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Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration —

Part 5: Method for evaluation of vibration containing multiple shocks

Vibrations et chocs mécaniques — Évaluation de l'exposition des individus à des vibrations globales du corps —

Partie 5: Méthode d'évaluation des vibrations contenant des chocs répétés

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 2631-5 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, Subcommittee SC 4, *Human exposure to mechanical vibration and shock*.

ISO 2631 consists of the following parts, under the general title *Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration*:

— *Part 1: General requirements*

— *Part 2: Vibration in buildings (1 Hz to 80 Hz)*

— *Part 4: Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport systems*

— *Part 5: Method for evaluation of vibration containing multiple shocks*

Introduction

The purpose of this part of ISO 2631 is to define a method of quantifying whole-body vibration containing multiple shocks in relation to human health. Examples of conditions that result in vibration containing multiple shocks include, but are not limited to, machinery travelling over rough surfaces, small boats in rough sea, aircraft in buffeting, presses and mechanical hammers.

Adverse effects on the lumbar spine are the dominating health risks of long-term exposure to vibration containing multiple shocks. Therefore, this part of ISO 2631 is basically concerned with the lumbar spine response. Annex A provides guidance on assessment of adverse health effects.

The assessment method described in this part of ISO 2631 is based on the predicted response of the bony vertebral endplate (hard tissue) in an individual who is in good physical condition with no evidence of spinal pathology and who is maintaining an upright unsupported posture. However, the assessment method and related models described in this part of ISO 2631 have not been epidemiologically validated.

Annex A provides guidance on assessment of health effects of multiple shocks. Annex B discusses the effects of multiple shocks and the posture on the intervertebral disc (soft tissue). Annex C gives information on the background of the calculation of spinal response in the vertical direction (z-direction). Annex D includes a software calibration check and an example of a computor program that can be used for the calculation of the vibration dose.

Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration —

Part 5:
Method for evaluation of vibration containing multiple shocks

1 Scope

This part of ISO 2631 addresses human exposure to mechanical multiple shocks measured at the seat pad when a person is seated.

The adverse health effects of prolonged exposure to vibration that includes multiple shocks are related to dose measures. The method described in this part of ISO 2631 is generally applicable in cases where adverse health effects in the lumbar spine are concerned.

The calculation of the lumbar spine response described in this part of ISO 2631 assumes that the person subjected to the vibration is seated in an upright position and does not voluntarily rise from the seat during the exposure. Different postures can result in different responses in the spine.

The limitations of the lumbar spine response models used in this part of ISO 2631 are given in 5.2. Caution is necessary when applying the method to extreme shock conditions.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2041, *Vibration and shock — Vocabulary*

ISO 2631-1:1997, *Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration — Part 1: General requirements*

ISO 5805, *Mechanical vibration and shock — Human exposure — Vocabulary*

3 Terms and definitions, symbols and subscripts

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 and ISO 5805 apply.

3.2 Symbols and subscripts

3.2.1 Symbols

a acceleration

A peak acceleration

c constant

D acceleration dose

f frequency

m dose coefficient

R factor

s displacement

S compressive stress

t time

u model acceleration term

v velocity

w, W model coefficients

ζ critical damping ratio

ω angular frequency

3.2.2 Subscripts

d daily, as in duration of daily exposure t_d

e equivalent, as in equivalent static compressive stress S_e

i, j counter

k counter (x, y or z)

l lumbar

m measured, as in measurement period t_m

n natural, as in natural frequency f_n

s seat

u ultimate, as in ultimate stress S_u

x, y, z reference axes

4 Vibration measurement

Vibration measurement, including the direction of measurement, location of transducers, duration of measurement, and reporting of vibration conditions, shall follow the requirements included in ISO 2631-1:1997, Clause 5. See also ISO 8041 for instrumentation specification, and ISO 10326-1 for information on the location of measurements on the seat and on design of the seat pad. During data collection, the subject shall remain seated and belted and shall not voluntarily rise from the seat.

For measurement of vibration including multiple shocks, it is important that the sign of acceleration signals (positive, negative) is correctly recorded.

The sampling rate for the x- and y-directions shall be appropriated to the analysis of an 80 Hz signal. Because of the requirements associated with the z-direction model, a sampling rate in the z-direction that is a multiple of 160 samples per second is recommended.

The duration of the measurement shall be sufficient to ensure that the multiple shocks are typical of the exposures that are being assessed.

5 Determination of the spinal response acceleration dose

5.1 General

The determination of the spinal response acceleration dose involves the following steps:

— calculation of the human response of the spine;

— counting of number and magnitudes of peaks;

— calculation of an acceleration dose by application of a dose model related to the Palmgren-Miner fatigue theory.

5.2 Computation of spinal response

5.2.1 General

Predictive models are used to estimate the lumbar spine accelerations (a_{lx}, a_{ly}, a_{lz}) in the x-, y- and z-directions in response to accelerations measured at the seat pad (a_{sx}, a_{sy}, a_{sz}) along the same basicentric axes. Two such models are provided below.

NOTE Other models than those given below for calculation of the spinal response, often more refined and complex, are used and developed in research. This is important for further development and should be encouraged.

5.2.2 Spinal response in horizontal directions (x-axis or y-axis)

In the x- and y-axes, the spinal response is approximately linear and is represented by a single-degree-of-freedom (SDOF) lumped-parameter model, having the following characteristics:

— natural frequency, $f_n = 2{,}125$ Hz ($\omega_n = 13{,}35\ s^{-1}$);

— critical damping ratio, $\zeta = 0{,}22$.

