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Whole-body vibration — Guidelines for vibration hazards reduction —

Part 1: Engineering methods by design of machinery

ICS 13.160; 17.160

British Standards

National foreword

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- aid enquirers to understand the text;
- present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep UK interests informed;
- monitor related international and European developments and promulgate them in the UK.

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Vibrations globales du corps - Guide pour la réduction des risques de vibrations - Partie 1: Mesures techniques lors de la conception des machines

Ganzkörper-Schwingungen - Leitfaden zur Verringerung der Gefährdung durch Schwingungen - Teil 1: Technische Maßnahmen durch die Gestaltung von Maschinen

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Contents

Foreword

This Technical Report (CEN/TR 15172-1:2005) has been prepared by Technical Committee CEN/TC 231 "Mechanical vibration and shock", the secretariat of which is held by DIN.

CEN/TR 15172 consists of the following parts:

CEN/TR 15172-1, *Whole-body vibration — Guidelines for vibration hazards reduction — Part 1: Engineering methods by design of machinery*

CEN/TR 15172-2, *Whole-body vibration — Guidelines for vibration hazards reduction — Part 2: Management measures at the workplace*

Introduction

This Technical Report deals with engineering methods for design of machinery transmitting vibration to the human body. Guidance on management measures at the workplace is given in CEN/TR 15172-2.

Significant whole-body vibration is mainly related to operators of mobile machinery. Mobile machinery transmits vibration and shock from the seat for seated operators, from the floor for standing operators, which may cause adverse health effects, primarily damage to the spine. The effects of vibration depend on its frequency, direction, intensity, presence of shocks and on the exposure time. They also depend on the operator's posture. It is important to understand that the design and manufacture of mobile machinery is complex, requiring extensive technical background.

The EC Directive 98/37/EC on the approximation of the laws of the member states relating to machinery (Machinery Directive), amended by Directive 98/79/EC, requires that the machinery is so designed and constructed that risks resulting from vibration produced by the machinery are reduced to the lowest level, taking account of technical progress and the availability of means of reducing vibration, in particular at source. Limiting vibration by design is one of the measures that EN ISO 12100-2 suggests machine manufacturers and designers should consider as part of a strategy to achieve safety by design of machinery in conformity with European Legislation.

The reduction of vibration by design of machinery can make an important contribution to the effective protection of people at work from the harmful effects of vibration. In practical situations, however, a combination of engineering measures and management measures may be necessary.

1 Scope

This Technical Report provides best practices and methods available for limiting the effects of mechanical whole-body vibration on operators' positions. The guidelines given outline practical ways in which whole-body vibration hazards associated with mobile machinery can be reduced by machinery design. The Technical Report covers four important aspects of the reduction of the effects arising from exposure to hazardous machinery vibration:

a) identification of main sources and operational modes producing vibration that might be hazardous to health and of additional factors worsening the adverse health effects of vibration on the operators;

b) reduction of vibration magnitudes at source;

c) reduction of transmission of vibration from source to the operator;

d) ergonomic adaptation of operators' position: posture, range of vision.

This Technical Report does not provide universal or detailed technical solutions but only a review of engineering methods available. It is not concerned with hand-arm vibration which is covered by CR 1030-1.

This Technical Report is primarily intended as a guideline for people involved in purchasing, using, supplying, marketing or inspecting mobile machinery. It is also intended to be a guidance for writers of type C standards for specific types of machinery.

2 Identification of main sources and operational modes producing vibration that might be hazardous to health

2.1 Identification of main sources and operational modes

The machine manufacturer should make a careful investigation of all possible causes of vibration and shock connected with the full range of likely use of the machinery. In case the machinery is used with tools, the investigation should include the range of tools likely to be used with the machine.

Internal sources of vibration in mobile machinery are engines, hydraulic devices and transmission.

Normally, the engine is not a problem unless it runs at low speed and has only a small number of cylinders. Generally, the engine may be a problem in older, poorly maintained machines and in machines where the user has made changes in the original construction.

Some machinery categories, e.g. vibratory rollers, include intentional vibrating sources. Machinery may also use vibrating attachment, e.g. separators, rotary snow-ploughs, street-sweeping machines, road milling machines, refuse collection lorries. Rough braking and handling of gears can cause large vibration and shocks.

The major source of vibration affecting operators of mobile machinery is the contact between wheels and ground at travelling. The severity is determined by the combination of ground surface, machine dynamics and travelling speed.

For machinery using tools, the contact between the tool and the material, e.g. in digging, rock drilling, loading, compaction, is of vital importance. The vibration magnitude depends on the characteristics of the material and the operator's skill.

Examples where the tools can be the dominant source of vibration are excavators using breakers.

In case of using a trailer, the design of the connection of the trailer to the machine (e.g. truck, lorry) is important as is the position of the centre of gravity of the trailer.

