On The Performance of Mechanical Shock Indicators

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ON THE PERFORMANCE OF MECHANICAL SHOCK INDICATORS

Abstract

Cost-effective mechanical shock indicators are widely used to warn if a package has been subjected to a shock event during distribution. Such devices are an important part of the quality control and monitoring process during the distribution of fragile products. As the distances over which goods are transported continues to increase, so does the reliance on such devices to ensure that, should product damage occur due to excessive shocks during distribution, some evidence of the cause is available. However, there is a growing number of cases where false or misdetection has been reported producing misleading or confusing information hence loss of confidence in the data. This paper presents an experimental investigation into the actual response characteristics of three commercially-available mechanical shock indicators (beam type, liquid-in-glass tube type and magnetic type). Specifically, this paper addresses the influence of shock pulse duration on the performance of shock indicators as well as evaluating the devices' repeatability across a broad range of shock pulse durations. Included in the paper are descriptions of the especially-adapted test apparatus which employs a pneumatic rubber bladder to generate half-sine shock pulses of varying durations by adjusting the bladder pressure. Results from experiments show that each device is sensitive to shock magnitude as well as shock duration to varying extents. The paper makes recommendations on the use of the devices and the findings highlight the need for establishing the shortest pulse duration experienced by any packaged product by means of drop tests before employing the devices.

Keywords: Shock indicators, shock detectors, shock duration, shock response spectrum.

INTRODUCTION

As a consequence of the global economy, distances over which goods are distributed continue to increase. As a result, so does the exposure to the environmental (dynamic) loads generated when the shipment is handled (mechanical or manually) and by transport vehicles. This leads to the increased (statistical) likelihood of accidental damage to the shipment and products within.

Protecting products against such distribution hazards broadly involves the following measures:

1. Introduce effective protective packaging to absorb the expected shocks during distribution
2. Control the level and occurrence of transient loads within the supply chain

The first measure relies on estimates of the maximum shock level (and duration) expected for any particular supply chain. This is achieved by using data recorders to undertake field surveys followed by statistical analysis. However, most supply chains are sufficiently complex that it is difficult to accurately predict or control the levels of hazards from sampled data. Instead, regular monitoring is required to identify whether shock events that exceed the predicted levels (usually accidentally) have occurred. This is particularly relevant for shipments of fragile and valuable products. In such cases damage during distribution is costly and often involves insurance claims. Invariably these claims lead to the attribution of culpability and the need to manage and control risk.

The management and control of risks requires regular monitoring of excessive shock levels during distribution and is often undertaken using affordable, often disposable, and easy-to-use impact or shock indicators. These devices (numerous types and models are available commercially) rely on mechanical activation and, as such, do not require a power source. The active elements within the devices are designed such that excessive acceleration (based on a pre-determined threshold) will result in excessive deflection of the element which is easily observable with the naked eye. One common characteristics of such passive shock indicators is that they rely on the deflection of a mass against a restoring force (such as mechanical spring or a magnetic field) to indicate excessive shock excitation. This behaviour can be approximated by that of a single degree-of-freedom (SDoF) system. One main drawback of such a design is that the trigger threshold is not purely dependent on acceleration but is also a function of the frequency content of the excitation waveform (shock). This drawback is a result of such devices exhibiting resonance and, since the means of indication is deflection or is related to deflection, the resonant frequency often exist in the region of the expected frequency content of the shocks to be detected. Significantly, such behaviour makes these devices highly dependent on shock duration which makes it difficult to establish the magnitude of the shock that causes the device to trigger as the shock duration is also unknown.

The shock duration dependence of a SDoF device is best illustrated by the shock response spectrum (SRS) which indicates the peak (maximum) response of a SDoF as a function of natural frequency. Such a spectrum is shown in Figure 1 for various shock pulse shapes and clearly reveals that the peak response amplitude is closely related to the ratio of the pulse duration and the natural frequency of the SDoF device.

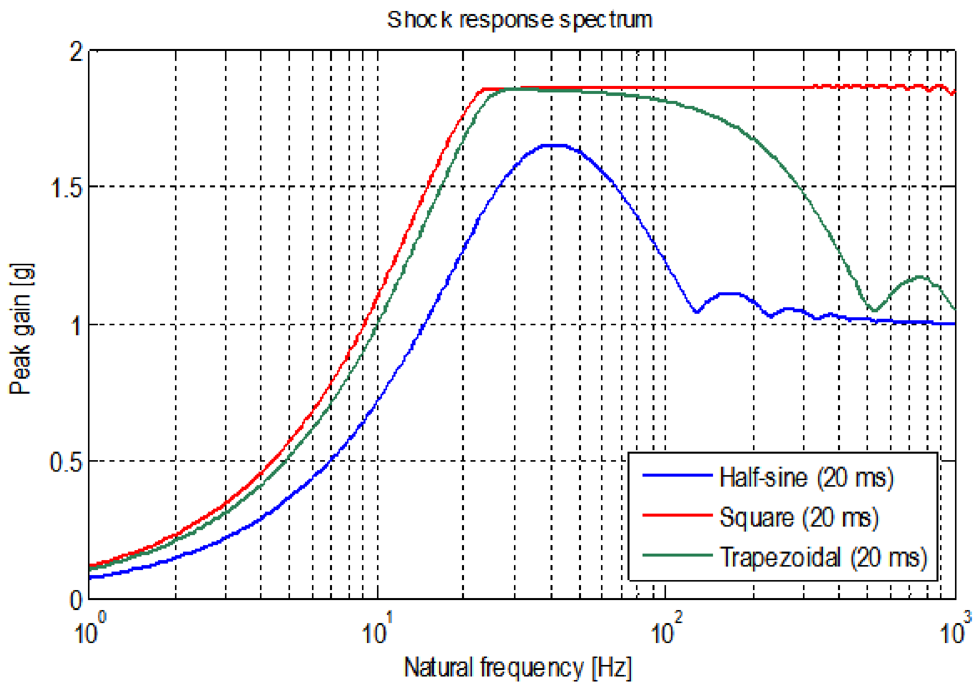

Figure 1. SRS for various shock pulse shapes.

