Industrial Health 2010, **48**, 530–537 **Original Article**

Time Domain Detection of Shocks and Impacts in Whole-body Vibration

Anthony J. BRAMMER[1, 2*], George RODDAN[3] and James B. MORRISON[4]

[1]Envir-O-Health Solutions, Massey Lane, Ottawa, ON K1J 8W9, Canada
[2]Department of Medicine, University of Connecticut Health Center, Farmington Ave., Farmington, CT 06030-2017, USA
[3]Roddan Engineering, 24th Avenue, Surrey, BC V4A 2E7, Canada
[4]Shearwater Human Engineering, Felton Place, North Vancouver, BC V7G 1Z9, Canada

Received July 2, 2009 and accepted March 17, 2010

Abstract: A method for detecting shocks and impacts in whole-body vibration time histories has been developed that is suitable for implementation as a computer algorithm. The procedure consists of comparing the magnitudes of a higher-order mean value and the impulsiveness calculated for successive time segments of the acceleration-time history. The indicators were the ratio of the 12th-order root mean value to the root mean square *RMT/RMS*, and the impulsiveness corresponding to a cumulative probability value of 0.97, *I*(0.97) (i.e., the magnitude of the positive and negative excursions exceeded 3% of the time divided by 2*RMS*). Both indicators have a value of 2.16 for random vibration with a Gaussian amplitude distribution, and deviate from this value when the motion possesses other characteristics. For seat motion in the Z-direction analyzed using frequency weighting W_b, and time segments of ~20 s, shocks and impacts could be identified when *RMT/RMS* ≥ 2.5, and *I*(0.97) ≤ 2.6. A subjective visual classification of 160 exposures to vibration recorded in a range of military vehicles operating under different conditions was performed by a jury of two observers. The subjective classification agreed with computer identification of shocks and impacts in 94% of the cases.

Key words: Shocks, Impacts, Identification, Seat vibration, Time histories

Introduction

The analysis of vibration exposure for potential health effects is influenced by the presence of mechanical shocks and impacts[1–3]. While in some circumstances isolated shocks and impacts may completely define the exposure (e.g., rapid deceleration and crash), there are many situations in which humans are exposed to whole-body vibration containing transient events including shocks and impacts (e.g., transportation vehicles). The question then arises, under what circumstances do shocks and impacts determine the human response, and, hence, under what exposure conditions do they need to be distinguished from more continuous vibration? A taxonomy could be constructed arbitrarily from vibration signatures for the response of interest, for different postures, body supports, and motional inputs (see, for example, Ref. 4), or systematically from some metric that attempts to distinguish vibration from shocks and impacts. The latter approach is the subject of the present contribution.

Strategies for identifying impacts and shocks in a "background" of near continuous vibration have received little attention in the literature. The classification of waveforms into random, periodic, intermittent and impulsive motion including shocks has been described briefly by Brammer and co-workers, using essentially a more complex formulation of the method described here[5]. The equivalent signal processing problem has, however, been considered for other applications. In probably the most closely related application, Erdreich, and Starck and Pekkarinen have described methods for classifying noise as impulsive based on the amplitude distribution of its time history[6, 7]. The method developed by Erdreich employs the kurtosis of the sound pressure evaluated during a time interval that is specifed on the basis of the physiological response of the ear to noise. In contrast, Starck and Pekkarinen introduce a metric related to the crest factor of the sound pressure that they term the impulsiveness. The metric is defined for a specified cumulative probability of the sound pressure amplitude distribution.

The identification of impulses or "glitches" embedded in a signal of a more continuous nature containing information, such as speech or music, or the transient signals within a noisy background that identify the edges of video images, have become staples of digital signal processing. In these cases the emphasis is on "denoising" the signal[8], though the components that constitute the desired signal are somewhat different. The procedure usually involves transforming the noisy signal in the time domain into a coordinate domain in which the desired components are represented by sufficiently large non-zero values to be separated from the unwanted "noise", which is ideally distributed throughout the domain with comparatively low values. Some knowledge of the characteristics

*To whom correspondence should be addressed.
E-mail: eohsolutions@rogers.com

of the desired and unwanted signals is necessary in order to select an appropriate transformed domain. The discrete wavelet transform has found considerable application for this purpose[9]. A wavelet technique has also been applied to the analysis of hand-arm vibration exposures, to provide a method for incorporating the presumed additional health hazard of impact power tools[10].

The availability of instrumentation for recording long-duration vibration exposures, for example by data logging or by dosimeters, introduces the potential for large data files containing acceleration-time histories or short-term averages consisting of multiple, mean squared acceleration-time histories[11]. For such data files, a time domain method for distinguishing impacts and shocks from continuous or intermittent vibration may be preferred. The method described here relies on the statistics of the acceleration-time history of the motion and, in particular, on the acceleration magnitude distribution evaluated during successive short time intervals. It builds on the methods described by Erdreich, and Starck and Pekkarinen, and relies on detecting the predominant characteristic of an impact, or shock, namely that its peak amplitude is sustained for an extremely small fraction of the time history. In the absence of a broadly agreed definition of a mechanical "shock" and "impact" as it affects man, a working definition needs to be introduced in order to proceed. For the purposes of the present work, a mechanical shock will be considered to be a nonperiodic time-varying disturbance characterized by suddenness and severity sufficient to cause relative displacements within the human body and to produce an adverse subjective response. The maximum forces are taken to occur within a few tenths of a second and the event has a total duration of the order of a second[4]. An impact occurs when an object collides with the human body, or vice versa.

