Chapter 2

Literature Review

2.1 Introduction

A comprehensive literature review on WBV has been presented in this chapter. In order to fulfill specific objectives of the study, reviews were made through available literature and pertinent research studies to acquire the basic concept of mechanical vibration, theory of WBV, and the guidelines & standards relating to vibration exposure at workplaces. Investigation on WBV in mines, effect of WBV on health, prevention against WBV, sensors and transducers, standards followed in the process of measuring WBV are discussed in brief. Various types of transducers and accelerometers used in the human vibration measurement are also explained.

2.2 Basics of Mechanical Vibration Analysis

Mechanism of vibration is reported by three parameters (Fig. 2.1) [17]:

(i). The maximum displacement from the central position, Amplitude, A;

(ii). The time taken to complete one cycle of vibration called Frequency, ω; and

(iii). The measure of the instant at which a vibration passes through the central position, called phase, Ø.

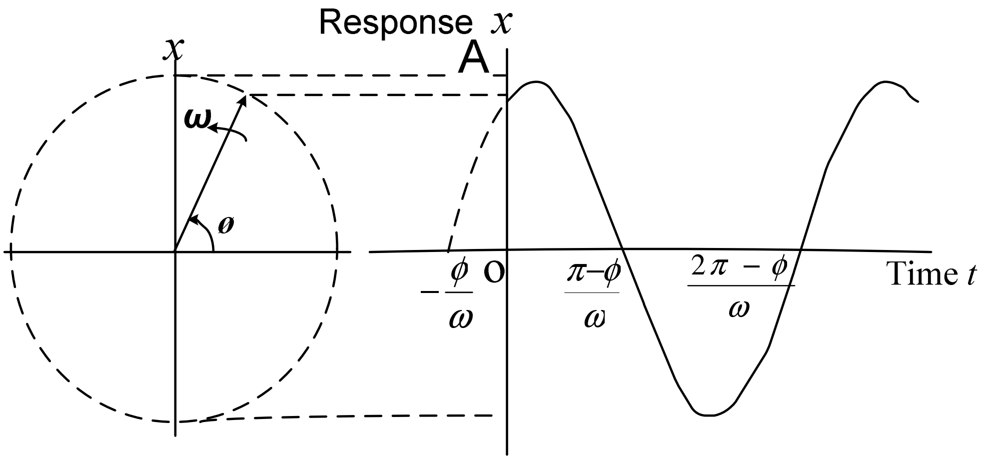

Figure 2.1 Sinusoidal vibration

Most vibration transducers produce an output that is related to acceleration. Therefore, acceleration in root mean squares (r.m.s.) has traditionally been used to describe hand transmitted vibration (a_{hv}). The r.m.s. relates to vibration energy, and hence, the vibration damage potential. The instantaneous equations representing sinusoidal motion are as presented in Eqs. (2.1)–(2.3):

$$y = A\sin(\omega t + \emptyset) \tag{2.1}$$

$$v = A\omega \cos(\omega t + \emptyset) \tag{2.2}$$

$$a = -A\omega^2 \sin(\omega t + \emptyset) \tag{2.3}$$

Thus

$$a = -\omega^2 y \tag{2.4}$$

Therefore,

$$\boldsymbol{a_{hav}} = \sqrt{\boldsymbol{a_x^2} + \boldsymbol{a_y^2} + \boldsymbol{a_z^2}} \tag{2.5}$$

where *y* = Vibration displacement, (m); *A* = Amplitude, (m); ω= Angular velocity, (rad/sec); *T* = Time, (Sec); Ø= Initial angle, (rad); *v* = Velocity, (m/sec); *a* = Vibration acceleration, (m/s^2); a_{hav}= Resultant of vibration acceleration, (m/s^2); a_x, a_y and a_z = Vibration acceleration in x, y and z-axes respectively (m/s^2).

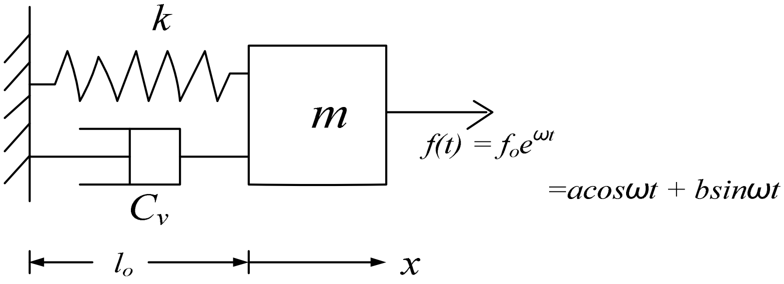

Figure 2.2 Damped forced vibration in mechanical systems

Mechanical systems are dynamic at varying degrees of frequencies; thus their motion in response to an external force depends on the nature of the exciting forces and the unpredictable dynamic characteristics of their mechanical structure (Fig. 2.2). Dong modelled a biodynamic response distribution of fingers and palm of the hand-arm system and demonstrated that concepts on studies of engineering material's fatigue may be applied in the study of the biodynamics of the hand-arm system [18]. The equation of motion can be analyzed using Newton's second law of motion, $F = ma$ with the aid of a free body diagram (Fig. 2.3). In engineering systems, the function $f(t)$ is the harmonic excitation in which the solution for the displacement $x(t)$ depends on the vibration embedded in a design (free vibration) and the nature of the forcing function shortly termed as complementary and particular solutions respectively.

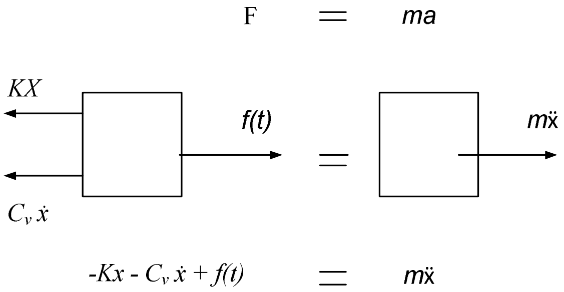

Figure 2.3 Free body diagram of damped forced vibration system

where K is spring constant, X is displacement, C_v is damping constant, and *f(t)* is the harmonic excitation.

The particular solution is of the form:

$$Xp(t) = \left(\boldsymbol{f}\mathbf{o}\middle|(\boldsymbol{k}^2 - \boldsymbol{m}^2\boldsymbol{\omega}^2)\right)\ \boldsymbol{Cos}\ \boldsymbol{\omega_n t}$$

(2.6)

If the initial conditions of the system are defined by the Eq. (2.7):

$$\begin{cases} \boldsymbol{x(t = 0) = X_0} \\ \boldsymbol{\dot{x}(t = 0) = V_0} \end{cases}$$

(2.7)

Then; the general solution representing the displacement of the system becomes:

$$X(t)=\boldsymbol{X_0 Cos\omega_n t} + \boldsymbol{{}^{V_o}/_{\omega_n} t} + \left(\boldsymbol{{}^{f_o}/_{(k^2 - m^2\omega^2)}}\right)\boldsymbol{Cos\ \omega_n t}$$

(2.8)

It is observed in Eq. (2.8) that, under the presence of forcing function into the system, the displacement amplitude tends to increase linearly with time.