Liquids cause vibration when sloshing in tanks. Tanks can be divided into smaller rooms, which will minimise the vibration.

Some information on methodologies for identification of vibration and shock during various operational modes can be found in EN 1032 and EN 14253.

2.2 Factors that can combine with vibration to increase the likelihood of injury

It is probably the combination of the stresses from poor position and vibration that causes back pain. The machinery manufacturer should make a careful investigation of all possible causes which might force the operator to adopt poor posture.

The ergonomic design should support a driving posture that minimises the adverse effects of the vibration transmitted to the body (primarily to the spine). An upright driving position is important.

Outside visibility always comes first. Even if it is detrimental to his posture, an operator will compensate to overcome the lack of good visibility essential for safe machine operation. Driving a counterbalance truck with a high load, cutting the grass with a tractor along the merge of a road are examples where the operators might bend forwards or backwards or twist the body in order to increase the visibility at travelling or operating of equipment.

When the vertical seat adjustment is insufficient, some operators can have difficulty to reach the floor pan or pedals with the feet. In fork lift trucks tall operators have to drive in bent position in order to avoid the head to get in contact with the overhead guard.

On some vehicles the operator’s legs cannot slip easily under the steering wheel. When this is the case, the operator might push his seat back to allow his thigh room to move and as a result he has to lean forward to operate the machine controls and steering wheel.

The adverse health effects of vibration can increase when the machine is operated on slopes and side slopes due to effects on operator’s posture, on efficiency of cab and seat suspension.

Jumping from machines could cause significant shock loads to the body. To minimise this risk, a well designed machine access system (including suitably placed hand holds and slip resistant steps) should be provided and the operator should be encouraged to use the access system instead of jumping from the machine. Machine specific standards for access systems should be used, such as EN ISO 2867 for earth-moving machines or EN 1553 agricultural machinery. When no machine specific access system standard is available, general guidelines for access systems can be obtained from the EN ISO 14122 series.

3 Reduction of vibration at source

3.1 Travelling on uneven surfaces

The vibration affecting the operator when travelling depends on the mechanical design of the machine. It also depends on the ergonomic design (e.g. visibility) that can help the operator to avoid excessive vibration, e.g. by choosing speed and route around obstacles.

It should be observed that also small obstacles may lead to high vibration levels for machines with small-size wheels, hard tyres, a short wheelbase or less suspension.

The vibration and shock caused by the contact between the machinery and the ground when travelling is affected by the design and dimensions of the wheels. Designers should aim at a low centre of gravity, located close to the cross point of the diagonal lines between the wheels. In some cases the centre of gravity can move when travelling, e.g. machinery carrying a tool such as a suspended boom. This movement should be taken into account.

Working equipment and tools mounted to the machinery might cause excessive vibration at travelling due to change of the centre of gravity. An example of avoiding this is the use of special suspension devices, e.g. hydraulic accumulators for boom suspension in earth-moving machinery. The manufacturer should give information on limitation of tools and the effects on the vibration by the use of tools.

3.2 Operating of working equipment (tools)

Examples of working equipment are:

- buckets of excavators,
- ploughs, balers or powered cultivators;
- cranes and processors (cutting devices) of forestry machines;
- grading devices of graders;
- drilling devices of mining machines;
- milling devices of road milling machines.

Generally, soft movements should be aimed at in the design of working equipment and its integration in the machine. Vibration should not be transmitted from the tool to the operator's position.

Hydraulic functions should be carefully adapted to provide soft operation.

Linkages should be correctly balanced and excessive play avoided. Accessories and loads can change the centre of gravity, changing the vibration characteristics when moving.

The controls of the tools should be placed so that the operator will maintain an upright position and avoid unnecessary twisting of the body when using the tools.

3.3 Information from the manufacturer on the use of tools and accessories

One important factor is to provide the right tool for the job. The machinery manufacturer should give good guidance on what tools to use and how to operate the tools in order to minimise the vibration without losing efficiency. Also the tool maintenance instructions are important.

The manufacturer should provide information on limitation of application of tools and the effects on vibration by use of tools. The manufacturer should also provide information on limitation of slope, limitation of loads, speed, etc.

Often problems occur when the machine and tool have been produced by different manufacturers.

Manufacturers should provide instructions on how accessories and loads should be carried in specific operating modes to minimise vibration, e.g. for earth-moving machinery, the boom should be raised when travelling (use of accumulators).

3.4 Vibrating tools mounted to the machinery

If a machine is equipped with optional vibrating hydraulic tools, e.g. hydraulic hammers, cutter crushers or screening buckets, this could contribute to the vibration of the operator. As a minimum, the operating frequency and level of excitation force of the tool needs to be known and the influence from this tool should be evaluated together with the vibration isolation systems of the main machine in order to minimise the vibration exposure of the operator.

The tools may be boom mounted or three-point linked.

