PRACTICAL APPROACH TO MEASUREMENT AND EVALUATION OF EXPOSURE TO WHOLE-BODY VIBRATION IN THE WORKPLACE

by

Erich Thalheimer, B.S.M.E.
Senior Acoustical Consultant

Correspondence:

Erich Thalheimer
KM Chng Environmental, Inc.
411 Waverly Oaks Road
Waltham, Massachusetts 02154
Phone: (617) 891-6780
Fax: (617) 893-5020

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I. Overview and Summary

An occupational related hazard which has gained more attention in recent years is that of the potentially adverse effects of vibration upon human beings. While not usually considered an immediate threat to laborers, vibrations can interfere or prohibit a laborer from adequately performing their given tasks. A growing body of medical and engineering research has shown that excessive levels of vibration absorbed by the human body can manifest in, or at the least exacerbate, physical maladies adversely affecting the laborer's hand/arm extremities or their lower back region. The damages that can result range from minor annoyance and slight lack of motion range and dexterity to complete loss of finger and hand use and permanently damaged spinal column disks. Though usually not induced immediately, long term exposure (perhaps measured in years) has been shown to produce negative cumulative effects in labor (groups) exposed to excessive vibration.

Fortunately, modern vibration measurement instrumentation and generally accepted recommended practices (and criteria standards) are available with which the potentially adverse consequences of occupational related exposure to vibration can be evaluated for severity. If necessary, steps can be taken to mitigate laborer's exposure to dangerous levels of vibration either through strategic job rotations, provision of protective vibration reducing equipment, or by reducing the generated vibration levels at their source. In any case, the assessment and evaluation of occupational exposure to vibration should be performed by expert acoustical or vibration engineers because the measurement of vibration severity, and more importantly, the appropriate control of excessive vibration, can be a complex engineering challenge. Specific vibration mitigation treatments need to be carefully evaluated beforehand, and then applied properly on a case-by-case basis. Inappropriately specified or applied vibration control measures can actually increase (amplify) the vibration levels affecting the laborers.

This paper will focus on vibration issues effecting the entire (whole) human body, rather than more localized vibration exposure to hand and arm segments, for example. While the latter should not be de-emphasized as hand-arm vibration, and its associated white-finger syndrome, pose an occupational related risk for about one million U.S. laborers[6], the former has the potential to adversely affect about seven million U.S. laborers[6]. Whole-body vibration is of more interest when issues such as the ability of workers to perform their given tasks and the likely exposure of pregnant women laborers are considered. Further, the types of occupations which may be exposed to excessive levels of whole-body vibration are quite diverse, and could include: truck drivers, construction equipment operators, farm vehicle operators, textile machine operators, foundries laborers, machine tool operators, miners, train operators, and even occupants in buildings in which the structure is vibrating. Obviously, as more women enter the work force, the numbers of women, and moreover, pregnant women, potentially exposed to excessive whole-body vibration has risen significantly.

Whole-body vibration occurs when the entire human body is excited by a vibrating surface, such as the floor upon which a person is standing or the vehicle in which the person is riding, is allowed to generate excessive levels of vibration within certain frequency ranges within which people are particularly vulnerable. As a result, a person can be exposed to vibration entering their body where it is either transferred through to other portions of the body or is absorbed by the body itself. Both the transmittal of vibration through the body and the unavoidable absorption of vibration into the body are potential areas of concern capable of damaging the body over the long term.

Biological Research History

During the 1960's, whole-body vibration was studied at Wright-Patterson Air Force Base (Von Gierke, Corman) with respect to the limits pilots could withstand while still maintaining their ability to perform given tasks (i.e. flying jet fighter aircraft). Many performance tests were conducted on air force personnel, and yielded the identification of the human body's resonance regions (4 to 8 Hz longitudinally, and 1 to 2 Hz laterally). These human performance results later lead to the world's first international standard on the subject of whole-body vibration.

From 1971 to 1984, the National Institute of Occupational Safety and Health (Wasserman) sponsored several health related studies on various U.S. worker populations, which included: intercity bus drivers; long distance truck drivers; and heavy equipment operators. The epidemiological studies showed that the combined effects of forced body posture, cargo handling, improper eating habits, *and whole-body vibration* were factors contributing to various medical disorders and pains experienced by these workers (e.g. vertebragenic pain, spinal deformities, sprains, strains, hemorrhoid disorders, musculoskeletal diseases, ischemic heart disease, gastrointestinal problems, and obesity of non-endocrine origin)[6].

During this time period, researchers (Guignard and King) chose to classify whole-body physiological effects into various systems based on vibration exposure and biological response, as follows[6]:

a) Muscular activity and maintenance of posture
b) Cardiovascular system effects
c) Cardiopulmonary effects
d) Metabolic and endocrinological effects
e) Central nervous system effects
f) Gastrointestinal system effects
g) Motion sickness effects

More recently, researchers (Wilder, Pope, Dupuis) have focused their attention on hard tissue (bone and cartilage) of the lower back and spine region, and have shown that whole-body vibration clearly stresses and degrades the spinal disks. They have found that vibration can remove moisture and can thin the disks, leading to micro-trauma induced herniations. Other researchers (Abrams) have concentrated their study on soft tissue. Vibration transmission loss characteristics through various subject animals' abdominal segments have been measured to assess the validity of previously assumed vibration isolation characteristics and the effects of vibration on unborn fetuses.