Apart from information published by manufacturers of passive shock detection devices, there is little evidence of published papers discussing the characteristics (especially duration) of the shocks and how they affect the performance of the devices in the distribution environment. Only one formal study [1] which investigates the reliability and sensitivity of a variety of such devices was found. The authors of the study were able to conclude that the trigger threshold of the devices does decrease with pulse duration; however, they did not systematically study the effect of pulse duration on the response of the devices. The lack of literature related to the effect of pulse duration on the triggering of the devices has prompted this experimental investigation. This study focuses on the influence of pulse duration on the trigger threshold of three types of commercially-available and commonly-used shock indicators with the ultimate aim of making recommendations on the effectiveness and use of the devices.

The three types of devices used for this investigation are buckled beam type, liquid-in-glass tube type and magnetic type.

Buckled beam type

The buckled beam type device consists of a thin nylon double beam mounted on a frame in pinned boundary conditions such that the beams are buckled as shown in Figure 2. Attached to the beam is a moulded plastic structure (shown in red in Figure 2) that serves both as a mass supported by the beam and as an indicator when the device is triggered. When the pre-determined level of impact is reached the deflection of the mass is sufficiently large to overcome the buckling force within the beams such that they are flipped in the alterative stable position as shown on Figure 2.

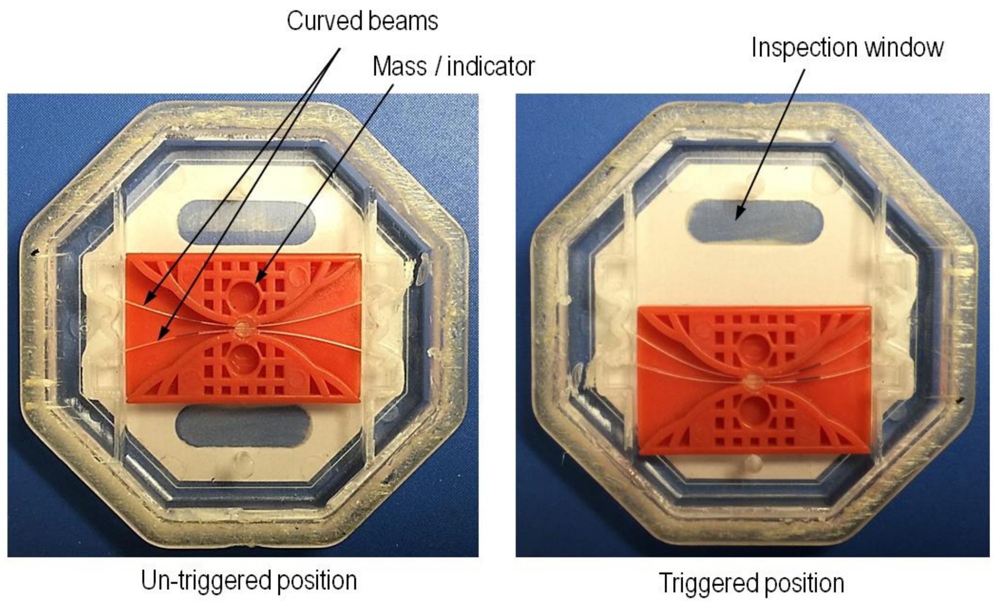

Figure 2: Buckled beam type shock indicator.

The beam type devices used were rated at 15 g ± 15% for a shock duration range of 0.5 – 50 ms. The acceleration required to activate (trigger) the device is given by the manufacturer as a function of (half-sine) shock pulse duration, *t*, in ms as follows [2]:

$$g = 180\, t^{-1.25} + 18.7 \qquad (1)$$

which contains an inconstancy as (1) decays asymptotically to 18.7 g instead of 15g.

Liquid-in-glass tube type

The liquid-in-glass tube type detector comprises a glass tube (mounted into a plastic housing as shown in Figure 3) containing two coloured fluids of different viscosities separated by a small air gap. At a pre-determined level of impact (acceleration), the two fluids come in contact and mix to produce a colour change thus providing an indication that the acceleration threshold has been exceeded by the device.

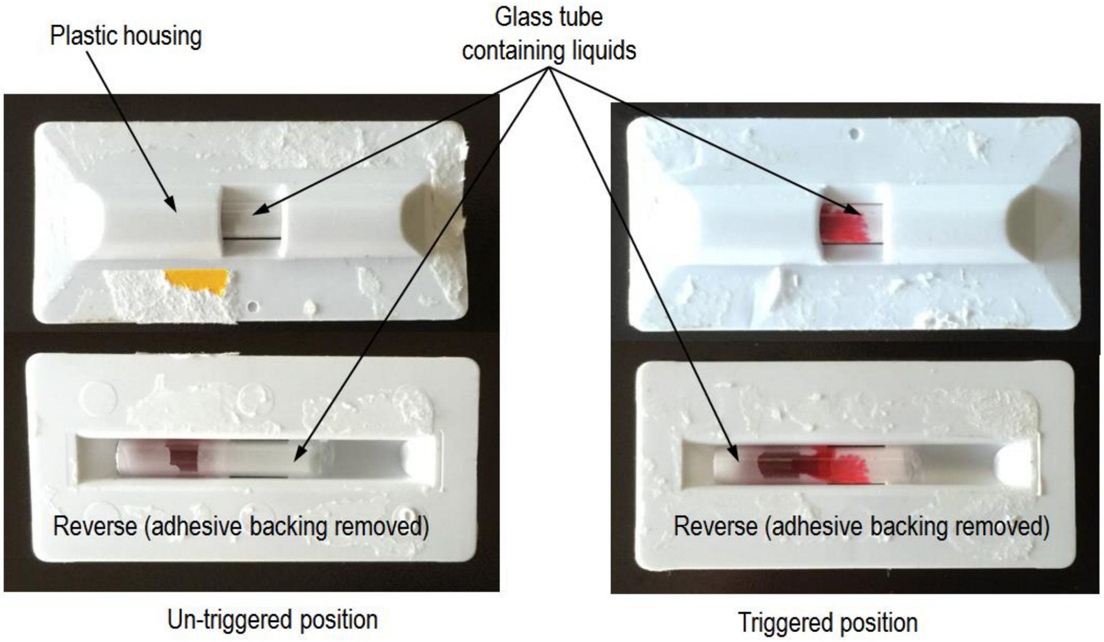

Figure 3: Liquid-in-glass tube type shock indicator.