In the case of machinery including vibration exciters, e.g. vibratory rollers, it is important that the frequency selected for the excitation is as high as feasible with regard to the work efficiency in order to enable an efficient isolation of the operator from the source. It is also important to avoid a conflict between this frequency and its harmonics and the resonance frequencies of the machine structure.

3.5 Engine

Vibration produced by the engine is unlikely to be of a magnitude that could cause a health risk, presumed that the engine is well balanced and resiliently mounted to the structure. For one-cylinder reciprocating engines, where balancing is not normally feasible, extra care needs to be taken in the mounting of the engine. It is of primary importance to avoid with good margins a coincidence between n times the rotational speed of the engine and resonance frequencies of the engine suspension and of the engine mounting structure (n is an integer).

4 Reduction of transmission of vibration from source to the operator

4.1 General

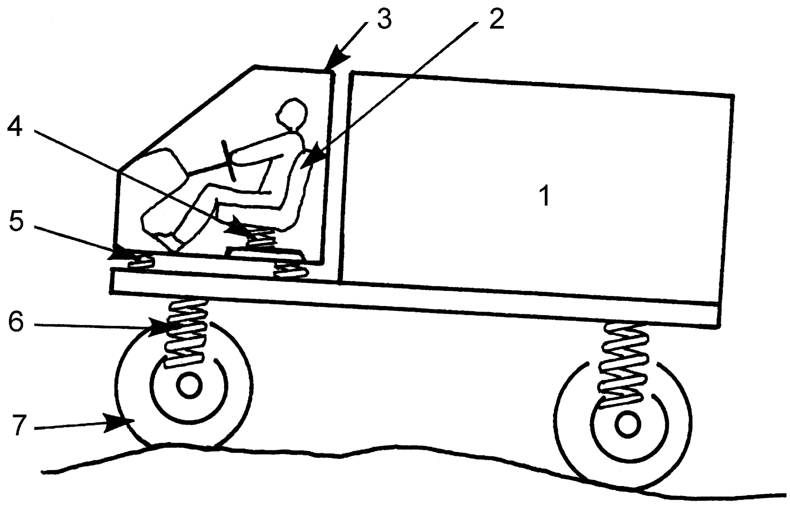
Reduction of transmission of vibration from source to the operator often includes use of resilient mounts, either by separating the source of vibration (e.g. engine) from the machine structure or by separating the operator from the vibration source or vibrating structure (vibration and shock isolation of wheels, chassis, operator's cab, seat).

Methods for vibration and shock isolation are well described in the literature and handbooks. It is important that the designer of resilient suspension systems and their integration in the machine has good knowledge of structural dynamics. The designer needs to know how to optimise the system with regard to resonance frequencies, internal damping in the isolating elements, and location and directivity of elements in relation to the centre of gravity of the part to be isolated.

Some general considerations in selection of vibration and shock isolating devices can be found in EN 1299.

Transmission of vibration and shocks from the contact between the ground and tyres to the operator can be reduced by means of vibration isolation elements (resilient suspension systems) positioned at different key points (see Figure 1):

- Tyres;
- wheels and chassis (vehicle body);
- cab;
- seat.



Key

1	vehicle body	5	cab suspension
2	seat	6	body suspension
3	cab	7	tyres
4	seat suspension		

Figure 1 — Schematic presentation of possible suspensions

When resilient suspension systems are designed and selected, it is important that prevention from both shock and vibration is taken into account. Ideally, a resilient suspension should be designed so that its highest cut-off frequency is significantly less than the dominant input frequency. Suspension travel should be sufficient to prevent bottoming or topping on end-stops. The lower the input and the cut-off frequency, the larger the required travel. A compromise should be developed for the specific machine between the capacity of reducing long-term low-level vibration and occasionally occurring high-level vibration and shock. Internal damping in the suspension system has a positive effect on vibration transmission at the resonance frequency of the suspension system, but insignificant effect on the reduction of occasional shocks or bumps.

Use of several resilient suspension systems in a suspension chain, e.g. simultaneous use of soft pneumatic tyres, resilient chassis suspension, resilient cab suspension and resilient seat suspension, requires high technical skill, due to the complex interaction of the suspension systems. It is also important that the characteristics of the suspension systems do not change over long periods of time (this is especially a problem for systems based on organic materials). The manufacturer should provide recommendations on replacement of the suspension system elements. It is important that such recommendations are followed.

Basic concepts of suspension systems are given in Annex A.

4.2 Wheel size and tyres

Tyres are normally selected according to their rolling resistance, grip, stability, cost, resistance to collision damage, etc.

The machinery manufacturer should carefully investigate the vibration generation characteristics of the tyres and recommend tyres and inflating pressures that minimise the vibration in the particular machine. Information should be provided on the appropriate selection of tyres for different use of the machine.