Guidelines and Criteria

Since the late 1960's, various exposure criteria and recommended guidelines have been promulgated intended to evaluate whole-body vibration severity for ride-comfort, fatigue decreased proficiency (FDP), and for protection of health and safety. The most significant whole-body guideline was first released in 1972 by the International Standards Organization and is entitled ISO 2631 "*Guide for the Evaluation of Human Exposure to Whole-Body Vibration*". This organization is comprised of volunteer experts assembled from countries all other the world. Here in the U.S., the aforementioned ISO standard was adopted, and with some minor changes, was published by the Acoustical Society of America (ASA) and the American National Standards Institute (ANSI) as their recommended practice entitled ANSI S3.18 (and ASA 38) "*Guide for the Evaluation of Human Exposure to Whole-Body Vibration*". Since the early 1980's, little progress had been made with respect to updating or further validating the exposure levels recommended in ISO 2631. However, more recently, the Federal Transportation Administration (FTA) has released officially recommended ground-borne vibration severity criteria in *"Transit Noise and Vibration Impact Assessment"*, DOT-T-95-16, dated April 1995, intended to protect occupants in vibration sensitive structures from annoying transportation-induced vibration levels. Most recently (September, 1995), the American Conference of Governmental Industrial Hygienists (ACGIH) agreed upon and published a set of occupation exposure whole-body vibration criteria in their 1995-1996 issue of *Threshold Limit Values (TLV's) and Biological Exposure Indices (BEI's)*.

Measurement Instrumentation

Evaluation of particular occupational related exposure potential to excessive whole-body vibration levels is possible now by utilizing sophisticated, yet easy to operate, vibration measurement systems. These systems have been designed and configured to properly measure and evaluate whole-body vibration in-situ (in the actual workplace). A laborer's specific exposure to vibration, and therefore the risk of excessive exposure, can be measured using calibrated scientific instrumentation. For whole-body vibration, a vibration transducer known as an accelerometer is most often used to transduce the vibrating surface's motion into a proportional electronic signal capable of being measured, analyzed, and recorded. Due to the complex paths through which vibration can propagate, vibration measurements are often performed in three mutually orthogonal directions (X, Y, and Z). In this manner, the worst case vibration component can be identified, and vibration control treatments can be better applied. The transduced vibration signal is then conditioned (amplified or attenuated, filtered, impedance matched) and sent to a data recorder or measurement device. The data recorder could be an analog cassette or tape-to-tape magnetic recorder (outfitted for low frequency (FM) recording) or a more recently available digital audio tape (DAT) recorder. In any case, the recorded signal can then be replayed and analyzed in the convenience of a vibration laboratory setting rather than directly in-situ in the field. Whole-body vibration analyzers have the ability to measure vibration in terms of an overall (or broadband) frequency weighted level, or can decompose the vibration signal into frequency dependant regions (known as filter bandwidths) to allow a more detailed examination of the spectral composition of the vibration signal. The overall vibration level is a relatively simple, single number, which can be evaluated against vibration severity guidelines expressed in similar overall levels. Though typically more complex to measure properly, spectral information is useful for gaining insight into the mechanisms producing the vibration, and for allowing more targeted applications of vibration control treatments. Spectral analysis may also be required if measured vibration conditions are being evaluated against certain whole-body vibration criteria requiring such analysis.

Practical Approach

With the background information provided above and more specific details in subsequent sections of this paper, a recommended practical approach[12] for the measurement and evaluation of whole-body vibration in the workplace is as follows:

1.) Recognition: An understanding of the fundamentals of vibration, and its sources and propagation characteristics, are essential in order to first identify potential whole-body exposure scenarios in the workplace. One must learn to recognize the conditions under which a laborer might be subjected to excessive whole-body vibration.

2.) Criteria: With an awareness of the various whole-body vibration exposure guidelines available today, select an appropriate guideline which contains severity criteria limits that address the types of vibration sources involved and have withstood test of time.

3.) Measurement: With a preferred guideline and criteria in place (step 2), assemble a whole-body measurement system configured to measure whole-body vibration levels in accordance with the selected criteria metrics. The measurement instrumentation (including the transducer) must be capable of measuring the expected dynamic range (0.1 to 10 G) and frequency range (third octaves, 1 Hz to 80 Hz) associated with whole-body vibrations. The measured data should be reduced to yield calibrated vibration levels in units readily comparable to the selected criteria limits. A form of data recording and archiving should also be provided.

4.) Evaluate: A comparison of the resulting measured vibration levels (step 3) against the selected criteria limits (step 2) will reveal if vibration impact conditions are present. If measured levels exceed the criteria limits, then vibration mitigation measures are warranted.

5.) Control: In general, vibration control treatments can be applied to the vibration source, the path over which the vibration propagates, or directly to the receiver (laborer). Source controls are the most effective, however are not always feasible. Path controls may involve vibration isolation or damping treatments. Receiver controls may involve limiting an individual's exposure through job rotations, for example. In any case, vibration control recommendations should be developed on a case-by-case basis by knowledgeable vibration control engineers.

II. Fundamentals of Vibration

This section will present some of the necessary fundamental physics of vibration. Related terminology; the behavior of objects when exposed to vibration; the propagation characteristics of vibration; the units of measure; and essential measurement concepts will be presented.

Sources

Vibration and its associated perception or adverse effects on humans can be generated by transportation systems (such as trains, subways, trucks, automobiles), construction activities (such as heavy earth moving equipment, blasting, pile driving), power generation or other large mechanical systems, or by actual seismic motion. While vibrational motion can be generated in all three directions (X, Y, and Z), traditionally only the vertical component (Z) has typically been addressed during environmental studies[4]. Usually this component contains more energy than do either of the other directions, and the ground's surface is less constrained to motion in the vertical direction than in the longitudinal or lateral directions. In buildings or when riding in vehicles, the most severe direction of generated vibration can come from any direction, and more often, appreciable vibration levels can be can be found in all components[1]. Consequently, studies in human exposure to vibration usually evaluate vibration in three mutually orthogonal directions (X, Y, and Z) and identify the most severe component. In addition, the vibration levels in several directions can be added together for a more conservative assessment of the overall vibration potential.

