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SURVEY OF TECHNICAL PREVENTATIVE MEASURES TO REDUCE WHOLE-BODY VIBRATION EFFECTS WHEN DESIGNING MOBILE MACHINERY

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Engineering solutions to minimize the effects on operators of vibrating mobile machinery can be conveniently grouped into three areas: (1) Reduction of vibration at source by improvement of the quality of terrain, careful selection of vehicle or machine, correct loading, proper maintenance, etc.

(2) Reduction of vibration transmission by incorporating suspension systems (tyres, vehicle suspensions, suspension cab and seat) between the operator and the source of vibration.

(3) Improvement of cab ergonomics and seat profiles to optimize operator posture. These paper reviews the different techniques and problems linked to categories (2) and (3). According to epidemiological studies, the main health risk with whole-body vibration exposure would appear to be lower back pain. When designing new mobile machinery, all factors which may contribute to back injury should be considered in order to reduce risk. For example, optimized seat suspension is useless if the suspension seat cannot be correctly and easily adjusted to the driver's weight or if the driver is forced to drive in a bent position to avoid his head striking the ceiling due to the spatial requirement of the suspension seat.

1. INTRODUCTION

During travel and work, drivers of forestry and agricultural tractors, earth-moving machines, lorries, fork-lift trucks, etc. are exposed to low-frequency whole-body vibration featuring such high amplitudes that they may even experience difficulty in maintaining their balance [1, 2]. This situation is often aggravated by working conditions requiring the adoption of an uncomfortable posture (for example, a tractor driver having to control an attachment at the rear of the vehicle) [3, 4].

Studies have shown that lower back disorders are more prevalent in the operators of such vehicles compared to the general population [5–7]. Exposure to whole-body vibration combined with a poor prolonged driving posture is believed to contribute to this health problem, which today incurs considerable cost [4].

Over the last 30 years, machine designers have developed engineering solutions to improve driver working conditions [8–10]. In addition to reducing vibration at source, there are two methods of minimizing the risk of lower back injury to operators of mobile machinery [11]:

- inserting suspension devices between the operator and the source of vibration;
- improving workstation ergonomics, seat profiles, cab dimensions and visibility.

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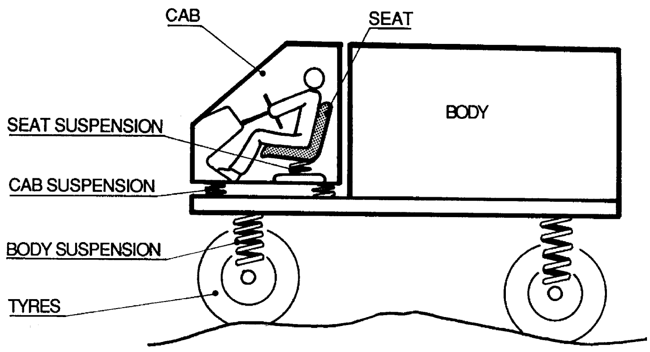


Figure 1. Possible positions for vehicle suspension systems.

Although independent, these actions are in fact complementary: they enable a closer match to be achieved between man, machine and the job to be performed.

The aim of the present paper is to review these different solutions and the difficulties in adapting them to a given machine are highlighted. Prior to designing a new machine, the relevant design constraints must be identified. One of the main difficulties is to select objective criteria to be taken into account to achieve the optimum compromise. Unfortunately, the scientific literature and standards raise more questions than answers for the design engineer.

2. REDUCTION OF VIBRATION TRANSMISSION

2.1. DESIGN OF SUSPENSION TO PREVENT HARMFUL EXPOSURE TO VIBRATION AND SHOCKS

Transmission of vibration to vehicle operator can be reduced by means of isolating suspension at different key points: tyres, chassis, attachment coupling, cab and seat (Figure 1). This approach is described in sections 2.2.–2.6. When designing a new suspension, human response to vibration must be considered and compromises in the suspension parameters accepted.

2.1.1. *Suspension in design is an art*

Mechanical engineering rules for designing any effective suspension are well known. Schematically, a suspension should be designed so that its highest cut-off frequency is less than the input dominant frequency. Suspension travel should be sufficient to prevent bottoming or topping at end stops. The lower the input frequency, the larger the required travel. Unfortunately, space is invariably limited, which means that there is a risk of impact in cases of high levels of vibration inputs. Experience shows that operators will primarily complain about impacts, which are unique and easily remembered events. The sensation of vibration will be mentioned second as it is perceived as a cause of fatigue. There is a tendency for some suspension manufacturers to highly damp their suspensions to prevent end-stop impacts, minimize suspension relative displacement and thus offer their customers only short-term satisfaction. Unfortunately, this is usually detrimental to suspension performance. Alternatively, suspension impacts could be accepted if shock peaks are significantly attenuated by incorporating effective soft end stops. However, such end stops require space, which may affect the capacity of the suspension system to reduce input vibration due to its shorter travel. The engineering art is to find the best compromise between all these factors to optimize operator protection by minimizing vibration and shocks. This assumes that there is a criterion for assessing the severity of vibration and repeated shocks. Unfortunately, international standards and the associated literature do not identify a clear procedure for evaluating severity of exposure to complex vibration combining simple vibration and shocks.