The lumbar spine response, a_{lk}, in metres per second squared, is calculated from the equation of motion of a SDOF system:

$$a_{lk}(t) = 2\,\zeta\,\omega_n(v_{sk} - v_{lk}) + \omega_n^2(s_{sk} - s_{lk}) \quad (1)$$

where

k is x or y;

s_{sk} and s_{lk} are the displacement time histories in the seat and in the spine;

v_{sk} and v_{lk} are the velocity time histories in the seat and in the spine.

The values for the SDOF resonance frequency and damping ratio given above, result in the following values for the multipliers in Equation (1): $2\,\zeta\,\omega_n = 5{,}87\ s^{-1}$ and $\omega_n^2 = 178\ s^{-2}$.

5.2.3 Spinal response in vertical direction (z-axis)

In the z-direction, the spinal response is non-linear and is represented by a recurrent neural network model.

The basis for this modelling technique is discussed in Annex C. Lumbar spine z-axis acceleration, a_{lz}, in metres per second squared, is predicted using the following equations:

$$a_{lz}(t) = \sum_{j=1}^{7} W_j \, u_j(t) + W_8 \tag{2}$$

$$u_j(t) = \tanh\left[\sum_{i=1}^{4} w_{ji}\, a_{lz}(t-i) + \sum_{i=5}^{12} w_{ji}\, a_{sz}(t-i+4) + w_{j13}\right] \tag{3}$$

The model coefficients in Equations (2) and (3) are specific to a sampling rate of 160 per second. Therefore, data collected at a different sampling rate shall be resampled to 160 samples per second.

The values to be used for W_j in Equation (2) and w_{ji} in Equation (3) are given in Tables 1 and 2.

NOTE The degree of precision indicated by the number of digits in the figures in Tables 1 and 2 is related to the neural network technology and should not be taken as an indication of an extremely high accuracy in the assessment.

Table 1 — z-axis model coefficients for Equation (2)

W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8
57,96539	52,32773	49,78227	53,16885	56,02619	−27,79550	72,34446	21,51959

Table 2 — z-axis model coefficients for Equation (3)

j	1	2	3	4	5	6	7
w_{j1}	0,00130	0,01841	−0,00336	0,01471	0,00174	0,00137	0,00145
w_{j2}	−0,00646	−0,00565	−0,00539	0,01544	−0,00542	0,00381	0,00497
w_{j3}	−0,00091	−0,02073	0,00708	−0,00091	0,00255	−0,00216	0,01001
w_{j4}	0,00898	−0,02626	0,00438	−0,00595	−0,00774	−0,00034	0,01283
w_{j5}	0,00201	0,00579	0,00330	−0,00065	−0,00459	−0,00417	−0,00468
w_{j6}	0,00158	0,00859	0,00166	0,00490	−0,00546	0,00057	−0,00797
w_{j7}	0,00361	0,00490	0,00452	0,00079	−0,00604	−0,00638	−0,00529
w_{j8}	0,00167	−0,00098	0,00743	0,00795	−0,01095	0,00627	−0,00341
w_{j9}	−0,00078	−0,00261	0,00771	0,00600	−0,00908	0,00504	0,00135
w_{j10}	−0,00405	−0,00210	0,00520	0,00176	−0,00465	−0,00198	0,00451
w_{j11}	−0,00563	0,00218	−0,00105	0,00195	0,00296	−0,00190	0,00306
w_{j12}	−0,00372	0,00037	−0,00045	−0,00197	0,00289	−0,00448	0,00216
w_{j13}	−0,31088	−0,95883	−0,67105	0,14423	0,04063	0,07029	1,03300

5.3 Calculation of acceleration dose

The acceleration dose, D_k, in metres per second squared, in the k-direction is defined as

$$D_k = \left[\sum_i A_{ik}^6 \right]^{1/6} \quad (4)$$

where

A_{ik} is the i^{th} peak of the response acceleration $a_{\text{l}k}(t)$;

$k = x$, y or z.

A peak is defined here as the maximum absolute value of the response acceleration between two consecutive zero crossings. For the x- and y-directions, peaks in positive and negative directions shall be counted. For the z-direction, only positive peaks shall be counted (compression of the spine is of primary interest for exposure severity).

In calculating the dose, peaks of a considerably lower (by a factor of three or more) magnitude than the highest peak will not significantly contribute to the value associated with the 6th power term in Equation (4) and may therefore be neglected.

For assessment of health effects, it is useful to determine the average daily dose, $D_{k\text{d}}$, in metres per second squared, to which a person will be exposed, using the following equation:

$$D_{k\text{d}} = D_k \left[\frac{t_\text{d}}{t_\text{m}} \right]^{1/6} \quad (5)$$

where

t_d is the duration of the daily exposure;

t_m is the period over which D_k has been measured.

Equation (5) may be used when the total daily exposure can be represented by a single measurement period. When the daily vibration exposure consists of two or more (n) periods of different magnitudes, the acceleration dose, in metres per second squared, for the total daily exposure shall be calculated as follows:

$$D_{k\text{d}} = \left[\sum_{j=1}^{n} D_{kj}^6 \frac{t_{\text{d}j}}{t_{\text{m}j}} \right]^{1/6} \quad (6)$$

where

$t_{\text{d}j}$ is the duration of the daily exposure to condition j;

$t_{\text{m}j}$ is the period over which D_{kj} has been measured.

5.4 Flowchart for calculation of the acceleration dose

The procedure for calculation of the acceleration dose is illustrated by the flowchart in Figure 1.

Guidance for development of programs for calculation of response and dose is given in Annex D.