The liquid-in-glass tube type devices used were rated at 35.4 g ± 15% (after correction for orientation at 90^o as its rating is 25g for an orientation of 45^o) also with a shock duration range of 0.5 – 50 ms. The acceleration required to activate (trigger) the device is given by the manufacturer as a function of (half-sine) shock pulse duration, *t*, in ms as follows [2]:

$$g = 284.4\, t^{-1} + 35.4 \quad (2)$$

Magnet type

The magnet type device uses a magnet to indicate if its (acceleration) trigger threshold has been exceeded. This magnet, which is free to move, is held in its untriggered (home) position by another identical magnet fixed within the device's body with a pre-set separation as illustrated in Figure 4. When the device is subjected to a sufficiently large acceleration impetus, the resulting inertial force applied into the free magnet overcomes the magnetic force and the friction force between itself and the body's surface and moves radially toward the outer ring that is made of magnetic metal in order to ensure that the free magnet remains in the triggered position for the remainder of the journey or until reset manually. The device also contains a ridge which assists in ensuring that the free magnet does not accidentally return to the home position.

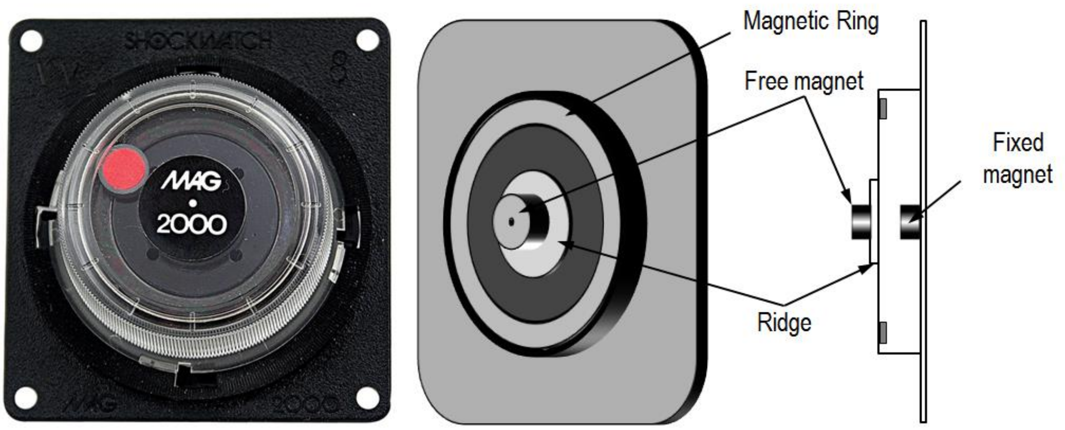

Figure 4: Magnet type shock indicator.

The magnet type devices used were rated at 4 g ± 10% and 10 g ± 10% and also with a shock duration range of 0.5 – 50 ms. In lieu of a mathematical function, the acceleration required to activate (trigger) the device is given as series of curves (one for each threshold) as a function of (half-sine) shock pulse duration [2].

METHODOLOGY & EQUIPMENT

Samples were subjected to half-sine shocks of pre-determined amplitude and durations using a guided platen that was allowed to free-fall onto a compliant element while the acceleration resulting from the impact was measured and recorded. Multiple samples from the same batch were mounted onto the platen concurrently in order to establish repeatability across samples. The platen drop height was incrementally increased and the status of each sample (triggered or un-triggered) was recorded. This was carried-out for a broad range of (nominally half-sine) shock pulse durations.

The generation of half-sine shocks of varying amplitudes is no trivial matter. In theory, as a mass falls on a linear compliant element (spring) the resulting acceleration follows that of a linear SDoF system resulting in a pure half-sine shock pulse. In practice, achieving this over a broad range of pulse durations is not straightforward. Following numerous exploratory experiments with foam and rubber pads (which were found to produce acceptable results only for shorter pulse durations), inflated pneumatic rubber bladders were used. The free-falling platen was also modified to include a hemi-spherical indenter attached to the under-side of the platen to eliminate high-frequency vibrations emanating from the impact of the flat platen with the spherical rubber bladder. To confirm the choice of bladder over foam pads, the compression characteristics of the inflated bladder with the indenter were measured (Figure 5) to establish the degree of linearity as well as to generate a calibration function for bladder compliance as a function of inflation pressure. A schematic of the shock testing apparatus is shown in Figure 6.