2.1.2. *Methods for quantifying whole-body vibration*

Methods for quantifying whole-body vibration exposure are defined in ISO 2631-1: 1997 [12]. This standard states that the primary quantity for expressing vibration magnitude is the weighted root-mean-square (r.m.s.) acceleration. Yet it indicates that r.m.s. magnitudes will underestimate motions featuring high peaks. This standard also defines additional methods entitled the "running r.m.s. method" and the "fourth power vibration dose method". It is remarkable and confusing that the standard does not provide clues as to which methods should be selected, as they are not equivalent and give different results. The "running r.m.s. method" is based on the worst shock occurring during 1 s and is unaffected by other motions or shocks. Caution is required when using this criterion because it rates a single isolated shock as being as severe as that of exposure to multiple shocks occurring within general vibration exposure. The "fourth power vibration dose method" (VDV) takes into account the magnitude and duration of the frequency-weighted acceleration history with respect to time.

$$VDV = \left[\int_0^T a_{w_k}^4(t)\,\mathrm{d}t \right]^{1/4} \quad (\mathrm{m/s^{1.75}})$$

The calculation applies the duration weightings as the vibration dose is built up, thus automatically incorporating a method for giving greater weight to occasional peaks in the motion. Griffin [13] reported that it would be naïve to assume that human responses (especially effect on health) are directly dependent on this fourth power relationship but, in the current state of knowledge, this does appear to be a reasonably straightforward basis for comparing exposure and furthering experience. Sandover [14] was the first to set assessment criteria on fatigue assuming that human vertebral end plates are the weak link in a spine subjected to shock and vibration. If the fatigue hypothesis is true, then high acceleration events which may generate peak compressive forces within the spine (including disc pressure increase), are likely to strongly influence spinal health—a small number of high spinal stress events are more likely to lead to fatigue damage than continuous exposure to low-level stresses [15]. This approach indicates that peak values are important and that major peaks dominate the risk. It would therefore appear preferable to base assessment on a criterion with a high acceleration exponent [16].

2.2. TYRES DESIGNED FOR OPTIMUM VIBRATION PERFORMANCE

Most all-terrain vehicles are fitted with pneumatic tyres because they filter out the small ground surface irregularities. An exception to this is off-road machines fitted with caterpillar tracks and industrial trucks which often are mounted on solid tyres to provide stability and resist puncture. Tyres are usually selected according to their rolling resistance, grip, stability, cost, resistance to collision damage, acceptability to the driver, etc.

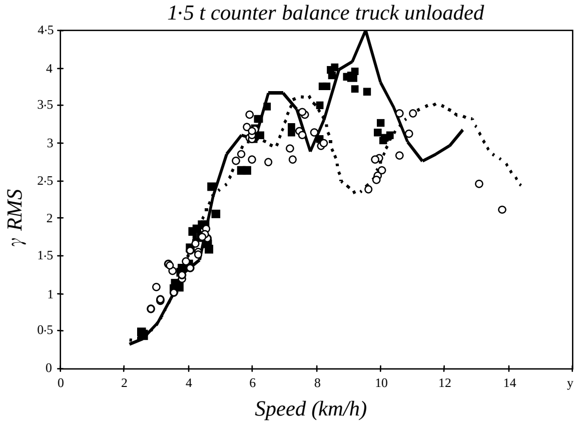


Figure 2. Comparison of acceleration values measured on a 1·5 t counterbalance truck fitted with two tyre types and running over an obstacle at various speeds. ■ Solid tires—experiment; ○, Pneumatic trees—experiment; ——, Solid tires—numerical simulation; ······ Pneumatic trees numerical simulation.

Other parameters, such as damping and stiffness, must be taken into account to absorb obstacle impact. However, even large tyres cannot absorb vibration energy as well as a shock absorber, so vibration builds up even on relatively smooth surfaces. Tyres are also far stiffer than a suspension system. Excessively soft tyres may induce low-frequency motions, including pitching. Lines *et al.* [1] state: "To improve their suspension properties significantly, tyres would need to absorb five to ten times more vibration energy and to be much larger and softer. Such a tyre would then also have a high rolling resistance and the heat build up in the tyre due to the rolling and the vibration would cause it to have a short life… In general, change in tyre pressure do not result in a simple increase or decrease in vibration, but rather have an effect which is dependent on other vehicle characteristics such as load, dimension… ".