Displacement, Velocity, & Acceleration

When a surface is excited by vibrational forces, any given vibrating point can be described by its instantaneous acceleration, velocity, or displacement relative to some equilibrium neutral position. An object's displacement is simply the distance away from some equilibrium position that motion oscillates about. This motion can also be described by the object's velocity, or the time rate of change of position. Similarly, the time rate of change of velocity represents an object's acceleration. It is the acceleration term which is most easily related to the forces acting upon an object due to its vibratory motion. However, human beings tend to sense (or feel) vibration velocity most easily[4].

Natural Frequency & Resonance

All real objects, including of course human beings, are made of real materials characterized by some degree of mass (weight), stiffness (spring-like), and damping (energy-absorbing). An object will vibrate if it is excited (moved) by either an initial displacement and then released, or by an external force continually acting upon it. With the former, the object will tend to vibrate at its "natural frequency" (or frequencies). An object's natural frequencies of vibration are determined by the relative combinations of its mass, stiffness, and damping attributes. In the latter case, an external force can excite an object and cause it to vibrate at the same frequency as the external force itself. When the external forcing frequency matches the object's natural frequency, a potentially serious vibration condition known as "resonance" can result. When an object is excited into resonance, its vibratory motion can grow or be amplified many orders of magnitude (depending largely on its damping)[10]. Solid structures and machines can literally shake themselves to pieces, glass can shatter, bridges can fall down, and human beings can be exposed to dangerously high levels of vibration.

Figure 1 illustrates this most important concept when dealing with vibration and its control. This figure shows the transmissibility (output/input) of an object's motion as a function of increasing forcing frequency. Actually, the frequency scale has been normalized into a dimensionless ratio of forcing frequency (f) over natural frequency (f_o). Since an object's natural frequencies are constant (due to its mass and stiffness), the families of curves (for various damping amounts) depicts how vibration transmission varies as the external forcing frequency increases. At low frequencies (where $f/f_o < 1$), the object's amplitude and motion (output) parallels that of the input force. However, as the forcing frequency increases, the object passes through a region of high output motion. Here, the transmissibility curves show a marked increase with a maximum centered around where the forcing frequency equals the object's natural frequency (where $f = f_o$). This region, as described above, is known as resonance, and the dangers of excessive vibration levels are at their greatest. The object's motion at resonance is heavily dependent on the amount of damping present, as the families of curves show. At higher forcing frequencies (where $f/f_o > 1.4$), the object's output motion can be reduced to levels below that of the input forcing frequency. This area on the transmissibility curves is called the "region of isolation", and is the desired condition which design engineers and vibration control engineers should be targeting. Here, an object's vibratory motion can be significantly less than that of the input force, and the object's vibration levels can therefore be minimized.

Consequently, engineers are constantly evaluating (measuring) vibrating objects in order to identify natural frequencies, and subsequently, attempting to ensure that forcing frequencies do not coincide with an object's natural frequencies. Avoidance of resonance is the key issue when vibration control is considered.

Being made of tissue and bones exhibiting some degree of mass, stiffness, and damping, various portions of the human body have been shown to exhibit several natural frequencies. Moreover, the entire body has been shown to have natural frequencies that differ slightly depending on the direction of vibration[6,7]. For example, a human being's longitudinal (foot to head) natural frequency is considered to be between 4 and 8 Hz. The transverse (back to chest, and, right to left) natural frequencies range from 1 to 2 Hz. Figure 2 shows vibration transmissibility ratios through various parts of the human body. When compared to Figure 1, it is clear that human bodies respond to vibration in predictable, and therefore controllable, manners. As we shall see, the recommended limits for exposure to whole-body vibration take into account the direction, magnitude, duration, and frequency (to avoid resonance) of the offending vibration.

Magnitude

The magnitude of vibration is the amount, or intensity, of vibrational energy present. The amount of vibrational displacement, velocity, or acceleration can all be quantified using similar magnitude metrics. Displacement levels can be in units of length such as inches (inch), milli-meters (mm), or microns. Velocity levels can be expressed in units of inches per second (inch/sec, or ips), milli-meters per second (mm/s), and the like. Finally, acceleration levels can be expressed in units of inches per second per second ($inch/sec^2$) or meters per second squared (m/s^2). In the English units system, acceleration units are most often expressed in equivalent gravitational acceleration units, or G's. Vibration levels expressed in these types of absolute units are called "engineering units". Some useful conversions between English and metric units follow:

For Displacement: 1 inch = 0.083 feet = 0.025 meters = 25.4 mm
For Velocity: 1 inch/sec = 0.083 feet/sec = 0.025 m/s = 25.4 mm/s
For Acceleration: 1 G = 386 inch/sec^2 = 32.17 feet/sec^2 = 9.81 m/s^2

Decibels

Due to the very large range over which vibration energy can be found (three to four orders of magnitude) and the fact that people tend to sense vibration on a logarithmic basis (where we are more sensitive to changes in low level vibrations, and less capable of perceiving vibration changes in the presence of high vibration), a more convenient decibel scale (abbreviated, dB) has been adopted. The decibel scale is a logarithmic relationship which allows compression of the large range of engineering units into a more practical scale through the following equation.

$$\text{Vibration Level (in dB)} = 10 \text{ LOG } (V/V_o)^2$$

In this equation, V_o represents a reference vibration level against which the measured engineering unit is relatively compared. By convention, it has been accepted in the U.S. that, for vibration velocity, V_o will equal 1 micro-inch per second (1 μ-ips); and for acceleration, V_o will equal 1 micro-G (1 μ-G). In point of fact, any quantity can be expressed as a decibel, however, the reference (re) level must be stated in order to have meaning.