Small-dimension wheels will cause excessive vibration also when travelling over small ground irregularities. It is therefore important that the wheel size is selected for the typical travelling conditions of the machine.

Although bogies are mainly used in trailers due to their better load carrying capacity, they will also generally improve the situation on vibration and shock because the trailer climbs over the obstacles smoother than a single-axle construction would do.

The vibration transmission characteristics of the tyres, chassis suspension, cab suspension and seat suspension should be combined in a manner to minimise the transfer of vibration from the contact between the wheels and the ground to the operator.

It should be noted that excessively soft tyres induce low-frequency motions that can cause severe pitching.

Most mobile machinery is fitted with pneumatic tyres. Exceptions are off-road machinery fitted with tracks and industrial trucks that are often fitted with solid tyres for stability reasons and for puncture resistance. Solid tyres should only be used on smooth ground.

In case of tracked machinery, the track division is important. Here, the excitation frequencies related to the normal speed and track division should not be close to the resonance frequencies of structure and suspensions.

4.3 Low-frequency wheel and chassis suspension

Low-frequency wheel and chassis suspension is typically used for cars and lorries. It is also used in some agricultural tractors. Low-frequency wheel suspension is not useful in cases of low resonance frequency of the tyres.

When wheel or chassis suspension is used, it is important that they are designed so that they don't enforce tipping or rocking and rolling movements. It may be especially harmful and unpleasant when tipping and rolling results in the operator being thrown forwards and backwards or sideways when travelling over rough surfaces. Means to minimise pitching and rolling include internal damping in the suspension system and localising the suspending elements so that the cross point of the diagonal lines between the elements is as close as possible to the rotational centre of the rigid-body motion of the machine.

The use of tilting cabs with forwards, backwards and sideways movement could be a way to minimise the effects of pitching and rolling on the operator.

A disadvantage of using resilient mounts in the wheel plane of the machine is that the cross point of the diagonal lines between the damping elements is below the centre of gravity of the machine and therefore creates rocking, pitching and rolling problems. This effect can be partly reduced by using unidirectional elements pointing to the centre of gravity.

4.4 Low-frequency cab suspension

Low-frequency cab suspension can be used to ensure vibration isolation in all directions. The advantage compared to rigid cab mounting combined with vibration isolation of the seat is that the operator is protected with respect to several degrees of freedom. Another advantage is that the isolated part includes a larger mass and therefore less displacement at the suspension resonance frequencies for a given excitation force and less space required for avoiding topping and bottoming.

Since the mass of the cab is large, it is very important to make sure that the vibration isolating elements are mounted to a rigid structure of sufficiently high impedance.

Experience of use of vibration isolated lorry cabs with very low isolation resonance frequencies (1 Hz to 2 Hz) show potential problems with motion sickness and drowsiness.

Similar considerations as for low-frequency chassis suspension apply to the localisation of the vibration isolation elements.

Cab suspension will reduce vibration in the steering wheel and controls, and the noise will also be reduced. Cab suspension is useful for reducing continuous vibration. Suspension of the seat needs normally to be added in order to take care of shock. Technical skill is needed in combining cab and seat suspension.

4.5 Seat suspension and seat design

The seat suspension should be designed with regard to the characteristics of the vibration to which it will be exposed. Low-magnitude vibration without pronounced shocks and high-magnitude vibration containing shocks create different demands on the seat suspension.

The seat suspension should be designed according to the dynamic characteristics of the machinery and with respect to the frequency content of the driving forces. Important parameters to take into account are resonance frequencies of the machinery and of the seat, and the characteristics of the suspension at the top and bottom positions of the stroke.

In EN ISO 7096 there are, for a number of earth-moving machinery, maximum values for the seat effective amplitude transmissibility (SEAT) as well as minimum requirements for the damping performance. Test codes for agricultural tractors and industrial trucks are given in ISO 5007 and EN 13490, respectively.

In certain machines, e.g. forestry forwarders and harvesters, automatic self-levelling seats can be used to compensate movements due to ground irregularities.

The seat should be designed with regard to the nature of the machine operation, it should be robust, have as little backlash as possible and be firmly fixed to the structure of the machine. Where appropriate, it should be designed for prolonged periods of work where the operator is required to face in different directions, e.g. allow backward tilting when work requires upward visibility, allow twisting when working sideways or reversing.

The seat suspension shall be easy to adjust according to the operator's weight and body size. Height, forward-backward and backrest adjustments are important.

The seat cushions should be ergonomically well designed with width and height according to the needs of the operator.

The damping of the seat should be sufficiently high to avoid excessive movements and the operator should be warned by the instruction from the manufacturer not to use the maximum position of the adjustment for avoiding large movements of the seat. Adjusting the weight setting to the maximum position might block the seat.

The seat manufacturer may use non-linear springs or non-linear dampers to attenuate shock.

