HUMAN RESPONSE TO VIBRATION AND MECHANICAL SHOCK

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1. INTRODUCTION

Human exposure to vibration, and mechanical shock, is commonly experienced in daily life, for example, in trains, cars, ships and buildings. All of these situations involve motion of the whole body transmitted through a seat, or from the floor in the case of a standing person, where the human response is commonly related to the sensation of motion or the relative motion of body parts. Exposures also occur in occupations involving operation of hand-held power tools, primarily to the hand and arms. The vibration, and shocks, become of consequence when comfort or activities are influenced (e.g., motion sickness), or health is threatened (e.g., back injury, or damage to the blood vessels and nerves of the hand).

Exposures are quantified by measurement procedures described in standards prepared by the International Organization for Standardization (ISO). The metrics to employ in some situations remain the subject of research, and form the subject of a companion paper.[1] The CSA Subcommittee on Human Response to Vibration has participated in, and its members have made important contributions to, the development of international standards in this field for over twenty years. The concepts underlying much of this work are summarized in this paper, and follow the description in a recent publication.[2] Many of these ISO standards are now being proposed for Canadian standards, a process similar to that already underway in the U.S.A.

2. DEFINITIONS AND METRICS[2]

Vibration is a time-varying disturbance of a mechanical, or biological, 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. A mechanical *shock* is a non-periodic disturbance characterized by suddenness and severity with, for the human body, the maximum forces being reached within a few tenths of a second, and a total duration of up to about a second. When considering injury potential, the size and shape of the object in contact with, or impacting, the body is important, as is the posture. In addition, for hand tools, both the compressive (grip) and thrust (feed) forces employed to perform the manual task need to be considered.

The magnitude of vibration is characterized by second, and higher, even-order mean values. For an acceleration that varies with time, t, as $a(t)$, the higher-order mean values are calculated from:

$$a_{RM} = \left[\frac{1}{T} \int_0^T [a(t)]^m \, dt \right]^{1/r} \qquad (1)$$

where the integration is performed for a time T, and m and r are numerical constants. By far the most common metric of the magnitude of whole-body or hand-transmitted vibration is the *root mean square* (RMS) acceleration a_{RMS}, which is obtained from eqn. 1 with $m = r = 2$, and is used for the assessment of perception, and discomfort. Other metrics include the *root mean quad* (RMQ) acceleration a_{RMQ}, with $m = r = 4$. The relationship between these metrics depends on the amplitude distribution of the acceleration-time history, and provides insight into the waveform.

In contrast, health disturbances are considered to be related to the exposure, which is constructed from the magnitude of the stimulus, its frequency content and duration:

$$E(a_w, T)_{m,r} = \left[\int_0^T [F(a_w(t))]^m \, dt \right]^{1/r} \qquad (2)$$

where $E(a_w,T)_{m,r}$ is the exposure occurring during a time T to a stimulus function that has been frequency weighted in an attempt to equate the hazard at different frequencies, $F(a_w(t))$. In general, $F(a_w(t))$ may be expected to be a non-linear function of the frequency-weighted acceleration, $a_w(t)$. A commonly used function is the so-called *energy-equivalent* vibration exposure for which $F(a_w(t)) = a_w(t)$ and $m = r = 2$. For an exposure continuing throughout a workday, $T \to T_{(8)} = 28\,800$ s, and eqn. 2 can be written:

$$T_{(8)}^{1/2} \left[\frac{1}{T_{(8)}} \int_0^{T_{(8)}} [F(a_w(t))]^2 \, dt \right]^{1/2} = T_{(8)}^{1/2} a_{w,RMS(8)} \qquad (3)$$

where $a_{w,RMS(8)}$ is the 8-hour, energy-equivalent, frequency-weighted, RMS acceleration. A second function, used for exposure to whole-body vibration, is the *vibration dose value*, *VDV*, for which $F(a_w(t)) = a_w(t)$ and $m = r = 4$. The function is thus more influenced by the large amplitudes in a fluctuating vibration than the energy-equivalent exposure.

The output of a single (uniaxial) sensor infrequently characterizes an exposure to vibration. This necessitates the measurement of orthogonal component accelerations (indicated by subscripts X, Y, and Z). The *overall vibration value* is then expressed by the frequency-weighted, RMS, vector acceleration sum, a_{WAS}, using values of the frequency-weighted, RMS, component accelerations, i.e.:

$$a_{WAS} = \left[a_{wX,RMS}^{\ 2} + a_{wY,RMS}^{\ 2} + a_{wZ,RMS}^{\ 2}\right]^{1/2} \qquad (4)$$

It should be noted that the frequency weighting employed differs for the X, Y, and Z directions for whole body vibration, but is the same for hand-transmitted vibration (subscript '*h*'). Exposures to the latter are described in terms of the magnitude of the 8-hour, energy-equivalent, frequency-weighted, RMS, vector acceleration sum, which is constructed from values of $a_{hX,RMS(8)}$, etc, using eqn. 4.