In the present paper, the theoretical basis for the method is presented, and a strategy for its implementation is proposed. Some waveform combinations that may be expected to compromise the reliability of the method are first examined by simulation. The application of the method to the identification of shocks and impacts in the vertical motion of vehicle seats is then explored. Plausible fence values for establishing the presence, or absence, of shocks and impacts are derived by considering the results of the simulations, and a series of accelation time-histories recorded at the seats of military vehicles operating both on-, and off-, the road. Fence values believed applicable to the seat motion data are finally used to identify shocks and impacts in an extensive series of seat-motion time histories. The results are compared with observations of the acceleration-time histories performed by a jury of two persons.

Methods

A time domain method for identifying the presence of shocks and impacts in a background of vibration can be constructed from the acceleration magnitude probability distribution of the time history of the motion, provided sufficiently short duration samples are formed to preserve the quasi-stationary nature of the process. In these circumstances, the probability that the motion will have an acceleration magnitude between α and β may be described by the probability density distribution evaluated during an appropriate time segment, s, of the motion, $P_s(\alpha)$[12]:

$$\Pr[\alpha \le a(t_s) \le \beta] = \int_{\alpha}^{\beta} p_s[a(t_s)]da = P_s(\beta) - P_s(\alpha) \qquad (1)$$

where $a(t_s)$ is the acceleration-time history, and $P_s(\alpha)$ and $P_s(\beta)$ are the corresponding values of the cumulative probability function for the selected time interval. The acceleration-time history, and corresponding probability density function for a random motion are illustrated in Fig. 1. The time history is displayed for a single time segment, which will have a duration of the order of seconds.

Now vibration is a time-varying disturbance of a system from an equilibrium condition for which the long-term average of the motion will tend to zero (and on which may be superimposed either translations or rotations, or both). In these circumstances, a meaningful mean value, also called the expected value of the distribution, will be obtained from the higher order terms defined by integer values of m:

$$E_s[a^m(t_s)] = \int_{-\infty}^{\infty} a^m(t_s) p_s(a) da \qquad (2)$$

where $E_s\ [a^m(t_s)]$ is the m-th order expected value evaluated during the time segment, s, and m is a positive even integer (e.g., m = 2, 4, 6, 8, . .). The restriction on m is introduced to obtain a non-zero expected value. For a distribution with an average value of zero, which is henceforth assumed applicable to each time segment, the expected values are related to the root mean values of the same order, that is, the root mean square (RMS) acceleration for the time segment, $a_{(s)RMS}$, may

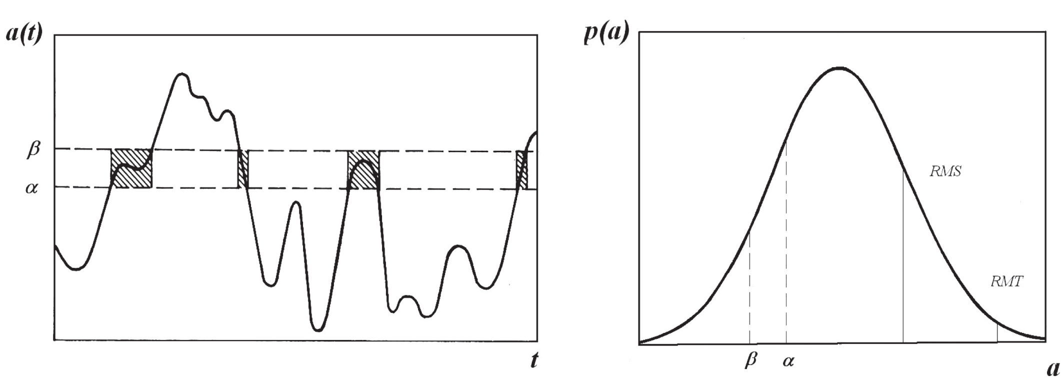

Fig. 1. Acceleration-time history, and corresponding probability density for a Gaussian random acceleration. The magnitude of the root mean square, *RMS*, and root mean twelfth, *RMT*, accelerations are also shown.

be expressed as:

$$(a_{(s)RMS})^2 = E[a^2(t_s)] = \int_{-\infty}^{\infty} a^2(t_s)\,p_s(a)\,da \qquad (3)$$

i.e., $m = 2$, and the root mean quad (*RMQ*) acceleration for the time segment, $a_{(s)RMQ}$, as:

$$(a_{(s)RMQ})^4 = E[a^4(t_s)] = \int_{-\infty}^{\infty} a^4(t_s)\,p_s(a)\,da \qquad (4)$$