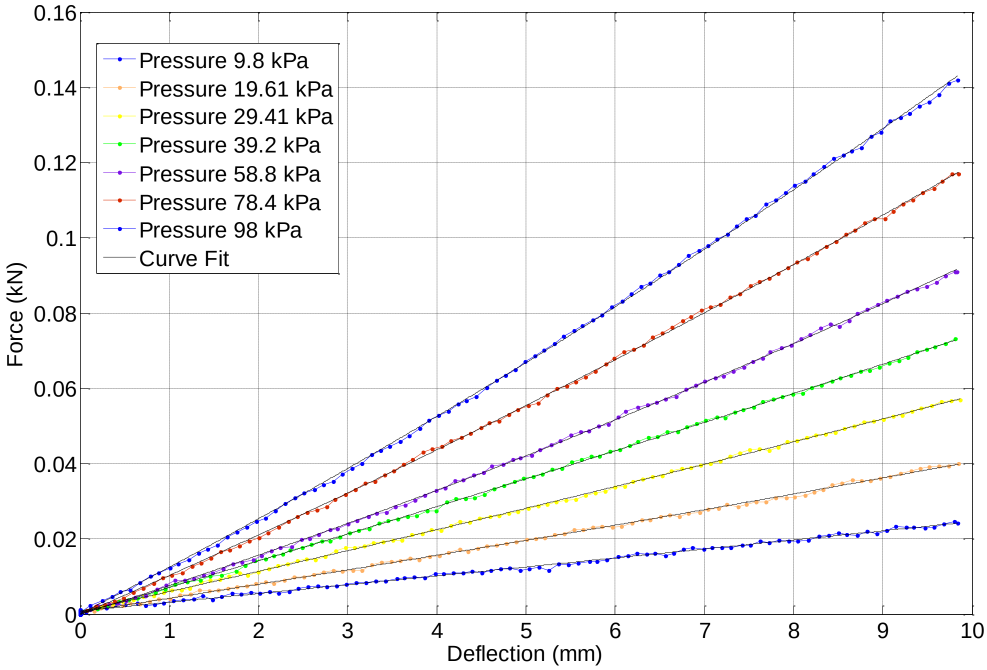

Figure 5. Inflated bladder / indenter compression characteristics

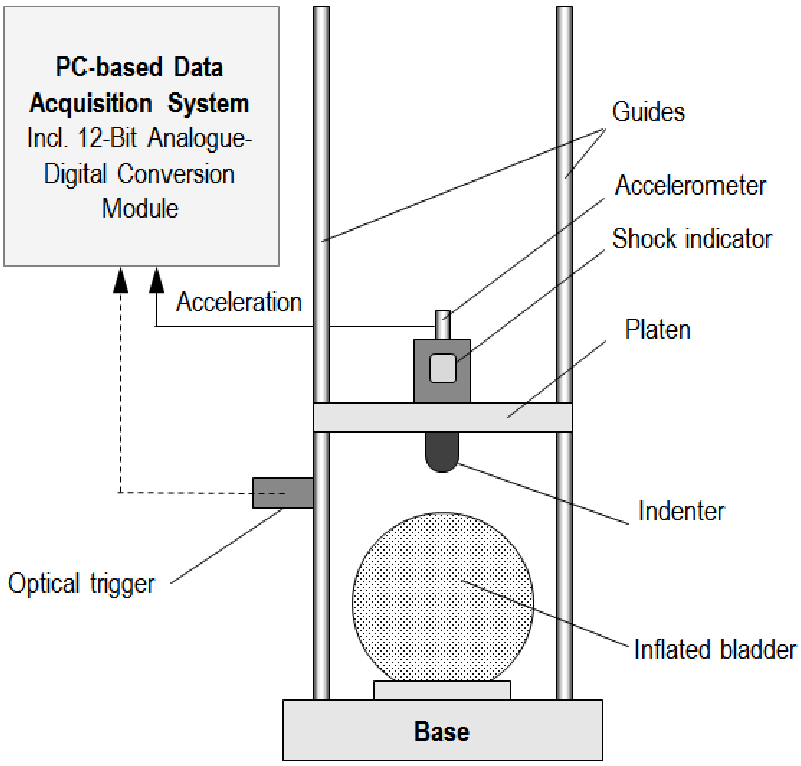

Figure 6. Free-fall shock generation apparatus.

The desired shock pulse duration was achieved by varying the bladder inflation pressure (thus affecting the spring stiffness) and adjusting the platen mass concurrently whereas the shock amplitude was varied by adjusting the drop height. It must be noted that, due to slight nonlinearities within the system, variations in drop height often resulted in small variations in pulse duration.

Determining peak acceleration and shock pulse duration

Because the main aim of the work is to establish the shock acceleration threshold of the device as a function of shock pulse duration, the way in which these values are estimated from measured acceleration data needs to be carefully addressed. Because shock pulses obtained from free-fall experiments rarely conform to a pure half-sine function, some treatment is needed to consistently extract the nominal peak acceleration and shock pulse duration from the data. Conventionally, a low-pass filter is applied to the signal to minimise any high frequency content within that is deemed to be extraneous to the shock pulse. However, this approach is essentially subjective and can introduce biased errors if due care is not applied. As for the shock pulse duration, natural distortion (departure from a pure half-sine waveform) at low acceleration levels (tail ends of the shock pulse) can have a significant influence on estimates. The duration at the zero-crossings is considered to over-estimate pulse duration and the crossing at 10 % of the peak acceleration is commonly used. For this study, a different approach, one based on curve-fitting a half-sine function of a portion of the data, was used to estimate both the peak acceleration and the pulse width duration. The only configurable parameter for this approach is the range of data points to be used to extract the best-fitting half-sine function. The data points to be extracted for curve-fitting are defined by a magnitude threshold based on the raw (unfiltered) shock pulse maximum. An example of this is shown in Figure 7 for a typical measured shock pulse and threshold values of 10%, 25% and 50% along with the corresponding SRS for the fitted half-sine functions.

