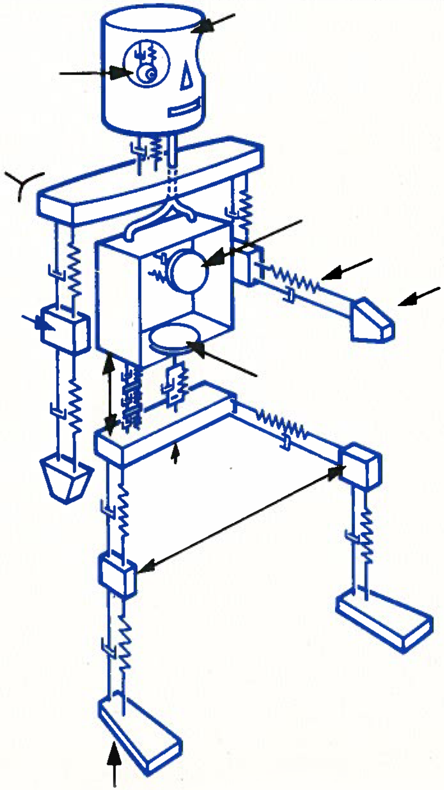
Human Vibration



Brüel & Kjær

This booklet is an introduction to human vibration. It explains what is meant by human vibration; why we are, or should be, interested in human vibration; how it is measured and what action can be taken to reduce human exposure to vibration.

Revision November 1989

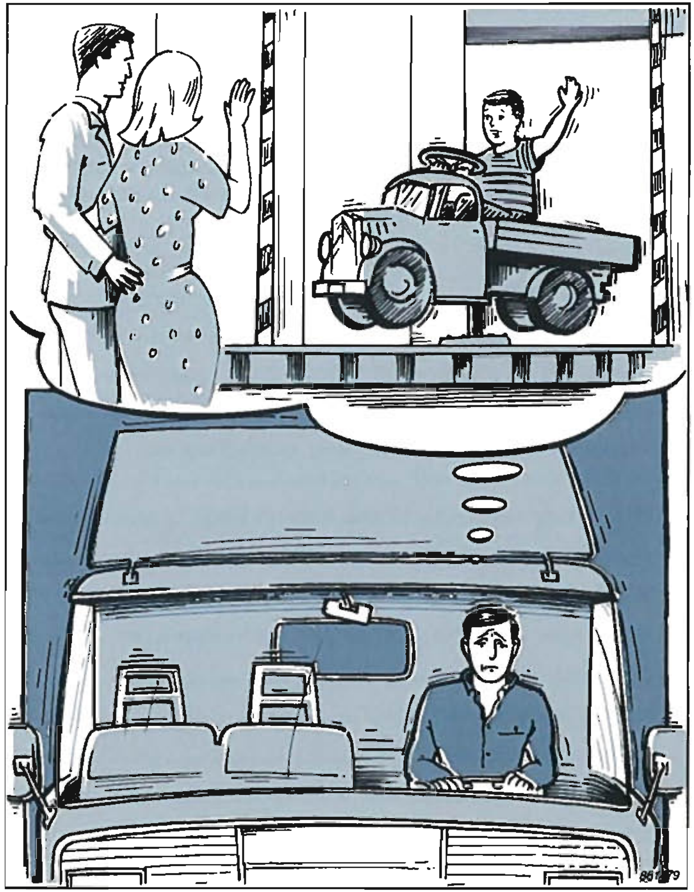
Introduction

Human vibration is defined as the effect of mechanical vibration on the human body. During our normal daily lives we are exposed to vibrations of one or other sort e.g. in buses, trains and cars. Many people are also exposed to other vibrations during their working day, for example vibrations produced by hand-tools, machinery, or heavy vehicles.

Just as sound can be either music to the ear or irritating noise, human vibrations can either be pleasant or unpleasant. We enjoy, and even create pleasant vibrations when we run, dance or take a trip on the merry-go-round, but we try to avoid exposing ourselves to unpleasant vibrations such as travelling on a bumpy road or operating hand-held power tools.

A good deal of research has been done in studying the effect of exposure to vibration on man, especially in his working environment. Some of the early research involved a study of people such as aircraft pilots, operators of heavy work vehicles and hand-tool operators. Their ability to perform complex tasks under adverse vibrational conditions formed part of the first investigations. Nowadays, human vibration research is also carried out in working environments and the results used to establish International Standards which allow human exposure to vibration to be evaluated.

In this booklet we will only discuss undesirable human vibrations: the effect of over-exposure to human vibration; the various factors which have to be taken into consideration when it is measured; how it is measured and evaluated, and what action can be taken to reduce harmful and/or dangerous sources of vibration.



Whole-body and hand-arm vibration

There are two main types of human vibration: whole-body vibration and hand-arm vibration.

Whole-body vibration is transmitted to the body as a whole, generally through the supporting surface (that is, feet, buttocks, back, etc.). A person driving a vehicle, for example, is subjected to whole-body vibration through the buttocks, and if there is back support, through the back as well.

Hand-arm vibration is transmitted to the hands and arms. It is mainly experienced by operators of hand-held power tools.

The whole-body system and the hand-arm system are "mechanically different" and they are therefore studied separately.

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Exposure to whole-body vibration

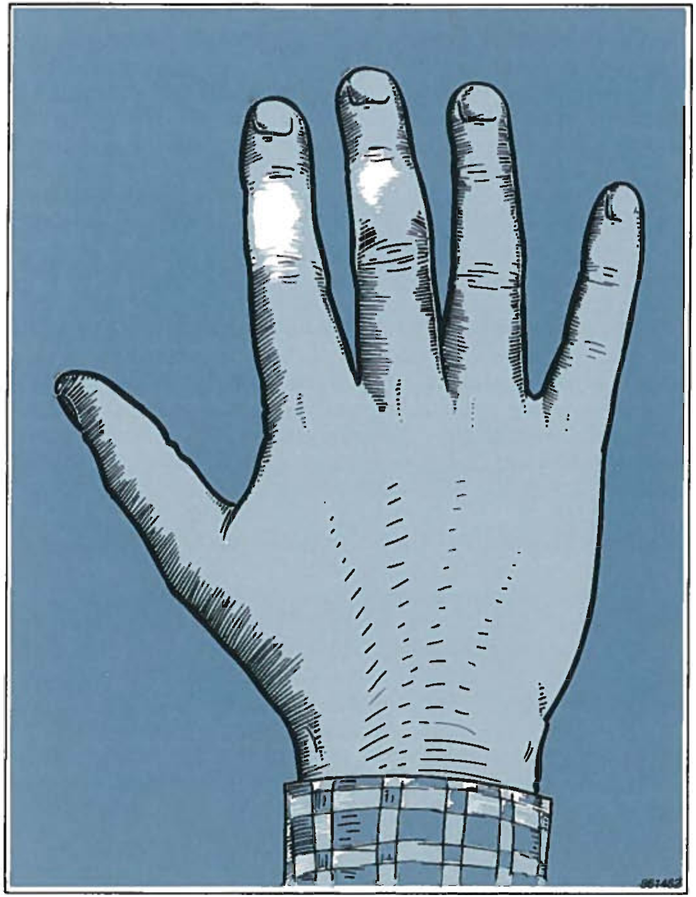
Exposure to whole-body vibration can either cause permanent physical damage, or disturb the nervous system.

Daily exposure to whole-body vibration over a number of years can result in serious physical damage, for example, ischemic lumbago. This is a condition affecting the lower spinal region. Exposure can also affect the exposed person's circulatory and/or urological systems. People suffering from the effect of long-term exposure to whole-body vibration have usually been exposed to this damaging vibration in association with some particular task at work.

Exposure to whole-body vibration can disturb the central nervous system. Symptoms of this disturbance usually appear during, or shortly after, exposure in the form of fatigue, insomnia, headache and "shakiness". Many people have experienced these nervous symptoms after they have completed a long car trip or boat trip. However, the symptoms usually disappear after a period of rest.

Exposure to hand-arm vibrations

Daily exposure to hand-arm vibration over a number of years can cause permanent physical damage usually resulting in what is commonly known as "white-finger syndrome", or it can damage the joints and muscles of the wrist and/or elbow.



White-finger syndrome, in its advanced stages, is characterized by a blanching of the extremities of the fingers which is caused by damage to the arteries and nerves in the soft tissue of the hand. The syndrome usually affects one finger first but will affect the other fingers also if exposure to hand-arm vibration continues. In the most severe cases both hands are affected. In the early stages of "white finger syndrome" the symptoms are tingling, numbness, and loss of feeling and control in those fingers which are affected. These symptoms are serious as they affect not only working activities but also leisure activities and they are, to a large extent, irreversible.