Frequency Analysis

Vibration forces and the objects the forces interact with can be excited by vibration composed of many frequencies. Frequency analysis allows the evaluation of vibration on a frequency basis, where vibration levels at certain frequencies can be identified. Such analysis allows engineers to gain insight into the forces and mechanisms producing the vibrations; understand how the vibration propagates through various media; and moreover, aids engineers to recommend appropriate mitigation treatments which target the offending vibration frequencies most efficiently.

Frequency is defined as the number of times a surface vibrates about an equilibrium point during a period of time. The number of times an object vibrates in one second has the units of cycles per second (or Hertz, Hz). Vibration spectra can be comprised of many frequencies all of which can be vibrating at unique levels. The frequency range, or spectrum, over which most whole-body vibration is measured ranged from less than 1 Hz to as high as 100 Hz.

Engineers use techniques known as "frequency analysis" to examine vibration signals on a frequency dependant basis. Measurement devices are able to filter selected frequency ranges (or bandwidths) for measurement. By doing this type of filtering at many different frequencies, the vibration's spectral composition can be determined. Two basic types of filters are typically used; constant bandwidth filters, and constant percentage bandwidth filters[11]. In both cases, a given filter bandwidth is identified by its center frequency. Also, a complete spectrum analysis can be performed using either filter in "serial" or "parallel" configurations. Serial means that a single filter is moved along the frequency scale and the analysis is done one bandwidth at a time. This approach is typically less expensive and acceptable for steady vibration signals, but cannot be used when evaluating fluctuating or transient vibration signals. Parallel filters are many filters arranged (stacked) side-by-side to cover the entire frequency range of interest. These parallel filters can then perform analysis of many bandwidths simultaneously, and as such, are faster and more expensive than serial filters, but do allow measurement of non-steady vibration signals.

Constant bandwidth filters are always a specified frequency range wide (e.g. 1 Hz, 10 Hz, 100 Hz), regardless of where throughout the frequency scale the filter is placed. As an example, a 10 Hz filter centered at 80 Hz would allow analysis of frequencies ranging from 75 Hz up to 85 Hz. Constant bandwidth filters offer equivalent resolution (ability to distinguish between different frequencies) throughout the spectrum, and as a result, these filters are most often employed when evaluating mechanical vibrations and the effects of vibration on structures. The bandwidths of these types of filters are not standardized, and therefore, the results of any analysis must include mention of the filter's bandwidth size.

Constant percentage bandwidth filters vary in bandwidth size as they are placed lower or higher along the frequency scale. These filters are always a specified percent of their center frequency in width. Octave bands are examples of constant percentage filters. If better resolution is needed, octaves can be subdivided into smaller bandwidths. Examples of these include third-octave, 12th-octave, and 24th-octave bandwidths. An octave (where the upper frequency is twice that of the lower frequency) represents approximately a 70 % wide filter, where the lower and upper frequencies are +/- 35 % that of the center frequency. As an example, the octave filter centered at 16 Hz allows analysis of frequencies ranging from 11 to 22 Hz. In comparison, a third-octave represents a 23 % wide filter, where the lower and upper frequencies are +/- 12 % of the third-octave's center frequency. In the lower frequency bands, constant percentage filters provide finer resolution than they do at higher frequencies. At higher frequencies, these filters can become very wide. Again for example, the octave centered at 125 Hz allows analysis of frequencies ranging from 89 to 178 Hz. With this distinction of filters in mind, research has shown that human beings perceive vibration on a logarithmic basis. Constant percentage filters lend themselves nicely to better accommodate human's sensitivity to vibration, and are therefore preferred when evaluating human exposure to vibration[1]. Octaves and fractional octaves have been standardized internationally with respect to their center frequencies and bandwidths. This is an important achievement for it ensures that measurements and analyses performed all over the world can be easily compared.

Time averaging of a filtered signal can also be performed to better accommodate fluctuating vibration levels. A vibration signal can be quantified through either a "peak" and/or an "RMS" (root-mean-square) level detector. The peak of a signal represents its instantaneous highest (or lowest) value; while an RMS level has taken the original signal, squared it, averaged its mean value, and has taken the square root of that mean value. The RMS value is a better indicator of average levels proportional the energy content in a signal, and has been shown to better simulate human being's perception of vibration when computed over a one-second (1 sec.) averaging time[4]. Spectrum averaging of many measured peak or RMS spectra over time is a very useful technique in frequency analysis in which random signals in each frequency band tend to cancel away as more and more spectra are averaged together, however real (repeatable) signals will tend to reinforce one another within each band[11]. Consequently, low level signals that may at first appear to be masked by background signal (noise) may be revealed through sufficient employment of spectrum averaging.

III. Standards & Guidelines

This section will present and discuss several of the more significant and currently relevant national and international standards which contain recommended criteria limits for exposure to whole-body vibration.

ISO 2631

The most widely known and significant whole-body vibration guideline is the International Standards Organization's (ISO) 2631 "*Guide for the Evaluation of Human Exposure to Whole-Body Vibration*"[1]. The research and discussions amongst ISO committee volunteers (including representatives of the U.S.) began as early as 1964, but the first official ISO publication did not result until 1972. The most recent revision to the guideline was released only as recently as 1985.

The standard details the biodynamic coordinate system, measurement methodology, and severity criteria limits for whole-body vibration exposure. Three mutually orthogonal directional components are defined, those being: longitudinal "Z" (from foot to head); transverse "X" (from back to chest), and transverse "Y" (from left to right). It goes on to state that, at the point where vibration enters the laborer, RMS vibration acceleration measurements (in units of m/s^2) should be performed along all three biodynamic (X, Y, and Z) axes. The acceleration levels within third octave bands ranging from 1 Hz to 80 Hz, inclusive, should be analyzed using a frequency analyzer. The standard also gives directions for ensuring an acceptable time-averaged result in the data if vibration conditions fluctuate throughout the work day.