Regular exposure to mechanical vibration of human operators while operating HEMMs as a part of their occupation can lead to Hand-arm vibration syndrome (HAVS), MSDs, or a combination of these depending on the exposure. There are two types of human vibration: HAV and WBV. Hand-arm vibration (HAV) is vibration exposure to the hand and arm of the person while operating hand tools. HAV in combination with repeated exposure, continuous work, heavy lifting and forceful movement, and awkward or static postures increase the potentials for hand-arm vibration syndrome, popularly known as HAVS. The frequency range of HAV is 8 to 1000 Hz. On the other hand, WBV is the vibration exposure to the whole body (head-to-toe) of human. WBV frequency range is 0.5 to 80 Hz which is transmitted to the seated body as a whole through the seat pan. In the present study, only WBV is taken into consideration.

This WBV normally, but not exclusively, comes from operating or riding within a self-propelled moving vehicle and acts upon the individual such that it contributes to, or creates, either physical and/or mental negative health.

2.3 Whole-Body Vibration

Vibration is a mechanical movement that oscillates about a reference point. It is a form of mechanical wave, and like all waves, it transfers energy but not matter. Vibration needs a mechanical structure to travel. The motion is by definition not constant but alternately greater and less than the average value [1]. WBV in a vehicle enters the driver's body via the seat. WBV can also occur during standing on a vibrating floor, travelling by ship, and lying in the cabin bed.

Human response to WBV is a very complex phenomenon. Several extensive surveys have been conducted to summarize the effects on the human being, and it can be concluded that responses are diverse [19], [20]. Human response to WBV can be divided into comfort, perception, and health. This thesis will focus on the measurement of WBV and the health impacts of musculoskeletal system. WBV affects musculoskeletal health by biomechanical constraints or by the physiological responses from exposure[21]. An association between exposure to seated WBV and lower back pain is reported in many studies [22]–[24].

There is sufficient literature to reveal the association of WBV exposure with neck & shoulder symptoms [21]–[23]. The study designs for WBV exposure and health outcome cross-sectional or case–control type, although these types of studies have a lower validity compared to prospective cohort studies. The effects of vibration have been known for a long time and utilized by various groups of therapists [25]. The main interest has concerned physical training in combination with vibration exposure to increase the muscular strength in the back or lower limbs [26]–[29]. It is important to understand the parameters and variables of vibration characteristics, i.e., magnitude, frequency, direction, duration and variation with time.

2.3.1 Magnitude

The extent of the oscillation determines the magnitude of vibration. Magnitude can be quantified by displacement, velocity and acceleration. For practical reasons, the magnitude of vibration is usually described by its acceleration.

2.3.2 Frequency

The repetition rate of the cycles of oscillation determines the frequency of vibration. The human body seems to be most sensitive for WBV within the frequency range of

0.1 to 100 Hz and usually the lower frequency components are attributed to the adverse health effects [1], [30], with some differences for the vertical and horizontal directions [21]. According to the ISO 2631-1:1997, analysis of the influence on health should be performed within the frequency range of 0.5 to 80 Hz. Separate frequency weightings for each direction and different frequencies is usually applied to account for the sensitivity of the human body.

2.3.3 Direction

The ISO 2631-1:1997 defines three mutually perpendicular axes of the human body in seated, standing, and recumbent positions. The basi-centric coordinate system is described by the axes that originate from which vibration is considered to enter the body. Translational motions are described along these axes. For a seated person, motions in the *x*-axis are back to front or fore-and-aft, in the *y*-axis are right to left or lateral, and motions in the *z*-axis are from foot to head or vertical [1].

2.3.4 Duration

Health risk assessments are primarily based on the magnitude of vibration and duration of exposure [31], [32]. Assuming that responses are related to energy, two different daily exposures are considered equivalent when

$$\boldsymbol{a_{w1}} \times \boldsymbol{T_1^{1/2}} = \boldsymbol{a_{w2}} \times \boldsymbol{T_2^{1/2}} \qquad (2.9\ )$$

where a_{wl} and a_{w2} are the weighted r.m.s. acceleration values for the first and second exposures, TI and T_2 are the corresponding durations for the first and second exposures respectively.

While considering VDV, the daily dose value can be calculated, indicating a time dependence according to Eq. (2.10).

$$a_{w1} \times T_1^{1/4} = a_{w2} \times T_2^{1/4} \tag{2.10}$$

Exposure to vibration is assessed over an 8 h period calculating the daily vibration exposure [30].

2.3.5 Variation with time

WBV can be divided into two sub-types depending on time: deterministic or stochastic [33]. Deterministic vibration is further divided into periodic or non-periodic. The simplest type of periodic vibration is sinusoidal. The stochastic vibration is not predictable and is also named noise. Continuous vibration with small variation in amplitude is called stationary, whereas a shock-type vibration (transient) is non-stationary and may appear during a short period with high amplitude [33].

2.4 Effect of WBV on Equipment Operators

The exposure to WBV and its impact has been reported in many studies [2], [34]. Most of the studies related WBV impacts to personal factors of operators, machine related parameters, and work environmental parameters. The findings related to personal factors of operators, as reported by many researchers, found that the age of the operator was a potential predictor of WBV exposure [2], [3]. Ozkaya et al. [35] observed lower levels of WBV with more experienced vehicle operators. Mani et al. [36] inferred that body mass index (BMI) is significantly associated with quad bike induced WBV and showed an association between WBV, BMI, and lower back pain in professional drivers. Smets et al. [11] inferred that there was a significant increase in muscle activity with an increase in vibration acceleration, and there was a significant interaction between vibration acceleration level, posture, and muscle activity.

While studying machine related parameters, Cann et al. [37] inferred that operators of transport trucks supplied by a manufacturer were exposed to significantly greater levels of WBV as compared to trucks supplied by another manufacturer. A study inferred that the age of equipment is not a significant factor for WBV [3]. In contrast, another study on buses found that older buses are associated with greater levels of WBV [9]. Poor design of operator's cab led to increased operator's complaints of discomfort [38]. Mayton et al. proved that NIOSH designed seats performed better than existing seats of shuttle car models. A study inferred that air spring suspensions produced lower levels of WBV and low back pain than steel spring suspension systems [39]. For dumpers, the impact of cab design/operators' seat and spring suspension system along with rough surfaces of haul roads in mines for their plying has a combined effect of WBV on dumper operators.