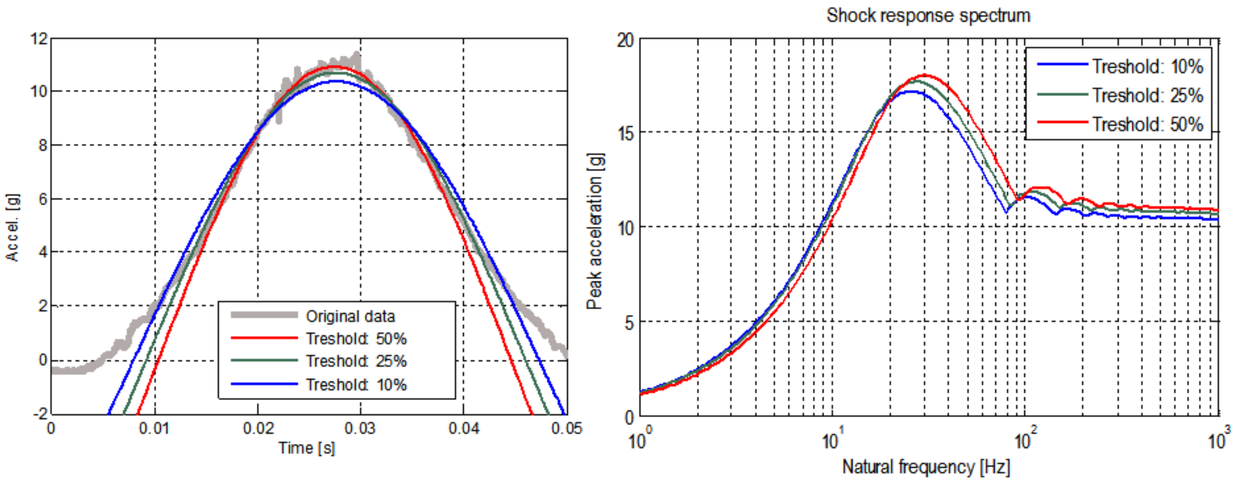

Figure 7. Effect of data extraction threshold on the duration and magnitude of the best-fitting half-sine pulse for one typical case. Left: Time waveform. Right: Corresponding SRS.

A more thorough analysis on a number of typical shock pulses representing the range of durations and magnitudes used during the experiments was undertaken by calculating the estimated durations and magnitudes for extraction thresholds ranging from 0% (all the data above zero) to 50%. Results showing how estimates of shock duration and magnitude vary as a function of threshold are presented in Figure 8, along with a summary in Table 1.

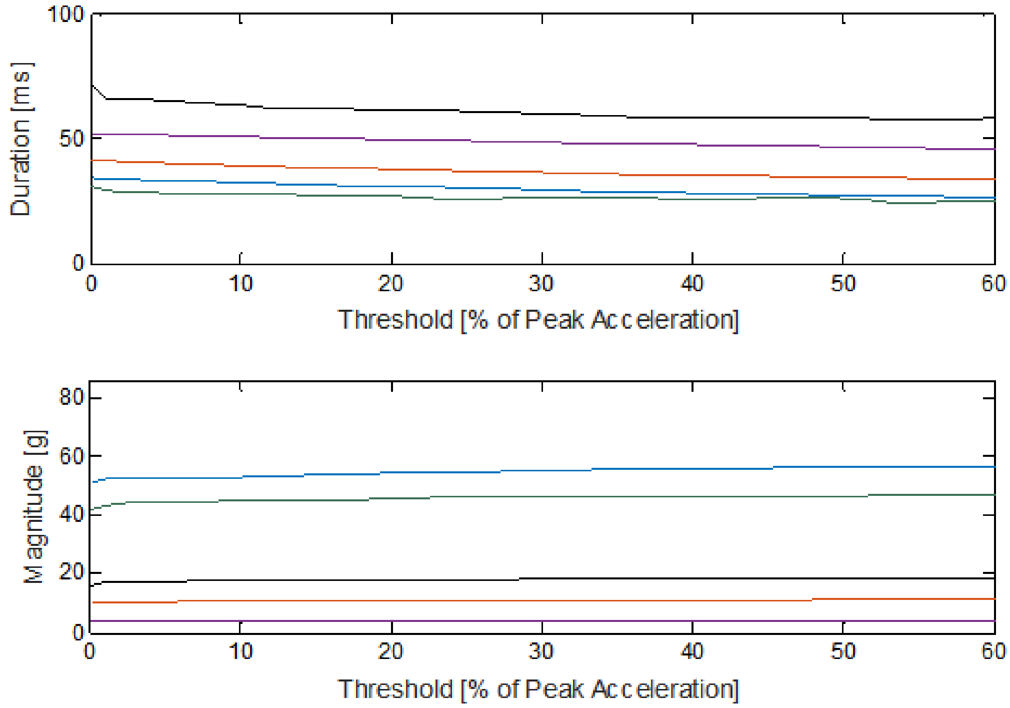

Figure 8. Effect of data extraction threshold on the duration (top) and magnitude (bottom) of the best-fitting half-sine shock pulse for a range of typical cases.

Table 1. Effect of data extraction threshold on the duration and magnitude of the best-fitting half-sine pulse for a range of typical cases.

Shock pulse duration [ms]						**Shock pulse amplitude [g]**					
Treshold (% of peak) :				**Difference 50:10**		**Treshold (% of peak) :**				**Difference 50:10**	
10%	**25%**	**50%**	**Mean**	**[ms]**	**[%]**	**10%**	**25%**	**50%**	**Mean**	**[g]**	**[%]**
27.8	26.2	25.9	26.6	-1.90	-7.1	3.80	3.80	3.90	3.8	0.10	2.6
32.3	30.3	27.5	30.0	-4.80	-16.0	10.40	10.70	10.90	10.7	0.50	4.7
39.4	36.8	34.3	36.8	-5.10	-13.8	17.80	18.10	18.50	18.1	0.70	3.9
50.6	49.0	46.7	48.8	-3.90	-8.0	45.00	46.20	46.50	45.9	1.50	3.3
63.2	60.9	58.3	60.8	-4.90	-8.1	53.20	54.90	56.50	54.9	3.30	6.0
				Overall:	**-10.6**					**Overall:**	**4.1**

The results show that there can never be a true estimate of shock pulse duration and magnitude for imperfect experimental data. In general, as the curve-fitting threshold is increased, duration estimates decrease and magnitude estimates increase, both monotonously up to a high threshold value (60%). Overall, for the cases shown here, the average reduction in shock pulse duration estimate between the 10% and 50% thresholds is 10% whereas the corresponding increase in magnitude estimates is 4%. For the results presented in this paper, a data extraction threshold of 25% was used to find the best-fitting half-sine function and the corresponding shock pulse duration and magnitude. This was found to give consistent results when used with the half-sine curve fit approach.

RESULTS

When using an experimental approach, the actual trigger threshold of a device can only be defined by specifying a range of acceleration and corresponding pulse duration values. That is, the highest acceleration the device can withstand without triggering and the lowest acceleration that will cause the device to trigger along with their corresponding pulse durations. In this particular case, the range will be affected by the magnitude of the incremental change in drop height of the platen. In order to enable easy-to-interpret experimental results, the data from individual drops were analysed to create two regions for each set of devices tested concurrently at each nominal shock pulse duration namely:

1. The untriggered region bounded by the smallest and largest of the highest acceleration peak achieved without triggering the device (and their corresponding pulse width duration).
2. The triggered region bounded by the smallest and largest of the lowest acceleration peak that caused the device to trigger (and their corresponding pulse width duration).

