Journal of Sound and Vibration (1999) **221**(5), 906–916
Article No. jsvi.1999.2015, available online at http://www.idealibrary.com on IDEAL

A DIGITAL VIBRATION DOSIMETER FOR FIELD MEASUREMENTS

D. R. Huston,†‡ C. C. Johnson,‡ C. Choukalos,† and J. P. Tranowski‡
†*Department of Mechanical Engineering and* ‡*The McClure Musculoskeletal Research Center*, *University of Vermont*, *Burlington*, VT 05405, *U.S.A.*

(*Received* 20 *October* 1998)

1. INTRODUCTION

This letter describes the design, development and testing of a portable, inexpensive, and easy-to-use whole-body vibration (WBV) dosimeter. High levels of seated whole-body vibration have been implicated in a wide variety of adverse health conditions including intestinal, circulatory, spinal disorders (such as low back pain) and excessive fatigue [1, 2]. Reports of low back pain are the largest cause of worker's compensation claims [3]. Most epidemiological studies have reported only minimal data on exposure to WBV and none have included measurements of long-term vibration exposure. The primary reason for this lack of data is that the current instrumentation for measuring WBV is expensive and requires experienced personnel to operate. Most epidemiological studies that identify a correlation between seated whole-body vibration and low back pain have depended on vibration dosages extrapolated from short-term field measurements [4–6]. To date, there have been few reports of actual long-term vibration exposure.

The most common method of measuring and reporting whole-body vibration exposure statistics is to analyze the seat pan acceleration in either one or all three axes as specified by the ISO 2631 standard [7]. Implementing the ISO 2631 standard requires a complex calculation that includes both frequency and time-weighting analyses for three axes of vibration simultaneously. Due to the complex statistical calculations required for accurate reporting of vibration exposure, previous testing methods used either expensive analog electronics for the frequency demodulation and weighting, or recorded lengthy acceleration time histories, with the analysis being done later. However, recent advances in the miniaturization of computer and electromechanical systems have allowed for the design and fabrication of WBV measurement systems that are smaller, less expensive, easier to use, and yet have more sophisticated data processing capabilities than current WBV test systems.

0022–460X/99/150906 + 11 $30.00/0

2. WHOLE-BODY AND RANDOM VIBRATIONS

Random vibrations and shocks often characterize the seated vibration environment. Processing random vibration acceleration signals invariably requires the use of statistical methods. A key issue is to measure and determine relevant parsimonious statistical measures of WBV that determine both the motion of the human body and the excitation sources, i.e., the seat cushion and floor pan. Random vibrations can be classified by certain properties, such as whether the amplitudes have a Gaussian probability distribution, whether the signals are stationary, and the amount of power in each frequency band, possibly as a function of time [8]. Figure 1 shows a sample time history of the vertical acceleration experienced by a vehicle operator; here the acceleration signal appears to be random.

Gaussian random vibrations have an amplitude probability distribution that is Gaussian:

$$p(x) = \frac{1}{\sqrt{2\pi}}\frac{1}{\sigma}\exp(-(x-m)^2/x\sigma^2), \tag{1}$$

where $p(x)$ is the probability density function, σ is the standard deviation and m is the mean. In the context of WBV, deviations from Gaussian distributions of accelerations usually result from large transients or shocks. Several statistical techniques have been proposed to account for large non-Gaussian shocks, including the RMQ statistic, which weighs shocks more heavily by averaging the fourth power of the amplitudes.

Random vibrations are either stationary or non-stationary. Vibrations are stationary if the probability distributions obtained from the ensemble of possible random time histories do not vary with time. This implies that all averages, including the mean and standard deviation, are independent of absolute time [8]. In reality, a random vibration signal must have a beginning and an end. This gives rise to the notion of a signal being locally stationary. A locally stationary

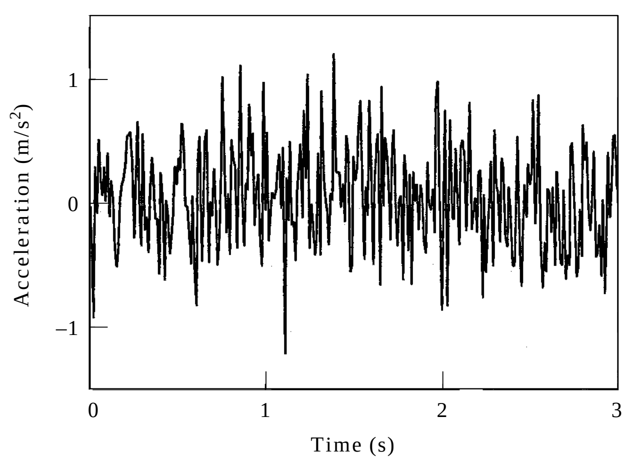

Figure 1. Acceleration time history at operator's seat.