Working environmental conditions do impact on WBV. Poor roads and uneven work areas contribute significantly to rough rides and discomfort. Park et al. [40] concluded that the asphalt pavement appears to lower the vibration dose measured on the highway and other roads. Park et al. compared the vibration level for speed of 80 km/h and 100–120 km/h as per ISO 2631-5:2004, and they found no significant difference in vibration measurement. The dumper operators in mines, by virtue of their occupation, are subjected to uneven haul roads, dust, and low illumination. A study investigated the relative role of WBV, posture and manual materials handling as risk factors for LBP [41]. ‘Combined exposure’ rather than the individual exposure to one of the three factors (WBV, posture, manual material handling) is the main contributor of the increased prevalence of LBP [41].

2.5 Investigation on WBV in Mines

WBV is a physical hazard that occurs in mining operators who operate HEMM. For many mine workers, the initial effects of WBV are no more than discomfort or fatigue, but increasingly ‘rough rides’ in a range of vehicles are common sources. There are many HEMMs used in opencast coal mines, such as shovel, dumper, drill, and dozer. These HEMMs are used in various mining activities such as overburden removal, drilling, loading, and transportation of minerals.

There are a number of serious symptoms of WBV, and the effects on humans of exposure to vibration at best may be discomfort and interference with activities, injury or disease. A review of WBV characteristics associated with low back disorders/problems is summarized in Table 2.1. A recent review of epidemiological studies by Stayner [42] showed no information that could be used for the health evaluation of exposure to occasional shocks in comparison with exposure more continuous vibration. Wolfgang’s measurements taken from 30 of the 32 trucks fell within the HGCZ defined by ISO2631-1:1997 for an 8 h daily exposure suggesting that ‘caution with respect to potential health risks is indicated’ [43].

HEMMs like dumpers, drill, excavator, grader, loader, dozers, surface miners, and shovels are operating in mines. The process of mechanization emphasized the need of use of HEMM in mines. In general, the HEMMs are operated in harsh conditions. The operators who operate these HEMMs are exposed to vibration and thus are sufferers from WBV syndrome.

Table 2.1 Investigation on WBV in mines

Author	Year	Contribution
Mandal & Srivastava [6]	2006	• Urgent need to develop a practical management strategy for evaluation, monitoring and control of equipment-induced vibration in the mining industry.
Mandal et al. [13]	2018	• Observed that the LPDT and LHD had the *x*-axis as the dominant axis of vibration. • Operators of three equipment i.e., water sprinkler, utility vehicle, and backfill material carrier, had high health risk with *z*-axis as the dominant axis of vibration.
Jeripotula et al. [15]	2020	• For dozer, the severe health risk was due to the translational vibration (i.e., in *x*-direction), • Vibration risk in the forward *x*-direction can be reduced by using seat belt and in rear *x*-direction it can be attenuated by placing lumber-assisted backrest. • Exposure time of dozer operators is associated with an increased risk of work-related lower back pain (LBP).
Prajapati et al. [44]	2020	• ISO 2631-1:1997 methodology has the upper hand during the prediction of WBV health risk as compared to ISO 2631-5.
Sharma et al. [45]	2020	• For safety of operators, long-term understanding of WBV should be carried out instead of short term vibration monitoring.

In the present research work, three types of HEMMs used in mines are considered for assessment of WBV, such as dumper, shovel, and drill machine operators.

2.5.1 WBV exposure of dumper operators

Dumpers are used in mines for the transportation of materials within the mining area. Dumpers were deployed mainly for transportation of coal/overburden material in mines. The WBV was measured for the entire cycle of operation of dumper, starting from loading the coal or overburden, travelling over the haul road, and unloading the coal or overburden to return to the face. Investigation on dumper operators is presented in Table 2.2.

Table 2.2 Investigation of WBV exposure on dumper operators

Author	Year	Contribution
Vanerkar et al. [46]	2008	• They indicated that the WBV exposure is not dependent on the type of mine but is dependent on the working condition and type of HEMM in operation.
Mandal & Srivastava [47]	2010	• Pain in the ankle (37.83%), shoulder (30%) and neck (37.5%) was higher among exposed personnel as compared to the control population (5, 0 and 15%, respectively).
Mandal et al. [16]	2012	• Dominant axis of vibration in dozers was found to be *x*-axis (front to back) in 80% of the equipment. • Transporting equipment like Dumpers have *z*-axis as dominant axis of vibration.

Author	Year	Contribution
		• It was observed that 27 (68%) of them showed moderate whereas 12 (30%) equipment showed high health risk.
Mandal et al. [13]	2017	• Prevalence of MSD due to exposure to WBV especially LBP is high among HEMM operators which affected their quality of life.
Kaviraj et al. [48]	2018	• The operators undertaken for the study registered WBV levels across different capacity dumpers that were above and within the HGCZ limit as per ISO 2631-1:1997 standard.
Kumar et al. [49]	2020	• HEMM operators are likely to suffer from WBV induced MSDs. The exposure was highest in the z-axis and least in the y-axis. • Dumper operators were highly exposed to WBV compared to shovel and drill operators.
Chaudhary et al. [50]	2020	• Transport equipment operators are more vulnerable to vibration hazards than the non-transport equipment operators.
Atal et al. [51]	2020	• The relationships between vibration magnitude, age of the operator and their years of exposure on LBP, BP and Diabetes was established. • The Bayesian Network model, revealed that the probability of VDV(8) values greater than 17 m/s1.75 was 69.1% and the probability of the LBP was found to be 52.6%.

The dumpers deployed in the coal mines were belonging to three manufacturers: Caterpillar, Bharat Earth Movers Limited (BEML) and Komatsu.

Caterpillar BEML Komatsu

Figure 2.4 Types of dumpers

There were two variants of Caterpillar dumpers, such as 777D of 100-ton and 777C of 85-ton capacity. Two models of BEML dumpers were deployed, such as: BH100T with 100-ton capacity and BH85T with capacity of the 85 tons. There were two types of Komatsu dumper models: L-series of 100-ton and K-series of 85-ton capacity.

2.5.2 WBV exposure of shovel operators

The WBV exposure of shovel operators is not dependent on the type of mine, but it is dependent on the working conditions and type of HEMM in operation [46]. The P&H shovel is electrically operated, but BE1600 is hydraulically operated. The manufacturer of P&H is Komatsu and that of BE1600 is by BEML. It is used for collection and loading of coal and overburden to the dumpers. The WBV of shovel operators is measured during the operation at the face and also during crawling between the faces.