Loss of feeling and control of the fingers, even for short periods of time, can present a direct and immediate danger. For example when periods of exposure (use of vibrating hand tools) are alternated with precision hand work. This job situation is often found e.g. in abattoirs, where butchers use both circular saws and sharp knives.

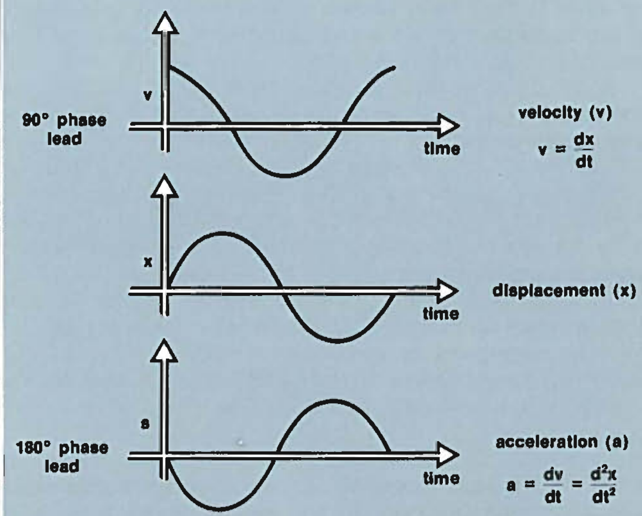
Damage to the wrist or elbow joints is often caused by long-term exposure to the vibrations produced by low blow-rate percussive tools (e.g. asphalt hammers and rock drills). This damage causes pain in the joints and muscles of the forearm and is accompanied by reduction of control and muscular strength in the forearm.

Measurement parameters & quantification of the vibration level

When the human body is in contact with a vibrating mechanical device it is displaced about its reference (stationary) position. Displacement is, therefore, one parameter which can used to describe the magnitude of a vibration. However, vibrations can also be described by velocity and acceleration parameters. The relationship between displacement, velocity and acceleration for a sinusoidal vibration is illustrated here. The shape and period of the vibration are the same whether displacement, velocity, or acceleration is used as a measurement parameter. Only the phases of the parameters are different.

The ISO Standards for human vibration measurement require that acceleration be the parameter used to measure vibration levels. Let us suppose that the acceleration of a vibrating platform is measured and that the instantaneous acceleration values measured are plotted on the time axis for a total measurement time, T (see illustration on the next page). There are several quantities which can be used to describe this vibration.

The **Instantaneous Root Mean Square value (RMS value)** of a vibration is obtained by taking an exponential average of the acceleration values measured during short time intervals (e.g. 1 second). Exponential averaging means that the most recently measured acceleration values have the greatest influence on this value. The acceleration values associated with most vibration signals fluctuate over a wide range and therefore the **instantaneous RMS value** of most vibrations also fluctuates widely. It is therefore difficult to assess a vibration by following its fluctuating **instantaneous RMS values**, especially over long periods of time. To remove the uncertainties associated with the assessment of such a fluctuating measurement parameter, the vibration signal can be averaged over a longer period of time (1 min. or



$$\text{RMS value} = a_{eq} = \sqrt{\frac{1}{T}\int_0^T a^2(t)\,dt}$$

RMS value for whole measurement time, T

$$\text{Crest Factor} = \frac{\text{Peak Value}}{\text{RMS Value}}$$

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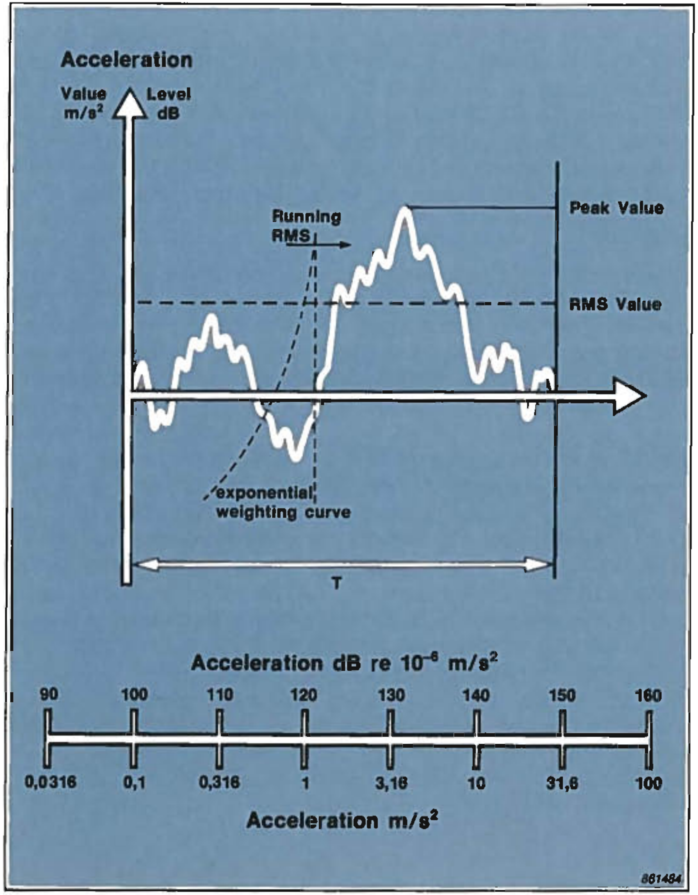
1 hour, for example) to give the **RMS value**, an acceleration which is related to the energy content of the vibration. The **RMS value** is therefore often referred to as the *equivalent acceleration value*, a_{eq} (m/s^2). This parameter (a_{eq}) can also be expressed on a logarithmic scale (decibels, dB) with reference to a scale where an acceleration of 10^{-6} m/s^2 = a_{ref}, which corresponds to 0 dB, by substituting in the following equation:

$$a_{eq} \text{ (in dB)} = 20 \log_{10} \left[\frac{a_{eq}(\text{in m/s}^2)}{a_{ref}(\text{in m/s}^2)} \right]$$

A vibration signal can be much more reliably assessed by measuring the *equivalent acceleration value*, a_{eq}, of the signal because all instantaneous accelerations measured during the averaging period are given equal weighting in the calculation of a_{eq}, and this value does not fluctuate as rapidly as the **instantaneous RMS value** during a measurement period because the averaging period is much longer.

The **Maximum peak value** is the maximum instantaneous acceleration measured during the measurement time, T. It is useful indicator of the magnitude of short duration shocks.

The **crest factor** defines the ratio between the **Maximum peak value** and the **RMS value** for the measurement time, T. The more impulsive (or more random) a vibration, the higher its crest factor. Because impulsive vibrations are considered to be more harmful than non-impulsive vibrations, the crest factor is a good indicator of the harmful content of a vibration.

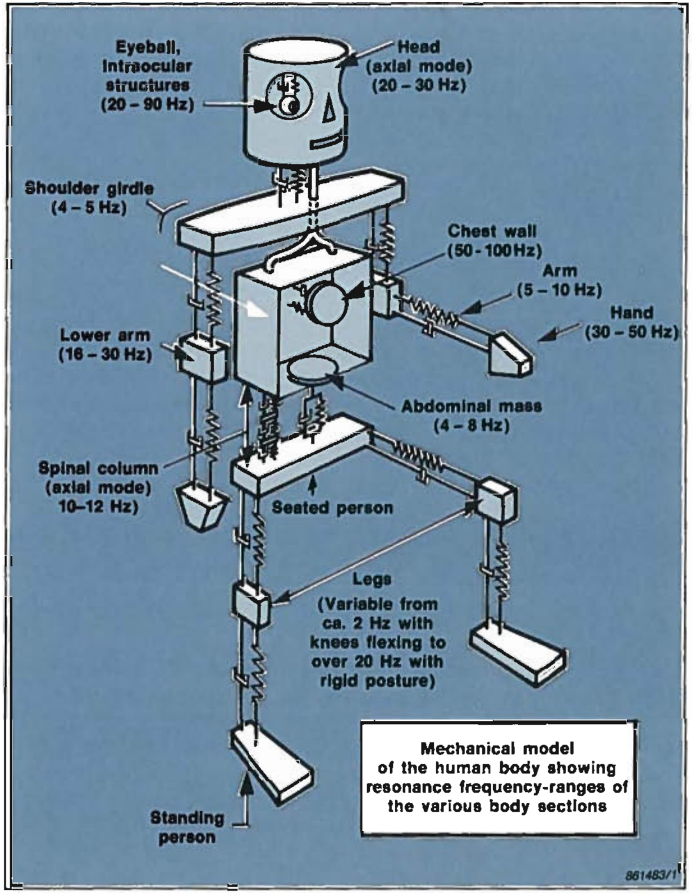


Frequency response of the human body

Mechanical vibration of a machine is caused by the moving components of the machine. Every moving component has a certain frequency associated with its movement so, the overall vibration transmitted to a human body in contact with the machine is made up of different frequencies of vibration occurring simultaneously. This is an important fact to take into consideration when measuring human vibration because the human body is not **equally** sensitive to all frequencies of vibration.