Three families of allowable exposure time curves ranging from 24 hours to 1 minute are provided in the standard for the longitudinal (Z), and transverse (X and Y) acceleration components. These frequency weighted curve shapes correspond to the resonance ranges associated with whole-body vibration (i.e. the longitudinal resonance region between 4 and 8 Hz, and the transverse resonance region between 1 and 2 Hz). Table 1 shows the relative adjustment factors to apply to each third octave band level relative to the bands of maximum sensitivity. In graphical form, the curves shown in Figures 3 and 4 represent the standard's mid-level of severity; that being "Fatigue Decreased Proficiency" (FDP), in the longitudinal and transverse directions, respectively. FDP limits are intended to preserve work efficiency and the laborer's ability to perform tasks. By shifting the limits (curves) downwards by a factor of 3.15 (-10 dB), the limits for "Reduced Comfort" are established. Similarly, by shifting the FDP curves upwards by a factor of 2 (6 dB), the "Exposure Limits" for health and safety are defined. However, due to a lack of clear epidemiological data to support these most severe limits, the exposure limits have not withstood scrutiny and should be used with great discretion, if at all[12].

The resulting third octave acceleration level breaching the highest exposure curve (i.e. shortest allowable time exposure) dictates the resulting exposure limit for the laborer under evaluation. Example vibration acceleration exposure limits expressed in m/s^2 for an eight-hour period for the longitudinal and transverse axes can be seen in Table 1. Other exposure limits for times ranging from 1 minute to 24-hours are also provided in the standard.

In more recent versions of the ISO 2631 guideline, it is recommended that when the vibration levels in the three orthogonal directions are similar in intensity, then a vector sum should be performed to yield a worst-case result. The standard recommends applying a directional weighting factor to the transverse components, and then vector summing the overall acceleration levels through the following equation:

$$A_{wt} = SQRT\ [\ (1.4\ A_{wx})^2 + (1.4\ A_{wy})^2 + (A_{wz})^2\ ]$$

where: A_{wt} = overall weighted total RMS acceleration
A_{wx}, A_{wy}, A_{wz} = weighted RMS directional acceleration

Indeed, more recent research studies (Hansson and Wilstrom) have shown that there is better correlation between the overall combined acceleration approach and the ability to perform tasks[6].

In 1987, ISO 2631 Part 2 was released entitled "*Human Exposure to Continuous Shock-Induced Vibrations in Buildings*". The guideline was intended to evaluate the potential for annoyance of human beings subject to building vibration. Buildings can vibrate due to internal mechanical systems (HVAC), nearby transportation systems, or simply by wind loading forces. The guideline provides recommended frequency weighting network factors and exposure criteria limits for avoiding whole-body vibration annoyance. Vibration limits are provided for the biodynamic longitudinal and transverse directions within the third octave frequency range from 1 Hz to 80 Hz, expressed in units of RMS and peak vibration acceleration and corresponding velocity levels. These limits can be uniquely tailored to an individual analysis based on land use, time of day, and type of vibration, by applying adjustment factors provided in the standard. This approach also was published in a standard dedicated to building vibration and occupant annoyance entitled ANSI S3.29[3].

Table 1

Weighting Factors Relative to the Frequency Range of Maximum Acceleration Sensitivity and Whole-Body Vibration 8-hour Exposure Limits Recommended by ISO 2631, ANSI S3.18, and ACGIH TLV

Third Octave Band (Hz)	Weighting Factors for		8-hour[a] Vibration Exposure Limit, m/s^2	
	Longitudinal (Z)	Transverse (X,Y)	Longitudinal (Z)	Transverse (X,Y)
1.0	0.50 (-6 dB)	1.00 (0 dB)	0.630	0.224
1.25	0.56 (-5 dB)	1.00 (0 dB)	0.560	0.224
1.6	0.63 (-4 dB)	1.00 (0 dB)	0.500	0.224
2.0	0.71 (-3 dB)	1.00 (0 dB)	0.450	0.224
2.5	0.80 (-2 dB)	0.80 (-2 dB)	0.400	0.280
3.15	0.90 (-1 dB)	0.63 (-4 dB)	0.355	0.355
4.0	1.00 (0 dB)	0.50 (-6 dB)	0.315	0.450
5.0	1.00 (0 dB)	0.40 (-8 dB)	0.315	0.560
6.3	1.00 (0 dB)	0.315 (-10 dB)	0.315	0.710
8.0	1.00 (0 dB)	0.25 (-12 dB)	0.315	0.900
10.0	0.80 (-2 dB)	0.20 (-14 dB)	0.400	1.120
12.5	0.63 (-4 dB)	0.16 (-16 dB)	0.500	1.400
16.0	0.50 (-6 dB)	0.125 (-18 dB)	0.630	1.800
20.0	0.40 (-8 dB)	0.10 (-20 dB)	0.800	2.240
25.0	0.315 (-10 dB)	0.08 (-22 dB)	1.000	2.800
31.5	0.25 (-12 dB)	0.063 (-24 dB)	1.250	3.550
40.0	0.20 (-14 dB)	0.05 (-26 dB)	1.600	4.500
50.0	0.16 (-16 dB)	0.04 (-28 dB)	2.000	5.600
63.0	0.125 (-18 dB)	0.0315 (-30 dB)	2.500	7.100
80.0	0.10 (-20 dB)	0.025 (-32 dB)	3.150	9.000

Note: a = eight-hour exposure limits used as example. Other exposure limits for times ranging from 1 minute to 24-hours are also provided in the standards.