process is one that is stationary for most of its lifetime, or one that can be divided into several separate periods, each of which is approximately stationary. The vibrations experienced while travelling on a route with both smooth and rough sections constitute one example. Both smooth and rough sections are considered to be locally stationary. An example of a non-stationary signal is the random vibrations produced by isolated impacts, such as those resulting from potholes or debris.

The power of the vibration signal determines the amount of shaking experienced. However, power produces different effects on the body at different frequencies. ISO 2631 specifically accounts for the frequency content of vibration signals by a weighting scheme. To determine the effects of a particular vibration signal on a human, one must determine the amount of vibratory power in a given frequency range. One method that is particularly amenable to digital signal processing techniques uses the 1/3 octave power spectral density (PSD) from digitized acceleration signals as a basis for calculating the ISO 2631 statistics.

As with any statistical estimation process, the nature of the data, as well as the sampling process, determines the accuracy of a PSD calculation. The vibration time history must be sampled at a rate sufficiently high enough to capture the highest frequencies of interest, and for a duration long enough to capture the lowest frequencies of interest. At a minimum, the data must be sampled at a rate over twice the maximum analog frequency of the signal; otherwise, aliasing will occur. The total sampling period must equal at least the reciprocal of the lowest frequency being resolved. In addition, the data must be sampled with sufficient amplitude precision to avoid quantization errors.

3. ISO 2631 STATISTICS

The ISO 2631 requirements regarding seated WBV give both standardized measurement and calculation procedures for pertinent WBV exposure statistics and recommendations for suitable WBV exposure doses for humans.

ISO 2631 recognizes that the sensitivity of humans to vibrations depends on the direction, frequency and transient characteristics of the vibrations. The co-ordinate system is Cartesian, with x being the fore–aft, y the left–right, and z the up–down direction, respectively. The vibration measurement location is specified as being the point of vibration input. For seated WBV, this is the seat-cushion interface. The intensity of vibration is assessed with acceleration measurements, usually in the frequency range of 1 to 80 Hz. The units of vibration are m/s^2 rms. The weighting factors given in Table 1 and plotted in Figure 2 account for the frequency-dependent and direction-dependent sensitivity of humans to vibrations. The frequency resolution of the weighting factors, and the rest of ISO 2631, is 1/3 octave bands. The weighting factors are set so that vertical vibrations in the range of 4 to 8 Hz and horizontal vibrations in the range of 1 to 2 Hz are weighted most heavily. The frequency weights given in Table 1 are applied to the frequency-domain version of the vibration signals by direct multiplication. In certain cases, it is necessary to obtain a time-domain frequency-weighted version of the vibration signals. Time-domain signals can be

TABLE 1
Frequency weighting factors prescribed by ISO2631 [7]

Frequency (center of 1/3 octave)	Longitudinal weighting factor	Horizontal weighting factor
1·0	0·5	1·00
1·25	0·56	1·00
1·6	0·63	1·00
2·0	0·71	1·00
2·5	0·80	0·80
3·15	0·90	0·63
4·0	1·00	0·5
5·0	1·00	0·4
6·3	1·00	0·315
8·0	1·00	0·25
10·0	0·80	0·2
12·5	0·63	0·16
16·0	0·50	0·125
20·0	0·40	0·1
25·0	0·315	0·08
31·5	0·25	0·063
40·0	0·20	0·05
50·0	0·16	0·04
63·0	0·125	0·0315
80·0	0·10	0·025

frequency-weighted either by converting the time-domain signals into the frequency domain with an FFT, applying the weights by direct multiplication, and converting back to the time domain with an inverse FFT, or by using a filter network (analog or digital) on the time domain signal with a frequency-dependent gain that equals the frequency weighting factors. The presence of large shocks or transients in the vibrations is assessed by the crest factor defined as the ratio of the peak acceleration to the frequency-weighted rms of the acceleration. The value of the crest factor may depend on the length of the measurement period. The minimum allowable length is 1 min. If the crest factor exceeds 6, then ISO 2631 exposure limits may not be applicable.