To understand why human beings are more sensitive to some frequencies than to others it is useful to consider the human body as a mechanical system. This system is complicated by the fact that: (a) each part of the body has its greatest sensitivity in different frequency ranges; (b) the human body is not symmetrical, and (c) no two people respond to vibration in exactly the same way. Nevertheless, adequate bio-mechanical models have been developed to simulate the response of the human body to vibration.

This illustration shows a greatly simplified mechanical model of the body, where each section is represented by a mass, spring and damper unit. The human body is a strongly damped system and therefore, when a part of it is excited at its natural frequency, it will resonate over a range of frequencies instead of at a single frequency (see the broad rounded peaks on the human frequency-response curve which follows). The human body is not symmetrical and therefore its response to vibrations is also dependent upon the direction in which the vibration is applied.



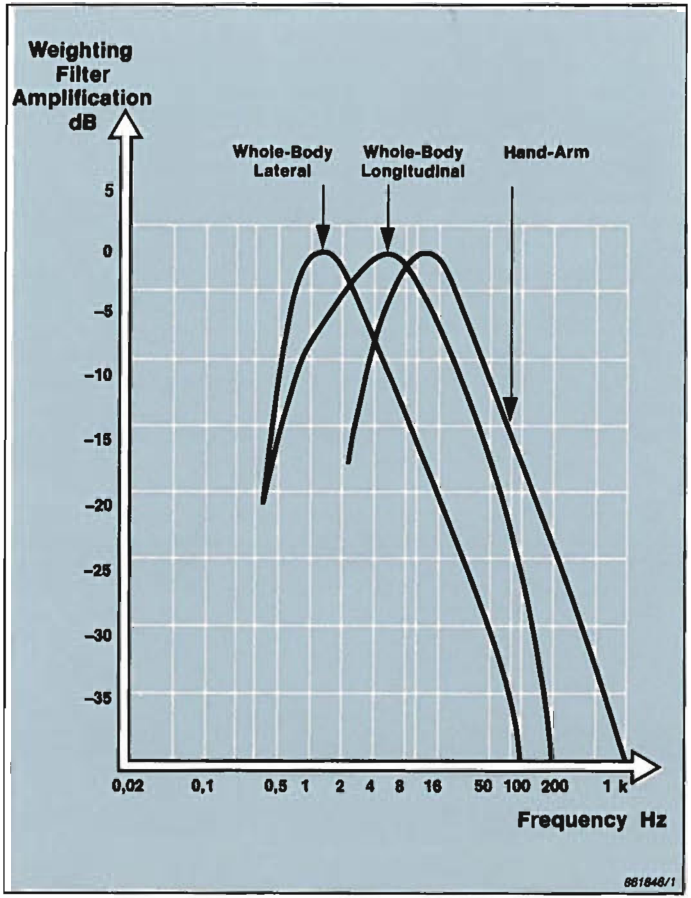
Mechanical model of the human body showing resonance frequency-ranges of the various body sections

Frequency weightings

The sensitivity of the human body to mechanical vibration is known to be dependent on both the frequency and the direction of excitation, as previously discussed. These factors need to be taken into account if the harmful effects of a vibration are to be assessed. The ISO (International Standards Organisation) has devised the three weighting curves, shown here, which can be used to take the aforementioned factors into account when assessing the harmfulness of a vibration (see ISO Standards 5439 and 2631 part 1).

When a vibration is measured in a particular direction the level of the vibration is measured at all frequencies within the human sensitivity range. Those frequencies to which the human body is most sensitive are given a much heavier weighting than those at frequencies to which the body is less sensitive. This weighting gives a good correlation between the measured vibration level and the subjective feeling or impact produced by the vibration. Noise levels are measured in a similar way — an A-weighting filter being used to simulate the response of the ear to noise.

The three main ISO weighting curves shown here will be discussed further on the following pages. Additional weighting curves are occasionally used when assessing vibrational levels associated with, for example, motion sickness, vibration in buildings and transportion in ambulances. In human vibration measurements vibrations occurring in the frequency range from 0,1 Hz - 1 500 Hz are of greatest interest. Those vibrations occurring between 1 Hz - 80 Hz are of particular interest when measuring exposure to whole-body vibration, and those occurring between 8 Hz - 1000 Hz are of special interest when measuring exposure to hand-arm vibration.



Vibration measurement

It is essential that human-vibration is accurately measured so that an assessment can be made of: (a) the discomfort produced by the vibration, and (b) the possible danger involved in being exposed to the vibration, so that the necessary steps can be taken to reduce both these factors. If people who are exposed to vibration are *over-protected* it could impose limitations on their freedom of movement, resulting in reduced efficiency, whilst *over-exposure* to vibrations can cause accidents in the short term and/or physical damage after long-term exposure.

The accuracy of human-vibration measurements is dependent on the quality of the vibration transducer and the analysis and recording equipment used. The transducer which is now almost universally used for vibration measurements is the piezoelectric accelerometer. It exhibits better all-round characteristics and stability than any other type of vibration transducer, and its response is linear through the frequency range of interest in human vibration measurements. As accelerometers are available in a whole range of sizes and weights it is possible to find one whose dimension and weight are sufficiently small so that (a) the vibration being measured is not modified by its presence, and (b) it does not disturb the tool-operator's grip when it is used to measure hand-arm vibrations.

It is extremely important when measuring human vibration, that the vibration is measured as close as possible to the point or area through which the vibration is transmitted to the body.

Whole-body transducers

For whole-body vibration, vibrations enter the body at the floor/foot, seat/back or seat/buttocks interface and so must be measured at these points. Brüel & Kjær has developed a Seat Transducer — a triaxial seat accelerometer moulded into a rubber pad — which can be positioned at the excitation point without disturbing the original position of the person or reducing his/her comfort. To measure vibrations transmitted to a vehicle driver, the driver may either sit on the transducer or strap it onto his back. To measure whole-body vibrations which are transmitted by the floor, the transducer is placed on the floor with a small weight on top of it to ensure good contact between the transducer and the vibrating floor.

The Brüel & Kjær triaxial seat accelerometer contains three independent accelerometers which simultaneously measure the vibration level in three orthogonal axes (x, y and z).

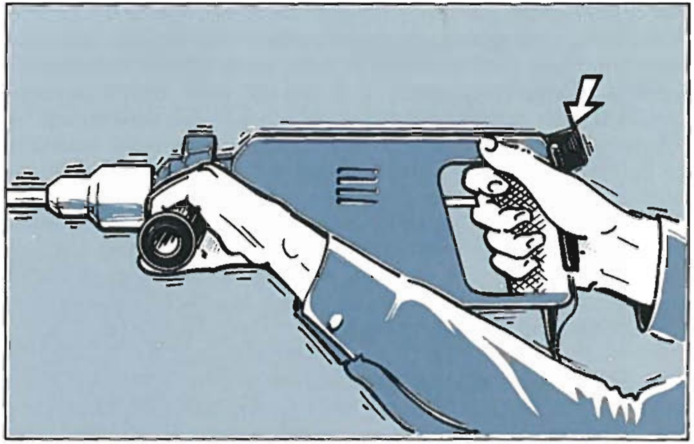
Hand-arm transducers

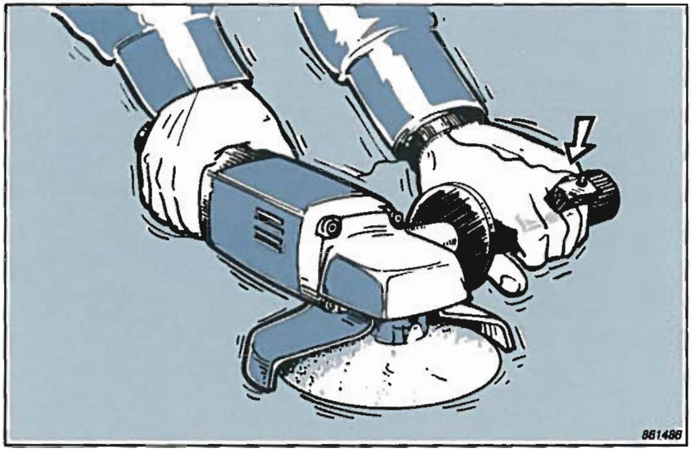
When a vibrating object is held in the hand it transmits vibrations to the hand and arm through the palm of the hand. The transducer should therefore be mounted somewhere on the surface of contact between the palm of the hand and the vibrating object.

Even a very small accelerometer located at the handle-hand interface tends to disturb the operator's grip and so leads to an incorrect measurement. Several transducer mounting methods have been suggested to overcome this problem. The most common method used is to mount the accelerometer on the tool as close as possible to the hand (see upper diagram). However, as tool handles are generally rounded, this means that the handle has to be machined to give a flat mounting base for the transducer. This mounting method is therefore not very practical or convenient.