The higher-order root mean values possess magnitudes that, with increasing order m, progressively approach the maximum accelerations of the motion during the time segment, as is illustrated in Fig. 1b, and thus reflect different cumulative probability values. They are also sensitive to the shape of the amplitude probability distribution. These properties of the higher-order mean values can be employed for the detection of shocks and impacts, by forming the ratio of a higher-order root mean value to the root mean square value, and comparing it to the value obtained for random vibration. For random vibration, which will possess a Gaussian (normal) distribution, the ratio is:

$$\frac{\left(E_s[a^m(t_s)]\right)^{1/m}}{a_{(s)RMS}} = \left[\prod_{k=1}^{r}(2k-1)\right]^{1/m} \qquad (5)$$

where $k = 1, 2, 3, 4, \ldots\ r$, and $r = m/2$. Values of this ratio for *RMQ/RMS*, and for the tenth- and twelfth-order root mean values (i.e., $m = 10$ and 12), *RMD* and *RMT*, respectively, are listed in Table 1 for random vibration. These values are applicable, separately, to each time segment. It can be seen from the Table that the rate of increase in the magnitude of the ratio decreases as the order of the mean value increases. Simultaneously, the cumulative probability $P_s(\beta) - P_s(\alpha)$ associated with these higher-order mean values progressively increases from 0.68 for the *RMS* to 0.97 for the *RMT*, for a time segment containing a Gaussian (normal) distribution.

A shock or impact occurring during exposure to random vibration will increase the maximum and/or minimum acceleration during the time segment in which it was experienced, and so will perturb the acceleration probability distribution during that time segment. The shocks or impacts will tend to extend the tails of the distribution to greater positive and/or negative accelerations, and the change will be registered by an indicator of the motion sensitive to the extremes of the distribution. Inspection of Table 1 reveals that the ratios of the *RMT/RMS*, or *RMD/RMS*, would appear to be suited to this purpose. In this paper, the ratio of the twelfth-order root mean acceleration to the root mean square acceleration (*RMT/RMS*) is taken as the preferred indicator. This corresponds to the 97th percentile of the positive and negative accelerations of a random Gaussian motion with zero average value (the definition adopted here for random vibration). The indicator will increase in value from that for random vibration (i.e., 2.16 - see Table 1) when a shock or impact occurs during a time segment.

From the essentially statistical nature of random vibration, the chosen indicator can be expected to provide a sensitive quantitative measure of changes to the extremes of the amplitude distribution during a suitable time segment. It is not immediately apparent that this conclusion may be drawn for shocks and/or impacts embedded in other than random vibration. The most extreme alternative to random motion may be considered to be deterministic motion. A single-frequency sinusoidal motion is known to possess a "U-shaped" amplitude probability density distribution[12]. For such motion the ratio *RMT/RMS* = 1.25, which is substantially less than the value expected for random vibration. However, combinations of deterministic motions, either with harmonically-related frequencies or not, can possess amplitude probability distributions similar to Gaussian distributions. Moreover, impulses can be generated by series of harmonically-related single-frequency components (i.e., a Fourier series), and so mimic, or form, shocks or impacts.

For these reasons, it is appropriate to introduce a second indicator, which responds differently to changes in the shape of the amplitude distribution, to facilitate identifying the presence of shocks or impacts. In contrast to the higher-order mean values, the impulsiveness possesses the property that it retains a given probability irrespective of the shape of the distribution function, and so may serve the needs of the present application. It may be defined for each time segment as:

$$I_{[P_s(\beta)-P_s(\alpha)]} = \frac{|\beta-\alpha|}{2a_{RMS}} \qquad (6)$$

In order to compare the magnitudes of the two indicators, the values of α and β are now chosen to be the accelerations that correspond to a cumulative probability, $P_s(\beta) - P_s(\alpha)$, of 0.97, henceforth written $I(0.97)$. For a Gaussian normal distribution, the value of this indicator will thus also be 2.16. However, the value of the indicator is expected to decrease when a shock or impact occurs in a time segment, in opposition to the expected changes in the higher-order mean values. $I(0.97)$ also tends to decrease when the backgound vibration is deterministic in nature, and possesses a value of 1.41 for single-frequency sinusoidal motion. The method then consists of comparing the magnitudes of these indicators for successive time segments of the acceleration-time history to detect the

Table 1. Relationships between moments, root mean values and *RMS* value, and cumulative probability for Gaussian random signals

Moment	Root Mean Value	Relation to RMS	Cumulative Probability
m			$P(\beta) - P(\alpha)$
2	$a_{(s)RMS}$	1.00	0.68
4	$a_{(s)RMQ}$	1.32	0.81
10	$a_{(s)RMD}$	1.98	0.95
12	$a_{(s)RMT}$	2.16	0.97