Armrests should be provided and fully adjustable in angle and height. This is very important for machines such as harvesters and forwarders, which have high levels of repetitive finger and hand movements. It can also be useful to incorporate headrest to the seat to offer comfort when working on slopes, control and support for the operator’s upper body, neck and head during normal tasks. The headrest should be adjustable fore and aft, as well as up and down.

5 Elimination of incorrect posture

5.1 General

An ergonomic posture of the operator is essential to bear the harmful effects of vibration. Optimising the operator’s posture for minimising the adverse health effects of vibration includes:

- reduction of the needs for awkward postures by improving external cab visibility and relocation of machine controls;

- improvement of the operator’s posture by providing a seat, with a profile and adjustment possibilities compatible with operators’ anthropometrical dimensions, cab internal dimensions, operator’s tasks, and the dynamic environment;
- allowing space for the legs to be able to move easily;
- inclusion of a cab levelling system/method with forward, backwards and side-to-side movement with reference to operators' operating position.

5.2 Improving external cab visibility

External visibility is important for making it possible for the operator to avoid obstacles and to adjust the driving speed to the ground conditions in order to minimise vibration and shock. Visibility in all directions (forwards, backwards, sideways, up- and downwards) shall be taken into account as appropriate. The operation of the machinery shall be met without requiring the operator to adopt unusual or awkward postures or movements (compared to the normal operation of the machinery). This shall be accomplished for operators of different stature, from the 5th to the 95th percentile of the intended operator population, under normal weather condition.

The visual information from outside should preferably be in the form of direct vision. If necessary, movable seats or cabins should be provided, to ensure that the level of visibility needed can be obtained without undue ergonomic consequences.

Partial rotation of the seat (15° to 20°) or cabin can be advantageous if multiple observation tasks are performed in a rearward turned position. This adjustment leads to less twisting of the torso and neck and therefore reduces corresponding muscle activity. Any rotation system shall be lockable.

Some fork-lift truck and long-reach excavator manufacturers have incorporated tilting cabs or seats which reduce the extent to which operators have to tilt the head backward and thus relieve neck tension when unloading at high levels.

Other factors that affect visibility and may need to be considered are, e.g.:

- site and terrain;
- operational types;
- weather;
- sun glare;
- night operation;
- reflective glare from external signs.

It is possible to fit large attachments to some types of machine (e.g. high-capacity buckets on wheel loaders). Whilst driving, these should be positioned such that good visibility is maintained.

Ancillary equipment, such as a video camera, can assist with vision and traversing difficult conditions. This may be particularly useful for reversing when loaded (e.g. forwarder) or when trailing ancillary equipment and avoiding the need to constantly twist in the seat to check operation.

5.3 Design of cab adapted to the operator dimension and task

5.3.1 Cab dimensions

Cabs shall be designed with proper regard to the body dimensions of the intended population of operators taking into account:

- Anthropometrics;
- ranges of body dimensions and joint movements;
- movement of body parts;
- body postures.

The cab dimensions should be sufficient to attain an upright position without touching the cab roof and to offer the operator sufficient leg and arm room. The seat should be able to move to offer adequate room for the operator.

The distance D between the seat base and the cab roof should not be less than

$$D = a + b + c + d + e \qquad (1)$$

where

a is the seat pan depth;

b is the suspension height measured with an operator and the suspension properly adjusted to its mid-range;

c is the seat vertical adjustment;

d equals 50 % of the suspension travel;

e is the distance between the seat pan surface and the top of the head for a person whose stature corresponds to the 95th percentile.

EXAMPLE If we assume an approximate seat pan depth of a = 150 mm, a seat vertical adjustment of c = 70 mm and a distance between the surface of the seat pan and the top of the head of e = 950 mm, then D = 1 170 mm + b + d. The suspension height, b, ranges from 30 mm for a compact seat to 170 mm for a large conventional suspension seat. The suspension travel, d, is dependent on the machinery category but its peak-to-peak value ranges from 30 mm (compact seats) to a maximum of 150 mm (e.g. dumper or wheel-loader seats). Both these dimensions depend on the vibration environmental properties for which the seat has been designed.

5.3.2 Location of controls

Controls shall be located, so that the operator can use them in a comfortable position without rotating the head and body and without static activation of muscles in the neck and shoulders.

Control levers should be able to multi-function. Specific machine controls could be potentiometer controlled to permit the operator to set speed of a certain function and effort required should be adjustable to suit individual operator requirements.

Frequently used control actuators, grips and pedals shall be placed within easy reach of the hands and/or feet when the operator is in the normal operating position. The steering wheel shall be adjustable.

5.4 Selection of seats adapted to the machine and task

The seat design should be such that it encourages the operator to adopt a good posture. Seats shall be designed with due regard to the nature of operation of the machinery.

Seat location shall allow proper use of the control actuators, especially it should be properly centred with the steering wheel.