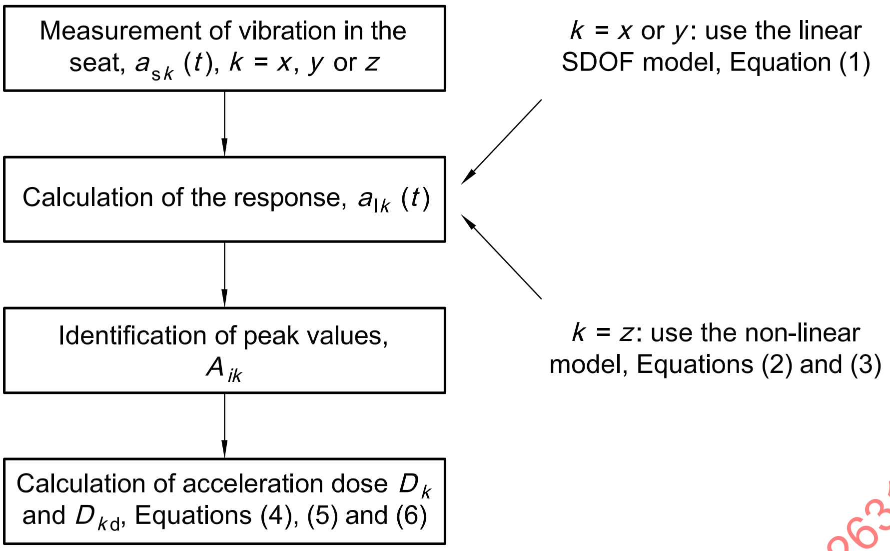


Figure 1 — Flowchart for acceleration dose calculation

5.5 Relationship between acceleration dose and adverse health effects

Guidance on assessment of the adverse health effects from the knowledge of the acceleration dose for multiple shocks is given in Annex A. The response calculations as given in this part of ISO 2631 are related to the prediction of the response of the bony vertebral endplate (hard tissue). Effects of multiple shocks and the posture on the intervertebral disc (soft tissue) are discussed in Annex B.

Annex A
(informative)

Guidance for assessment of health effects of multiple shocks

A.1 Relationship between acceleration dose and health effects

This guidance applies to people in normal health who are regularly exposed to vibration containing multiple shocks. Individuals with previous disorders affecting the spine, including those suffering from latent osteoporosis or other spinal disorders, may be more susceptible to injury. The guidance in this part of ISO 2631 applies to rectilinear x-, y- and z-basicentric axes of the human body. It does not apply to high-magnitude single-event shocks such as may result from a traffic accident that causes trauma.

It is assumed that multiple shocks cause transient pressure changes at the lumbar vertebral endplates that over time may result in adverse health effects, arising from material fatigue processes. Essential exposure-related factors are the number and magnitudes of peak compression in the spine. The peak compression in the spine is affected by anthropometric data (body mass, size of endplates) and posture.

Adverse health effects of long-term whole-body multiple-shock exposure includes an increased risk to the lower lumbar spine and the connected nervous system of the segments affected. Excessive mechanical stress and/or disturbances of the nutrition of and diffusion to the disc tissue may contribute to the degenerative processes in the lumbar segments. Multiple-shock and vibration exposure may also worsen certain endogenous pathological disturbances of the spine.

For the evaluation of the effects of internal pressure changes, the Palmgren-Miner approach is applied. Experimental data show that the value of the Palmgren-Miner exponent varies with biological tissue and test methodology from 5 to 14 for cortical and trabecular bone to 20 for cartilage. For the purpose of estimating adverse health effects, a conservative exponent of 6 has been selected here.

The relationship between the predicted pressure changes and the predicted total tolerance of the exposed person can be used to assess the potential of an adverse health effect. The predicted response is of the bony vertebral endplate (hard tissue). The assessment is based on upright posture. A bending forward or twisting posture is likely to increase the adverse health effect.

The effects of posture and multiple shocks on intervertebral discs (soft tissue) are discussed in Annex B.

A.2 Assessment of health effects

By use of a biomechanical model, based on experimental data, it has been shown that there is a linear relationship between the part of compressive stress that is due to the input shocks and the peak acceleration response in the spine. An equivalent static compressive stress, S_{e}, in megapascals, is calculated as follows:

$$S_{\mathrm{e}} = \left[\sum_{k = x, y, z} \left(m_k D_k \right)^6 \right]^{1/6} \qquad \text{(A.1)}$$

where D_k is the acceleration dose in the k-direction.

Recommended values of m_k are

$m_x = 0{,}015$ MPa/(m/s^2)

$m_y = 0{,}035$ MPa/(m/s^2)

$m_z = 0{,}032$ MPa/(m/s^2)

The daily equivalent static compression dose, S_{ed}, is obtained from Equation (A.1) by normalizing D_k to the acceleration dose D_{kd} for the average daily exposure time using Equation (6):

$$S_{ed} = \left[\sum_{k = x, y, z} \left(m_k D_{kd} \right)^6 \right]^{1/6} \tag{A.2}$$

In general, a factor R can be defined for use in the assessment of the adverse health effects related to the human response acceleration dose. R should be calculated sequentially taking into account increased age (and reduced strength) as the exposure time increases. It is defined as follows:

$$R = \left[\sum_{i=1}^{n} \left(\frac{S_{ed} \cdot N^{1/6}}{S_{ui} - c} \right)^6 \right]^{1/6} \tag{A.3}$$

where

N is the number of exposure days per year;

i is the year counter;

n is the number of years of exposure;

c is a constant representing the static stress due to gravitational force;

S_{ui} is the ultimate strength of the lumbar spine for a person of age $(b + i)$ years;

b is the age at which the exposure starts.

A value of c = 0,25 MPa can be normally used for driving posture.