A practical solution for on-site measurements is to mount an accelerometer on an adaptor which is then held in contact with the handle-hand interface by the natural grip of the operator (see lower diagram). Both the adaptor and accelerometer must be lightweight in order to minimize the risk of introducing resonances.

When hand-arm vibrations are measured in work situations, care should be taken to protect the cable connecting the accelerometer to the measurement-recording equipment.



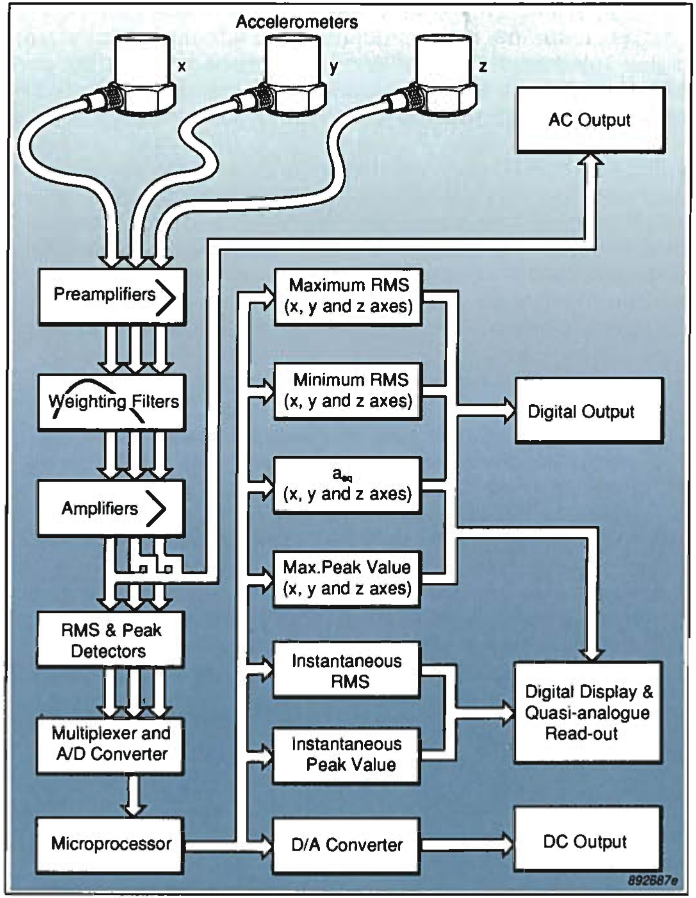


A vibration measurement system

The illustration shows a simplified block diagram of a Brüel & Kjær human-vibration measurement system. Accelerometers are used to measure vibration levels. If triaxial measurements are required, three accelerometers may be connected up to the measurement system so that vibrations in the x, y and z directions can be measured and recorded either simultaneously or consecutively.

The signal from the accelerometer is first passed through a preamplifier. This amplified signal is then weighted — to allow for the variation of human response to vibrations of different frequencies — by passing it through a frequency weighting filter. Different filters are available to weight whole-body, and hand-arm vibrations measured in the x, y and z directions. A special filter is also able to weight whole-body vibration and shock transmitted through building structures. Frequency-weighting is in accordance with all the current ISO Standards. After the signal has been weighted, it is amplified again and rectified in the RMS detector before being converted into a digital signal which is then passed to a microprocessor which enables the following parameters to be read out during a measurement: *Instantaneous and equivalent RMS Values; Instantaneous and Maximum Peak Values; Maximum and Minimum RMS values,* and the following parameters when the measurement is complete: *the total equivalent acceleration value* a_{eq}, *Maximum Peak Value, Maximum RMS;* and *Minimum RMS* for the total measurement time, T. All these quantities can be displayed on a digital and a quasi-analogue read-out.

The AC output enables vibration signals to be tape recorded for further analysis — for example, third-octave analysis as recommended in the relevant ISO Standards (see later section in this booklet). A digital output enables measurement results to be plotted and/or printed out.



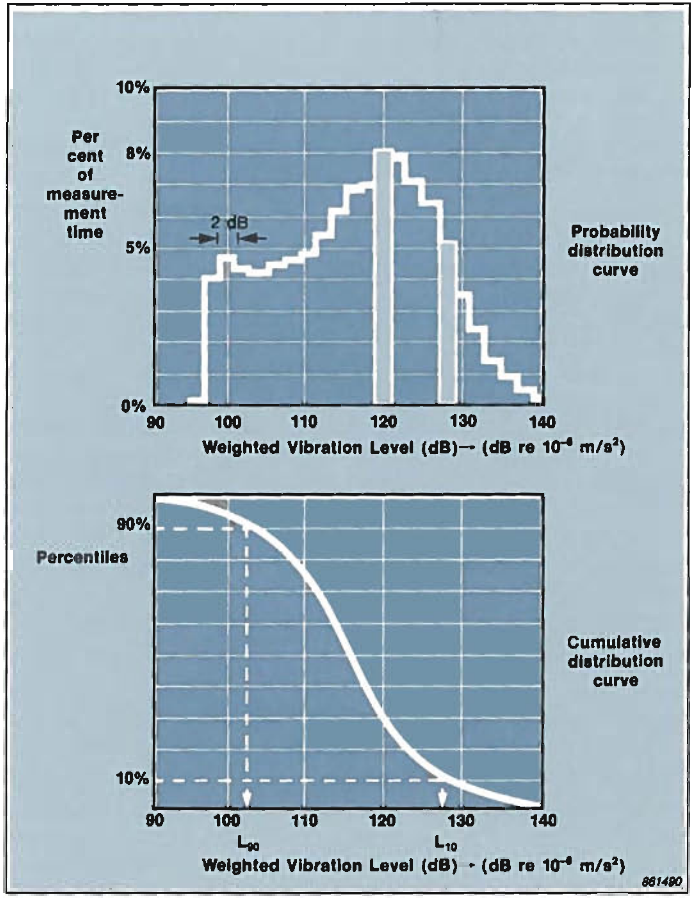
Statistical analysis

The equivalent acceleration value (a_{eq}) and the peak acceleration value are single quantities describing a vibration signal measured during the measurement time, T. By performing a simple statistical analysis of measurement results one can find out how the vibration levels varied during the time, T.

A probability distribution curve plots the percentage of the total measurement time that the vibration had a value between two levels L_n(dB) and $(L_n + L_x)$(dB). In the example illustrated here $L_x = 2$dB. It can be seen that for 8% of the measurement time the level was between 119 dB & 121 dB and for 5% of the time between 127 dB & 129 dB.

A cumulative distribution curve is another way of presenting information about the same vibration. This distribution curve plots the percentage of the total measurement time for which the given vibration level was **exceeded**. Percentiles can be read directly from the graph. In this example, L_{10} (which is the level exceeded for 10% of the measuring time) = 128 dB (re. 10^{-6} m/s^2) and L_{90} = 103 dB.

The value $L_{10} - L_{90}$ has been proposed as a measure of the variation of the vibration level. In this case $L_{10} - L_{90}$ = 25 dB. This quantity together with $\mathbf{L_{eq}}$ gives a more complete picture of the vibration. Instruments which statistically analyze vibration measurements and give both the above-mentioned distributions in graphical or printed form are available from Brüel & Kjær.

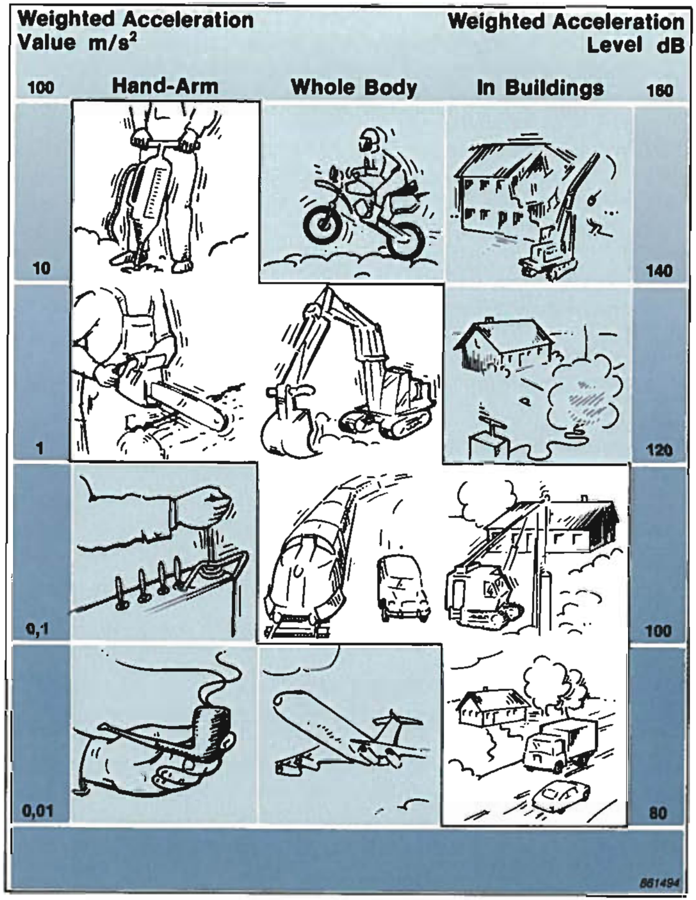


Vibration levels in different situations

The frequency-weighted RMS acceleration values (a_{eq}) associated with occupational exposure to hand-arm vibrations normally range from 2 - 50m/s^2, whilst those encountered in whole-body vibration range from 0,1 - 40m/s^2. Some typical work and leisure situations are illustrated here, together with their range of frequency-weighted RMS acceleration values/levels. The unshaded area of the diagram illustrates situations of particular interest in human-vibration measurement. By taking measurements in these kinds of situations, an evaluation of the effect of vibration-exposure can be made.