The generation of the un-triggered and triggered regions from raw data is illustrated in Figure 9.

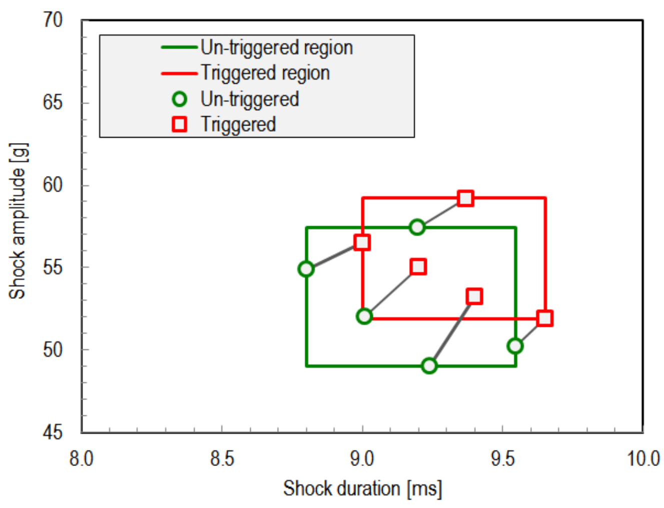

Figure 9. Establishing the un-triggered and triggered regions for concurrent shock tests on multiple samples.

Beam type indicator

Experiments on the beam type indicator (rated at 15 g ± 15%) were undertaken over a broad range of shock durations and the results are shown in Figure 10. This shows that, in general, the measured trigger threshold follows the published data although the measured values are consistently lower than the mean published threshold across the entire shock duration range used. Moreover, the range (variation) in the measured threshold was found to be quite large relative to the actual threshold as shown in Figure 10.

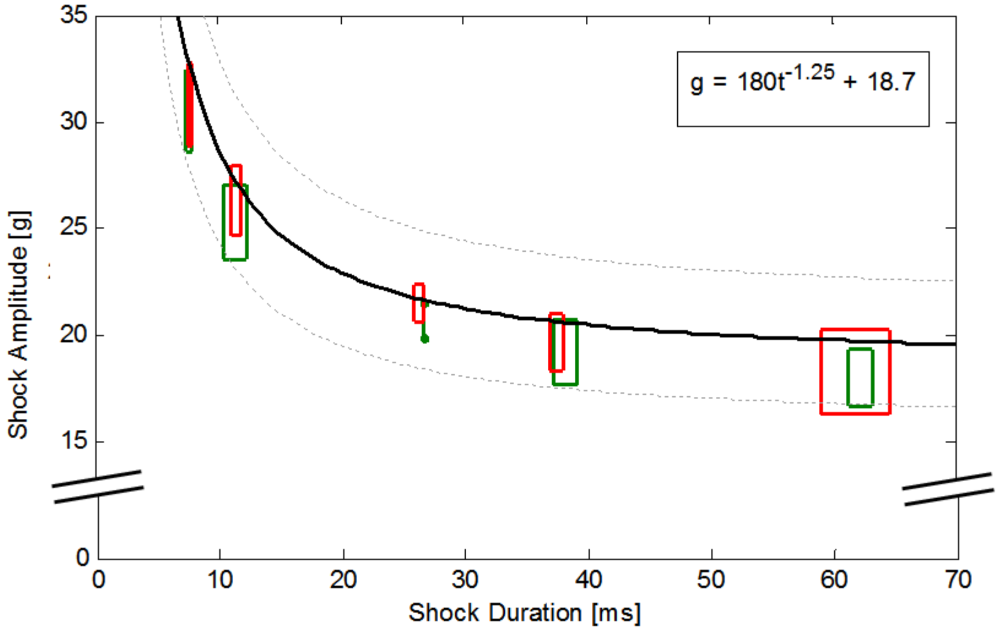

Figure 10. Measured trigger thresholds for beam type indicator (15 g ± 15%) along with published threshold function.

The untriggered / triggered thresholds remain relatively constant (18.5 ± 2.3 g and 18.7 ± 2.5 g respectively) for shock pulse durations exceeding 25 ms as shown in Table 2. However, over this range, the average of the measured untriggered and triggered thresholds (18.6 g) exceeds the threshold listed on the device (15 g) by 24%. This difference is not insignificant and can lead to the misinterpretation of data.

Table 2. Mean triggered and triggered thresholds for beam type indicator (15 g ± 15%).

Untriggered				**Triggered**			
Duration [ms]	**Amplitude [g]**			**Duration [ms]**	**Amplitude [g]**		
Region mean	**Region mean**	**Mean (>25 ms)**	**± Range (>25 ms)**	**Region mean**	**Region mean**	**Mean (>25 ms)**	**± Range (>25 ms)**
7.7	30.3			7.7	30.6		
11.4	25.7			11.5	26.6		
26.8	20.6	**18.5**	**2.3**	26.6	21.2	**18.7**	**2.5**
38.0	19.4			37.4	19.7		
54.9	16.1			55.7	16.1		
62.0	17.9			61.8	17.9		

Liquid-in-glass tube type indicator

Experiments on the liquid-in-glass tube type indicator (rated at 35.4 g ± 15% after correction for 90^{o} orientation) were undertaken over a narrower range of shock durations due to the limitation free-fall test rig which requires larger drop-heights for long-duration shocks. The results shown in Figure 11 reveal quite a different behaviour to that of the beam-type indicator. Although the average measured thresholds are significantly higher (40%) than the rated value, the device appears not to be significantly affected by the shock pulse duration. Over the 10 – 32 ms shock pulse duration range, the average range in the untriggered and triggered thresholds respectively are ± 3.5 and ± 4.0 g (Table 3) which for a device that triggers, on average, at 50 g, is not excessive. Despite not conforming to the published threshold function, this behaviour is in fact an important benefit as it approaches that of an 'ideal' shock indicator; that is one that is not influenced by shock duration. Unfortunately, due to the limitation of the experimental facility used, it was not possible to confirm this behaviour for longer shock durations.