The seat shall have a sufficient wide base (seat part) to allow the operator to move, and not be too long to allow the operator to rest on the legs, to keep his position and descent from the vehicle. The base (seat part) shall be slightly reclined to the rear and covered in a material which is not smooth to avoid slipping forward as a result of a jolt. The height of the seat depends on the task of the vehicle: the backrest shall come up to the shoulders with a headrest in vehicles where the operator has only a forward task, and below the shoulder blades in vehicles where the operator has to turn around frequently in order to reverse or control a piece of equipment attached to the rear. In this case, the stress can also be relieved by visual aids or a seat which turns slightly to the side by about 15°. The backrest shall be curved laterally in order to support the operator when the vehicle is turning. The backrest shall not be too firm, and in all cases less firm than the seat base part.

The seat should be easily adjustable to suit different size operators. Vertical, forward and rearward, backrest and weight adjustments should be available. In some machines, a seat height adjustment is also essential.

In general, seats shall

- be strongly constructed and firmly mounted in the machinery,
- be easily adjustable in order to suit operators of different sizes (from the 5th to the 95th percentile of the European working population),
- incorporate a backrest to give a firm support to the lumbar spine without restricting necessary twisting of the torso, e.g. when driving backwards,
- have a seat-depth that does not impose pressure on the back of the knees/lower part of thighs of the operator (also for the 5th operator),
- have a seat cushion that is wide enough for the 95th percentile operator to sit comfortably and allow him/her to move on the cushion,
- allow for movements and change of posture while seated,
- prevent harmful exposure to vibration and bumps,
- have a cushion of heat insulating material, which is porous to permit ventilation and provides enough friction to prevent sliding off and
- have a proper maintenance program in the instructions for use.

Where appropriate, seats should

- be designed to compensate for prolonged work facing different directions, e.g. be possible to tilt backwards when work requires looking upwards, turn sideways when working sideways and can be locked in that position,
- be provided with properly arranged height adjustable armrests that do not obstruct arm movements and
- be provided with a headrest which is adjustable fore and aft as well as vertically.

It is essential that all seat adjustments are

- intuitive with clear and easily understood instructions,
- easily accessible when the operator is seated,
- convenient to use with no big effort required and
- strong and reliable.

Computer adjustable seats are preferred because of easy use and assurance that correct adjustments are always made for individual operators.

6 Summary of questions to be considered when evaluating the design of mobile machinery in view of protecting operator's safety and health

6.1 General

Designing mobile machinery which assures the operator a correct posture and low level of vibration exposure is a process which includes the following stages:

- What is the objective of the new design?
- For which tasks?
- What will be the consequence for the machine/operator interaction?

Other ergonomic demands than a correct posture and low level of vibration shall also be satisfied, such as ergonomic display, temperature, low noise, but they are outside the scope of this Technical Report.

6.2 Visibility

- Is the operation of the machinery met for the 5th to the 95th percentile operators without requiring the operator to adopt unusual or awkward postures or movements (compared to the normal operation of the machinery)?
- If no, what are the dispositions adopted to ensure that the level of visibility needed can be obtained without undue ergonomic consequences?

6.3 Cabin construction

- Is the cabin designed with proper regard to the body dimensions of the intended population of operators, and taking into account body postures and movements of body parts?
- Can the operator drive without touching the roof during the operation?
- Are the controls located and sufficiently adjustable (especially the steering wheel), so that most operators can use them in a comfortable position without rotating the head and body and without static activation of muscles in the neck and shoulders?
- Can the legs move freely under the steering wheel?
- Are the frequently used control actuators, grips and pedals placed within easy reach of the hands and/or feet?
- Are the joints of the body in neutral positions during the driving and operation of the mobile machinery?

- Is the cabin efficiently suspended to reduce low-frequency vibration?

6.4 Selection of seat

- Is the seat adapted to the operator anthropometrics, cabin dimension and task?
- Is the seat correctly located to allow proper use of the control actuators?
- Is the seat sufficiently adjustable (vertically and longitudinally) to allow correct external visibility?
- Does the seat have a base (seat part) sufficiently wide to allow the operator to move and not so long that it disables the operator to rest on the legs and to keep his/her position, especially when exposed to vibration?
- Is the base (seat part) slightly reclined to the rear and covered with a material that is rugged enough to avoid slipping forward as a result of a jolt?
- Is the height of the seat backrest (and headrest) adapted to the task of the operator, especially if the operator has to turn around frequently?
- In this case, can the seat turn slightly?
- Is the backrest enough curved laterally to support the operator when the vehicle is turning?
- Is the backrest inclination adjustable?
- Is the seat equipped with a vertical (and horizontal) suspension adapted to the dynamic characteristics of the machinery?
- Is the seat suspension adjustable for the weight?
- Is there a risk of topping/bottoming of the seat suspension?

For information to be provided in the instruction manuals for the specific type of machinery, see the relevant type C standard.