Vibration exposure situations vary enormously and thus different criteria are required in order to assess acceptable exposure limits. For example, acceptable exposure to vibration during a long train journey would be dependent on whether one was: (a) assessing the decreased-proficiency of the train-driver due to the fatigue effect of vibration-exposure, or (b) assessing the comfort of the train passengers.

Acceptable whole-body vibration produced by the vibration of buildings borders on the threshold of feeling — RMS acceleration values of 0,003m/s^2 can be perceived and considered unacceptable by e.g. a person who is trying to sleep. Assessment of this kind of vibration is discussed in part II of the ISO Draft Proposal 2631. We shall, however, limit ourselves on the following pages to a discussion of other whole-body vibrations and hand-arm vibrations.



ISO Evaluation of human exposure to whole-body vibration

There are four important physical factors to consider when assessing the effect of a vibrational environment on the human-body, namely, the equivalent acceleration value (a_{eq}) of the vibration; the various frequencies which make up the vibration; the direction of excitation of the vibration; and the time of exposure to the vibration. The ISO Standard 2631 for whole-body vibration distinguishes three main human criteria which can be used to assess vibrations in different situations:

a) the preservation of working efficiency (**the 'fatigue-decreased proficiency boundary'**);

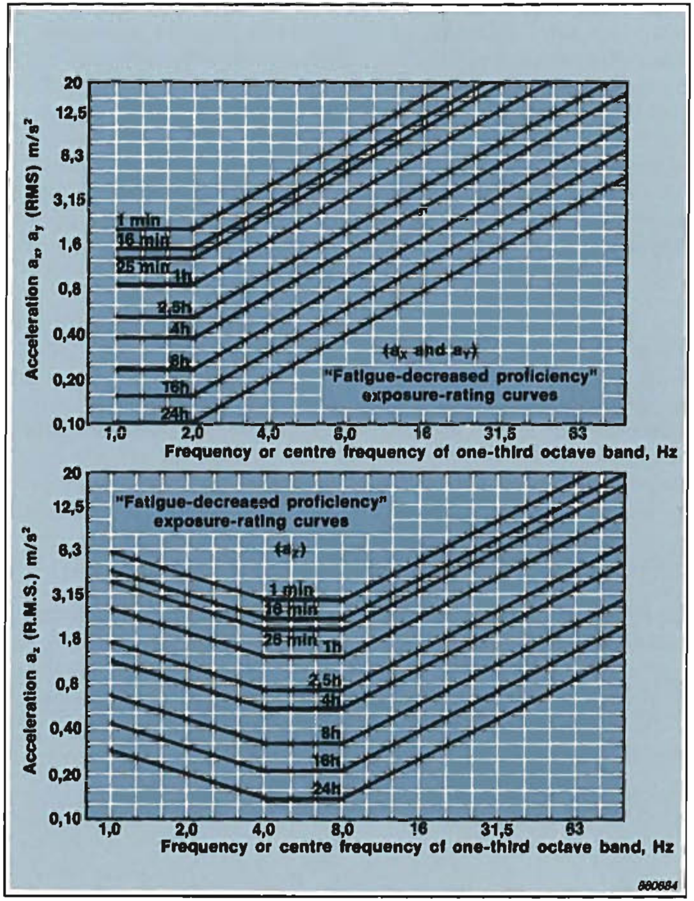
b) the preservation of health or safety (**'exposure limit'**), and

c) the preservation of comfort (**'reduced comfort boundary'**).

The recommended limits of exposure, set according to these three criteria, are defined graphically for the lateral equivalent acceleration value (a_X & a_Y) and the longitudinal equivalent acceleration value (a_Z). All three criteria relate RMS acceleration values with the frequency of the vibration being measured, and the allowed exposure time.

The **fatigue-decreased proficiency boundary criterion** is used to assess exposure limits for the kinds of task where time-dependent effects (i.e.'fatigue') are known to impair performance (e.g. in flying, driving, operating heavy vehicles).

The **exposure limit criterion** is used to assess the maximum possible exposure allowed for whole-body vibration. If the exposure limit defined by this criterion is exceeded, the exposed person's health is likely to be impaired. Exceeding the exposure limit is not recommended.



The **reduced comfort boundary criterion** is used to assess the comfort of people travelling in aeroplanes/ boats/trains. Exceeding these exposure limits would make it difficult for passengers to carry out such tasks as eating, reading and writing when travelling.

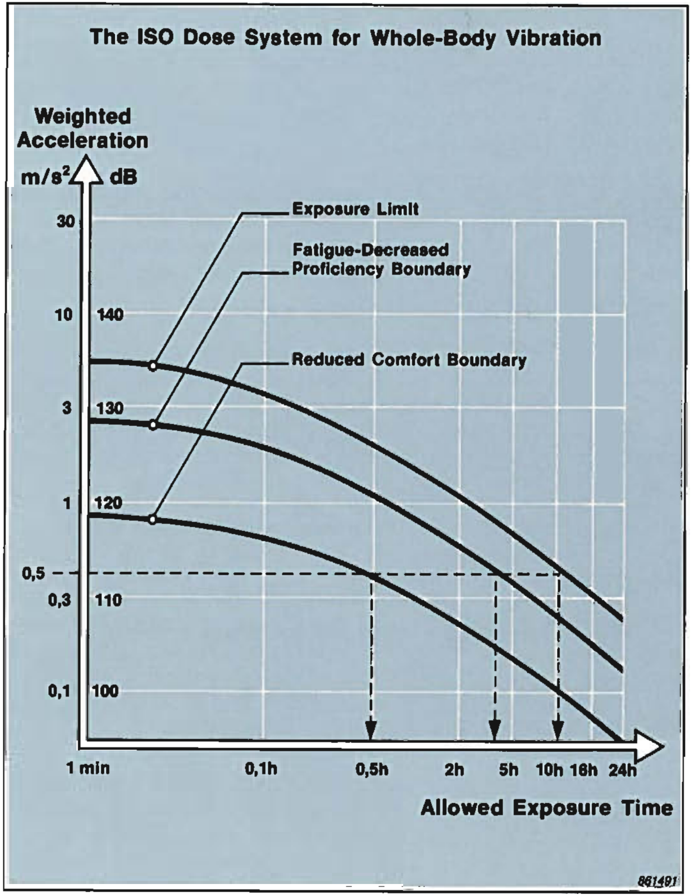
If the RMS accelerations shown in the ISO standards are frequency-weighted and plotted against the exposure time allowed according to the three criteria, the relationships can be represented as shown in the figure here. For example, the exposure time allowed for vibrations whose weighted RMS acceleration value is $0{,}5\,m/s^2$ is only 30 min/day if comfort is the criterion, 4 h/day if proficiency is the criterion and 11 h/day if health is the criterion.

In order to assess a vibration which takes place in more than one direction simultaneously the ISO 2631 suggests that the effect of such a vibration can be calculated by taking the vector sum, **a**, of the three weighted acceleration values, a_X and a_Y and a_Z as follows:

$$a = \sqrt{[(1{,}4a_X)^2 + (1{,}4a_Y)^2 + a_Z^2]}$$

Brüel & Kjær has a measuring system capable of automatically calculating this sum.

The actual exposure time expressed as a percentage of the total allowed exposure time is known as the equivalent exposure percentage. In the example given above the equivalent exposure percentage is 25% if proficiency is the criterion and the actual exposure time is only 1h.