Figure 2 compares r.m.s. acceleration values measured for a 1·5 t loaded counterbalance truck fitted with solid or pneumatic tyres and running over an obstacle at different speeds. Acceleration variations resulted from phase interference between the free response of the counterbalance truck after the front tyres had run over the obstacle and the impact of the rear tyres with it [10]. In some cases, it may be judicious to select solid tyres with a carefully selected internal filling, which would offer optimized damping of the vibration induced by impact with an obstacle. However, research is required to develop a suitable design.

2.3. WHEEL SUSPENSION

Unlike cars and lorries, most all-terrain machines have no suspension system between wheel-axles and chassis, to reduce the effect of ground roughness. Some manufacturers (Caterpillar, Volvo, etc.) have developed pneumatic systems with which to equip their dumpers or graders. The suspension system can be incorporated in graders either at the front between the axle and the chassis or at the articulation point to minimize vertical, pitching and rolling motions.

JCB Fast-Tract has developed a full wheel suspension for agricultural tractors. This has required a complete redesign of the vehicle so that lifting and lay back motions are interdependent to prevent obstruction when raising working attachment (Figure 3).

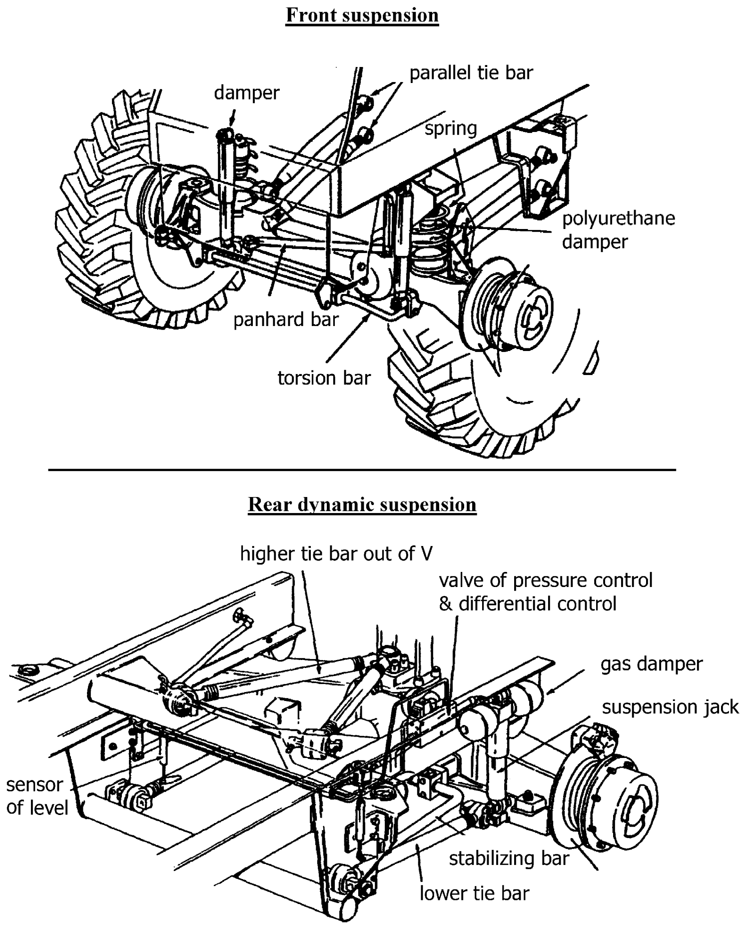


Figure 3. Example of wheel suspension used on tractors.

Another option offered by high-power tractors is the use of front wheel height-controlled suspension. However, a tractor driver sits almost directly over the rear axle, and this kind of suspension offers only marginal benefits in terms of driver protection (about 20% in the vertical, pitch and roll axes) [1]. It should be noted that a better vibration environment as well as improved steering and handling may encourage operators to drive faster, which could increase the risk of accidents.

Semi-elliptic lorry suspension systems are progressively being replaced by parabolic or pneumatic systems, which allow improved friction control.

2.4. WORKING ATTACHMENT AND EQUIPMENT SUSPENSION

Wheel-loader manufacturers such as Caterpillar have developed a pneumatic suspension system to make off-road machines and their buckets independent. A heavily loaded bucket may be the source of pronounced pitching motions.

Similarly, a FENDT tractor can be fitted with a suspension system for rear-mounted equipment or working attachments in a raised position. Most manufacturers of agricultural