KOMATSU **BEML**

P&H (Electrical) BE1600 (Hydraulic)

Figure 2.5 Types of shovels

2.5.3 WBV exposure of drill machine operators

The WBV exposure to operators of drill is mainly observed during drilling the hole. The major vibration is felt at the starting of the drilling operation. The research works conducted on drill machine operators for WBV assessment is presented in Table 2.4.

Two types of drill machines used in the mines are shown in Figure 2.6. The drill machines, IDM70E & RECP750, were electrically operated, and REL-650 & IDM-30 were diesel operated. The manufacture of IDM70E is Atlas Copco, and that of REL-650 is Revathi.

Table 2.3 Investigation on drill operators

Author	Year	Contribution
Vanerkar et al. [46]	2008	• They indicated that the WBV exposure is not dependent on the type of mine, but is dependent on the working condition and type of HEMM in operation.
Chaudhary et al. [3]	2015	• Predicted health risk of operators based on daily r.m.s. exposure shows that only 3.6% of drill machine operators were found between the upper and lower limit of HGCZ of ISO 2631-1:1997.
Chaudhary et al. [34]	2015	• Based on VDV evaluation method, all the drill operators were found above the recommended upper limit of HGCZ of ISO 2631-1:1997.
Mandal et al. [13]	2017	• Prevalence of MSD due to exposure to WBV especially LBP is high among HEMM operators which affected their quality of life.
Chaudhary et al. [50]	2020	• Transport equipment operators are more vulnerable to vibration hazards than the non-transport equipment operators.

(a). Atlas Copco
IDM70E(Electrical)

(b). Revathi
EL-650(Diesel)

Figure 2.6 Types of drill machines

2.6 Effect of WBV on Human Health

The review of Burström et al. states the existence of scientific evidence of exposure to WBV increases the risk of LBP and sciatica [52]. The findings of 'Okunribido et al.' showed that interaction effects due to posture and one or both of vibration and manual material handling, rather than the individual exposure effects, are the main contributors for precipitation of LBP [53]. WBV is capable of producing a wide variety of effects on human health as presented in Table 2.5 [1]. Both simple and complex activities can be disturbed by vibration affecting the various components of a task, from the input of information to the body (e.g., vision) through to the output of information from the body (e.g., hand control) [54].

Table 2.4 Some parameters in the context of human response to vibration

Subjective	*Activity*
Absolute thresholds	Vision
Subjective equality	Hearing
Subjective order	Touch
Equality of intervals	Proprioception
Equality of ratios	Vestibular function
Rating of stimuli	psychomotor performance
Cross modality judgments	Cognitive performance
Differential thresholds	vigilance
Physiological	*Biodynamic*
Skeletal	Body impedance
Muscle	Hand impedance
Nerve	Body transmissibility
Cardiovascular	Head movements
Respiratory	Hand movements
Central nervous system	Organ movements
Endocrine/metabolic	Energy absorbed

2.7 Standards for WBV Measurement

Standards are documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions of characteristics, to ensure that materials, products, processes, and services are fit for their purpose.

The vibration in 100 vehicles were measured, evaluated and assessed according to British Standard, BS 6841:1987[55] and International Standard ISO 2631-1: 1997 [32]. Assessments made using the procedure defined in ISO 2631-1:1997 tend to underestimate any risks from exposure to WBV compared to an evaluation made using the guidelines specified in BS 6841: 1987. Consequently, ISO 2631:1 "allows" appreciably longer daily exposures to WBV than BS 6841 [56]. A study characterized WBV exposures in a set of vehicles that operate in open-pit mines and compared three daily exposure parameters (e.g., A(8), VDV(8), and $S_{ed}(8)$ based on the ISO 2631-1:1997 [32] and ISO 2631–5: 2004 [57] standards [58]. A study analysed the WBV transmitted to drivers associated to a typical operation with agricultural tractor [59]. This measurement was based on the models defined in ISO 2631-5:2004 [57], and ISO 2631-5:2018 [60]. The study had been carried out in order to make a comparison between the standards. The R factor (defined in the ISO 2631-5:2004 to estimate the lumbar spine response acceleration), and Ra factor (defined in the ISO 2631-5:2018 [60]) to estimate internal spinal forces were calculated to predict adverse effects in the lumbar spine. In their case study, they observed that both standards provide similar assessment, and concluded that low probability of an adverse health effects of agricultural tractor drivers [59].

The following guidelines, standards and evaluation methods were considered for assessing whole-body transmitted mechanical vibration and shocks during the study: International organization for standardization ISO 2631-1:1997 [61].

2.7.1 History of development of ISO 2631-1:1997 Standards

The International Organization for Standardization (ISO) based in Geneva was established in 1947 to harmonize the national standards that were being developed with the intention of removing barriers to international trade.

The preparation of ISO 2631-1:1997 commenced around 1966. First publication came in 1974 in order to give numerical values for limits of exposure for vibrations transmitted from solid surfaces to the human body in the frequency range 1 to 80 Hz [4]. To correct incidental errors in the tables and figures republication came in 1978 with editorial changes. In 1982, an amendment was issued, giving significant modifications and intended to reduce areas of ambiguity in the standard. A series of addendum were planned to define specific applications or extensions of the standard to buildings, motion sickness, ship vibration and railway vibration. Since 1979 the basic standard has been undergoing complete revision so as to eliminate remaining ambiguity, to remove or replace those aspects of the document which have been found to be either untenable or unnecessary, and to provide additional guidance where the standard is known to be insufficient. Not with standing these known problems, the executive of the responsible ISO sub-committee authorized the republication of the old standard in 1985 and a few countries are proceeding to adopt national standards based on the original version of the old ISO 2631. The ISO 2631-1:1997 replaced an earlier version of the standard (ISO 2631, 1985) that contained different frequency weightings and different criteria.

Presently ISO 2631 is in five parts. Part 1 is for general requirements; part 2 is for vibration in building (1 to 80 Hz). Part 3 is withdrawn which dealt in evaluation of exposure to whole-body z-axis vertical vibration in the frequency range 0.1 to 0.63 Hz. Part 4 outlines the guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport systems — amendment 1. Part 5 presents the method for evaluation of vibration containing multiple shocks.

2.7.2 ISO 2631-1:1997 Standard

The first part of ISO 2631-1:1997 refers to mechanical vibration and shock, specifically providing the guidelines for evaluation of human exposure to whole-body vibration. This Part 1 of the standard is the most widely used for WBV measurement and assessment. The scope of the ISO 2631–1:1997 includes methods for measuring periodic, random, and transient WBV, with annexes that provide guidance on the interpretation of the measurements. The first annex provides a definition of the frequency weightings and is normative (i.e., it forms part of the standard). The other four annexes are informative and therefore do not form part of the standard itself. Nevertheless, the content of these annexes forms the focus of much discussion regarding the standard. The standard states that vibration should be measured at the interface between the human body and the vibration source. Measurements on a seat should be made beneath the ischial tuberosities (the bony points that can be felt if one sits on one's hands) using an accelerometer mount.