The value S_{ui} varies with the bone density of the vertebrae, which normally is reduced with age. From *in-vitro* studies, the following relationship between S_{ui} (in megapascals) and $b + i$ (in years) has been derived:

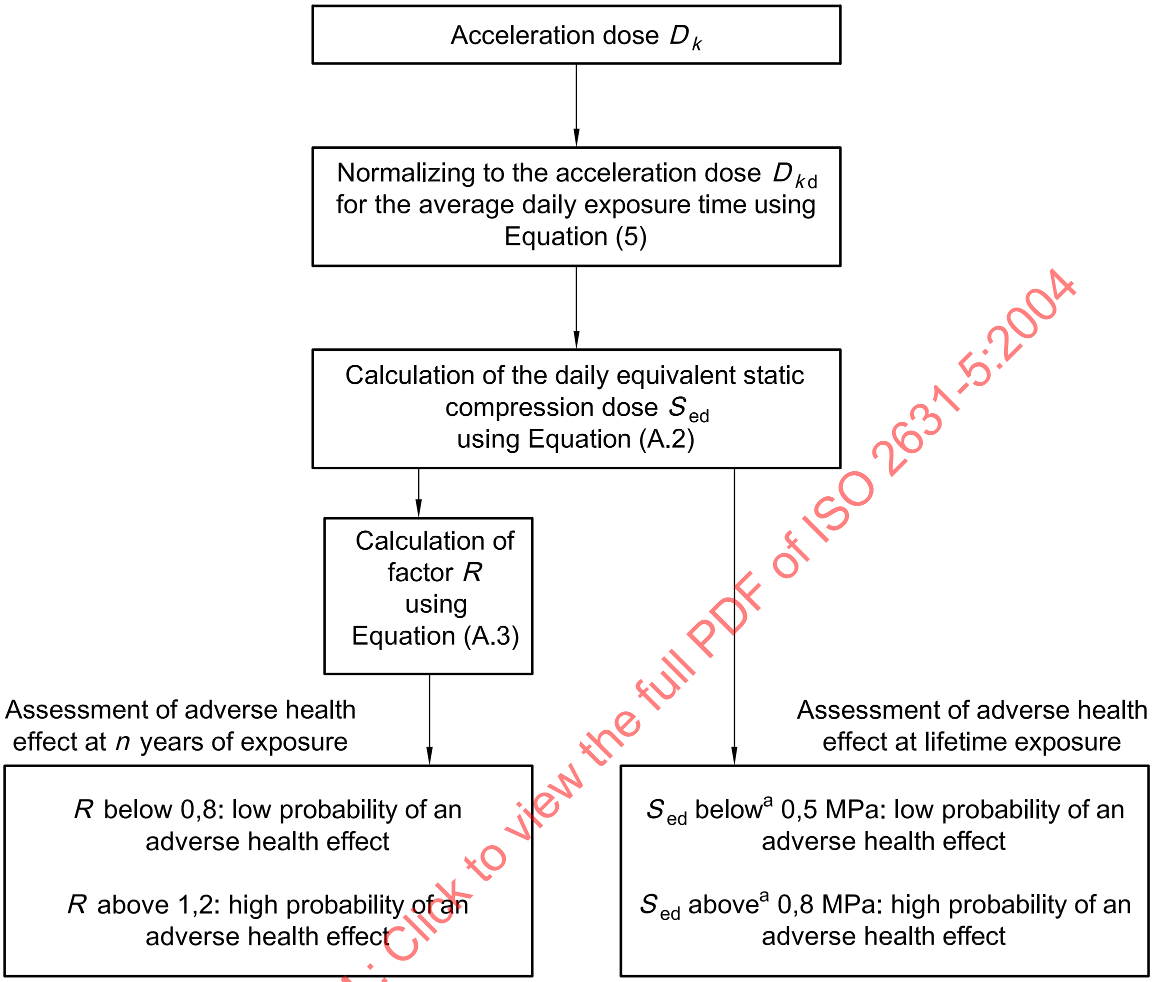
$$S_{ui} = 6{,}75 - 0{,}066\,(b + i) \tag{A.4}$$

There is a significant human variability and $R < 0{,}8$ indicates a low probability of an adverse health effect; $R > 1{,}2$ indicates a high probability of an adverse health effect.

A sequential calculation according to Equation (A.3) for a person who starts being exposed at the age of 20 years ($b = 20$) will reach $R = 0{,}8$ at the age of 65 ($n = 45$) if the daily dose S_{ed} is equal to 0,5 MPa. The same person will reach $R = 1{,}2$ at the age of 65 if the daily dose S_{ed} is equal to 0,8 MPa. This calculation is based on 240 days of equal exposure (N) per year. For application to another number of days of exposure per year, the appropriate S_{ed} limits are achieved by multiplying the values 0,5 MPa and 0,8 MPa by $(240/N)^{1/6}$.

NOTE When more experience of use of this part of ISO 2631 has been gained, comparison between these S_{ed} values and existing experience of adverse effects of long-term exposure may justify a re-evaluation of the values.

The procedure for assessment of adverse health effects from the acceleration dose is illustrated by the flowchart in Figure A.1.