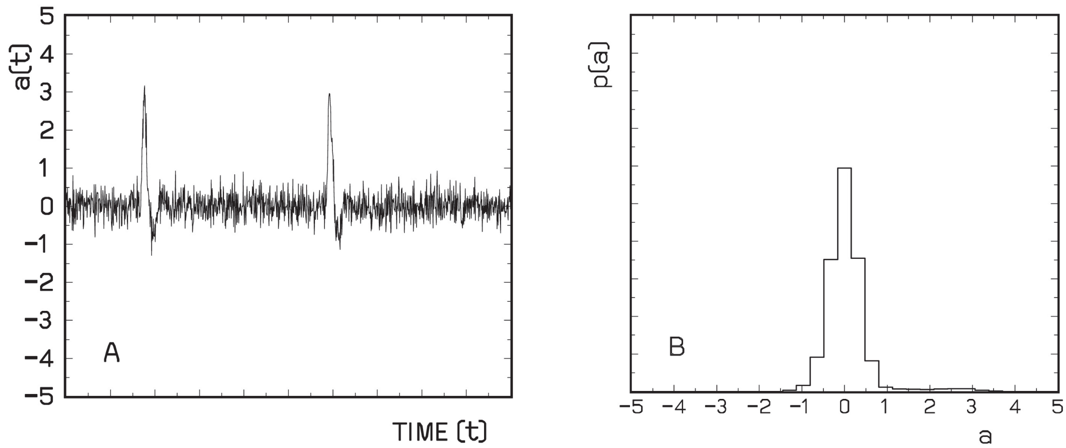

Fig. 2. Simulation of single and repeated shocks-like accelerations: Time series (waveform) and histogram of probability density distribution.

presence of impacts and shocks.

Results

The performance of the method is first explored for different waveforms to identify its limitations, and to assist in the selection of fence values to discriminate between the presence, and absence, of shocks and impacts. The indicators are then constructed for a selection of motions recorded by a seat pad accelerometer mounted under the buttocks. The accelerometers sensed the motion at the seats of tactical ground vehicles operating on ride courses at the US Army Aberdeen Proving Grounds[13)]. The courses consisted of paved and unpaved gravel roads, prepared concrete washboard (2", and 6" pitch), Belgian block (granite blocks in concrete), and cross country selections graded from moderate to rough. The waveforms selected for analysis have been chosen to challenge the performance of the proposed method for identifying shocks and impacts.

Simulation of single and repeated shock-like signals

The waveform was constructed from a damped sinsusoid embedded in a Gaussian random signal, and is shown for repeated shock-like signals in Fig. 2A. The probability density distribution calculated from the time series is shown by the histogram in Fig. 2B. The change in shape of the histogram from a normal distribution is evidenced as an increased probability of near zero amplitudes, and an increased, but small, probability of extreme amplitudes. This is most readily seen for positive excursions in this example.

For the single "shock" case, the first impulse of the waveform shown in Fig. 2A was used for calculation. The probability density distribution for this waveform is similar to that in Fig. 2B, but is not the distribution shown in the diagram. The extremely short fraction of the time history that the single shock-like waveform possesses large amplitude renders the extremes of the distribution indistinguishable from zero probability for the scale used in the histogram, which has been chosen to be the same for all the simulations. For this combination of a single shock-like and random signals, *RMT/RMS* = 5.16, and $I(0.97)$ = 1.95. The values differentiate the signal from a Gaussian random signal by *RMT/RMS* increasing above, and $I(0.97)$ decreasing below, the values expected for random vibration (2.16). The tendency for *RMT/RMS* > 2.16, and, simultaneously, for $I(0.97) < 2.16$ is characteristic of the response of the indicators to single shock- and impact-like waveforms, and provides a baseline for establishing fence values.

For the combination of a repeated "shock" embedded in random vibration, shown in Fig. 2, *RMT/RMS* = 4.2, and $I(0.97)$ = 2.6. Note that compared to the single shock-like waveform, *RMT/RMS* has decreased somewhat while $I(0.97)$ has increased rapidly as the number of "shocks" in the time segment is increased, and a condition has been reached in which *RMT/RMS* > 2.16, and $I(0.97) > 2.16$. In these circumstances the test fails if the fence value is 2.16, and this suggests that a larger fence value may be more appropriate for $I(0.97)$ if a waveform containing more than a single shock-like signal is to be detected by the indicators.

Simulation of modulated deterministic signal

The waveform was constructed from a two-frequency modulated combination of sinsusoids, and is shown in Fig. 3A. There is no Gaussian random signal. The probability density distribution for this waveform is shown by the histogram in Fig. 3B, where the shape can be seen to be not unlike that of a normal distribution (e.g., Fig. 1B), and has completely lost the "U-shaped" amplitude distribution characteristic of a single-frequency sinusoidal waveform. For this waveform, *RMT/RMS* = 2.5, which is greater than 2.16, and so from the previous discussion would suggest the presence of a shock and/or inpact in this time segment. However, $I(0.97)$ = 2.7 for this waveform, and the dual condition necessary for the presence of a shock or impact, provisionally described by *RMT/RMS* > 2.16, and $I(0.97) < 2.16$, is not satisfied.