ISO Guidelines for the assessment of human exposure to hand-arm vibrations

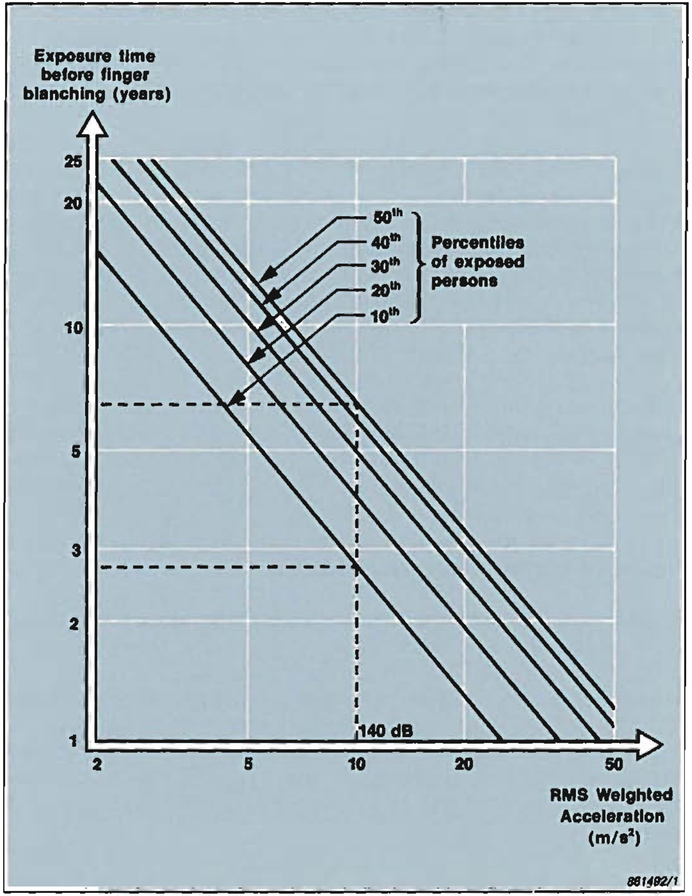
The ISO Standard 5349 (1986) for hand-arm vibration does not define the limits for safe exposure it only provides guidelines for the measurement and assessment of hand-arm vibration.

Annex A of the ISO 5349 provides information which allows one to predict the probability of white-finger syndrome as a function of the frequency-weighted energy equivalent RMS acceleration value for a daily period of 4h., and the exposure time in years (see graph).

In order to assess the long-term effect of a T hours daily exposure to hand-arm vibration which has a frequency-weighted RMS acceleration value of a_{eq}, one must calculate the RMS acceleration value $a_{eq(4h)}$ which would produce an equivalent amount of energy in a 4 hour period of exposure. This can be done by using the following formula:

$$a_{eq(4h)} = a_{eq}\,[T/4]^{1/2} = 4\text{h energy-equivalent value}$$

If a worker is exposed to a hand-arm vibration where $a_{eq(4h)}$ is 10 m/s^2 then the dose-effect probability curves shown here can be used to predict the effect of this daily exposure. The curves predict that if 100 persons are exposed to this daily exposure, half of them risk developing white-finger syndrome after 7 yrs. of exposure and a 10 of them risk developing it after nearly 3 years of exposure.



The ISO 5349 Standard provides details of the calculations required to convert all kinds of daily exposure into 4 h energy-equivalent acceleration values. For example, where daily exposure involves the use of different hand-tools for varying periods of time.

The ISO 5349 Standard recommend that hand-arm vibration is measured in each of the three orthogonal axes (i.e. a_X, a_Y and a_Z) and that assessment is based on the component with the largest RMS acceleration value.

The information contained in the ISO 5349 represents the best guidance available to protect the majority of workers against serious health impairment. It is left up to each National Standardization Board (N.S.B.) to use the information in these guidelines to set their own limits of acceptable exposure.

In practice this means that a N.S.B. will specify that a maximum frequency-weighted acceleration of $\mathbf{a_L}$ m/s^2 can be tolerated for a maximum continuous period of $\mathbf{T_L}$ h. It is stated in the ISO Standard that it is reasonable to assume that the biological effects of hand-vibration might depend to a large extent, on the energy transmitted. The actual energy which is transmitted to the hand during exposure to the vibration specified above is a measure of the vibration 'dose' and, as long as this 'dose' is not exceeded, vibration exposure is considered acceptable.

$$\textbf{vibration 'dose'} \leqslant \mathbf{a_L^2\, T_L} = \text{constant } (\mathbf{k}) \text{ set by N.S.B.}$$

If the frequency-weighted acceleration of a vibration is known to be $\mathbf{a_{eq}}$, the allowed exposure time can be calculated as follows:

$$\mathbf{a_{eq}^2\, T_{allowed} \leqslant a_L^2\, T_L}$$

Thus:

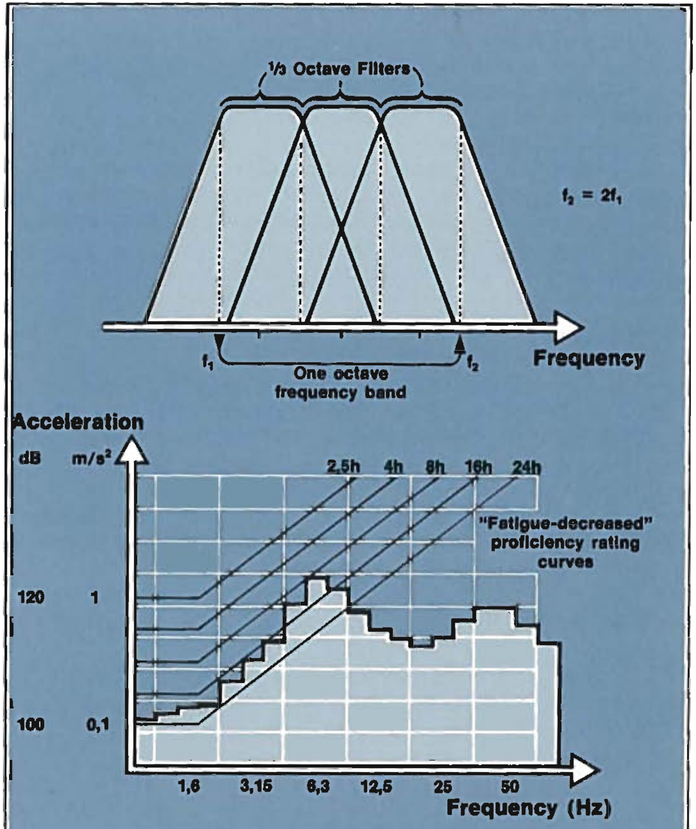
$$\mathbf{T_{allowed} \leqslant k/a_{eq}^2}$$

1/3 octave frequency analysis

ISO standards recommend that human-vibration signals are analyzed in 1/3-octave frequency bands. An octave is a frequency band where the upper frequency limit is twice the lower limit. An octave band has three, 1/3-octave bands of equal width on a logarithmic scale (see upper diagram). The bandwidth of a 1/3-octave filter is 23% of its centre frequency.

If the signal is frequency-weighted before being analyzed in 1/3-octave bands, then the most harmful frequency component is that which has the highest RMS acceleration value, and therefore the lowest allowed exposure time, associated with it. In the diagram on the next page it can be seen that the most harmful component of the vibration is that occuring around 8Hz. This is the kind of vital information a machine designer needs in order to ensure that the overall vibration level of a machine, as well as the vibration levels produced by its individual components, fall within acceptable limits.

A large amount of existing human vibration documentation is in the form of unweighted 1/3-octave spectra, such as the spectrum which is shown here together with the ISO 2631 Standard rating curves for the assessment of the exposure time using the criterion of proficiency. The frequency band which touches the highest rating curve is considered to be the most harmful/disturbing to the operator of such a machine because it is this vibration (centred at 6,3 Hz in this example) which limits the operator's exposure time to 8 h, whereas all the other frequency bands allow longer exposure times. It should be noted that the highest unweighted frequency band is not necessarily the most harmful. For example, if in the spectra shown here there was a peak acceleration of 3,16 m/s^2 (130 dB) in the frequency band centred at 25 Hz, this would not be as harmful as the one centred at 6,3 Hz because it touches the lowest rating curve which allows a maximum exposure time of 24 hours.