For broadband vibrations, such as occur while driving on a rough road, ISO 2631 allows the determination of a single number for vibration dosage. This number is calculated from the rms values of the frequency-weighted acceleration signals for each direction. If a_{wx}, a_{wy}, and a_{wz} are the frequency-weighted rms values of the acceleration measured in the x, y, and z directions, respectively, then the total weighted acceleration, a_w, is given by

$$a_w = [(1{\cdot}4a_{wx})^2 + (1{\cdot}4a_{wy})^2 + (a_{wz})^2]^{1/2}. \qquad (2)$$

The levels of acceptable vibration dosage depend on the magnitude and duration of the vibrations. ISO 2631 gives three levels of dosage assessment for exposure durations up to 24 h. Labelled in terms of increasing severity the

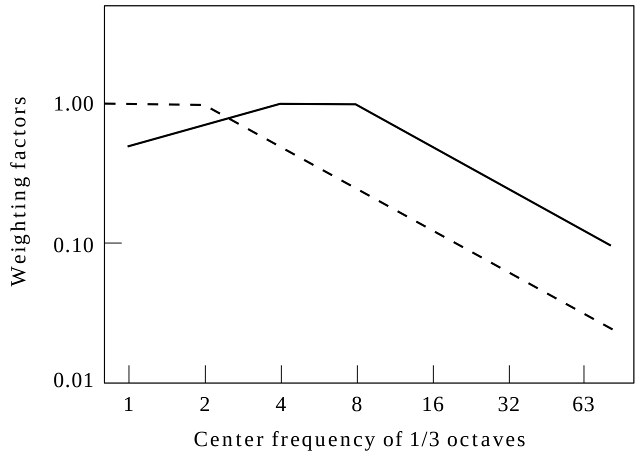

Figure 2. ISO 2631 weighting factors for transverse and longitudinal accelerations: —, transverse; - - -, longitudinal.

limiting vibration dosage values are known as the reduced comfort limit, the fatigue decreased proficiency limit, and the exposure limit. The reduced comfort limit is recommended for passenger comfort, the fatigue decreased proficiency level is recommended for maintaining vehicle operator efficiency. Fatigue decreased proficiency (FDP) limits for 1, 8, and 24 h exposures are plotted in Figures 3 and 4, for the longitudinal and transverse directions, respectively. The exposure limit is the level at which the health and safety of the operator becomes threatened. For an 8-hr exposure, the reduced comfort limit, fatigue decreased proficiency limit, and exposure limit of weighted rms vibrations are 0·100, 0·315, and 0·730 m/s^2 respectively. If the vibration environment is transient, but can be divided into a sequence of short-duration, stationary events then an equivalent exposure time can be calculated by the following procedure. First, a set of vibration exposures with duration t_i and amplitude A_i is recorded. Next, a

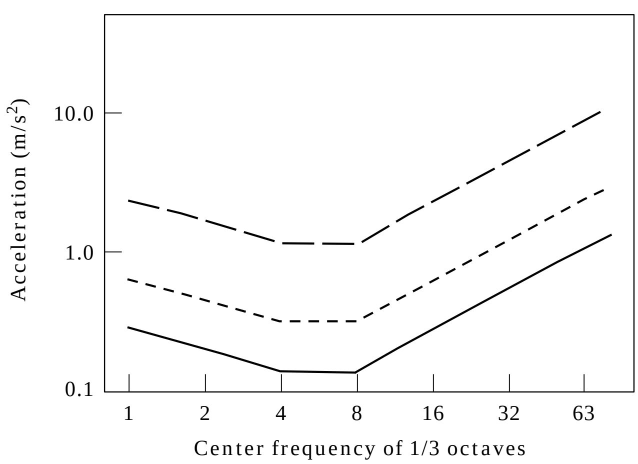

Figure 3. ISO 2631 longitudinal fatigue decreased proficiency (FDP) limits: —, 24 h; - - - -, 8 h; – –, 1 h.