ANSI S3.18

Here in the United States in 1979, the American National Standards Institute (ANSI) in cooperation with the Acoustical Society of America (ASA) published Standard ANSI S3.18-1979 (ASA 38-1979) "*Guide for the Evaluation of Human Exposure to Whole-Body Vibration*"[2]. With additional clarifications, the ANSI Standard was taken directly from ISO 2631 and accounts for a laborer's exposure to vibration level, frequency, direction which vibration enters the body, and exposure time. As with ISO 2631, third octave band RMS vibration acceleration levels (in m/s^2) are to be measured in the bands ranging from 1 Hz to 80 Hz. Three different exposure severity criteria families of curves are provided: "Fatigue-Decreased Proficiency" (FDP) used when task performance ability is of concern; "Exposure Limit" (FDP plus 6 dB) used to evaluate health and safety exposure; and "Reduced Comfort" (FDP minus 10 dB) used to evaluate ride comfort in vehicles. Different frequency weighted exposure limit curves are provided for evaluating the biodynamic Z axis (foot-to-head), and the X (back-to-chest) and Y (right-to-left side) axes. The standard calls for RMS vibration acceleration measurements to be conducted at the point where vibration enters the body, and provides general suggestions for appropriate measurement and calibration equipment. Third octave band measured levels should be weighted by the appropriate filter network factors shown in Table 1. As an alternative for simplicity, a single overall frequency weighted RMS acceleration level can be measured using frequency filter networks conforming with these relative factor shapes. Allowable exposure times are provided for each third octave band, examples of which can be seen in Table 1 for an eight-hour exposure period.

New ACGIH TLV's

In September, 1995, the American Conference of Governmental Industrial Hygienists (ACGIH) finally officially incorporated whole-body vibration exposure into their annual recommended guidelines publication entitled "*Threshold Limit Values (TLV's) and Biological Exposure Indices (BEI's)*"[5]. This much respected booklet contains recommended limiting values of many occupational related hazards and exposures. The ACGIH is a volunteer organization of public and private sector experts, and their recommended TLV's often lead the way towards nationally adopted standards.

The new whole-body vibration evaluation procedure is largely taken from ISO 2631 in that vibration is assessed in third octave format ranging from the 1 Hz band to the 80 Hz band. Again, three mutually orthogonal (biodynamic coordinates) vibration acceleration components are measured, and exposure time limits are recommended depending on the severity of the vibration. The limiting values are guides in the control of whole-body vibration exposure, but should not be regarded as defining a boundary between safe and dangerous levels[5]. The frequency weighting factors for the Z-axis and the X- and Y-axes were taken directly from the Fatigue Decreased Proficiency (FDP) limits in ISO 2631. However, in this case, the ACGIH committee member's consensus was to adopt the ISO 2631 FDP limits as health and safety limits. Whereas the ACGIH is solely concerned with health and safety, no other severity limits, such as ride comfort, were offered. The weighted results in three mutually orthogonal directions can be vector summed, and the resulting overall level is recommended not to exceed an RMS acceleration level of 0.5 m/s^2 over an eight-hour dose period. This level, as will be shown in the next section, was selected to be consistent with newly recommended European Union (EU) machinery directives. During a more detailed assessment, exposure times for each third octave band ranging from 1 Hz to 80 Hz are also provided. Table 1 shows the recommended 8-hour exposure times for the longitudinal (Z) axis and the transverse (X and Y) axes.

New EEC Machinery Directive

The European Economic Community (EEC), know better known as the European Union (EU), in an effort to establish health and safety standards applicable to goods traded within member countries, recently promulgated whole-body vibration acceptance directives called 89/392/EEC and 91/368/EEC[8]. Contained therein, the Machinery Directive was scheduled to come into effect on January 1, 1995. Now, manufacturers of heavy equipment must design their products to reduce the risks associated with excessive vibrations, and must make this information readily available to interested parties (such as customers and users). Heavy equipment, for example, must be tested and certified before it is traded within the European Union. If the equipment produces overall whole-body vibration levels at the operator's position of less than 0.5 m/s^2, then a label indicating so must be placed on the vehicle. However, if the vehicle produces whole-body vibrations in excess of 0.5 m/s^2, then the actual tested level must be labeled on the vehicle.

Federal Transit Administration Criteria

Recommended environmental vibration criterion for evaluating ground-borne vibration impact on nearby sensitive receptors has recently been promulgated by the Federal Transit Administration (FTA). Vibration impact analysis methods and criteria limits can be found in the FTA's *"Transit Noise and Vibration Impact Assessment Manual"*[4], DOT-T-95-16, dated April 1995. The recommended criteria relate to ground-borne vibration causing <u>human annoyance</u>, and are shown in Table 2. The vibration criteria is based on RMS vibration velocity expressed in VdB re 1 μ-ips for various categorized land uses and frequency of vibration events (i.e train passbys). Buildings where low ambient vibration is essential for interior operations are considered to be Category 1 receptors. Residential receptors are considered as Category 2, while institutional buildings are placed in Category 3. "Frequent" events are defined in the table as more than 70 events per day; this category includes most transit systems. "Infrequent" events are defined as fewer than 70 events per day, and most commuter and inter-city rail systems fall into this category. In addition, specific vibration criteria have been established for special buildings such as concert halls, TV and recording studios, auditoriums and theaters.

Table 2
FTA Criteria for Ground-borne Vibration Annoyance Impact

Land Use	Receptor Description	Ground-Borne Vibration Levels (RMS Velocity Level in VdB re 1 μ-ips)	
		Frequent Events	Infrequent Events
Category 1	Buildings where low vibration is essential for interior operations	65 VdB	65 VdB
Category 2	Residences and buildings where people normally sleep	72 VdB	80 VdB
Category 3	Institutional land uses with primarily daytime use.	75 VdB	83 VdB

IV. Measurement & Evaluation

As discussed previously, the severity of occupational exposure to whole-body vibration can be measured using sophisticated, yet easy to operate, vibration analysis instrumentation. Several issues exist of which the measurement engineer must be aware, and include: the calibration of the measurement system; the capability of the transducer (and the entire measurement system) to properly measure the dynamic levels and frequency ranges associated with the measurement; the mounting techniques employed when attaching the vibration transducer to the vibrating surface; the proper configuration of the measurement systems to yield vibration metrics of interest; and the recording of the vibration data and results for further processing or archival purposes. This section will discuss recommended methodologies and techniques associated with the transduction, measurement, analysis, and recording of whole-body vibration.