1/3 Octave spectrum of operator's seat in a loading machine

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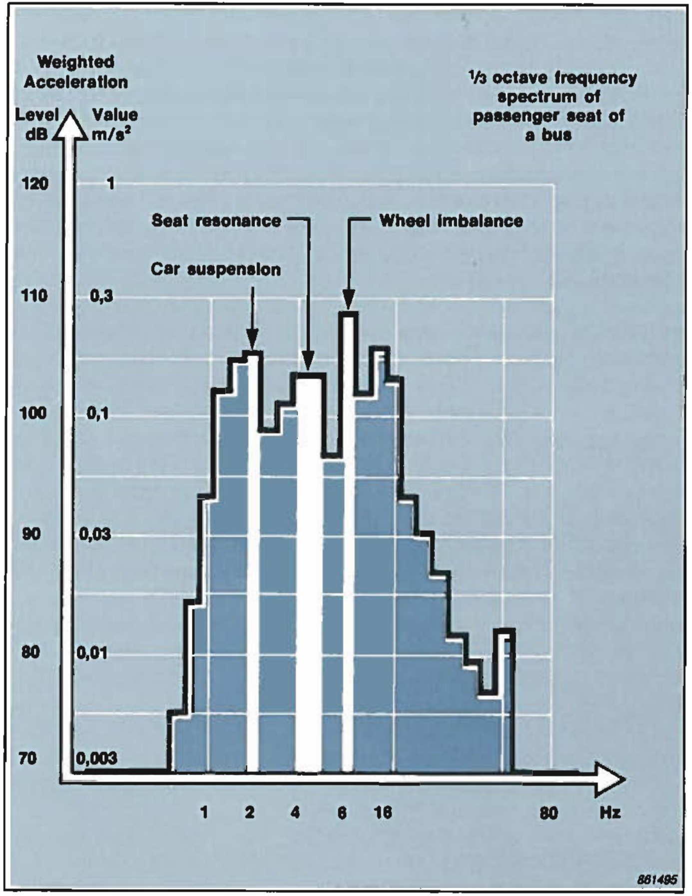
Further analysis

So far we have discussed the way in which a vibration is measured and then frequency-weighted (in order to obtain the equivalent weighted acceleration value) so that the recommended maximum exposure time for this vibration can be obtained from the ISO standards for whole-body vibration, and from the National Standards for hand-arm vibrations. However, machine designers and researchers are more interested in finding out which moving part of a machine is responsible for producing the most harmful vibrational frequency. This information can be obtained by doing a 1/3-octave frequency analysis of the vibration over the frequency range of interest (e.g. for whole-body vibration from 1 - 80Hz). Using 1/3-octave frequency filters the RMS acceleration is measured in each frequency band and these values are then frequency-weighted and the results plotted.

The 1/3 octave frequency-weighted spectrum of a passenger seat on a bus is illustrated here. A wide range of vibrational frequencies are generated in the seat by the various components of the bus, for example, the suspension system, the resonance of the seat, and the imbalance of the bus wheels. The most harmful vibration is produced by the component with the highest RMS weighted acceleration — in this case the wheels.

Using the information provided by frequency-weighted spectra, steps can be taken to redesign and/or dampen the machine components which produce the most harmful frequencies.



Vibration control

Vehicles which drive over rough terrain (e.g. on building sites, in open fields or forests) have vibrations induced in them by the uneven surfaces over which they travel. If these vehicles had no suspension system every bump over which the vehicle travelled would be directly transmitted to the vehicle's operator. Inclusion of a suspension system in the vehicle absorbs some of the most damaging vibrational frequencies. However, a suspension system introduces its own resonance frequency to the vehicle and therefore the magnitude of the vibration produced at this resonant frequency will be greater.

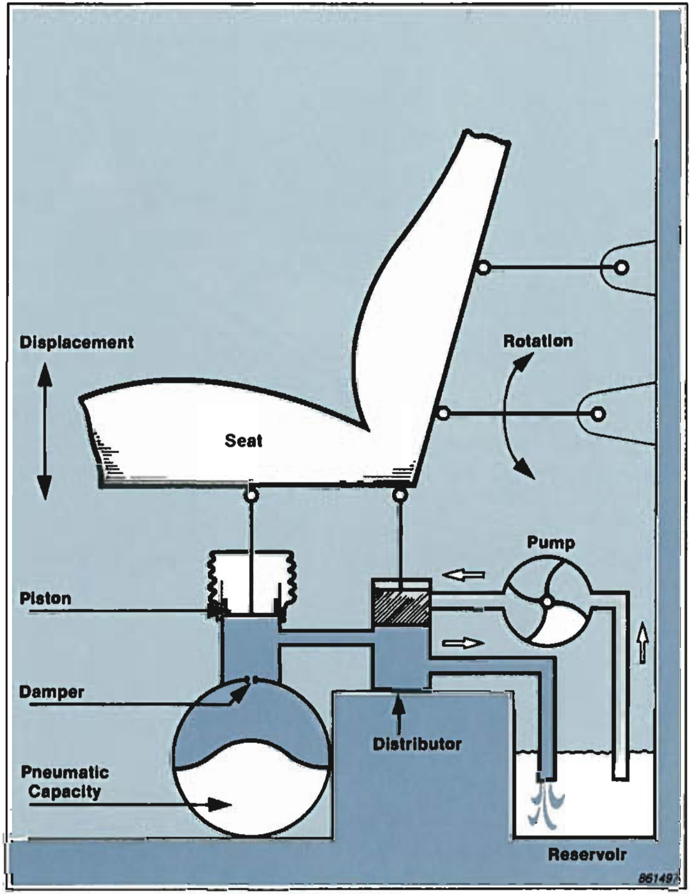
Hand tool vibrations are mainly generated by the moving parts of the tool. There are a variety of methods to reduce tool vibration but these damping methods sometimes also introduce new resonance frequencies to the tool. It is therefore very important to ensure that: (a) the method used to dampen the vibration of a machine or tool introduces only resonance frequencies which lie **outside** the range of frequencies to which the human body is sensitive, and (b) that those frequencies of vibration of the machine/tool which do lie within the human sensitivity range are efficiently damped.

Whole-body vibration damping

One of the most important features of many working vehicles is their ability to work with heavy loads. This feature requires the vehicle to have a stiff suspension and therefore 'bumps' are not very effectively damped. In this situation the usual method of protecting the operator from the dangerous/disturbing vibrations induced in the vehicle by the rough terrain, is to provide the operator's **seat** with a suspension system which can efficiently dampen these vibrations.

One of the simplest methods of absorbing the harmful vibrations produced in a vehicle's seat is to place a soft cushion between the driver and the seat. Another common method is to mount the seat on a suspension system built of spring and damper elements. A more sophisticated method is to use an oleo-pneumatic seat with automatic position correction. The working principle of such a seat is shown in the figure opposite.

Once again the main aim is to reduce the amount of harmful vibration experienced by the driver by damping the existing resonances of the vehicle without introducing new resonant frequencies in the human-sensitivity range. The damping required depends to some extent on the weight of the operator and some seats are available which can be individually adjusted to suit the operator's weight. The ISO 7096 specifies a standard method of testing seat vibrations.



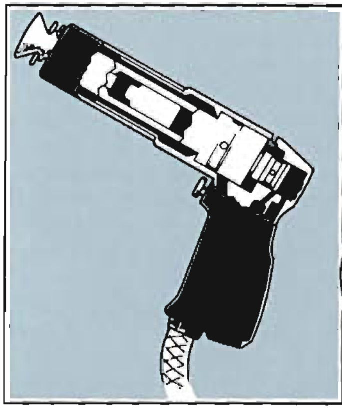
Hand-arm vibration damping

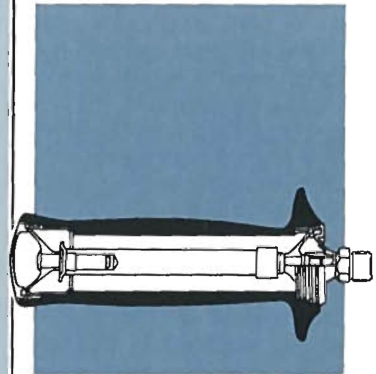
There are four principle ways in which a hand-tool operator's exposure to harmful vibrations can be decreased:

1. By damping the tool internally.
2. By inserting damping between the tool housing and the hand.
3. By operating the tool remotely,
4. By decreasing the operator's daily exposure time e.g. by introducing job rotation. This method also applies to whole-body vibration.

All these methods will be discussed in the following pages.

It is important to remember that it is often difficult, and in some cases impossible, to dampen vibrations in a tool which has already been manufactured. Therefore, when new hand-tools are selected care should be taken to check that the tool does not produce harmful non-dampened vibrations. In addition it should be remembered that tools in good working condition not only work more efficiently, but also produce lower levels of vibration.