The process of making a health assessment according to ISO 2631-1:1997 is complex and can be confusing. If two individuals were asked to make measurements according to ISO 2631-1:1997, a wide range of results could be attained. However, at the core of the standard is the method of using frequency-weighted r.m.s., and this is the primary method that most users apply. Many of the superfluous options that are allowable could be deleted in future versions without impacting the majority of users. A simplified flowchart that can be followed for most assessments is shown in Figure 2.7 [4]**.**

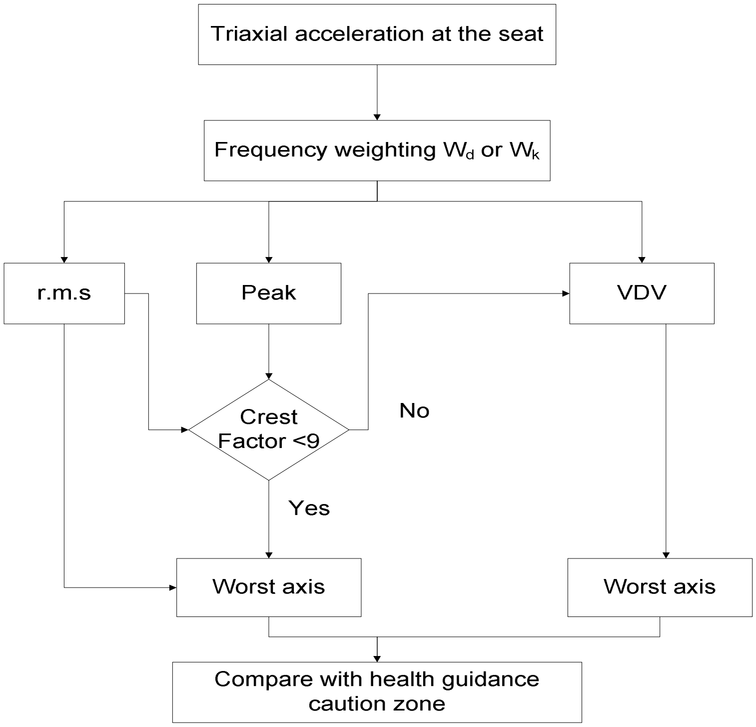

Figure 2.7 Method of evaluation and assessment of WBV according to HGCZ

Health guidance caution zone

Assuming responses are related to energy, two different daily vibration exposures are equivalent, as presented in Eq (2.9). A HGCZ is indicated by shading in Figure 2.8. For exposures below the zone, health effects have not been clearly documented and objectively observed. In the zone, caution with respect to potential health risks is indicated and above the zone health risks are likely. This recommendation is mainly based on exposures in the range of 4 to 8 h as indicated by the shading in Figure 2.8. Shorter durations should be treated with extreme caution. Other studies indicate a time dependence according to Eq (2.10). The HGCZs for Eqs. (2.9) and (2.10) are the same for durations from 4 to 8 h for which most occupational observations exist.

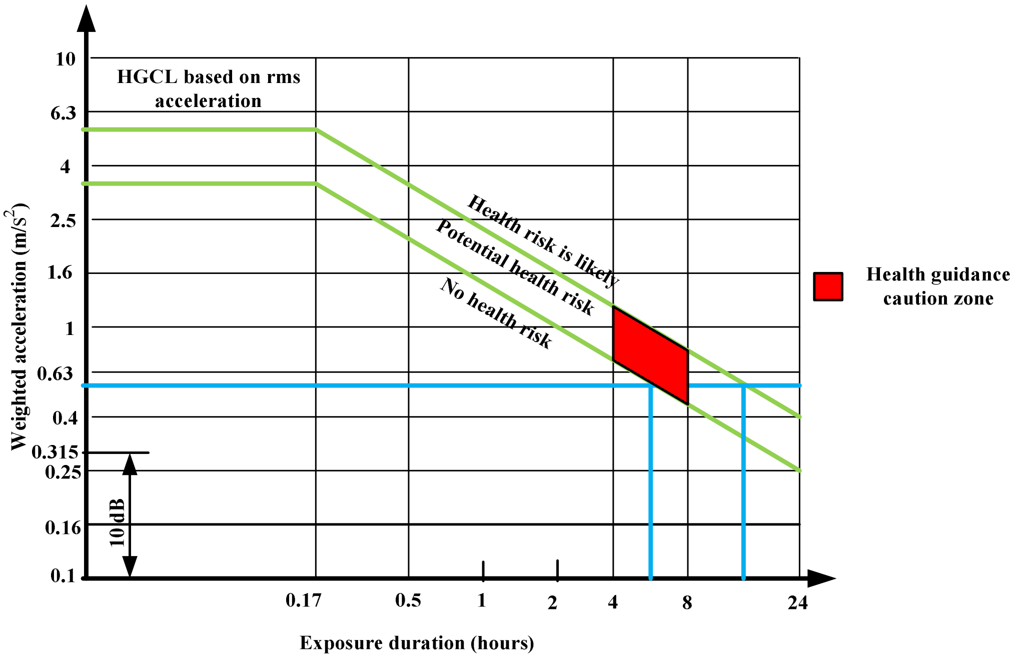

Figure 2.8 Health Guidance Caution Zone of ISO

The r.m.s. value of the frequency-weighted acceleration can be compared with the zone shown in Figure 2.8. To characterize daily occupational vibration exposure, the

8 h frequency-weighted acceleration *a* can be measured or calculated according to Eq. (5.2) with 8 h as the time period T. The summary of WBV exposure limits and predicted health risk based on HGCZ as prescribed in ISO 2631-1:1997 is presented in Table 2.5.

Table 2.5 WBV exposure limits and their HGCZ as per ISO 2631-1:1997

Exposure zone	Predicted health risk	Exposure parameter	
		A(8), m/s^2	VDV(8), $m/s^{1.75}$
< HGCZ	No health risk	<0.45	<8.50
Within HGCZ	Potential health risk	0.45–0.90	8.50–17.00
>HGCZ	Likely health risk	>0.90	>17.00

Note: *A*(8) = daily frequency-weighted r.m.s. acceleration; *VDV*(8) = daily vibration dose value; *HGCZ* = health guidance caution zone.; WBV = whole-body vibration.

2.7.3 History of development of European Union (EU) Directive 2002/44/EC

European Directives are developed through a legal process by the European Union and must be implemented in member states. Within the context of human response to vibration, the most important Directives are the Machinery Directive and Physical Agents (Vibration) Directive. Those responsible for occupational health in the workplace may also be affected by the Physical Agents Directive.