Inspection of the waveform in Fig. 3A invites the question as to whether the large amplitude excursions will be experienced as shocks, or not, if present in seat motion. In view of the residual uncertainty surrounding the definition of a mechanical shock, it seems inappropriate to pursue further this subject without the human response to such motion. Nevertheless, *RMT/RMS* remains > 2.16 for similar waveforms

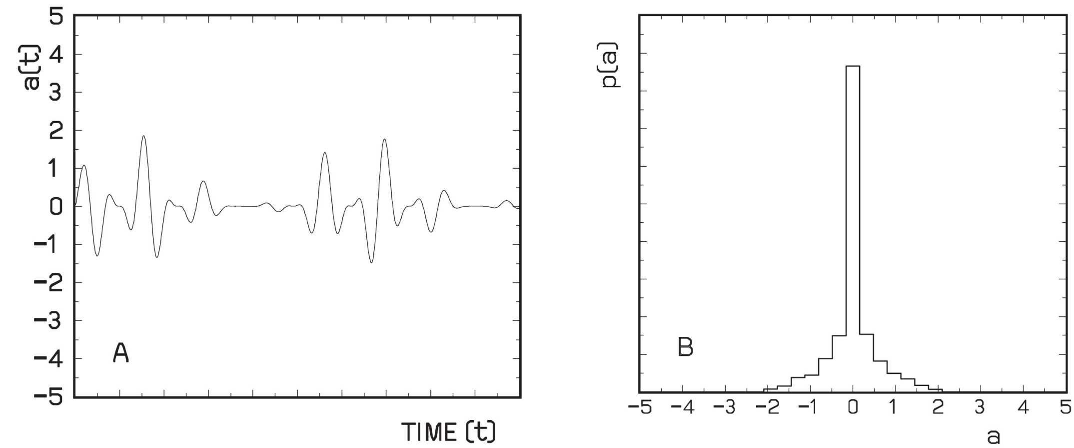

Fig. 3. Simulation of modulated deterministic accelerations: Time series (waveform) and histogram of probability density distribution.

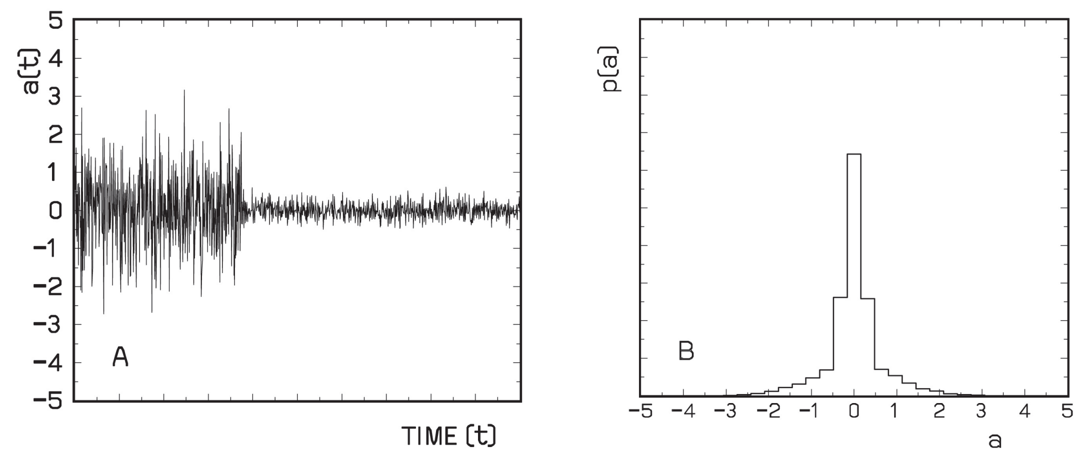

Fig. 4. Simulation of successive Gaussian random accelerations of different amplitudes: Time series (waveform) and histogram of probability density distribution.

as the peak amplitude decreases, suggesting that a larger fence value for this indicator may be appropriate.

Simulation of successive Gaussian random signals of different amplitudes

The waveform was constructed from two Gaussian random signals of different amplitude, and is shown in Fig. 4A. The probability density distribution for this waveform is shown by the histogram in Fig. 4B, where the shape can be seen to contain similarities to those of the previous distributions (Figs. 2B and 3B), even though the waveform consists solely of purely random components. Note, again, that the scales of the three diagrams are identical, and so both waveforms and distributions can be directly compared. For the successive Gaussian random signals of different amplitudes. *RMT/RMS* = 3.2, but *I*(0.97) = 2.8, and so the dual condition necessary for the presence of a shock or impact is not satisfied. However, the time fraction for each random signal can be adjusted until *I*(0.97) < 2.16. This is obtained by reducing the fraction of the larger amplitude random signal in the total waveform, and represents a condition under which the test will fail. This occurs when the larger amplitude Gaussian random signal constitutes about 5% of the signal.

Vehicle travelling cross country - example #1

The time history of the seat motion in the Z-direction specified in ISO 2631 is shown in Fig. 5A for the Commander of a M2HS Bradley fighting vehicle. It was recorded on the so-called rough cross-country course, while the vehicle was travelling at 20 m.p.h. The waveform has been frequency weighted according to the filter characteristics of W_b contained in BS6841[14]. A time segment of 17.5' duration has been selected for the analysis.