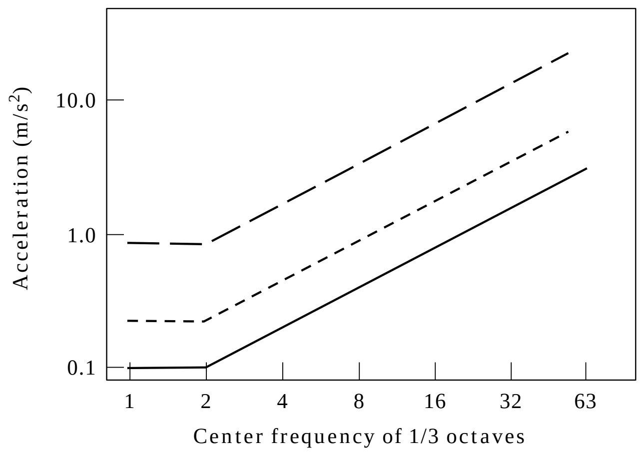

Figure 4. ISO 2631 transverse fatigue decreased proficiency (FDP) limits: key as in Figure 3.

nominal reference acceleration. A', and exposure time, τ', are selected, e.g., a fatigue decreased proficiency limit of 8 h and 0·315 m/s^2. For each interval i, calculate the permissible time τ_i, for each A_i The equivalent exposure time, T, is then calculated as

$$T = \sum_i \frac{t_i \tau'}{\tau_i} \qquad (3)$$

The equivalent exposure time is then compared with the nominal reference acceleration and exposure time. For example, a 4-h ride with $a_w = 0{\cdot}53$ m/s^2 would have an equivalent time equal to 8 h, if the 8-h fatigue decreased proficiency limit is used as the nominal reference vibration level. From the equivalent exposure time, it may be possible to derive a useful long-term dosage exposure.

4. HARDWARE

The core of the measurement equipment is a 586-133 MHz industrial computer made by Octagon Systems (Westminster, CO). The CPU card fits into a card cage that measures approximately 203 × 127 × mm^3 Also housed in this cage are a power supply, an 8-bit analog-to-digital (A/D) converter card, and a floppy drive controller card. This card cage, along with a 12-V, 17-A-h sealed lead-acid battery, is housed in a portable aluminum enclosure box with outside dimensions of approximately 8″ × 10″ × 8″. Mounted to the box face are a 4 × 4 numeric keypad, 4 × 80 character LCD display floppy drive, voltmeter, battery-charging jack, accelerometer input jack, and on–off switch (Figures 5 and 6). The components can withstand temperature from −40 to 70°C, 20 g of shock and 5 g of vibration. A three-axis micro-machined accelerometer (NeuwGhent Technology, LaGrangeville, NY) with on board amplification was embedded into a silicone rubber seatpad. This seatpad is approximately 15 mm high in the center, tapering down to an outer diameter of 220 mm.

Figure 5. Digital vibration dosimeter and three-axis accelerometer seatpad.

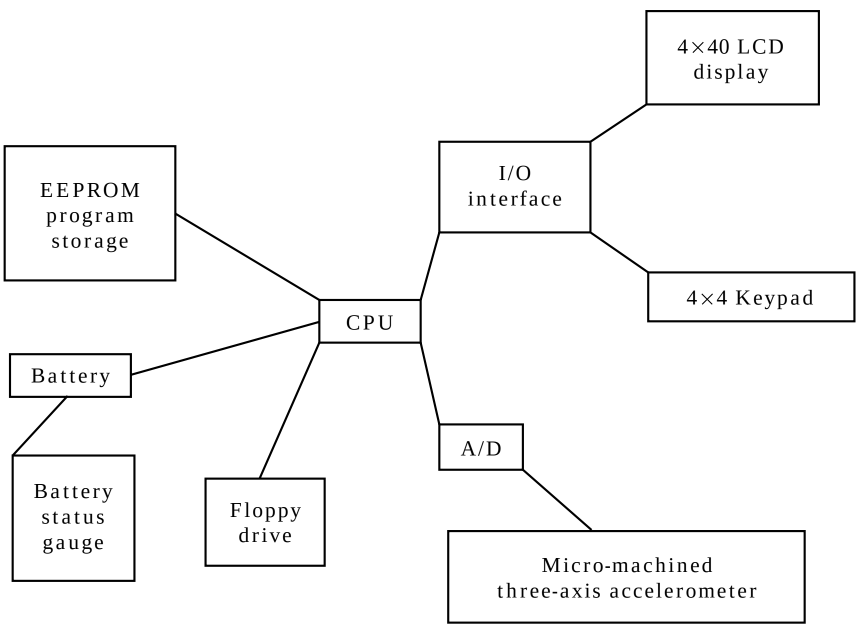

Figure 6. Hardware schematic.