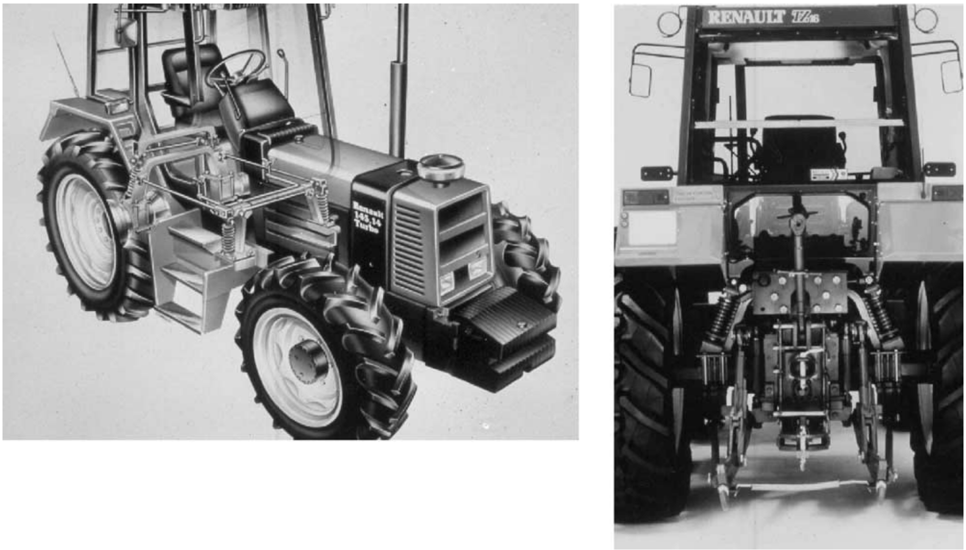


Figure 4. Example of a cab suspension system used by a tractor manufacturer.

trailers with a capacity of over 10 t offer drawbars mounted on a semi-elliptic suspension system to make the tractors independent of trailer pitching movements.

2.5. LOW-FREQUENCY CAB SUSPENSION

A distinction should be made between cabs which are isolated from vehicles by rubber blocks, and cabs fitted with low-frequency two- or four-point mechanical suspension systems. Only low-frequency suspension cabs (with a natural frequency below the vehicle dominant frequency) and preferably fitted with four-point suspension are efficient enough to reduce the vibration transmitted to the operator when moving around a site. The advantage of a low-frequency suspension cab over a suspension seat is that the driver's whole-body is protected with respect to several degrees of freedom. Low-frequency suspension cabs can be designed to ensure isolation in all three linear axes but the main purpose is to reduce vertical movement as well as rolling and pitching.

The full suspension cab is now a common feature of most articulated lorries and has been developed successively for agricultural tractors, for example by Renault Agriculture (Figure 4). Also Fendt, Deutz, Same, Steyr, and other have developed a simple and cheap cab suspension which can be simply fitted on tractors in series production. Their suspension system works with the principle of a suspended seesaw (single axis suspension), i.e., the cab is fixed elastically on front mounting points while the rear cab mountings are replaced by mechanical or pneumatic suspension damper elements. Tests conducted at the Federal Institute of Agricultural Engineering in Wieselburg showed that only an optimal tuned combination of the three suspension systems (front axle suspension, cab suspension and suspension seat) enables a 50% vibration reduction compared to similar tractors with no suspension [17].

Acceleration measurements taken at the workplace for different articulated lorries show that cab suspension systems mainly reduce vibration in the vertical axis, which is usually the

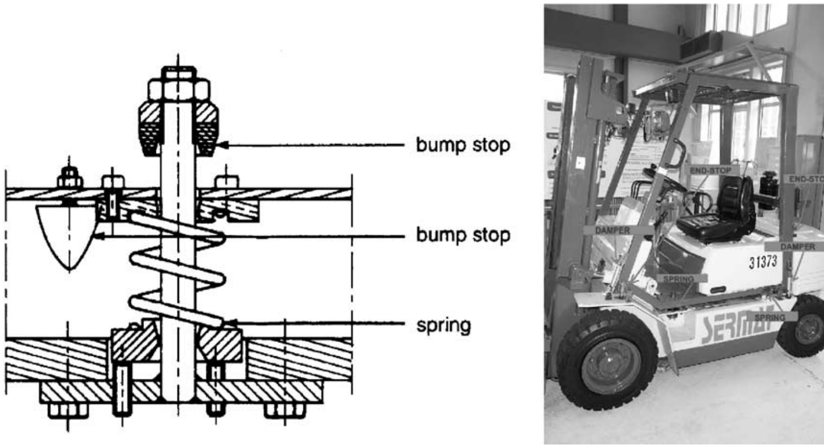


Figure 5. Example of a suspension cab developed by INRS for a counterbalance truck.

predominant direction of motion [18]. On average, a 30% reduction in overall acceleration is achieved (a mean value of 1 m/s^2 was found for lorries fitted with a conventional cab compared with 0·7 m/s^2 for vehicles fitted with a low-frequency cab).

On the other hand, suspension cabs have never been properly used for industrial trucks to our knowledge. Suspension cabs currently marketed by certain manufacturers for counterbalance trucks have been shown to be only suitable for reducing engine vibration with a frequency higher than 10 Hz [3].

A suspension cab prototype has been designed by INRS for currently produced lorries with a capacity ranging from 1·5 to 2·5 (Figure 5). Although the suspension travel was only 3 cm, the whole-body vibration transmitted to the driver was reduced by 50% [19].