Transducers (Accelerometers)

The measurement of vibration entails making contact with the vibrating surface of interest. Contact is usually done by mounting a vibration sensor to the vibrating surface directly. In the past, vibration transduction was accomplished through the use of strain gages to measure a surface's movement. Similarly, peizo-resistive devices could be used, particularly for whole-body vibration study, because of the more than adequate low frequency capability (DC to 150 Hz). However, the frequency response of these devices were less than ideally linear; the mounting techniques were cumbersome; and because these transducer worked on Wheatstone bridges requiring electronic balancing, they were subject to temperature and time drifts in sensitivity. More recently, non-contact laser based transducers have been marketed which offer the advantage of bouncing a laser off a vibrating surface from some distance away (with about 10 feet) and then, using a technique known as the "Doppler shift", produce an electronic signal proportional to the actual surface's vibration velocity behavior. However, by far the most popular transducers currently are peizo-electric devices known as accelerometers. This paper will concentrate on these more traditional sensors.

Accelerometers are small vibration sensors which are mounted directly on the vibrating surface under study. An accelerometer is typically a sealed device within which a small piece of piezo-electric material is sandwiched between the accelerometer's base (or housing) and a small attached moving mass. As the mass accelerates (moves) due to the surface under study vibrating, the piezo-crystal is stressed and produces an electronic signal proportional to the acceleration of the surface[9]. This acceleration signal is thus the basic electronic signal used to measure vibration. The signal will need to be conditioned, amplified, and filtered before it is ready to be analyzed. Some accelerometers have such conditioning circuitry built into the sensor itself, and will typically output an electronic fluctuating voltage signal proportional to the surface's vibration acceleration. Other accelerometers do not have built-in conditioners, and produce an output charge (current) signal proportional to acceleration. Signal conditioning, and the eventual conversion into a voltage signal, are performed by dedicated devices usually placed between the sensor and a measurement device.

The size and sensitivity of the accelerometer are essential attributes to consider when selecting an appropriate transducer for a given measurement challenge. In general, the larger the size (weight) of the accelerometer, the greater its sensitivity will be, but the more limited its upper dynamic and frequency range will become. Sensitivity of an accelerometer indicates the amount of signal a transducer will generate given some normalized amount of vibration. A large (500 grams) accelerometer will generate more signal than a smaller one (2 to 3 grams), a factor which can be important when ensuring that sufficient signal is available for the measurement device to distinguish from background noise signals. For example, a fairly insensitive (small) accelerometer may generate 1 milli-volt for every G of vibration to which it is exposed (expressed as 1 mV/G). Such accelerometers are typically used for measuring high vibration level producing machinery. More moderate sensitivities can range from 10 to 100 mV/G, and are intended for general purpose machinery and structural vibration measurements. Larger accelerometers with sensitivities ranging from perhaps 1 to 10 V/G are intended for building structural vibration, transportation-induced ground-borne vibration, and earth (seismic) motion. As a trade-off however to decreased sensitivity, the smaller accelerometers can measure very high dynamic levels ranging from 0.001 to upwards of 10,000 G over a wide frequency range of perhaps 5 to 20,000 Hz. A medium sized accelerometer generally is limited to dynamic levels ranging from 0.0001 G to 2,000 G over a frequency range of 1 to 5,000 Hz perhaps. And large accelerometers are limited to dynamic levels from about 0.000002 to 2 G and are limited in their useful frequency ranges from as low as 0.1 Hz to about 1,000 Hz.

An accelerometer's output sensitivity should ideally be linear (the same) at all frequencies. However, the frequency range over which an accelerometer can be used is dependent on the mounted resonance frequency of the sensor[9]. Being made of real materials having some degree of mass, stiffness, and damping associated with it, an accelerometer's response and its sensitivity (output) will increase as the sensor is exposed to higher frequencies which pass through its own resonance frequency region (see Figure 1). A rule-of-thumb states that an accelerometer's useful frequency range should be limited to one-third to one-half that of its resonance frequency[9]. By adhering to this rule, the stated sensitivity of the accelerometer can be assumed to be quite linear at all frequencies up to this operational frequency limit. One other consideration when selecting an appropriate sized accelerometer involves an effect known as "mass loading". Mass loading occurs when the accelerometer mounted on a vibrating surface is too heavy and actually influences the way the surface vibrates. A rule-of-thumb suggests that an accelerometer's mass should not exceed one-tenth the mass of the vibrating surface[9].

Choosing the appropriate size accelerometer involves careful consideration of required dynamic ranges and the frequency range of interest, all of which must be provided in an accelerometer sensitive enough to produce sufficient signal to be measured. If the signal is too weak, it can be contaminated or even masked by (somewhat unavoidable) random electronic signals generated by electronic devices or due to ambient (background) vibration conditions. For whole-body vibration measurements, a medium sized accelerometer (with nominal sensitivity of 100 mV/G) specifically design with a low frequency ability of less than 1 Hz should serve well under most whole-body vibration measurement scenarios.

Mounting Techniques

The method with which the accelerometer is attached (or mounted) to the vibrating surface can play a significant role in the resulting capabilities of the sensor to transduce vibration[9]. Care must also be practiced to ensure the sensitive direction (or axis) of the accelerometer is orientated in the direction in which vibration data is desired. Accelerometers generally work in one linear direction only (longitudinally), and in fact are designed to be very insensitive to other directional vibration interference (transverse). Several methods are available, and in general, the more stiff the mounting technique, the better the surface vibration will couple and transfer to the accelerometer. The following mounting methods are presented in descending order of stiffness, and as a result, the upper frequency capability of the accelerometer is reduced through a mechanical low-pass filtering effect.