3. MEASUREMENT ISSUES

Non-contact methods are, in principle, preferred for measuring the motion of soft tissues, but are not considered in current standards. In consequence, measurements are specified at the interface between the skin and a source of vibration, such as a vehicle seat pan or tool handle, and involve the use of specialized mounts for the transducer(s). In some circumstances the vibration of a mechanical structure in contact with the body is recorded using accelerometer(s) rigidly attached to the seat or tool handle. Triaxial accelerometers are available for measurement of component accelerations in three orthogonal directions. The orientation of sensors is prescribed. The use of piezoelectric accelerometers to measure shocks requires the transducer to be mounted on a mechanical low-pass filter, to reduce errors resulting from internal crystalline changes introduced by motion at the sensor's resonance frequency.

4. SUMMARY OF HUMAN RESPONSES

Estimates of exposures and vibration magnitudes necessary for selected human responses are summarized in Table 1. Included in the Table are the metric employed, the source of information, and a representative value for the response, or health effect. The perception of vibration depends on the stimulus frequency and body site. Note that the "whole body" response is specified in terms of a frequency-weighted component acceleration. Adverse response to building vibration (e.g., from underground railway trains) occurs at close to the threshold of perception, and employs a combined frequency weighting for all directions. The discomfort experienced in passenger transportation is largely associated with interference with activities such as reading or drinking, and is related to the magnitude of the stimulus. Vertical vibration at low frequencies (0.1 - 0.5 Hz) may result in motion sickness. The metric employed is an energy-equivalent exposure in which the stimulus function is expressed as a frequency-weighted acceleration in eqn. 2. The value cited is for a 10 % prevalence of vomiting in the general population (men and women). Thresholds for the onset of health effects are given for regular, near-daily exposure, and are expressed in terms of the daily dose. The metrics, however, differ. For hand-transmitted vibration the onset of the hand-arm vibration syndrome (HAVS) is expressed in terms of the 8-hour frequency-weighted acceleration sum, while for whole-body vibration the onset of back injury is estimated in terms of the *VDV*. The latter may also be specified in terms of an energy-equivalent exposure. The risk of injury from vertical (headward) shocks is described by the response of a non-linear biodynamic model. The model employs a neural network to produce an estimate of the spinal response. This forms the input to an exposure metric that sums the number of shocks using the acceleration peak value, i.e., $F(a_w(t)) = a_{peak}$, with $m = r = 6$ in eqn. 2. An equivalent, daily, static compressive stress is then calculated to assess the risk of injury.

5. REFERENCES

1. Peterson DR, et al., *Can Acoust Assoc J* (elsewhere in this volume).
2. Brammer, AJ, et al., in Kutz, M (ed.) *Standard Handbook for Biomedical Engineering*, McGraw Hill, New York (2002).

Table 1: Estimates of typical human responses to vibration, and mechanical shock, with sources (after Ref. 2)

Human Response	Source	Metric	Typical Value
Perception (mean)			
whole body	ISO 2631-1, 1997	$a_{wZ,RMS}$	0.015 ms^{-2}
fingertips	ISO/FDIS 13091-2, 2002	a_{RMS}	0.0075 ms^{-2} (4 Hz)
			M - 0.25, F - 0.32 ms^{-2} (125 Hz)
Building vibration	ISO 2631-2, 1989	$a_{wC,RMS}$	0.007 ms^{-2}
Discomfort (transportation)			
not uncomfortable	ISO 2631-1, 1997	a_{WAS}	< 0.315 ms^{-2}
uncomfortable	ISO 2631-1, 1997	a_{WAS}	0.8 – 1.6 ms^{-2}
very uncomfortable	ISO 2631-1, 1997	a_{WAS}	> 2.0 ms^{-2}
Motion sickness (10 %)	ISO 2631-1, 1997	$E(a_{wZ},T)_{2,2}$	30 ms$^{-1.5}$
Health effects (onset)			
hand (HAVS)	ISO 5349-1, 2001	$a_{h,WAS(8)}$	1.0 ms^{-2}
whole body	ISO 2631-1, 1997	*VDV*	8.5 ms$^{-1.75}$
shocks (vertical)	ISO/DIS 2631-5, 2002	$E(\Sigma a_{peak})_{6,6}$ in spine → static compression	> 0.5 MPa