2.6. SUITABLE AND EFFECTIVE SEAT SUSPENSION

Seat suspension. Suspension of the seat itself (if any) constitutes the final stage of suspension before the operator. It is also the only stage of suspension which exists in some vehicles (e.g., lift-trucks fitted with solid tyres). Seat upholstery alone is ineffective in reducing vibration due to ground unevenness. The majority of suspension seats are designed to ensure isolation only in the vertical axis (see Table 1).

In practice, measurements taken on a wide range of vehicle seats reveal that suspension seats are frequently vibration amplifiers (Figure 6). A typical example is provided by cheap suspension seats, which are quite often mounted on self-driven lawnmowers and comprise a forward tilting upholstered section mounted on two over-flexible rear springs which are often vibration amplifiers.

It is important to choose a suspension seat carefully according to the dynamic properties of the mobile machinery on which it is to be mounted. Suitable seats do exist, but it is difficult for a buyer to select them because manufacturers provide few or no technical details and buyers are, in general, poorly informed about selection criteria for a suitable suspension seat.

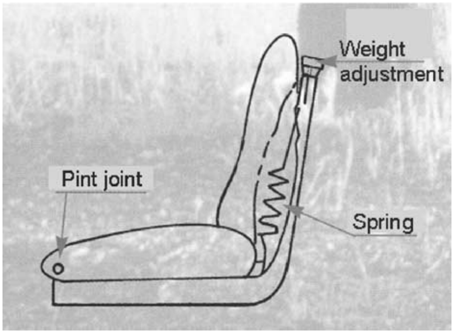
Table 2 summarizes the parameters which should be considered when choosing a seat. From this table, it follows that a seat should be mounted only on vehicles whose dominant

TABLE 1

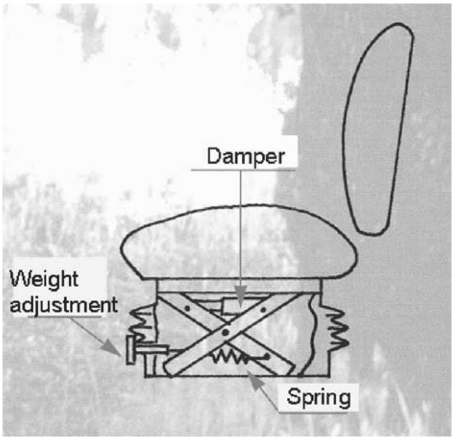
Different types of seat suspensions

Different types of vertical suspension

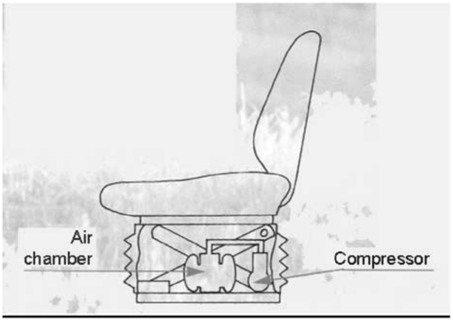
Compact mechanical suspension: Such a suspension has a travel of around 3–4 cm. In most cases, it is pin-jointed at the front of the seat-cushion and the spring or springs is/are incorporated either inside the backrest or beneath the seat-cushion. There is no height adjustment. Compact suspension seats are mainly mounted on fork-lift trucks with a load capacity of less than 2·5 t, "mini" machines or self-driven lawnmowers. They are not recommended for other machines



Non-compact mechanical suspension: Suspension travel exceeds 4–5 cm. Seat-cushion and backrest vertical motion is obtained by a mechanism located behind the backrest or beneath the seat cushion



Pneumatic suspension: In a pneumatic suspension system, the spring is replaced by an air pressure chamber which traps a volume of air. This suspension is easier to use and therefore more effective than a mechanical system because it allows automatic weight adjustment after actuating a control or by simply sitting on the seat. It requires a source of compressed air, which is supplied by a vehicle battery-powered compressor located inside the seat. In general, greater efficiency is noted with pneumatic suspension seats



motion frequencies are higher than the seat "attenuation" frequency. Seat suspension cut-off frequency and travel should be known. When a vibration frequency is less than the cut-off frequency, the seat suspension effectively amplifies the vibration. A suspension seat must therefore be chosen such that its highest cut-off frequency (calculated for the weight of the lightest driver) is lower than the cab floor vibration dominant frequency. Suspension travel must be sufficient to prevent bottoming or topping against end stops [20]. In general,

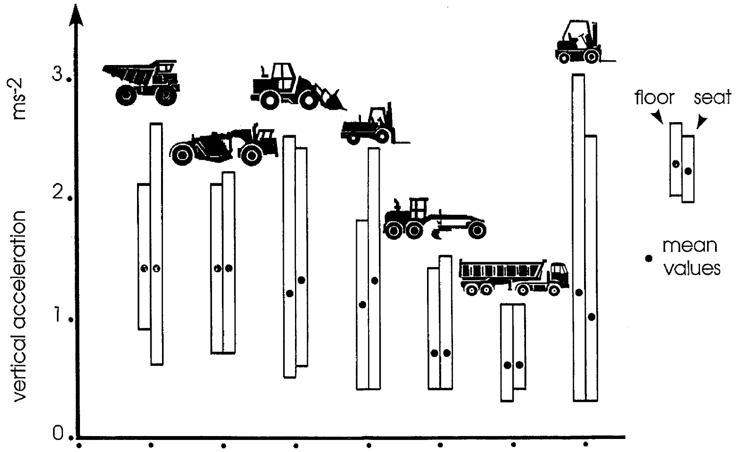


Figure 6. Comparison between weighted r.m.s. accelerations measured in the vertical axis at the seat pan and on the floor of different vehicles.