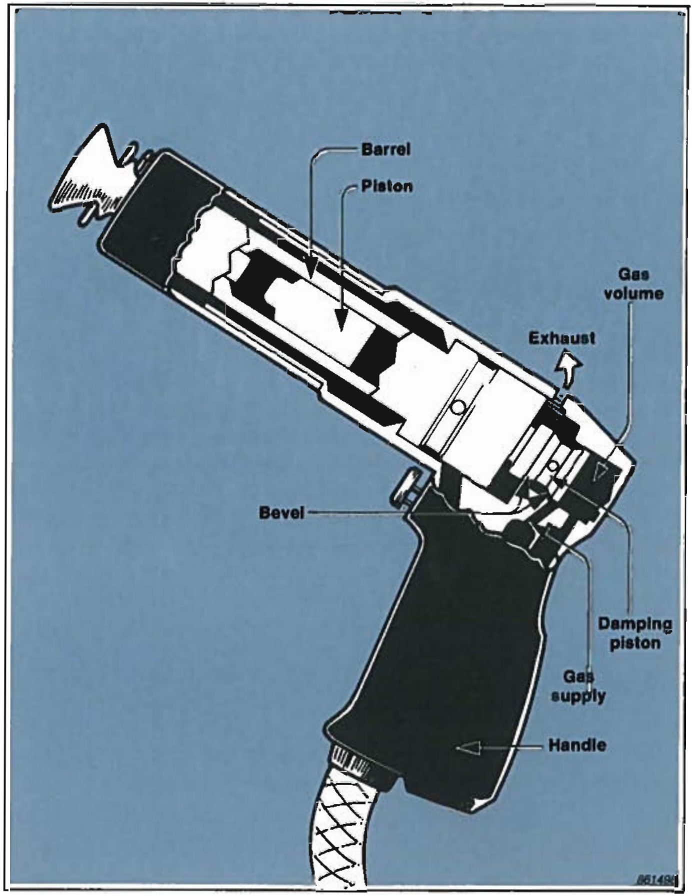




Internal damping

Internal damping of tools is an effective method by which harmful vibration levels can be minimized and it is the most common damping method used by tool designers.

A successful method of damping pneumatic percussive tools has been developed and implemented by many manufacturers. The principle is to introduce an extra piston and gas cavity behind the driving-piston gas cavity. By phasing the two gas streams correctly, the recoil from the driving piston can be considerably reduced (damped). The same effect can be obtained by a spring arrangement.



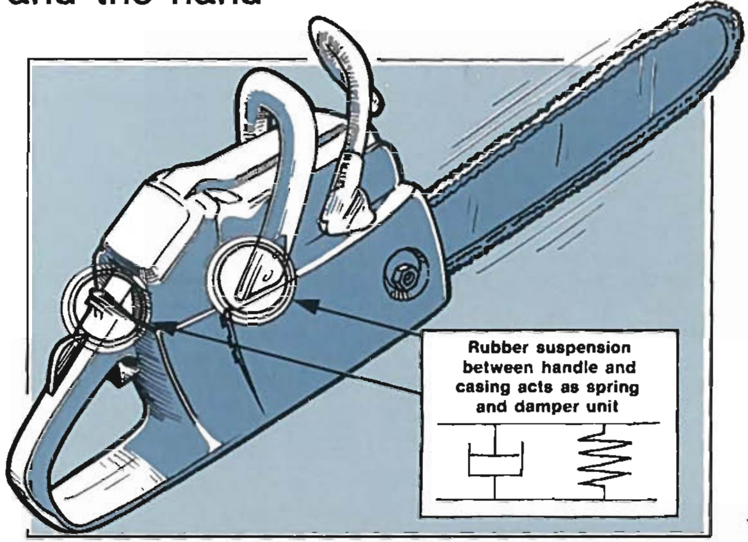
Damping between the tool housing and the hand

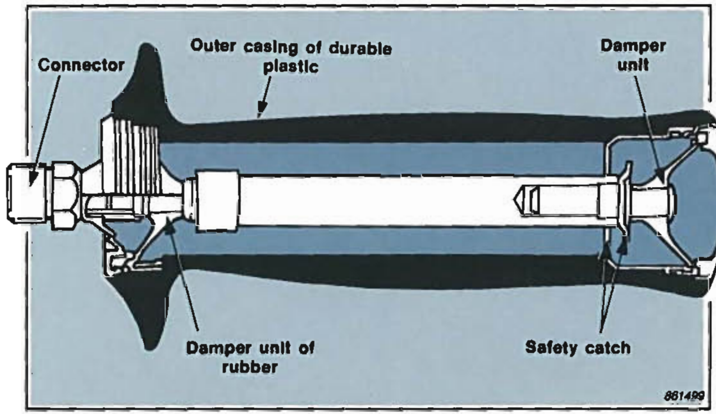
Introducing damping material between the tool housing and the hand is an effective and widely used method of reducing hand-tool vibration levels. This damping could be introduced by:

1. placing damping material between the tool casing and the tool handles;
2. coating the handles with rubber;
3. using rubber gloves to hold the tool.

In general rubber, and other visco-elastic materials commonly used for this purpose, dampen the high but not the low frequency content of the vibration. In fact it can introduce a low frequency resonance. Tools with fast running parts, which produce predominantly high frequency vibrations, can therefore be efficiently damped by using visco-elastic materials (see upper diagram), whereas tools which produce predominantly low frequency vibrations are not necessarily damped by introducing a layer of visco-elastic material between the hand and handle.

The vibrations produced by the motor/chain system of most modern chain saws are isolated from the handle by a rubber suspension. This method of damping can reduce the weighted vibration level by 70% e.g. from 10 m/s^2 to 3 m/s^2 — a substantial decrease. The main problem with this method of damping is that the damping material itself tends to wear out faster than the saw and therefore has to be replaced regularly during the life-time of the saw.





Remote operation

Undoubtedly the most effective, but unfortunately the most expensive, method of damping is to operate tools by remote control. Remotely-controlled tools are often more efficient and more precise than manually-operated tools. However, remotely-controlled tools are generally larger, more specialized and more complicated than the equivalent manually-operated tools.

There are many working situations where remotely controlled tools are used, e.g. a rock drill mounted at the end of an hydraulic arm, an asphalt hammer mounted on a small manually operated vehicle, or a plate vibrator remotely controlled via a cable (as illustrated here).

Decreased exposure time

The ultimate method of reducing exposure to vibration is to reduce the daily exposure time. This is the only solution left when all the other damping methods have either failed, or not been considered feasible.

We have mentioned that each National Standardisation Board (N.S.B.) is responsible for setting its own limits of acceptable exposure to hand-arm vibrations. If the maximum continuous period of exposure for a frequency-weighted RMS acceleration of a_L m/s^2 was set at T_L h we found that the allowed exposure time, $T_{allowed}$, for a frequency-weighted acceleration of a_{eq} m/s^2 could be found using the equation which follows:

$$a_{eq}^2 \, T_{allowed} \leqslant a_L^2 \, T_L$$

Thus:

$$T_{allowed} \leqslant k/a_{eq}^2$$

It follows, therefore, that if a worker has to work with a tool which has a frequency-weighted acceleration of $2 \times a_L$, the allowed exposure time is reduced by a factor of 4, that is,

$$T_{allowed} = 1/4 \; T_L$$

Jobs which involve exposure to high frequency-weighted accelerations should therefore be 'shared' by several workers in order to reduce individual exposure to dangerous vibrations. This can be done by introducing job rotation, as shown here. This method of reducing exposure involves a great deal of planning and is not always easy to implement.

Further reading

Further information on this subject can be found in the following Brüel & Kjær literature and in the relevant Standards:

Booklet:	*"Measuring Vibration"* BR 0094-12.
Brochure:	*"Instrumentation for human vibration measurements"* BG 0205-11
Application Note:	*"Hand-arm vibration measurements"*
Technical Review:	*"Human body vibration"* 1982-1
Handbook:	*"Piezoelectric Accelerometers and Vibration Preamplifiers"* – BB 0694

Relevant Standards:

ISO 2631:	Evaluation of human exposure to whole-body vibration
ISO 5349:	Guidelines for the measurement and assessment of human exposure to hand-transmitted vibration
ISO/DIS 8041:	Human response vibration measuring instrumentation
ISO 7096:	Earth moving machinery, operator seat — measurement of transmitted vibration
ISO/DIS 7505:	Chain saw — measurement of hand-transmitted vibration
DIN 4150:	Vibration in buildings
DIN 45669:	Measurement of vibration immission
DIN 45671:	Measurement of occupational vibration immission
DIN 45675:	Effect of mechanical vibration on the hand-arm system
VDI 2057:	Effect of mechanical vibration on human beings
BS 6841:	Measurement and evaluation of human exposure to whole-body vibration
BS 6842:	Measurement and evaluation of human exposure to vibration transmitted to the hand
BS 6872:	Evaluation of human exposure to vibration in buildings (1 Hz – 80 Hz)
JIS B 4900:	Method of measurement and description of hand-transmitted vibration level
JIS C 1510	Vibration level meters
JIS C 1511:	Vibration level meters for hand tools

We hope this booklet has been a useful introduction to the subject of human vibration. If you have any questions about instrumentation, methods, etc. please contact your local Brüel & Kjær representative or write directly to:

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Taiwan (02) 713 9303 · United Kingdom and Ireland (0181) 954-2366 · USA 1 800 332 2040
Local representatives and service organisations worldwide

Printed in Denmark: K. Larsen & Søn A/S · DK-2600 Glostrup

English BR 056–121