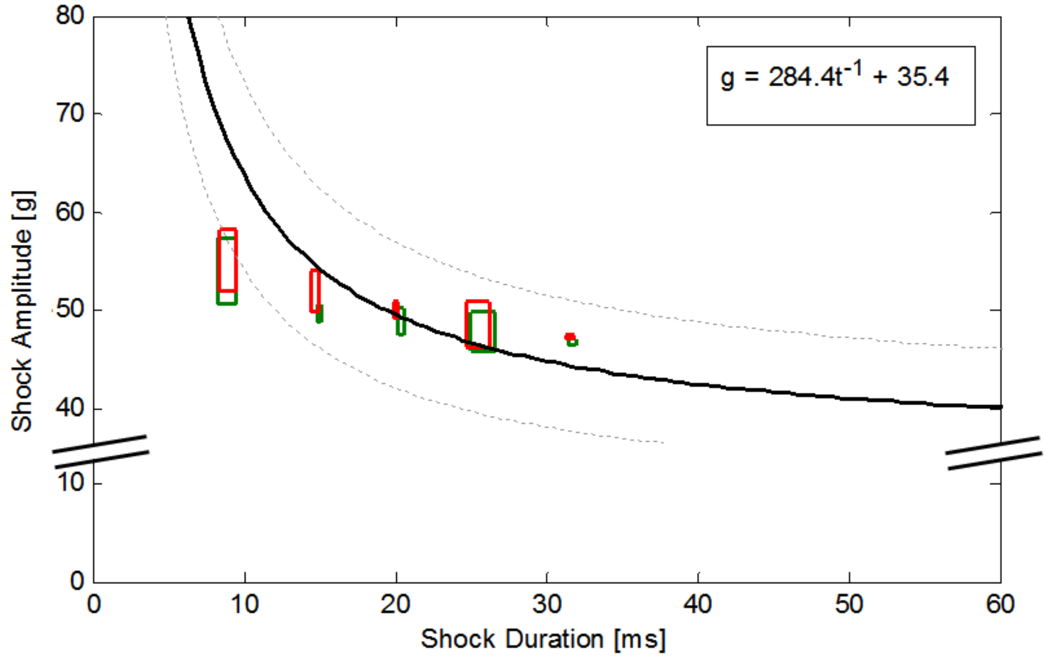

Figure 11. Trigger thresholds for liquid-in-glass tube type indicator (35.4g rated threshold) along with published threshold function.

Table 3. Mean triggered and untriggered thresholds for liquid-in-glass tube type indicator (35.4 g ± 15%).

Untriggered				**Triggered**			
Duration [ms]	**Amplitude [g]**			**Duration [ms]**	**Amplitude [g]**		
Region mean	**Region mean**	**Mean (overall)**	**± Range (overall)**	**Region mean**	**Region mean**	**Mean (overall)**	**± Range (overall)**
9.1	53.9	**49.5**	**3.5**	9.2	55.3	**50.6**	**4.0**
15.1	49.8			14.7	51.9		
20.4	49.0			20.1	50.0		
25.8	47.8			25.5	48.5		
31.7	46.9			31.5	47.3		

Magnet type indicator

Experiments were carried-out on two models of the magnet type indicator, one with a rated threshold of 4 g ± 10% and the other at 10 g ± 10%. Tests were undertaken over a broad range of shock pulse durations spanning approximately 10 – 65 ms. In general, the magnet type indicators were found to conform quite closely to the published threshold values with smaller variations in threshold levels than the beam and liquid-in-glass tube types as shown in Figures 12 and 13. Although the discrepancies between measured and published thresholds for shorter shock pulse durations are large, for shock pulse lasting in excess of 25 ms, the magnet type indicators' dependence on shock pulse duration is slight. Over this range, the mean untriggered and triggered thresholds for the 4 g device were measured at 4.1 g and 4.3 g respectively with corresponding ranges of ±1.1g and ±1.2g (Table 4). This is in reasonably close agreement with the rated threshold of the device (4 g).

A similar behaviour was found for the 10 g device with mean untriggered and triggered thresholds of 10.4 g and 10.6 g respectively with corresponding ranges of ±1.6 g for shock pulse durations of 25 ms and above (Table 5).

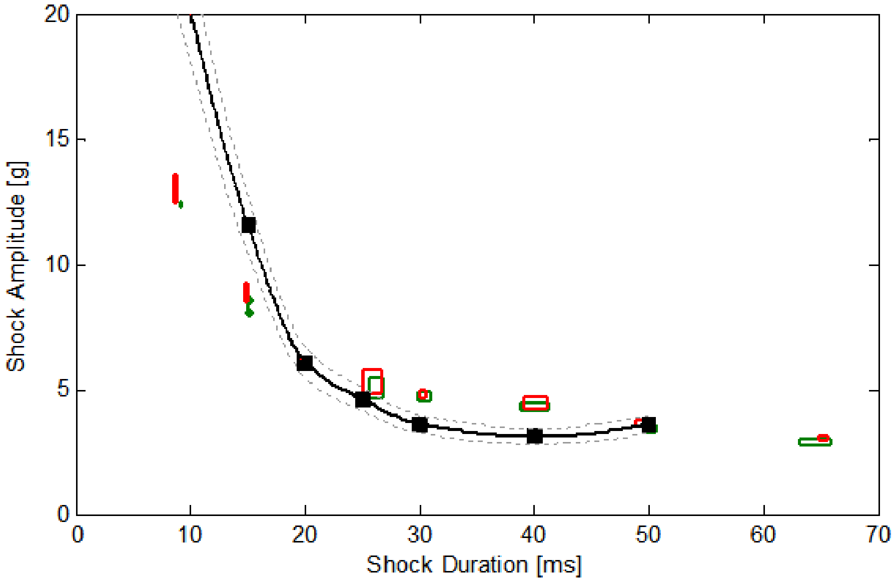

Figure 12: Trigger thresholds for magnet type indicator (4 g) along with published threshold values.