TABLE 2

Important parameters when selecting a suspension seat

Suspension "attenuation" frequency (f_a). A suspension seat only attenuates vibration above this frequency. At lower frequencies, it causes amplification particularly at the resonance frequency (f_r, f_a) can be derived from f_r using the equation $f_a = f_r \sqrt{2}$

Suspension damping must be sufficient to:

- avoid excessive amplification when the motion frequency is close to the seat resonant frequency;
- minimize suspension bottoming and topping due to transient motion

Suspension travel. The lower the attenuation frequency, the longer the required seat suspension travel (from 3 cm above 3 Hz up to about 15 cm at 1·5 Hz). When a long travel is required, complex mechanisms are used to allow the driver to maintain control of driving pedals and to reduce seat internal friction

Weight adjustment. A suspension seat is effective in reducing vibration transmitted to the operator unless it is properly adjusted for the operator's weight. This adjustment is often neglected by drivers. Weight adjustment for each new operator alters spring tension so that, the seat is at or close to mid-travel when the operator is seated. One of the advantages of pneumatic suspension seats is that weight adjustment is automatic

End-stop buffers. A suspension system is fitted with top and bottom end-stop buffers (usually thick conical rubber components) to prevent metal-to-metal contact when a suspension seat is topping or bottoming due to high-magnitude shocks. Research has shown that shock effects can be significantly reduced by carefully designing these end-stop buffers, which should feature non-linear stiffness and damping properties [20]

mechanical suspension seats will only isolate vibration at frequencies higher than about 2 Hz.

Seat test codes. Test codes have been developed for different specific families of machinery to assist vehicle manufacturers and buyers in selecting suitable suspension seats. Standards pr EN 13490 [21] for industrial trucks (drafting still in progress), ISO 7096: 2000 [22] for earth-moving machines, ISO 5007: 1990 [23] for agricultural tractors (c.f. also European Directive 78/764/CEE amended by 83/190/CEE and 88/465/CEE [24]) specify acceptance levels for seat effective amplitude transmissibility (the ratio between the r.m.s. weighted acceleration measured on the seat pan and that at the seat base). These levels should be complied with.

Most of the time even properly matched suspension seats do not necessarily guarantee the operator full protection against vibration and shock effects. Seat effective amplitude values for suspensions properly suited to the dynamic properties of mobile machinery will range between 0·4 and 1·0 according to the dominant frequencies to be filtered. Moreover, the seat effective amplitude value will vary significantly with the excitation intensity, even for a given seat and vehicle.

Horizontal suspension. Some articulated and agricultural tractor seats are mounted on both vertical axis and forward and rearward directional suspensions. This latter horizontal suspension is generally mounted below the vertical device. It is especially useful when such vehicles are pulling a trailer. Suspension travel is usually limited to 2–4 cm to allow the driver to maintain control of the driving pedals. Unlike a vertical suspension, the main purpose of a horizontal suspension is not to reduce vibration magnitude but to allow the driver's body to move in phase with seat motion. Without horizontal suspension, at about 2 Hz, a driver may move forwards while the seat moves backwards or vice versa, i.e., the seat may strike the driver in the back.

Semi-active suspension. Some investigative work has been carried out with semi-active seat suspension systems but no obvious benefit has been found compared to a good conventional seat design. It is possible that the driver could subjectively feel more comfortable because of a reduction in seat flotation and, in addition, semi-active systems could minimize contact with seat motion end stops.

3. OPERATOR POSTURE OPTIMIZATION

3.1. POSTURE AND DYNAMIC ENVIRONMENT

A person will react to the vibrating environment better if he is in the best possible position. It is probably the combination of positional and vibration stresses which causes back pain. It has been shown that high flexing and lateral bending of the body result in a significant increase in lumbar disc pressure. The effect of posture is important when relating peak accelerations and the resulting stress peaks at points in the lumbar spine [15, 25]. What one does not know is if the posture assumed to be good for static loading is also good for dynamic loading. According to Sandover [14] the "good posture" should allow some slight bending, which will allow some relief of the compressive loading on the discs and less transmission up the spine. A better position of the trunk centre of gravity will reduce muscle loading compared to a more straight posture. In heavy vehicles straight spine posture is generally observed.