Inspection of the time history in Fig. 5A reveals a succession of large shocks, and probably impacts, of differing magnitudes culminating in a very large transient event occurring some 16–17 s after the record commenced. The waveform is conceptually similar in the balance between shock magnitudes and random vibration to that of the simulation in Fig. 2A. For this combination of shocks and random signals, however, *RMT/RMS* = 4.5, and *I*(0.97) = 2.5. There is no doubt that the time history contains multiple shocks, and this observation confirms the need to adjust the fence value for *I*(0.97) from that applicable to a Gaussian random distribution. A value

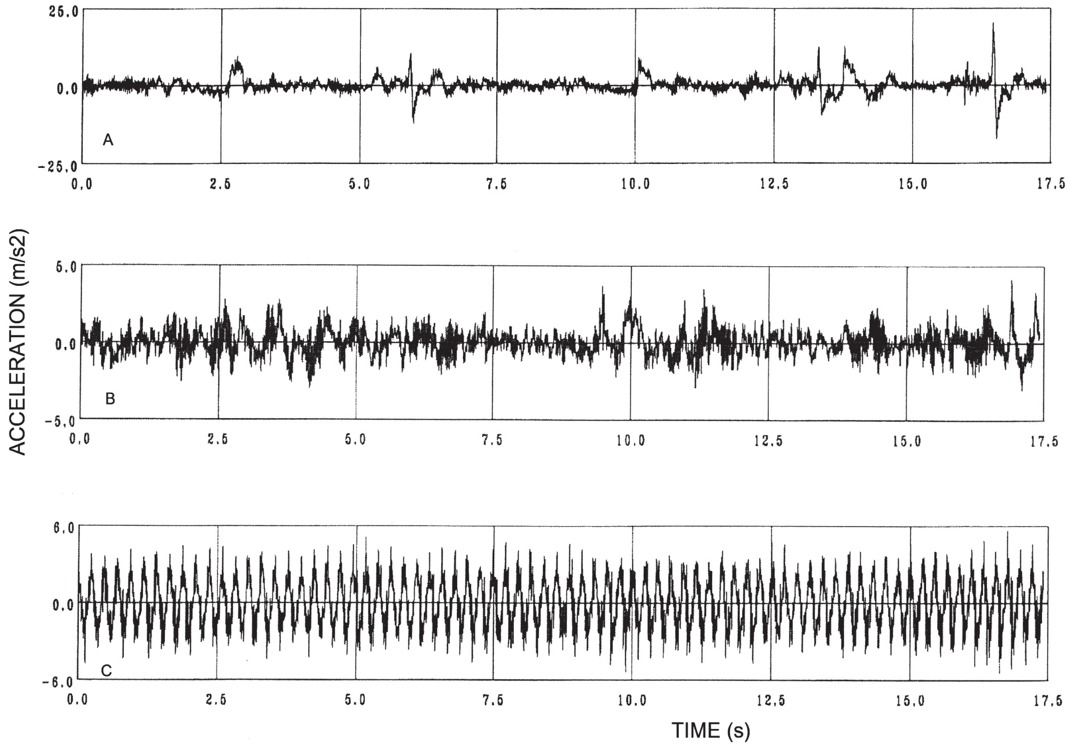

Fig. 5. Frequency-weighted acceleration-time history of the Z-direction motion at the seat of a M2HS Bradley fighting vehicle travelling: A - cross country at 20 m.p.h.; B - cross country at 15 m.p.h., and; C - over 6" pitch washboard.

close to 2.5 would appear more appropriate for the frequency of shocks experienced in this example of the vehicle traversing rough terrain.

Vehicle travelling cross country - example #2

A second time history of the seat motion in the Z-direction specified in ISO 2631 is shown in Fig. 5B for the Commander of a M2HS Bradley fighting vehicle. As in the previous example, it was recorded on the so-called rough cross-country course, in this case while the vehicle was travelling at 15 m.p.h. The waveform has again been frequency weighted by W_b, and a time segment of 17.5' duration selected for the analysis.

Inspection of the time history in Fig. 5B reveals a succession of shocks, of differing magnitudes, culminating in a large shock occurring some 17 s after the record commenced. The waveform contains a different balance between shock magnitudes and random vibration to that of example #1. For this combination of shocks and random signals, *RMT/RMS* = 2.5, and *I*(0.97) = 2.3. There seems little doubt that the time history contains at least one shock, and this obervation again confirms the need to increase the fence value for *I*(0.97) from that applicable to a Gaussian random distribution.

Vehicle traversing washboard - example #3

A third time history of the seat motion in the Z-direction specified in ISO 2631 is shown in Fig. 5C for the Commander of a M2HS Bradley fighting vehicle when the vehicle was traversing 6" pitch washboard at 25 m.p.h. The waveform has again been frequency weighted by W_b, and a time segment of 17.5' duration selected for the analysis.

Inspection of Fig. 5C reveals a repetitive pattern of sudden up-and-down motions of substantial amplitude, which possess an almost sawtooth profile. There are some extremely high-frequency positive or negative excursions forming the peaks. While the primary repetitive frequency of the motion is from 4 to 5 Hz, the excursions possess components at frequencies from 30 to 50 Hz, the magnitude of which will be particularly sensitive to a frequency weighting that reflects the subjective human response to vibration. While the ride quality will clearly be judged very uncomfortable and most probably unpleasant, as the predominant frequency of the motion will excite the abdominal viscera, it may be questioned whether the sawtooth would be judged to consist of repeated shocks. For this near triangular waveform, *RMT/RMS* = 1.7, and *I*(0.97) = 2.0. The indicator based on expected values has clearly identified the repetitive, harmonically-related, multi-frequency sinusoidal signal that forms the basic waveform, while the impulsiveness appears to have responded less to this characteristic and more to the shock-like nature of the waveform.

