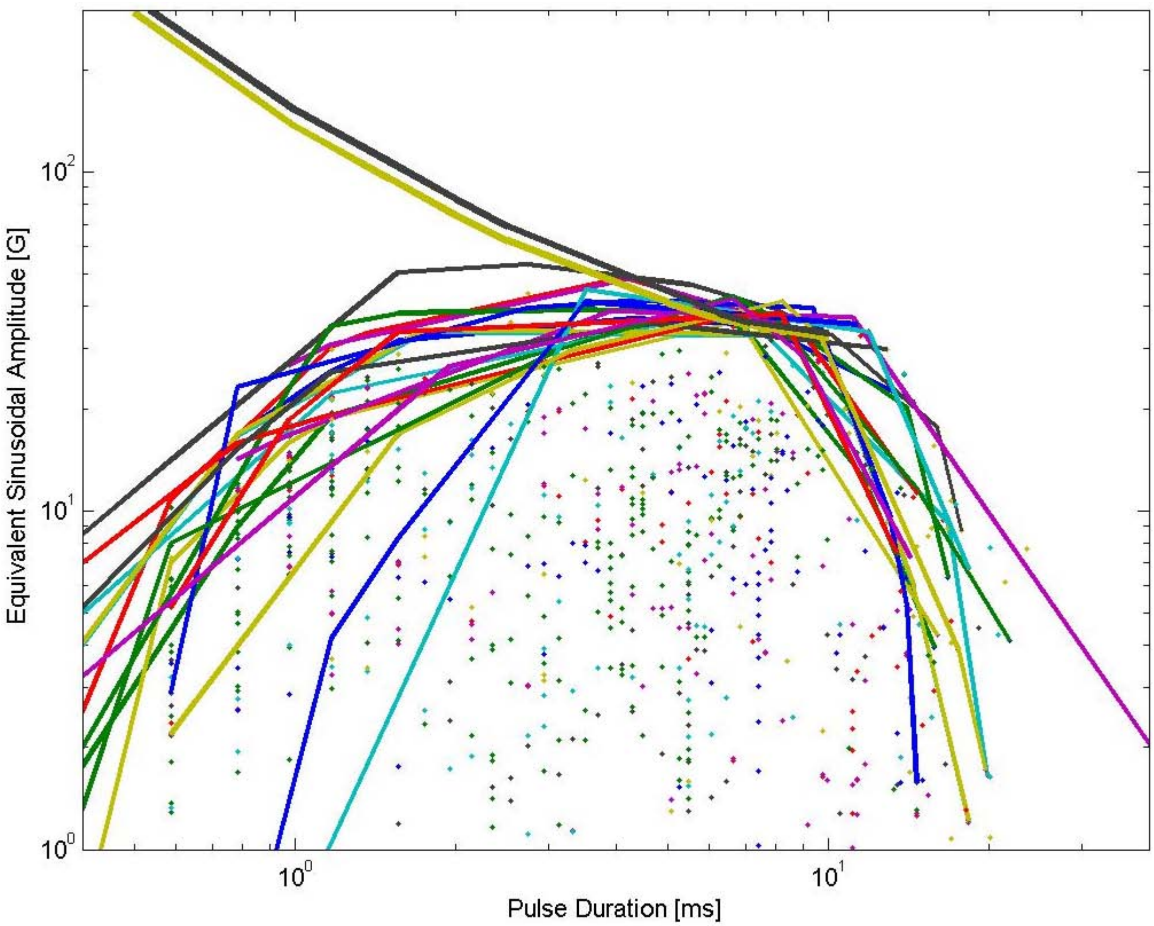

Figure 14: Bounding curves for 20 acceleration time histories, each scaled up by the average closure level for that time history, and compared to measured characteristic curve (shown in black/gold) for switch no. 7.