The approach for optimising a mobile machinery operator's working posture can be broken down into two areas:

1. Reduce the need for awkward postures by improving cab visibility and relocating machine controls [9, 26].
2. Improve the driver's posture by providing a seat with the correct profile and adjustments, which is compatible with driver anthropometrical dimensions, cab internal dimensions, driver tasks, and the dynamic environment.

3.2. A GOOD VISIBILITY CAB SUITED TO DRIVER DIMENSIONS AND TASKS

Visibility always comes first. Even if it is detrimental to posture, a driver will compensate to overcome the lack of good visibility essential for safe machine operation. Multi-directional visibility (forward, rearward, lateral, upward and downward) should be taken into account. Machine operation should be possible without requiring the operator to adopt unusual or awkward postures or movements. This requirement should be met for operators of different stature (from 5th to 95th percentile). External visual information should preferably be available through direct vision. If necessary, movable seats or cabs should be provided to ensure that the required level of visibility can be obtained without undue ergonomic consequences.

Partial seat rotation (15–20°) can be advantageous [27] 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. The rotation system must be lockable in various positions and facilitate climbing into and out of the cab by swivelling the seat.

There may be a need to look up to high levels from fork-lift trucks. Some manufacturers have incorporated tilting cabs (or seats), which reduce the extent to which the operator has to tilt his head backward and thus relieve neck tension.

Cab dimensions. When operators sit in a machinery cab, their feet should be in contact with the floor pan, whether or not pedals are fitted; their head should not touch the overhead-guard providing protection against concussion damage which could occur in the event of cranial impact.

The cab should be dimensioned in such a way that the operator can sit upright without touching the overhead guard. The minimum distance D between the seat base and the overhead guard or cab roof can be determined from the following equation [28]:

$$D = a + b + c + d + e \text{ (in mm)},$$

where a is the seat pan depth; b the suspension height measured with an operator and the suspension properly adjusted to its mid-range; c the seat vertical adjustment; d half the suspension travel and e the distance between seat pan surface and top of head for a man whose stature corresponds to the 95th percentile.

If we assume an approximate seat pan depth (a) of 150 mm, a seat vertical adjustment (c) of 70 mm and a distance between seat pan surface and top of head (e) of 950 mm, then $D = 1170 + b + d$ (in mm). Suspension height (b) ranges from 30 mm for a compact seat to 170 mm for a large conventional suspension seat. Suspension travel (d) is dependent on the machinery category but ranges peak-to-peak 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.

Seat location. Seat location should allow proper use of controls. The operator's legs should be able to slip easily under the steering wheel. Should this be impossible, the driver has to push his seat back to allow his thigh room to move and as a result, he will have to lean forward to operate the machine controls and steering wheel.

Cab access. Poor access in and out of the cab may be detrimental to the spine. Jumping down from a machine, especially after long hours of work in the seat is particularly hazardous. Access system design should allow the operator to maintain three point foot and hand contact when climbing in and out of a mobile machine. Access system components should be arranged so that they form a continuous natural route rather than a series of "stepping stones". The inclusion of 90° bends in the access route should be avoided.

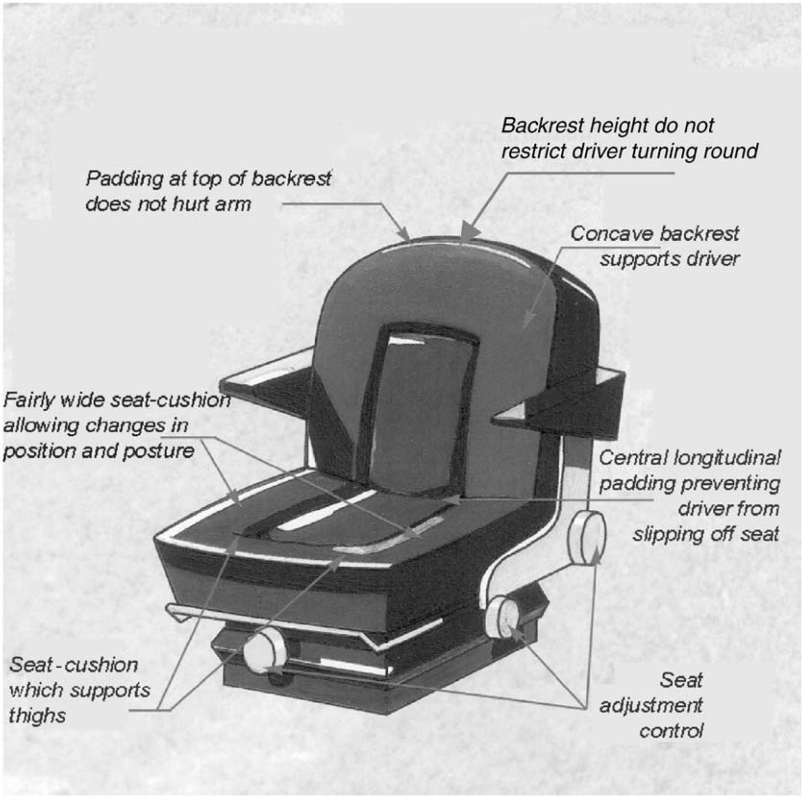


Figure 7. Ergonomics of a tractor seat on which the operator has to turn round frequently.