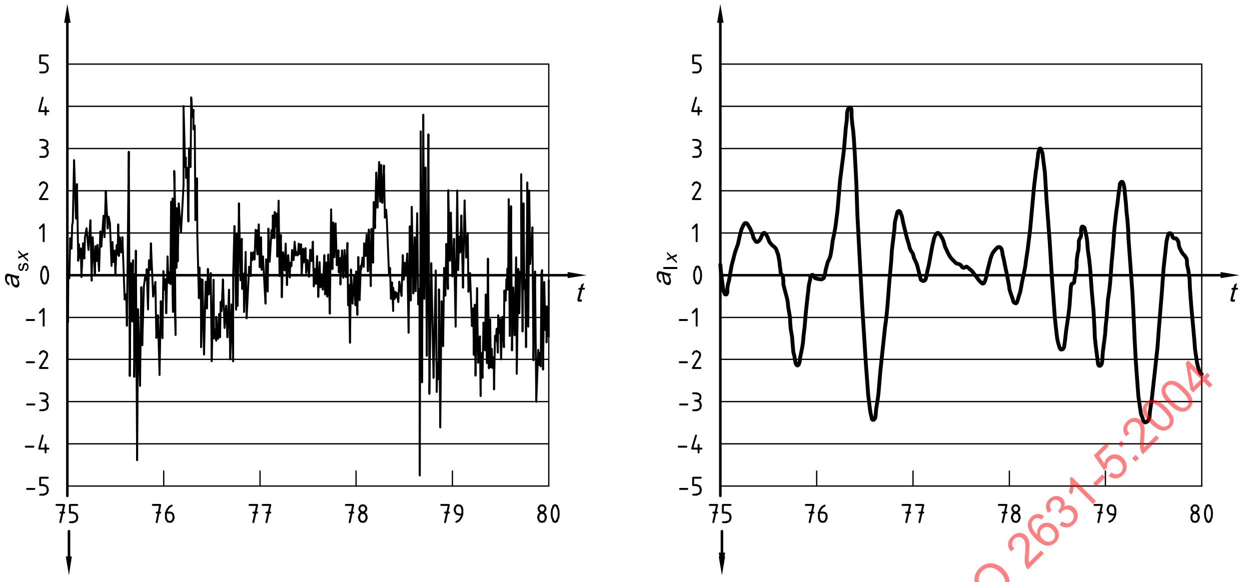
a If the number of days of exposure per year is significantly different from 240, the figure shall be multiplied by $(240/N)^{1/6}$.

Figure A.1 — Flowchart for assessment of adverse health effects from vibration containing multiple shocks

A.3 Example of assessment of adverse health effects

Measurements have been made for a period of 2,5 min on the seat pad at the operator's seat of an off-road machine during travelling.

The response in the spine is calculated using Equations (1), (2) and (3). Figure A.2 shows the input and responses in the x-direction for the time period between 75 s and 80 s.



Accelerations a_{sx}, a_{lx} are in metres per second squared.

Time t is in seconds.

Figure A.2 — x-axis acceleration input and lumbar response for the time period from 75 s to 80 s

In order to calculate the dose according to Equation (4), the absolute acceleration values of the positive and negative peaks in the x- and y-axes response and the acceleration values of the positive peaks in the z-axis response are determined.

The dose values over the 2,5 min record are calculated by taking the 6th root of the sum of the 6th power of the peaks. The results are:

$$D_{x,\ 2{,}5\text{min}} = 8{,}6\ \text{m/s}^2$$

$$D_{y,\ 2{,}5\text{min}} = 13{,}6\ \text{m/s}^2$$

$$D_{z,\ 2{,}5\text{min}} = 7{,}2\ \text{m/s}^2$$

Assume that the record of the acceleration time history is representative of the conditions to which the driver is subjected, and that the exposure lasts, on the average, a period of 30 min per workday. The average daily dose is then according to Equation (5):

$$D_{x\text{d}} = 8{,}6\ (30/2{,}5)^{1/6} = 13{,}0\ \text{m/s}^2$$

$$D_{y\text{d}} = 13{,}6\ (30/2{,}5)^{1/6} = 20{,}6\ \text{m/s}^2$$

$$D_{z\text{d}} = 7{,}2\ (30/2{,}5)^{1/6} = 10{,}9\ \text{m/s}^2$$

From Equation (A.2) the equivalent daily static compressive stress is calculated:

$$S_{\text{ed}} = [(0{,}015 \times 13{,}0)^6 + (0{,}035 \times 20{,}6)^6 + (0{,}032 \times 10{,}9)^6]^{1/6} = 0{,}72\ \text{MPa}$$

The results indicate a moderate adverse health effect (0,5 MPa $< S_{\text{ed}} <$ 0,8 MPa) for a person who is exposed to these conditions during the whole working life.

Annex B
(informative)

Effects of multiple shocks and of posture in the lumbar spine

The intervertebral disc, and paraspinal ligaments and muscles (soft tissue) can be at risk of injury in multiple mechanical shock environments for the following reasons, which have been documented.

a) The seated posture can be mechanically stressful on the disc.

b) Different postures can change the way the body responds to multiple loads, inconsistent with the model constraints.

c) The intervertebral disc can change internal pressure, soften, tear and/or buckle with exposure to multiple loads.

d) The intervertebral motion segment depends on the proper functioning of the neuromuscular control system for active and passive stabilization, and therefore to prevent buckling.

e) Impact can be uncomfortable and can be considered an unexpected, sudden load and leads to an overcompensating response in the trunk muscles.

f) Impact, especially following multiple load exposure, may trigger a buckling event in the motion segment due to an inability of the neuromuscular control system to respond fast enough in a coordinated fashion.

References relating to the posture and soft tissue are given in the Bibliography.

Annex C
(informative)

Recurrent artificial neural network used to model the lumbar acceleration response to z-axis multiple shocks

Experimental data have shown that linear models of lumbar acceleration response result in underestimation of the response of large-magnitude shocks compared to the response of smaller-magnitude shocks. A non-linear modelling approach will yield a more accurate result. A recurrent artificial neural network (RNN) is used to model the lumbar acceleration response to z-axis accelerations applied at the seat. The response is based on a person who is seated in an upright relaxed posture with no back support.