Selection of fence values for indicators

The selection of fence values for the indicators will remain somewhat arbitrary, unless the duration of the time segment and the bandwidth, and frequency weighting, of the waveform are specified. The simulations and examples of seat motion suggest that the value for Gaussian random vibration (2.16) is inappropriate. For the analysis of seat motions that precipitated this study[15], three of which are reported here, a review of 30 seat motions was used to establish fence values applicable to time segments of approximately 20 s duration, when the accelerations were frequency weighted for the Z-direction by W_b. The seat motions contained a selection of presumed shocks and impacts, continuous, intermittent and transient vibrations, and included both random and deterministic components. From the subjective assessment of the essential features of the 30 waveforms, suitable fence values for interpreting the motion recorded from the seats of the military ground vehicles were *RMT/RMS* = 2.5, and *I*(0.97) = 2.6. By reference to the examples of seat motion, these fence values will classify examples #1 and #2, that is the time histories of Figs. 5A and 5B, to contain shocks and/or impacts, and example #3 (Fig. 5C) not to contain shocks. The classification of the last mentioned waveform remains moot.

Identification of shocks and impacts for military vehicles

The fence values deduced empirically for ~20 s duration time segments were then applied to all the motions recorded from the seats of tactical ground vehicles. Seat pan acceleration-time histories were available from a range of military vehicles. These were the: M1A1 - a tracked, low profile, armoured primary assault weapon; M1A1 HTT - a variant of the M1A1; M2HS Bradley - the Bradley fighting vehicle; M109A3 - a self-propelled howitzer; M923A2 - a 5-ton cargo truck, and; M1026 HMMWV - a high mobility, multi-purpose wheeled vehicle. The vehicles were operating on the courses described at the Aberdeen Proving Grounds.

Computer classification of seat acceleration-time histories into those with shocks and/or impacts, and those without such motion was compared with a subjective visual classification performed by two observers. There were 160 records available for the comparison between the visual classification and computer classification, which employed the two indictors and the selected fence values. Computer identification of shocks and/or impacts in the seat acceleration-time histories recorded from the tactical ground vehicles was found to agree with the jury classification in 94% of the cases.

Discussion

The extremes of the amplitude probability distribution have been calculated in two ways, one based on cumulative probability ($P(\beta) - P(\alpha)$), and the other from the expected values of the distribution (*RMT/RMS*). As already noted, the value of both indicators is 2.16 for continuous random vibration. It would appear both from simulations and from seat pad accelerations that the method shows promise for the detection of shocks and impacts embedded in continuous vibration. Discrepancies between visual and computer identification of shocks and impacts may result from shortcomings of the method, human error in the visual analysis, and from the imprecise definition of shocks. Extension of the method to a more detailed classification of waveforms (e.g., random, periodic, intermittent, and impulsive) would appear possible[5].

Optimum duration of the time segment

For most situations in which the human body is exposed to vibration, the motion will contain random, and/or deterministic, components, in addition to the transient events that are to be detected. A time domain method for identifying the presence of shocks and impacts in such signals can be constructed from the instantaneous acceleration probability density distribution of the motion, as described here. Such an approach implicitly assumes that the motion may be treated as a stationary process, that is, formally, its properties may be described by parameters calculated from a sample drawn from the complete time history, and that the results from each and every sample will be identical within the limitations imposed by statistical precision. In practice, vibration exposures tend to vary with time (e.g., vehicles start and stop, and operate at varying speeds on uneven terrain), so that the complete time history of the motion cannot be treated as a stationary process. In these circumstances, it is necessary to subdivide the time history into segments, each of which may be treated as containing a quasi-stationary process.

The failure to identify short-duration random vibration in a background of lower-level continuous random vibration is known to be a consequence of the signals being non stationary[12]. In principle, this may be addressed by reducing the duration of the time segment until the motion becomes quasi-stationary. For the indicators employed in this analysis, reducing the fraction of the time segment containing the larger amplitude Gaussian noise from the approximately 40% shown in Fig. 4B to 5% would result in *I*(0.97) decreasing to less than 2.0, and the resulting waveform would then be classified as shock- or impact-like by this indicator. Restoring the fraction containing the larger amplitude Gaussian noise, for example by correspondingly shortening the time segment, would reinstate the non-shock classification of the waveform. Reducing the duration of the time history to less than 20 s for each time segment would also assist the detection of multiple shocks in waveforms such as those in Fig. 5. A lower limit for the duration of each time segment will be set by the effective duration of a single, or compound, shock and impact.

Shock definition

A working definition of a mechanical shock has been used for this analysis. The definition provides little guidance on the rapidity of the growth and decay rates of a shock. Hence analysis of, for example, the simulation of modulated deterministic signals or seat motion #3 for the presence of shocks and impacts is inconclusive. The definition does suggest that the duration of the effects of shocks on humans is of the order of a second. From this perspective, a time segment with a duration of only a few seconds, say 5 s, could be considered.