The procedure for legislation within the EU involves three institutions: the European Parliament, the Council of the European Union, and the European Commission. The agreed text is published in the Official Journal of the European Communities that contains details of when the Directive must be complied with.

2.7.4 European Union Directive 2002/44/EC

European Directives are developed through a legal process by the EU and must be implemented in member states. Within the context of human response to vibration, the most important Directives are the Machinery Directive and Physical Agents (Vibration) Directive is presented in Table 2.8

Table 2.6 European Union Directive 2002/44/EC

Parameter	No health risk	Potential health risk	Likely health risk
A(8) in m/s^2	< 0.5	0.5 – 1.15	> 1.15
VDV(8) in $m/s^{1.75}$	< 9.1	9.1 – 21	> 21

2.8 Research Works on Prevention of WBV

A study concluded that wet clothing, cold working conditions, heavy lifting, previous work as a driver and driving certain vehicles were associated with LBP, but vehicles with WBV levels above action value were not associated with LBP [62]. For better prevention of LBP, improved cabin conditions and clothing should be emphasized [62].

There are many actions that can be taken to minimize or eliminate the risks from WBV [63]; and some of these are relatively simple to put into practice [64]. These actions can be conveniently grouped under the following headings: (*i*) selecting the right equipment, (i*i*) isolating the vibration, (*iii*) changing work processes, operator good practice; and (*iv*) training and education. More detailed discussion on prevention strategies is presented hereafter.

(i) Selecting the right equipment

This can be considered in terms of: i) company purchasing policy, in seeking to only purchase (or lease, hire etc.) vehicles that have been engineered to minimize WBV; and ii) ensuring that selected vehicles are the most appropriate for their proposed task(s). WBV exposure can be significantly reduced by using vehicles that are designed and manufactured to minimize the transmission of vibration to the operator; so potential owners/operators should always discuss with machinery manufacturers the latest developments in lower vibration equipment before purchase [64]. In any event, all new machinery on sale within the UK should be 'CE' marked - which indicates that the machine meets the relevant health and safety requirements of Schedule 3 of the Supply of Machinery (Safety) Regulations [65], and this includes the manufacturer's duty to minimize risks by design and to provide information on vibration emissions[64]. Certain vehicles have in-built vibration dampers or isolation devices such as those incorporated between chassis and cab, or cab and seat - these devices are discussed in the next section. Other 'design' purchase considerations might include: selecting machinery that uses (well balanced) rotating components in preference to reciprocating ones because the latter cause greater magnitudes of vibration; choosing a vehicle with pneumatic tyres in preference to solid ones; or purchasing a machine with servo-hydraulic systems in preference to direct linkages.

In the context of WBV, it is important to specify and use the right equipment or vehicle for the proposed task. It should be decided in terms of adequate load capacity; having wheels and tyres appropriate for likely obstacles; and being large (powerful) enough for the job [64]. As a practical example, consider a mini-excavator that is excavating to its maximum depth in hard ground. While the mini-excavator is an invaluable tool when used in the correct setting, this scenario of a small machine being wrongly selected for the job in hand would expose the operator to much more vibration than were a larger machine with much more power and digging-depth-capability used instead [63] . It has also been found that smaller and lighter agricultural tractors transmit more vibration into their operators than do larger and heavier ones [66].

(ii) Isolating the vibration

In the case of workers that operate, but do not necessarily drive, a vibrating machine (such as a drop forge hammer), then some protection can be afforded by isolating as much as possible the source of vibration from the operative. In such circumstances, this might be achieved by fixing the machine on its own independent concrete slab, or by supporting the machine on springs, dampers or some other type of shock-absorbing mechanism. This same principle of ‘isolation’ applies to vehicles. Anything that can be ‘engineered in’ to dampen the magnitude of vibration reaching, or isolate vibration from, an operator, is beneficial. This isolation may be a function of many aspects of the machine including things like: tyres; suspension; cab damping mechanisms; and seat suspension. Pneumatic tyres are preferred to solid tyres as those found on some types of forklift truck [64]. It is also important that pneumatic tyres are regularly checked, to ensure that they are inflated to their correct pressures for the given operating conditions. This is important because it has been found that in certain circumstances tyre pressure can help moderate WBV magnitude [67]. A vehicle without suspension between its axle(s) and chassis, such as found on some smaller and ‘basic’ agricultural tractors, will transmit much more WBV to the operator than a vehicle with suspension [66]. Indeed, in the case of agricultural tractors it has been identified that control of WBV exposure depends largely on the suspension system [68]. As with all mechanical components, maintenance is key to maintaining mechanical efficiency [69] so maintenance regimes should ensure that suspensions are working properly and that faulty components (such as shock absorbers) are promptly replaced. Suspension ‘improvement’ has been suggested as one way of reducing WBV transmission, although exactly how this might be achieved in practice seems open to some individual interpretation. Some vehicles are manufactured in such a way as to isolate the cab from the chassis using secondary suspension, or damper, systems. These are designed to reduce WBV transmission to the operator and again need to be appropriately selected for the proposed working conditions or particular working environment. They must be well maintained to ensure that they remain in full working order. Employers might be well advised to discuss with manufacturers the engineering design and limitations of such systems before purchase. Seat suspension may be provided in some types of vehicle. If it is not, sometimes a suitable suspension seat can be obtained and fitted. It has been stated that optimizing the dynamic performance of seats is an important means of minimizing exposure to WBV. Choice of suspension seat is a complex topic – and careful matching of seats to machines is required -

otherwise there is a risk that the seat will actually amplify the original vibration. Seats may also be designed (or configured) to either reduce shocks (high acceleration events), or continuous vibration. Again, and particularly where retrospective (vis-à-vis factory) fitting is being considered, technical discussion with manufacturers is strongly advised before purchase. Suspension seats use any combination of springs, dampers, shock absorbers or pneumatic systems. It is often the case that these systems can wear out before the vehicle to which they are fitted [68], so they may need replacing at some stage during a vehicle's working life. Obviously, a system that no longer works will offer no protection [70]or indeed, may exacerbate the problem of WBV. It is also important to check that the seat has been adjusted to suit the weight of the driver in accordance with the manufacturer's guidance (some suspension seats do this automatically). Suspension seats should be checked for adjustment regularly and always be adjusted every time the operator of a particular machine changes.