An artificial neural network is a computational algorithm that can model an unknown system based on its input-output data [see Equations (2) and (3)]. The structure consists of a number of interconnected processing elements or neurons. Each neuron produces an output, $u_j(t)$, that is a non-linear function of its weighted inputs.

Information about the system is encoded in the connection weights, w_{ji}, through a training algorithm. The network output consists of a linear summation of the weighted outputs of the processing elements. An RNN has connections which feed back delayed outputs $a_{\mathrm{l}z}(t - i)$ as inputs to the network. Thus, the inputs to the network consist of delayed samples of the system input (seat acceleration, $a_{\mathrm{s}z}$) and delayed network outputs ($a_{\mathrm{l}z}$). Since every output is a function of all the previous inputs and outputs, an RNN is essentially a non-linear infinite impulse response filter.

The RNN for the z-axis was trained using vibration and shocks in the range of –20 m/s^2 to 40 m/s^2 and 0,5 Hz to 40 Hz. As the model is non-linear, this constitutes the range of applicability of this part of ISO 2631.

Annex D
(informative)

Development of programs for calculation of response and dose

D.1 General

The calculation of the response acceleration, a_{lk}, from recorded acceleration time histories, a_{sk}, in the x- and y-directions can be handled by any program having facilities for shock spectrum calculations. There is no standard program which does the calculation in the z-direction, but such a program can easily be developed using various standard mathematical programs as basis. An example of a code written for MATLAB® is given in D.3[1)]. Another alternative is the freeware SCILAB, which includes a translator.

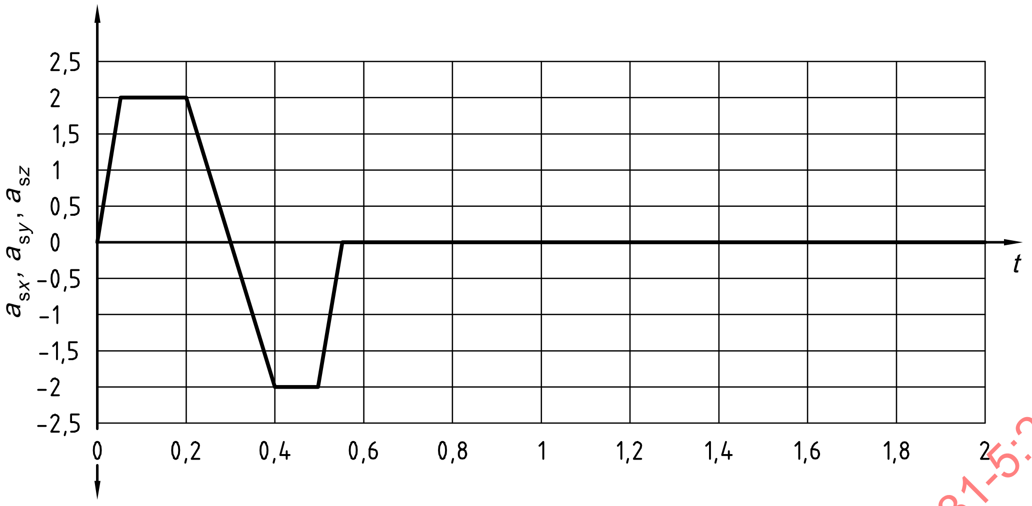
D.2 Software calibration check

An example that can be used for calibration check of the software is presented below. The input seat acceleration, $a_{sk}(t)$, in all three directions is a piecewise function consisting of six line segments. Each line segment is represented by a linear function, $a_{sk}(t) = c_1\, t + c_2$. The coefficients c_1 and c_2 are given in Table D.1. Calculation of the lumbar spine response should produce the responses shown in Figure D.1.

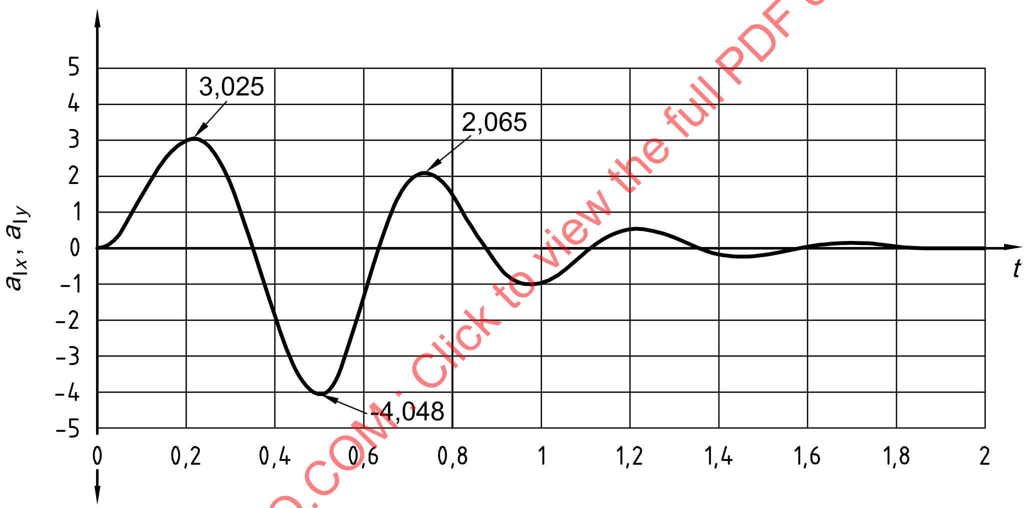
Table D.1 — Calibration signal line segments

Segment No.	c_1 m/s³	c_2 m/s²	Range of t s
1	40	0	$0 \leqslant t \leqslant 0{,}05$
2	0	2	$0{,}05 < t \leqslant 0{,}2$
3	−20	6	$0{,}2 < t \leqslant 0{,}4$
4	0	−2	$0{,}4 < t \leqslant 0{,}5$
5	40	−22	$0{,}5 < t \leqslant 0{,}55$
6	0	0	$0{,}55 < t \leqslant 2$

1) MATLAB® is an example of a suitable product available commercially. This information is given for the convenience of users of this part of ISO 2631 and does not constitute an endorsement by ISO of this product.