Annex A
(informative)

Vibration isolation

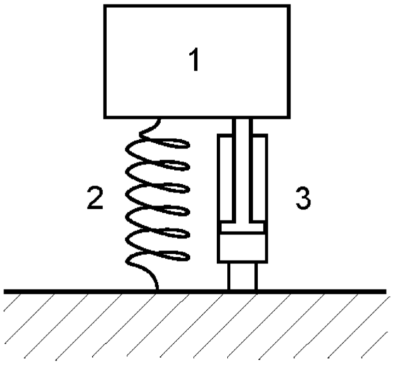
A.1 Introduction

The reduction of transmission of vibration from source to the operator often includes the use of resilient mounts, either by separating the source of vibration (e.g. engine) from the machine structure or by separating the operator from the vibration source or vibrating structure (vibration and shock isolation of wheels, chassis, operator's cab, seat).

This annex discusses some basic concepts of the design considerations of suspension systems. The dynamics of a mobile machine is complex and cannot be fully described by a simple, single-degree-of-freedom (SDOF) system. Some basic vibration concepts can, however, be illustrated using a SDOF system. A more extensive understanding of the technically challenging field of vibration analysis, modelling and reduction by means of suspension systems can be obtained from course work, textbooks and vibration experts.

A.2 Basic concepts of suspension systems

A suspension system is designed to provide reduction in vibration transmission. Passive suspension systems are based on the mass-spring-damper concept, the simplest form being the single-degree-of-freedom system illustrated in Figure A.1.



Key

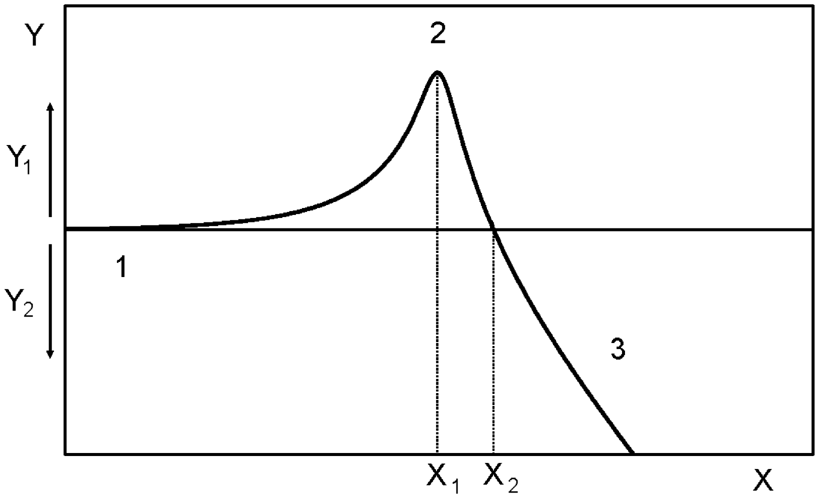
1 mass

2 spring

3 damper

Figure A.1 — Single-degree-of-freedom system

For a vibration input, a suspension system will have a characteristic response. Figure A.2 shows the response of the SDOF system. For more complex suspension systems, the details of the response might be different but the basic elements will be similar.



Key

X	frequency	Y	response	1	low-frequency zone: response ≈ stimulus
X_1	resonance frequency	Y_1	amplification	2	resonance frequency zone: response > stimulus
X_2	cut-off frequency	Y_2	attenuation	3	high-frequency zone: response < stimulus

Figure A.2 — Characteristic response of a SDOF system

Above the cut-off frequency, the suspension system attenuates the vibration. Below the cut-off frequency, there can be a region in which the suspension amplifies the vibration, due to resonance behaviour. Below the resonance, the suspension simply transmits the vibration.

The exact values of the resonance and cut-off frequencies and the magnitude at the resonance depend on the spring and damper characteristics and on the mass. As load is added to the suspension, the resonance and cut-off frequencies decrease. It is therefore easier to provide effective vibration isolation for larger masses.

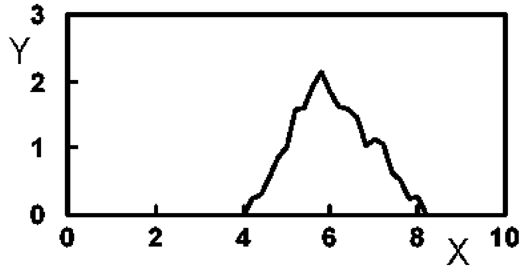
More efficient and adaptable vibration isolation can be obtained by use of semi-active or active suspension systems.

Semi-active suspension systems include actuators by which damping characteristics can be changed during an operation. This enables suspension to be adapted to travelling on different surfaces. The adaptation is usually based on an algorithm that changes the actuator dynamics based on sensor information. There are different theories and methods to create the algorithms but the basic suspension theory is the same as with passive suspension.