(iii) Changing work processes

It may well be possible to remove WBV risk by changing the way in which work is carried out [70]. The best way to start this approach is to first conduct a review of the work processes and activities. If it is found that the WBV risk is great, then it might be worth considering how the processes can be removed altogether. Where a process must use vehicular transport then the next consideration must be, as far as practicable, to provide a smooth and level roadway to drive on. Job rotation may also be considered as a means of minimizing the period of time that an operator is subjected to WBV. In fact, if all other practical mitigation measures have been implemented, but a degree of exposure remains, then this may be the only way of safeguarding operators from exceeding the Exposure Limit Value (ELV) [63]. Therefore, wherever possible, rotation of operators should be carried out, perhaps with operators doing other types of (non-WBV-exposure) job in between. The rotation of operators is essential where a specific job, or type of work might create exceptionally high levels of vibration. The provision of adequate rest and recovery time has also been suggested as a way to decrease exposure

(iv) Training and education

It has been highlighted that the use of untrained or inadequately trained operators is a major cause of accidents. It follows therefore, that if operators possess an understanding of WBV as a result of training and education, then it can help them to look for the risks and try wherever possible to avoid, or minimize them [68]. Operators should at least understand the level of WBV risk to which they might be exposed, how that risk is caused and what the possible negative health effects might be [70]. They should also have some understanding of how to reduce magnitudes of vibration. They must always be instructed on how to set up (configure) suspension seats for given work applications; both with respect to their weight and with respect to reducing high acceleration ‘shocks’ and/or ‘continuous’ vibration. Training and education can be delivered via any mix of: oral explanations, computer-based training, counselling, leaflets, handouts, films and other recordings, or short dedicated training sessions. More comprehensive guidance on the design and delivery of training, specifically for plant operators, is provided in Edwards [69]. Many occupations associated with WBV also involve manual handling [42]. Manual handling is recognized as a significant contributory factor to back problems [70], so common sense is called for when performing such activities and training in manual handling techniques can also be beneficial [68].

2.9 Human Vibration Analyzer

There are many manufacturers of Human Vibration Analyzer, viz. PCE, CESVA, Svantek, Delta-OHM, Music Managers Forum (MMF), Larson Davis, Castle, and Bruel & Kjaer. In this research work, Human Vibration Analyzer Type 4447 of manufactured by Bruel & Kjaer is used.

Human Vibration Analyzer Type 4447 is a small, lightweight, easy-to-use analyzer designed primarily for use in Health and Safety at Work applications. It is a rugged, robust and versatile instrument that can be carried by a worker to assess his or her vibration exposure.

The instrument is targeted at EU Directive 2002/44/EC [31] and complies with the technical requirements of ISO 8041:2005 [71], ISO 2631–1: 1997 [61], ISO 5349–1: 2001 [72], ISO 5349–2: 2001 [73].

2.9.1 Sensors and transducers used in Human Vibration Analyzer

Vibration magnitude could be expressed in terms of acceleration, velocity or displacement observed for a vibration process. All three make sense because the human body responds to any of the them, depending on the frequency of motion. However, in many standards related to the measurement of human vibration, acceleration is the agreed upon quantity for expressing magnitudes. This is mainly a matter of convenience since the classical vibration sensor is the accelerometer; which delivers the signal proportional to acceleration.

In general, accelerometer signals will be filtered and frequency weighted before further processing. Filtering is applied because the analysis should only include those frequencies that are thought to be important for hand-arm or whole-body vibration, as per the requirement. Further, the frequencies included are weighted differently. The weighting reflects the likelihood of damage from vibrations at different frequencies. Therefore, depending on the place of measurement (e.g., feet, seat, backrest) and the direction, different frequency weightings may be used, as defined in ISO 2631-1:1997[61]. The reason is that the 'human' dynamic system reacts differently depending on where and in which direction the vibrations enter the body. For example, fore and aft motion of a seated person is very different from side-to-side motion for the same person.

The purpose of the subsequent analysis is to quantify the acceleration appropriately. Typically the so-called time-averaged weighted acceleration value, a frequency-weighted r.m.s. of a vibration signal, is determined and reported in order to quantify the vibration to which a worker would be exposed. In context with human vibration, it is a measure for the average amount of vibration energy that would enter the human body.

The r.m.s. vibration magnitude is a good representation of processes whose vibrations are continuous or intermittent rather than shock like. Tools such as drilling machines, chain saws and vibrating plate tampers fall into that category. Even impact-wrenches can be well described with r.m.s. vibration magnitude even though each single operation cycle may last only a few seconds. WBV for HEMM, buses, trucks, tractors are also well described with an r.m.s. value. However, care must be taken when investigating shocks and processes with transients (i.e., sudden changes in the acceleration) – particularly when dealing with WBV. For example, a vehicle driving across bumps in the road or construction machines operated may easily cause shock-like vibrations. For such events, averaging across times much longer than the event's duration would not capture the essence of the problem. The intensity (magnitude) of a single shock, a few shocks or the sudden changes in acceleration may be beyond what the human body can accommodate, but if they are averaged out over a long period of time, their significance would be missed. Therefore, the total energy in the event and the maximum vibration values reached during the operation should be looked into. Better descriptors for such vibration scenarios are the VDV, which is a cumulative measure, and the maximum transient vibration value (MTVV), which is the maximum of the so-called running r.m.s. acceleration value, an r.m.s. vibration magnitude with one second integration time.

Since MTVV is based on a short integration interval, it will indicate the top vibration magnitudes to which the worker would be exposed. This parameter is especially useful when logged with a short (1 s) interval because the logging profile quickly gives an overview, whether any large vibration magnitude was an exception, appeared often or was constant. VDV is well suited to reflect the total exposure; it accumulates the vibration energy the worker would be exposed to, thereby putting more weight on peaks and/or sudden changes in the acceleration.

The instrument used in WBV measurent is a Human Vibration Analyzer, Type 4447. Vibration Explorer Software BZ-5623, included with type 4447, enables the transfer of measured data to a PC for post-processing.

Whole-body vibration exposure measurements were recorded according to ISO 2631-1:1997 standard, which are applicable to the vibration in the frequency range of 0.5 Hz to 80 Hz.