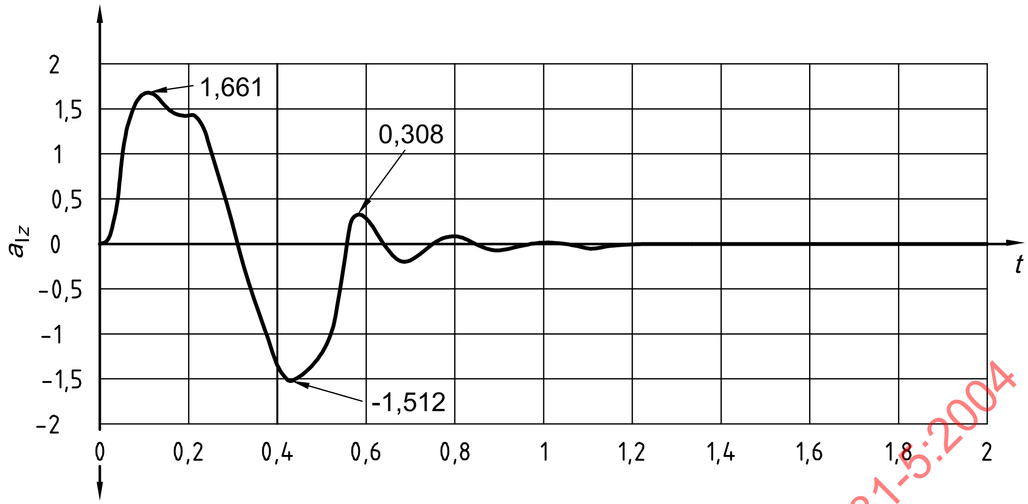


a) Input seat acceleration



b) Lumbar *x* and *y* responses

Figure D.1 (*continued*)



c) Lumbar *z* response

Accelerations a_{sx}, a_{sy}, a_{sz}, a_{lx}, a_{ly}, a_{lz} are in metres per second squared.

Time t is in seconds.

Figure D.1 — Software calibration function and expected responses computed by the software, showing key peak values

D.3 Example of a code written for MATLAB®

D.3.1 General

The response calculations in the x- and y-directions use a filter technique. The functions a and b are related to the damping $Q = 1/(2\,\zeta)$ with ζ being the critical damping ratio, natural frequency $\omega_n = 2\pi \cdot f_n$ and sampling frequency f_{sample} as follows:

$$a = [1, -2\cos(B) \cdot \exp(-A), \exp(-2\,A)]$$

$$b = [1 - \exp(-A) \cdot \sin(B)/B,\ 2\exp(-A) \cdot \sin(B)/B - \cos(B),\ \exp(-2\,A) - \exp(-A) \cdot \sin(B)/B]$$

where

$$A = \omega_n/(2\,Q)/f_{sample}$$

$$B = \omega_n/f_{sample} \cdot \text{sqrt}(1 - 1/(2\,Q)^2)$$

In the program below, the values of a and b correspond to the natural frequency $f_n = 2{,}125$ Hz ($\omega_n = 13{,}35\ s^{-1}$), the critical damping ratio $\zeta = 0{,}22$ and the sampling frequency $f_{sample} = 160$ Hz. The computer program is written for an input acceleration that is sampled at 160 samples per second but the calculations in the x- and y-directions can be made with another sampling rate (higher than 160 samples per second) by changing the a and b values in the program accordingly.

For the response calculation in the z-direction, the process follows directly from the formulae. In the z-direction a sampling rate of 160 samples per second is a requirement for correct results (see 5.2.3). If sampling has been made with another sampling rate, a resampling shall be made before entering the zfile value. This can be made in MATLAB with the command zfile=resample(z,160,f) where z is the record sampled with the frequency f.

The program code shall be copied or written into a MATLAB editor and saved as four separate functions. Open the MATLAB Command Window and type **edit** to enter the code. The lines initiated by % may be left out (this is the MATLAB comment/help text).

The four functions shall be saved separately with the filenames **SpineAcc**, **SpineAccXY**, **SpineAccZ** and **CountPeaks** and with the extension **.m**. The files shall be saved in a directory that has to be created under **C:\...\Matlab\Toolbox** and that is preferably called **SpineAcc**.

The directory **C:\...\Matlab\Toolbox\SpineAcc** must then be associated with MATLAB. Open MATLAB and double-click on the **Path Browser** (the icon with the file structure). From the menu of the **Path Browser**, choose **Path** and then **Add to path**. Use the browser to find the directory **SpineAcc**, and click OK.

The code is written for MATLAB® 5.0 and later versions.

D.3.2 Input data

As input data, an ASCII file with the extension **.txt**, and with two columns shall be used. The first column shall contain the time data, and the second column shall contain the measured acceleration in the seat, a_{sk}. The input data can be placed under any directory, since the path is given in the function call.

D.3.3 Output data

As output data, one file for each calculated direction will be created under the same directory as the input data. The output file names will be the same as the input file names, but with addition of **_al**. In the last row and second column, the calculated dose values D_k are listed. The output data is also plotted immediately in MATLAB, but the figures are not saved.