5. SIGNAL PROCESSING

The calculation of the ISO 2631 statistics involves several steps.

(1) The vibration acceleration signals for each axis are discretized at a rate of 240 Hz.

(2) The time histories are conditioned by estimating and subtracting the mean and then passing the signal through a high-pass filter with a cutoff frequency of 0·5 Hz.

(3) The discretized time histories are separated into segments of lengths of 16 1384 points for a duration of 68·3 s.

(4) The unweighted root mean square of each conditioned signal is estimated by direct calculation.

(5) For each time segment the power spectral density is estimated by the periodogram technique in which the discrete Fourier transform (DFT) is calculated with the Fast Fourier Transform algorithm, and the normalized magnitude of the DFT is the spectral density estimate [9]. If each sampled data point is denoted c_j then the DFT is given as

$$C_k = \sum_{j=0}^{N-1} c_j \exp(2\pi ijk/N), \quad k = 0, 1, \ldots, N-1, \tag{4}$$

where k is the frequency index, N is the length of the time history, and $i = (-1)^{1/2}$. The periodogram estimate of the power spectral density for zero and positive frequencies less than the cutoff frequency f_c is given by

$$P(f_0) = \frac{1}{N^2}|C_0|^2, \quad P(f_k) = \frac{1}{N^2}[|C_k|^2 + |C_{N-k}|^2, \quad k = 1, 2, \ldots, (N/2-1), \tag{5, 6}$$

$$P(f_c) = P(f_{N/2}) = \frac{1}{N^2}|C_{N/2}|^2, \tag{7}$$

where

$$f_k = k/(N\Delta t) \quad \text{and} \quad f_c = 1/(2\Delta t).$$

One feature of the discrete Fourier transform is that it uses data sampled at evenly spaced intervals in the continuous time domain. The discrete Fourier transform then converts the discrete time history into a discrete frequency domain representation with values at evenly spaced frequency points. However, the original continuous time history often has power in frequency components that lie between those given by the discrete Fourier transform. One way to minimize this leakage problem is to use a time-domain window such as the Hanning window. Since the ultimate purpose of the conversion to the frequency domain is to use the broad-banded 1/3 octave spectral estimate in the ISO 2631 statistical calculations, leakage is not a big concern.

(6) The 1/3 octave spectrum is calculated by summing the power spectral density over each 1/3 octave frequency band with a center frequency given in Table 1 according to the formula

$$S_i = \frac{1}{N\Delta t} \sum_{k=k_{i-1}}^{k=k_i} P(f_k), \tag{8}$$

where S_i the 1/3 octave spectrum value for the ith 1/3 octave band, k_i is the frequency index of the upper frequency of the 1/3 octave band.

(7) ISO 2631 statistics for each interval are calculated including the weighted root mean square of equation (7) and the equivalent time based on an 8-h fatigue decreased proficiency limit.

Implementing the above procedure so that data are acquired and processed simultaneously requires using a double buffer scheme in which the data are acquired into one buffer and processed in the other. An interrupt-driven process provided the switching between acquisition and processing (Figure 7).

6. RESULTS AND DISCUSSION

Data were collected on a campus shuttle bus during an 8-h shift. A plot of the vertical vibration data is shown in Figure 8. The thinner line is the actual vibration level recorded at the driver's seat. Also shown on this plot is the 8-h

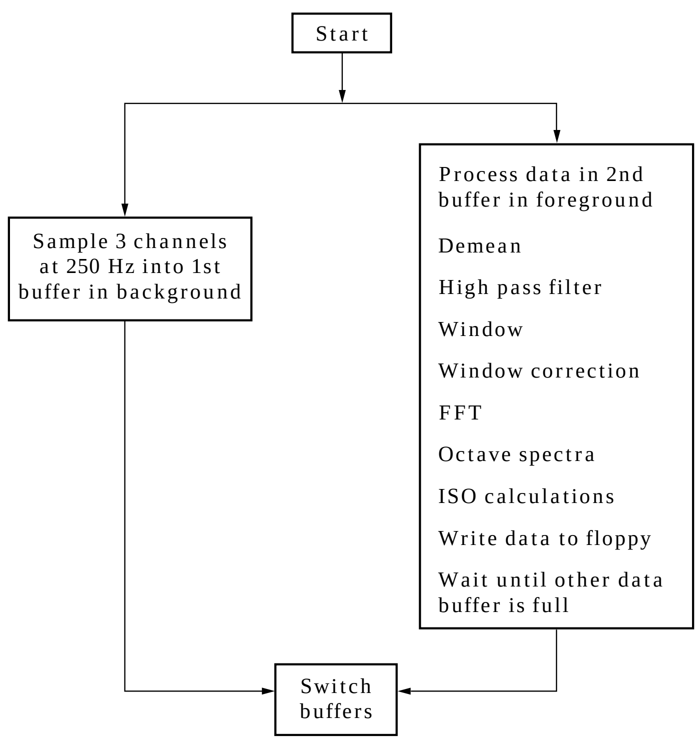

Figure 7. Software flow.