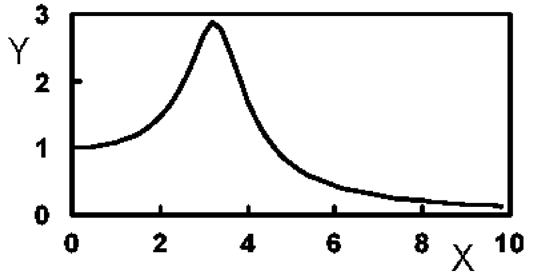
Use of active suspension systems is the most advanced way to control vibration. Active suspension systems include actuators that can generate a force to cancel the vibration from the source. This requires a more complex algorithm and system design. In mobile machinery, active vibration isolation is usually done with hydraulic or electro-mechanical devices since amplitudes and masses are large. Active suspension systems require more expensive components and more advanced knowledge of control theory than the other methods.

A.3 Matching suspension systems to vehicle characteristics

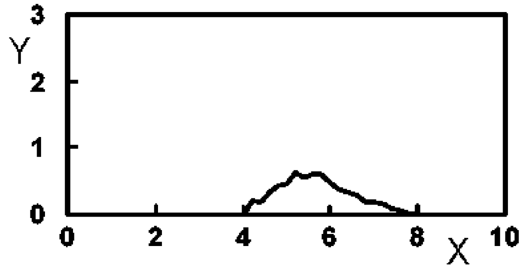
When designing or selecting a suspension system for a vehicle, it is essential to consider the vibration characteristics of the vehicle. Figure A.3 illustrates an ideal situation, where the suspension system has a cut-off frequency below the natural frequency of the vehicle. However, when the suspension system's resonant frequency is close to a natural frequency of the vehicle, then the suspension systems can amplify the vibration. This condition is illustrated in Figure A.4.



a) Driving acceleration spectrum



b) Suspension characteristic



c) Resultant spectrum (attenuated by suspension)

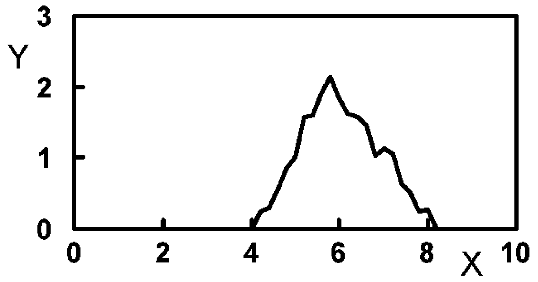
Key

X frequency, Hz

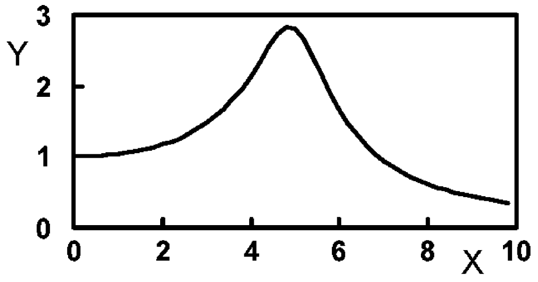
Y acceleration, m/s^2

NOTE The vehicle's natural frequency is higher than the suspension cut-off frequency.

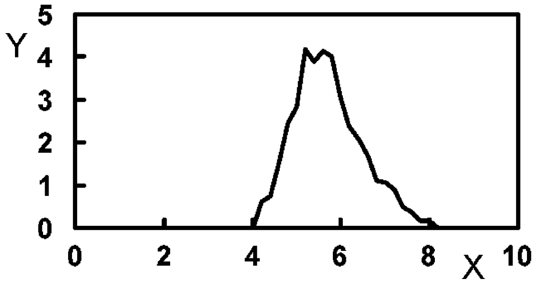
Figure A.3 — Vibration reduction effect



a) Driving acceleration spectrum



b) Suspension characteristic



c) Resultant spectrum (amplified by suspension)

Key

X frequency, Hz

Y acceleration, m/s^2

NOTE The suspension resonant frequency is close to the vehicle's natural frequency.

Figure A.4 — Vibration amplification effect

Care should be taken when mounting suspension systems on non-rigid surfaces which themselves can behave as suspension systems. For example, a suspension seat mounted on a flexible battery or engine cover can have a very different response to vibration to that of the seat alone.

A.4 Suspension end stops

When a vehicle meets a large obstacle, the suspension system might over-travel. This is usually prevented by end-stops on the suspension system. When the suspension hits the end-stops a substantial shock can be generated.

Shocks from hitting end-stops can be controlled in a number of ways, e.g:

- soft end stops;
- non-linear dampers;
- active suspension.

A.5 Changing suspension characteristics for specific operating modes

The suspension system characteristics might need to be altered for specific driving conditions, e.g. an off-road vehicle might need a firm suspension setting for running at speed on a tarmac road surface, and change to a softer one when running over uneven ground.

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