D.3.4 Function calls (commands to start the calculation)

The commands for starting the calculations are entered in the MATLAB Command Window. To start the calculations, open the MATLAB Command Window, type the command:

```
SpineAcc(path,xfile,yfile,zfile);
```

and press **enter**. The path to the directory under which the input files are placed is **path**; **xfile**, **yfile** and **zfile** are the input file names with the extension **.txt** left out. The path and the file names shall be given as strings, i.e. inside two apostrophs (**' '**). The first file in the command will be interpreted as the file with the measurements in the x-direction, the second with the y-direction and the third with the z-direction. If one or two of the directions are not being calculated, an empty string, **' '**, is entered in the call, instead of the filename.

The function **SpineAcc** calculates acceleration responses and doses in all three directions (x, y and z) by calling the subfunctions **SpineAccXY**, **SpineAccZ** and **Count Peaks**. This is done automatically.

EXAMPLE If the input data is placed under **C:\Documents** and the input files for the three directions are named **Mp1x.txt**, **Mp1y.txt** and **Mp1z.txt**, the function call is:

```
SpineAcc('C:\Documents\','Mp1x','Mp1y','Mp1z');
```

To calculate only the x- and the z-directions, the function call is:

```
SpineAcc('C:\Documents\','Mp1x','','Mp1z');
```

D.3.5 Program code (in MATLAB®)

```
function SpineAcc(path,xfile,yfile,zfile)

%SpineAcc:          Calculates the human response of the spine, alx, aly and alz, and also Dx, Dy and Dz,
%                   from acceleration measurements in the seat.
%path:              Directory in which the measurement files are located.
%xfile, yfile, or zfile: ASCII file with a time vector in the first column and the measurement result in the x-, y- or
%                   z-direction, asx, asy, or asz, in the second column.
%If any of the filenames is given as an empty string '', calculations will not be performed in that direction.

% subfunction calls
if xfile ~''
   figure(1)
   clf
   SpineAccXY(path,xfile, 'x');
end
if yfile ~''
   figure(2)
   clf
   SpineAccXY(path,yfile, 'y');
end
if zfile ~''
   figure(3)
   clf
   SpineAccZ(path,zfile);
end

function SpineAccXY(path,file, XorY)

%SpineAccXY:   Calculates the human response of the spine, alx, aly, Dx and Dy from acceleration
%              measurements in the seat. The result is stored in the file  file_al.txt, along with the time
vector.

%load input file
as=load([path,file,'.txt']);

%separation of input time data and measurement data
time=as(:,1);
as=as(:,2);

%calculation of al(t)
a=[1,-1.957115,0.963949];
b=[0.0192752,0.00433451,-0.0167763];
al=filter(b,a,as);

%call the function CountPeaks to calculate Dk
Dk=CountPeaks(al,XorY);

%plot the result
plot(time,al)
title(file)
legend(['D',XorY,' = ',num2str(Dk)],1)

%add the time column to the calculated response and the calculated value Dk to the last row and second
%column
al=[time,al;0 Dk];
eval(['save',path,file,'_al.txt al -ascii -tabs'])
```

```
function SpineAccZ(path,zfile)

%SpineAccZ:   Calculates the human response of the spine, alz and Dz from acceleration measurements in
%             the seat. The result is stored in the file zfile_al.txt, along with the time vector.
%path:        Directory in which the measurement files are located.
%zfile:       ASCII file with a time vector in the first column and the measurement result, asz, in the
%             second column.

%load input file
asz=load([path,zfile,'.txt']);
(['save', path,file, '_al.txt alz -ascii -tabs'])

%separation of input time data and measurement data
time=asz(:,1);
asz=asz(:,2);

%extension of asz with 8 samples
asz=[0;0;0;0;0;0;0;0;asz];

%preallocation of memory
alz=zeros(size(asz));
x=zeros(length(asz),7);

%constants
w=[0.00130 0.01841 -0.00336 0.01471 0.00174 0.00137 0.00145;
-0.00646 -0.00565 -0.00539 0.01544 -0.00542 0.00381 0.00497;
-0.00091 -0.02073 0.00708 -0.00091 0.00255 -0.00216 0.01001;
0.00898 -0.02626 0.00438 -0.00595 -0.00774 -0.00034 0.01283;
0.00201 0.00579 0.00330 -0.00065 -0.00459 -0.00417 -0.00468;
0.00158 0.00859 0.00166 0.00490 -0.00546 0.00057 -0.00797;
0.00361 0.00490 0.00452 0.00079 -0.00604 -0.00638 -0.00529;
0.00167 -0.00098 0.00743 0.00795 -0.01095 0.00627 -0.00341;
-0.00078 -0.00261 0.00771 0.00600 -0.00908 0.00504 0.00135;
-0.00405 -0.00210 0.00520 0.00176 -0.00465 -0.00198 0.00451;
-0.00563 0.00218 -0.00105 0.00195 0.00296 -0.00190 0.00306;
-0.00372 0.00037 -0.00045 -0.00197 0.00289 -0.00448 0.00216;
-0.31088 -0.95883 -0.67105 0.14423 0.04063 0.07029 1.03300];

W=[57.96539 52.32773 49.78227 53.16885 56.02619 -27.79550 72.34446, 21.51959];

%calculation of alz(t)
for t=(9:length(asz));
   for j=1:7
      x(t,j)=sum(alz(t-1:-1:t-4).*w(1:4,j))+sum(asz(t-1:-1:t-8).*w(5:12,j))
      +w(13,j);
      x(t,j)=tanh(x(t,j));
   end
   alz(t)=sum(W(1:7).*x(t,1:7))+W(8);
end
alz=alz(9:length(asz));

%call the function CountPeaks to calculate Dz
Dz=CountPeaks(alz,'z');

%plot the result in figure 3
plot(time,alz)
title(zfile)
legend(['Dz = ',num2str(Dz)],1)
```