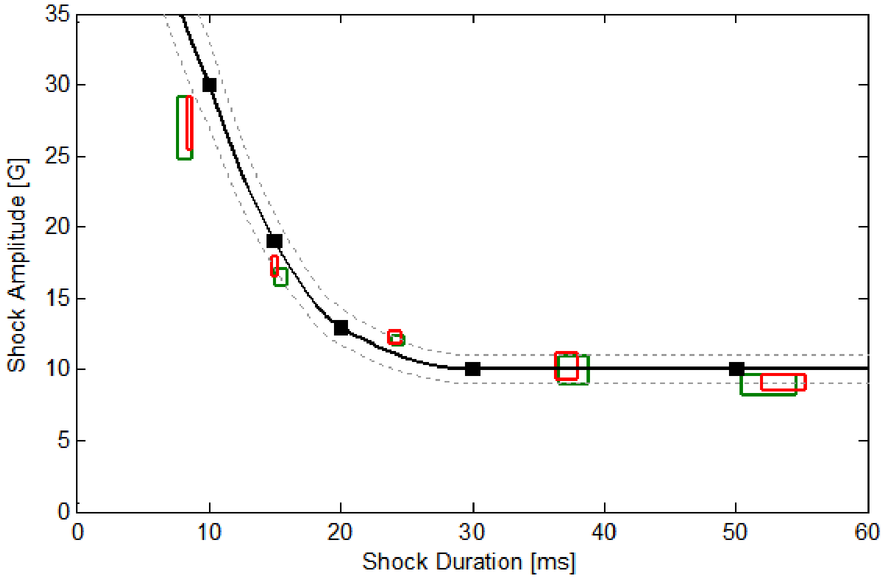

Figure 13: Trigger thresholds for magnet type indicator (10 g) along with published threshold values.

Table 4. Mean triggered and untriggered thresholds for magnet type indicator (4 g ± 10%).

Untriggered				**Triggered**			
Duration [ms]	**Amplitude [g]**			**Duration [ms]**	**Amplitude [g]**		
Region mean	**Region mean**	**Mean (>25 ms)**	**± Range (>25 ms)**	**Region mean**	**Region mean**	**Mean (>25 ms)**	**± Range (>25 ms)**
9.0	12.4			8.7	13.0		
15.1	8.3			14.9	8.8		
26.1	5.1	**4.1**	**1.1**	25.8	5.3	**4.3**	**1.2**
30.5	4.7			30.3	4.8		
40.2	4.3			40.1	4.5		
50.1	3.5			49.4	3.7		
64.8	2.9			65.2	3.0		

Table 5. Mean triggered and untriggered thresholds for magnet type indicator (10 g ± 10%).

Untriggered				**Triggered**			
Duration [ms]	**Amplitude [g]**			**Duration [ms]**	**Amplitude [g]**		
Region mean	**Region mean**	**Mean (>25 ms)**	**± Range (>25 ms)**	**Region mean**	**Region mean**	**Mean (>25 ms)**	**± Range (>25 ms)**
8.5	26.4			8.5	27.2		
15.3	16.6			15.0	17.4		
24.4	12.0	**10.4**	**1.6**	24.4	12.3	**10.6**	**1.6**
37.5	10.2			37.2	10.4		
53.0	8.9			53.1	9.0		

DISCUSSION

For the beam type and liquid-in-glass type indicators, the measured trigger threshold was consistently lower than the rated threshold. The difference for the liquid-in-glass type indicator was very large with the device triggering, on average, at levels 40% higher than the rated threshold (50 g compared with 35.4 g). However, the behaviour of the device revealed and unexpected but important feature: its low dependence on shock pulse duration across the measured range namely 10 to 32 ms.

For the beam type device, the variation in threshold across five devices subjected to the same shock pulse was found to be quite large but the range over which dependence on shock pulse duration is least was found to span 25 – 62 ms. Over this range, the measured threshold for the beam type devices was found to exceed the threshold listed on the device by 24 % on average.

Both models of the magnet type devices evaluated were found to conform quite closely to the published values. For shock pulses with durations exceeding 25 ms, the magnet type devices consistently triggered at a more-or-less constant threshold (4.2 ± 1.1 g and 10.5 ± 1.6 g respectively).

Neglecting the sometimes large differences between published and measured threshold, one important characteristic of the devices was revealed, namely their ability to trigger largely independently of shock pulse duration for particular shock durations ranges: above 25 ms for the beam and magnet types and above 10 ms for the liquid-in-glass tube type. This is a very important attribute as the range of shock pulse durations that a particular packaged product experiences during distribution is not always known. However, the applicability of these devices to produce consistent and reliable results will remain unknown unless it can be ascertained, beforehand, that the shortest pulse duration that can be experienced by a particular packaged product during distribution exceeds the lower shock pulse duration at which the devices dependence on same becomes sufficiently small.

CONCLUSIONS

This study focused on the influence of pulse duration on the trigger threshold of three types of commercially-available and commonly-used shock indicators with the ultimate aim of making recommendations on the effectiveness and use of the devices. The results from the study showed that the triggering of each of the devices was, to varying extents, dependant on shock duration and magnitude and demonstrated that the individual rating listed on the device does not always correspond to the actual triggering threshold which is likely to lead to misuse.

Interestingly, the shock duration dependence of the devices was found to be generally low for shock durations exceeding 25 ms (10 ms for the liquid-in-glass type type). This means that shocks exceeding a predetermined threshold can be determined using the devices provided that the minimum shock duration is at least 25 ms. Therefore, in order for these devices to be used correctly, pre-distribution tests are required to determine the minimum shock duration that is likely to be experienced by the packaged product. Further work on the development of passive shock indicators that are not influenced by the type and duration of the shock waveform is required to allow for the use of such devices regardless of shock duration to remove the need for pre-distribution testing.

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