3.3. A SEAT WITH THE CORRECT PROFILE AND ADJUSTMENTS

Properly choosing a suspension seat involves taking all its components (suspension, upholstery, adjustments) into consideration and adapting them to dimensional, dynamic and functional properties of the vehicle in which the seat is to be fitted.

The dual aim of mobile machinery seating is to take the weight off the operator's feet and to provide a stable base from which to work [29]. Seat design should be such that it encourages the occupant to adopt a good posture and discourages poor postural habits. Design of the seat and its surrounding environment should allow the occupant to make frequent postural changes without hindrance [30]. Observations of off-road vehicle drivers at work show that seats are not always adapted to their tasks: fixed back rests may be too low to offer sufficient back support or too high, thereby hindering driver upper body movement when reversing [31]. Non-profiled upholstery may offer insufficient lateral support to hold the operator when turning his vehicle, PVC seat coverings will not prevent the driver from slipping under the effect of vibration. Seats are indeed often dilapidated (torn upholstery, inoperable adjustments, broken suspensions) and sometimes poorly dimensioned and shaped with the result that drivers have to adopt a poor posture, which may contribute to backache. For example, an operator who does not have the option of properly adjusting the backrest angle may be forced to drive with his back not directly in contact with the backrest.

Seats should be designed with due regard to the nature of machine operation (Figure 7) [32]. They should be strongly built and strongly mounted on the machine. Where appropriate, seats should be designed to compensate for prolonged work requiring the operator to face in different directions, e.g., backward tiltable when work requires upward visibility, laterally tiltable when working sideways and they should offer the possibility of locking in a given position.

Seat base cushion. The seat should have a base cushion that is wide enough for the 95th percentile operator to sit comfortably and to allow movements and changes of posture. Its depth should not cause pressure on the back of the operator's knees or lower part of his thighs and should allow the operator to rest on his legs to maintain his position and climb down from the vehicle [33]. The seat pan should be slightly reclined to the rear and be fitted with material which prevents sliding off following a jolt.

Seat backrest. The seat should incorporate a backrest providing firm support to the lumbar spine without restricting necessary twisting of the torso, e.g., when reversing. Backrest height depends on the vehicle task: it should extend up to the shoulders and incorporate a headrest in vehicles in which the operator only performs a forward task. The backrest should extend to just below the shoulder blades in vehicles in which the operator has to turn round frequently either to reverse or to control a rear-mounted working attachment. In the latter case, positional stress can also be relieved by visual aids or a seat which swivels slightly to the side by about 15°. The backrest should be curved laterally to support the operator when the vehicle is turning.

Seat foam. As regards foam material, the backrest should not be too firm (and invariably softer than the seat base cushion).

Seat adjustments. In general, a seat should be easily adjustable to suit different size operators (from the 5th to the 95th percentile of the European working population). There are four basic adjustments which should be fitted on all suspension seats: vertical, forward and rearward, back rest inclination and weight adjustments. In some vehicles, a seat height adjustment is also essential. Operators have been known to set the weight adjustment to the heaviest setting, which raises them so that they can look downwards outside, in response to a lack of seat height adjustment. This, of course, completely negates the seat's vibration isolation effectiveness.

Where possible, seats should be provided with properly positioned adjustable height armrests which do not obstruct operator arm movements.

It is important that all seat adjustments are:

- intuitive with clear and easily understood instructions;
- easily accessible when the operator is seated;
- convenient to use with no great effort required;
- strong and reliable;
- avoiding any risk of injury to the hands and fingers.

4. CONCLUSIONS

Machinery Directive 89/392/EEC and its amendments came into force in 1996 [34]. Under this directive, mobile machinery manufacturers are required to improve the safety of their products by reducing the emission values of physical agents (namely noise and vibration) to the lowest possible level by taking into account all the available technical developments, if possible, at design stage and to provide information on whole-body vibration transmission operators if the weighted r.m.s (root-mean-square) acceleration measured under the feet or under the buttocks exceeds $0{\cdot}5 m/s^2$.

This Directive represents an important step for the protection of mobile machinery users against vibration hazards. New machines are increasingly designed to transmit low-level vibration, but unfortunately no action has been taken to improve operator posture, which may be the prime contributor to spinal disorders. A new CEN standard dealing with common ergonomic aspects of mobile machinery operability is currently being drafted by CEN TC122 [28]. This standard is of special interest because it covers interactions between different stresses exerted on the operator.

Further research should be conducted to evaluate the interaction of different suspension devices when mounted in combination on a vehicle.

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