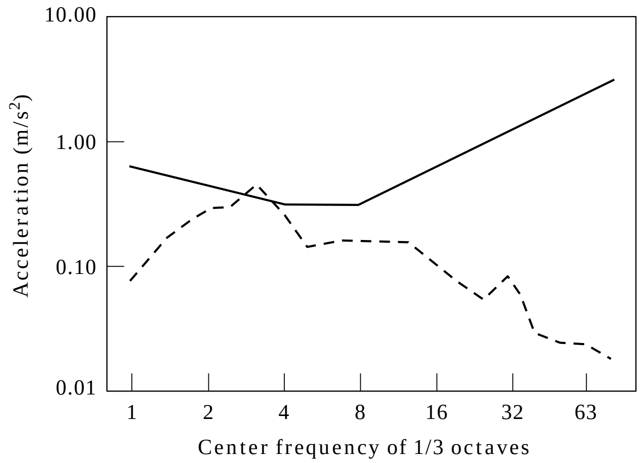

Figure 8. Vibration data from a campus shuttle bus plotted with the 8-h fatigue decreased proficiency boundary: —, 8-h limit; ----, bus seat.

fatigue decreased proficiency (FDP) level according to ISO 2631. The boundary specifies a limit beyond which exposure to vibration carries a risk of impairing working efficiency in many kinds of tasks, particularly those in which time-dependent effects (fatigue) are known to worsen performance—for example, in vehicle driving.

The actual degree of task interference in any situation depends on many factors, including individual characteristics and the nature and difficulty of the task. Nevertheless, the limits recommended here show the general level of onset of such interference. The data on which these limits are based come mainly from studies on aircraft pilots and drivers.

This data plot shows the average level of vibration recorded (in this test it was coincidentally recorded over 8 h) at any given time and not a cumulative exposure. If one were to follow the guidelines set forth by this international committee, a driver in this vehicle should not drive for eight continuous hours, without a substantial break since the vibration at 3·15 Hz exceeds the 8-h level.

7. CONCLUSIONS

An inexpensive digital whole-body vibration dosimeter prototype has been successfully designed, constructed, and tested. The operation of the device has been automated such that a driver need only insert a floppy disk, place the seatpad on the vehicle seat, and switch on the unit. Preliminary data have been collected and forwarded to the university's transportation department with recommendations.

ACKNOWLEDGMENTS

This work was funded by Volvo North America Corporation, and the National Institute on Disability and Rehabilitation Research.

REFERENCES

1. H. Dupuis and G. Zerlett 1986 *The Effect of Whole-Body Vibration*. Berlin: Springer.
2. J. Kelsey and R. Hardy 1975 *American Journal of Epidemiology* **102**, 63–73. Driving of motor vehicles as a risk factor for acute herniated lumbar intervertebral disc.
3. B. Webster and S. Snook 1994 *Spine* **19**, 1111–1116. The cost of 1989 workers compensation low back pain claims.
4. J. Helmkamp, E. Talbott and G. Marsh 1984 *American Industrial Hygiene Association Journal* **45** 162–167. Whole body vibration—a critical review.
5. C. Hulshof and van B. Zanten 1987 *International Archives of Occupational and Environmental Health* **59**, 205–220. Whole-body vibration and low back pain—a review of epidemiological studies.
6. H. Seidel 1993 *American Journal of Industrial Medicine* **23**, 589–604. Selected health risks caused by long-term whole-body vibration.
7. ISO 1985 2631/1 1985-05-15, International Standards Organization.
8. D. Newland 1993 *An Introduction to Random Vibrations, Spectral & Wavelet Analysis*. Essex: Longman Scientific & Technical.
9. W. Press, B. Flannery, S. Teukolsky and W. Vetterling 1986 *Numerical Recipes*. Cambridge: Cambridge University Press.