The need to adopt a biologically compatible time duration was recognized by Erdreich when describing his method for classifying the effects of impulse noise on hearing[6]. A physiological basis was suggested for specifying the duration of the time segment involving both the fatigue and recovery of hearing acuity. From this perspective, a time segment with duration of 11 s and a maximum number of impulses of 10/s were proposed. While it is beyond the scope of this contribution to propose a more definitive description of a shock or impact as it affects the human body, a segment duration in the range of 5–10 s would encompass immediate physiological responses and hence may be plausible.

Fence values

The fence values have been shown to depend on the duration of the time segment, and will depend on the bandwidth, and hence the frequency weighting, of the waveform. While the role of seat motion frequencies has not been directly addressed, it will affect the visual perception of waveforms, such as that shown in Fig. 5C, and will influence the physiological responses to vibration. In this paper, the potential influence of different vibration frequencies has been addressed by frequency weighting the acceleration-time histories to produce a waveform in which all frequencies are presumed to produce an equal subjective response. However, there is some latitude in the frequency weightings to consider applicable to these motions. For example, analysis of seat motion #3 by the frequency weighting for the Z-direction contained in ISO 2631-1[1)], W_k, rather than W_b, would de-emphasize the high frequencies somewhat and so reduce the magnitude of the high-frequency spikes in Fig. 5C, rendering its visual appearance more like multi-sinsusoidal motion.

Conclusions

A method for detecting shocks and impacts in whole-body vibration time histories has been developed that is suitable for implementation by a computer algorithm. The procedure consists of comparing the magnitudes of a ratio constructed from higher-order mean values (*RMT/RMS*) and the impulsiveness (*I*(0.97)), which are calculated for successive time segments of the acceleration-time history. Both indicators have a value of 2.16 for random vibration with a Gaussian amplitude distribution, and deviate from this value when the motion possesses other characteristics. Waveform simulations and examples of seat motion demonstrate that suitable fence values will differ from those derived from Gaussian random vibration, and will need to be set by reference to the motions to be classified. For motion in the Z-direction recorded at the seats of military vehicles and analyzed using frequency weighting W_b and time segments of ~20 s, shocks and impacts were identified when $RMT/RMS \geq 2.5$, and $I(0.97) \leq 2.6$. A subjective visual classification of 160 exposures to vibration recorded in these vehicles operating at different speeds on various terrains agreed with computer identification of shocks and impacts in 94% of the acceleration-time histories.

Acknowledgement

Part of this work was performed for the United States Army Aeromedical Research Laboratory under contract DAMD17-96-R-0142. The financial support of the sponsors and their provision of recordings of acceleration-time histories for military vehicles operating on the Aberdeen Proving Grounds are gratefully acknowledged.

References

1) ISO 2631-1 (1997) Mechanical vibration and shock - Evaluation of human exposure to whole body vibration - Part 1: General requirements, 2nd Ed., International Organization for Standardization, Geneva.
2) ISO 2631-5 (2004) Mechanical vibration and shock - Evaluation of human exposure to whole body vibration - Part 5: Method for evaluation of vibration containing multiple shocks, International Organization for Standardization, Geneva.
3) Brammer AJ (2010) Human response to shock and vibration. In: Harris' shock and vibration handbook, Piersol AG and Paez TL (Eds.), 6th Ed., Chapt. 41, McGraw-Hill, New York.
4) Brammer AJ (2007) Effects of mechanical shock on people. In: Handbook of noise and vibration control, Crocker MJ (Ed.), 354–63, John Wiley & Sons, New York.
5) Brammer AJ, Roddan G, Village J, Morrison J (1993) Machine identification of waveform characteristics, with application to seat motion. Can Acoustics **21**, 21–2.
6) Erdreich J (1986) A distribution based definition of impulse noise. J Acoust Soc Am **79**, 990–8.
7) Starck J, Pekkarinen J (1987) Industrial impulse noise: crest factor as an additional parameter in exposure measurements. Appl Acoustics **20**, 263–74.
8) Weiss S, Stewart R, Davis G (2002) Noise and digital signal processing. In: Noise reduction in speech applications, Davis G (Ed.), 4–44, CRC Press, Boca Raton.
9) Walker JS (1999) A primer on wavelets and their scientific application. CRC Press, Boca Raton.
10) Kim J, Welcome DE, Dong RG, Song WJ, Hayden C (2007) Time-frequency characterization of hand-transmitted vibrations using analytic wavelet transform. J Sound Vib **308**, 98–111.
11) Peterson D, Brammer AJ, Cherniack MG (2008) Exposure monitoring system for day-long vibration and grip force measurements. Int J Ind Ergon **38**, 676–86.
12) Bendat JS, Piersol AG (2000) Random data analysis and measurement procedures, 3rd Ed., Wiley, New York.
13) Report TOP 1-1-011 (1981) US army test and evaluation command test operations procedure - Vehicle test facilities at Aberdeen proving ground. US Army Test and Evaluation Command, Aberdeen Proving Ground.
14) BS6841 (1987) Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock. British Standards Institution, London.
15) Roddan G, Brammer AJ, Village J, Morrison J (1993) Development of a standard for the health hazard assessment of mechanical shock and repeated impact in army vehicles: Phase II report. Report DAMD17-90-R-0142 for Army Aeromedical Laboratory, Fort Rucker.