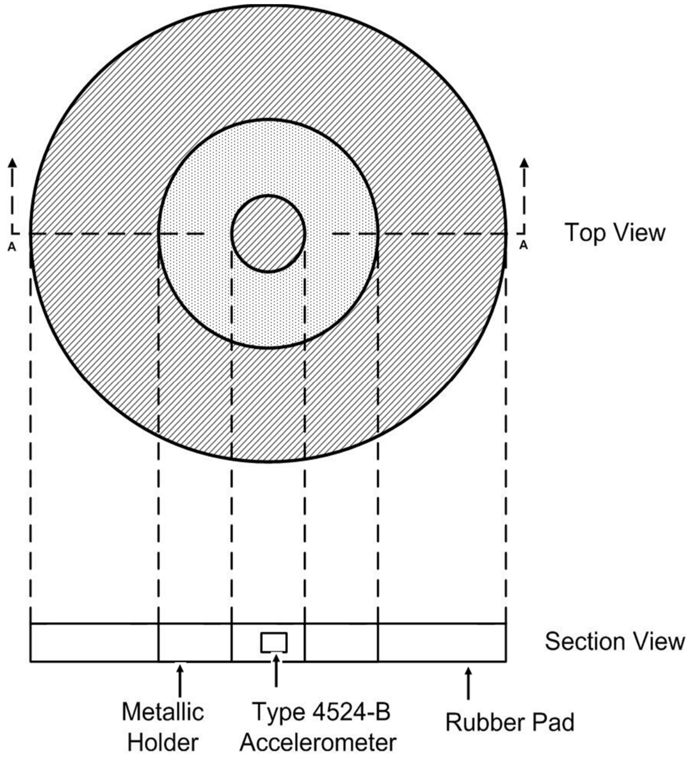

Figure 2.9 Line diagram of seatpad of human vibration analyser

Measurements were recorded at the operator-seat interface with a tri-axial seat pad accelerometer in combination with a control panel which records the vibrational exposure in the form of signals called vibration analyser type 4447. Fig. 2.9 shows the line diagram of seat pad of human vibration analyser. The seat pad contains accelerometer (Type 4524-B) at the centre. It is mounted on the seat. The operator sits on it while operating the equipment. The accelerometer measures vibration in three translational axes with reference to the human basi-centric axes namely, fore-and-aft (x-axis), lateral (y-axis), and vertical (z-axis) axes.

2.9.2 Transducers

(i). Variable capacitance transducers

A capacitive body is a body that stores an electrical charge. The concept of mutual capacitance occurs when two parallel conductors (often associated with plates) are isolated from each other. The capacity of this system is therefore, a function of the distance between these two plates. In the case of a capacitive transducer, the measured displacement is directly related to the distance between the two conductive bodies. A variation in capacitance, and thus, a variation in voltage in the electrical system is observed. In the case of the vibration measurement, the seismic mass m is associated with a first mobile conductive plate while the second fixed plate is associated with the sensor frame. When the seismic mass is subjected to an acceleration A, the distance l between the two plates varies, it is therefore, possible to determine the value of the reaction force of the spring and the acceleration of the mass as a function of the variation in capacity C.

(ii) Piezoelectric transducers

A piezoelectric material is a material that is electrically charged under the action of mechanical stress. A piezoelectric transducer will therefore observe the stresses which are imposed by the detection element by means of a voltage variation. In the case of the vibration measurement, the spring element is therefore a piezoelectric element (crystal) which emits an electrical signal V as a function of the stress σ applied to it by the seismic mass m. In this case, the sensor measures the inertial force induced by the seismic mass, which is a function of the acceleration undergone by this mass and expressed as a voltage variation

(iii) Piezoresistive transducers

The evolution of micro-fabrication techniques based on silicon micromachining and microelectronics have allowed the production of miniature systems. These micro electro mechanical systems (MEMS) come in various forms, from simple structures without moving elements to highly complex electromechanical structures. MEMS are typically assigned to sensor or actuator functions [74]. The use of MEMS technology for accelerometers is quickly expanding, thanks in particular to the automotive industry, which carries these small electronic components in different parts of the vehicles (airbag, belt, seat, etc.). The use of MEMS accelerometers can be found in many other application areas such as mobile telephony, machine monitoring or video game consoles. In addition to presenting the advantages of the transduction principles presented above, MEMS accelerometers offer other advantages. First, their extreme miniaturization allows them to take innovative measures at strategic points of the system studied. Moreover, these components benefit from a very low cost due to the silicon collective machining technologies used in the microelectronics industry. Several studies have shown that MEMS accelerometers can be a suitable solution for human vibration exposure[75]–[79]. These systems allow the development of on-board instrumentation at low cost without the need for specialized equipment. These electronic components are used on measuring devices for the study of vibrations on the human body, such as the Svantek SV38 accelerometers (for seat measurement) and SV105 (for hand measurement)

2.9.3 Accelerometers technology

The evolution of micro-fabrication techniques based on silicon micromachining and microelectronics have allowed the production of miniature systems. These micro electro mechanical systems (MEMS) come in various forms, from simple structures without moving elements to highly complex electromechanical structures. MEMS are typically assigned to sensor or actuator functions [74]. The use of MEMS accelerometers can be found in many other application areas such as mobile telephony, machine monitoring or video game consoles. In addition to presenting the advantages of the transduction principles presented above, MEMS accelerometers offer other advantages. First, their extreme miniaturization allows them to take innovative measures at strategic points of the system studied. Moreover, these components benefit from a very low cost due to the silicon collective machining technologies used in the microelectronics industry. Several studies have shown that MEMS accelerometers can be a suitable solution for human vibration exposure[75]–[79]. These systems allow the development of on-board instrumentation at low cost without the need for specialized equipment. These electronic components are used on measuring devices for the study of vibrations on the human body, such as the Svantek SV38 accelerometers (for seat measurement) and SV105 (for hand measurement)

2.10 Specification of Accelerometers

Table 2.7 Accelerometer specification

Vibration	Transducer	Nominal sensitivity	Filter	Frequency range	Linear operating Range[a]	Instrument noise
Hand-arm	4524-B-001	1 mV/(m/s^2)	Wh	2 Hz to 7 kHz	1 m/s^2 to 3200 m/s^2	<0.1 m/s^2
Whole-body	4515-B-002	10 mV/(m/s^2)	Wd, Wk	0.25 Hz to 900 Hz	0.1 m/s^2 to 320 m/s^2	<0.01 m/s^2

[a] Linear operating range is the instrument's measuring range. It is specified according to ISO 8041:2005. Outside this range, either 'Overload' or 'Under-range' is indicated.

2.11 Research Gap

When the HEMM operators operate their machine, vibration is transmitted through the operator–seat interface and can lead to musculoskeletal disorder. Though there has been a considerable amount of research works on WBV exposure, there is a lack of systematic investigation of confounding factors on WBV and its related MSDs. Discomfort analysis of HEMM operators exposed to vibration, proposed in this thesis, could not be found in the literature.

2.12 Summary

This chapter covered different literature and research studies on the basic concept of mechanical vibration, theory of whole body transmitted vibration, the guideline and standards relating to vibration exposure at workplaces. The guidelines and standards considered in the review are those developed by International organization for standardization [32]. Investigation on whole-body vibration in mines showed the impact of vibration on operators' health. Prevention from WBV, showed the different ways to protect from vibrational hazards. Different types of transducers and accelerometers are explained. The next chapter discusses the proposed work plan of the thesis to meet the research objectives.