DISCUSSION

In the first round of testing on the no. 7 switch using the 20 realized acceleration time histories, two switches were mounted in the same axis and direction. This configuration was originally of interest, but it was determined that a more optimal use of two switches was to mount them in the same axis but opposite directions. To make use of the results obtained in the first round of testing on switch no. 7, the last column of Table 1 shows the expected closure level if one switch were mounted in both the positive and negative directions. This expected closure level is simply the lower of the two closure levels measured in the test. (This is valid since, in this first round of testing, the recorded closure level was the level required to cause both switches to close.)

These inferred results indicate that the switches would never close for shocks at or below the never-detect level, and that at least one of the switches would always close at or above the always-detect level. The average closure level was 5.4dB above the never-detect level and 4.1dB below the always-detect level, so it was nearly centered in the range of interest, although slightly biased to the high side. For the 20 realized acceleration time histories, the lowest shock level resulting in switch closure was 3.0dB above the never-detect level, and the highest shock level required to cause closure (of at least one switch) was 1.5db below the always-detect level. The results of this testing were promising, but a more thorough round of follow-on testing was warranted.

In the second round of testing, several test units were evaluated, each containing a pair of no. 7 switches mounted in the same axis but opposite directions. As shown in Fig. 13, the switches never closed for shocks at or below the never-detect level, and at least one switch always closed at or above the always-detect level. The average closure level was 5.8dB above the never-detect requirement and 3.7dB below the always-detect level. As in the first round of testing, this average closure level was slightly biased to the high side of the range of interest. For the realized acceleration time histories, the lowest shock level resulting in switch closure was 3.5dB above the never-detect requirement, and the highest shock level required to cause closure (of at least one switch) was right at the always-detect level.

The second round of testing accounted for many potential sources of variation in the performance of the switches:

- several test units were evaluated, each containing a pair of switches;
- all units were tested using each of the 20 unique acceleration time histories; and
- all testing was repeated at cold, ambient, and hot temperatures.

In total, 360 different measurements of the switch closure level were measured. As shown in Fig. 13, the results seem to be normally-distributed, although one would have expected a few units to register closures at the -7.0dB level (i.e., 7.0dB below the always-detect level). No discernable dependence on temperature was observed in the measured closure levels.

The second round of testing was sufficient to allow for an assessment of the design margin over the requirements (that is, margin “above” the never-detect level, and margin “below” the always-detect level). As shown graphically in Fig. 13, the margin over the never-detect level is 1.5 to 2.5dB, depending on the confidence level desired. On the other hand, the margin over the always-detect level is zero, since in a few cases (4, to be exact) the full-level shock was required to close the switch.

Figure 14 shows that for a given acceleration time history, the measured closure level tends to correspond fairly well with the amplitude at which the bounding curve for that time history intersects the characteristic curve for the switch. This, of course, was the working hypothesis of the method outlined in this work, which focused on selecting a switch with the appropriate dynamic characteristics to meet a set of shock detection requirements. It is easy to see how the method could also be used to answer other, more straight-forward questions, such as determining whether or not a given switch would detect a specified shock environment.

CONCLUSION

Unidirectional acceleration switches were investigated for detecting shock environments specified using shock response spectrums (SRS). The design requirements included an SRS for a lower shock level, at or below which the switch should never close, and an SRS for a higher shock level, at or above which the switch should always close. Part of the research was to quantify the amount of separation needed between the two SRS requirements, in order to characterize the resolution with which the switch could reliably distinguish between shock levels.

An analysis technique was developed that permitted a rapid means of identifying a switch that would meet a specified set of never-close and always-close requirements. The analysis technique was developed with a specific focus on taking into account the inherent variability of the shock environments encompassed by a given SRS. In this analysis, the lower and upper bounds of the half-sine-like content was estimated for a suite of acceleration time histories. The results were then used, in conjunction with an analysis of several candidate switches, to select a switch with the appropriate dynamic characteristics.

Two subsequent rounds of testing using hardware prototypes demonstrated that the selected switch met the design requirements, which were separated by 9.5dB. The achieved margin over the always-detect level was 1.5 to 2.5dB, depending on the desired confidence level. The achieved margin over the never-detect level is zero, since in a small percentage of cases the full-level shock (i.e., at the always-detect level) was required to close the switch.

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