1.) *Stud Mounting*, where the accelerometer is directly screwed to the vibrating surface using a short mounting stud (note: both the surface and the accelerometer must be drilled and tapped.)

2.) *Adhesives*, such as cyanoacrylate (super glue), are routinely used to mount accelerometers to flat clean surfaces. Glues have excellent tensile strength.

3.) *Magnetic Mounts* are available which screw into the bottom of accelerometers and allow the sensor to be placed firmly on ferrous (metal) surfaces.

4.) *Bees Wax* can be used to stick accelerometers to flat surfaces which do not get particularly warm (else the wax melts).

5.) *Direct Placement* of the accelerometer on the vibration surface can be done providing the vibration levels are not approaching 1 G (else the accelerometer will bounce).

With respect to whole-body vibration, a moderately sensitive accelerometer (roughly 100 mV/G) is typically selected and is mounted either to the vibrating surface, or placed directly on the surface inside a rubber disc-shaped pad (affectionately known in the industry as a “whoopee-cushion”)[12]. Such a pad allows the laborer to sit on, or against, the accelerometer directly in-situ while performing their given occupation (be it vehicle operation or structural dependant)[13]. In this manner, vibration is transduced at the point where it enters the laborer's body. One, two, or more often, three mutually orthogonal accelerometers are assembled together in such a cushion, thus allowing for vibration components in several directions to be simultaneously measured. Finally, note that the laborer being tested should first sit on the cushion before the vibration data is collected[12]. Sitting on the transducer generates a transient very high signal which should not be confused with actual vibration-induced signal.

Vibration Calibrators

In order to ensure that measured vibration signals are properly recorded, and to ensure that measurement instrumentation are properly configured and connected for analysis, a known calibration signal (and source) is essential. A vibration calibrator produces a known vibration level at a known frequency, which can be used to generate what should be a known response from a vibration measurement system. If the system fails to measure the calibration level properly, then the test engineer must identify what the problem may be, and take corrective actions to ensure accurate data collection and reduction.

A vibration calibrator is a small, portable, vibrating device to which the transducer is attached, which produces a known vibration acceleration level of, for example, 10 m/s^2 at 159 Hz. This calibration level easily converts to velocity and displacement levels of 10 mm/s and 10 μ-m, respectively. Other calibrators may use other levels and frequencies, but in any case, the calibration level must be clearly indicated. In any case, the calibrator should be able to produce a steady vibration source level after it has been adjusted (sometimes automatically) for the weight of the given transducer attached to it.

Further, the calibrator must be certified to a higher level of calibration standard. Typically, calibration certification traceable to the U.S. National Institute of Standards and Technology (NIST, formerly NBS) are provided by the manufacturer. This ensures the user that the calibrator they are relying upon to give an accurate vibration source level has, itself, been calibrated to a higher accuracy reference.

Signal Conditioners

After the vibration signal has been transduced from the vibrating surface, various types of signal conditioning are routinely applied to the electronic signal before the signal is analyzed[9]. Devices are available to filter the signal into more limited bandwidths for analysis. This form of filtering is usually broadband in nature and is used to eliminate unwanted or excessive signals at either very low and/or high frequencies. Only the frequency range of interest should be analyzed, and consequently, the signal-to-noise (S/N) ratio of the signal will be maximized. A signal conditioner can also apply various degrees of signal amplification or attenuation, again intended to maximize the signal's S/N ratio. Gain adjustment steps are usually offered in 10 dB increments (where 10 dB = a factor of 3.16, and 20 dB = an order of magnitude). A signal conditioner can also perform an electrical integration of the original acceleration signal and convert it into signals proportional to either velocity or displacement. Finally, a signal conditioner performs an electrical impedance reduction which takes the signal from the transducer (at high impedance) and steps it down considerably to a low impedance level, making it acceptable for further input into an analyzer. [Note, for accelerometers needing a charge amplifier, the signal conditioner also acts to convert the transducer's proportional charge signal into a voltage proportional signal.]

Portable Whole-Body Vibration Meters

At the time of this writing, one instrument company continues to provide measurement equipment dedicated for human vibration assessment. Bruel & Kjaer personnel have played a significant role in establishing human vibration standards worldwide and in pioneering the development of dedicated human vibration measurement instrumentation.[12]

Battery powered portable instrumentation has been commercially available since the early 1980's with the development of a *Human Response Vibration Meter*[7]. This analog meter could perform overall (broadband) frequency weighted whole-body vibration measurements in accordance with ISO 2631 filter shapes for the Z-axis, and the X- and Y-axes. Three accelerometer signals could be plugged directly into the meter, however, only one signal was analyzed at a time. The resulting output from the meter gave each directional component's overall weighted vibration level (in m/s^2 or dB re 1 μ-m/s^2) and gave the exposure dose in percent (%). Time averaging of the input signal(s) was performed to better accommodate fluctuating vibration levels, and the signal was quantified through both a "peak" and an "RMS" detector. The results could be read on a numeric display, or could be transmitted through a digital interface or analog (AC and DC) outputs to data storage devices such as tape recorders and strip chart graphics plotters.

A more sophisticated, portable, human vibration meter was developed in the late 1980's. The *Human Vibration Unit* could be used in conjunction with a programmable *Sound Level Meter* (configured with appropriate firmware)[13]. The sound level meter simply acted as a precision voltage meter, and as such, the microphone was removed for this application. This system was capable of taking three accelerometer (X, Y and Z axes) inputs directly into the unit, and performing appropriate overall frequency weighted measurements in accordance with ISO 2631 on each signal simultaneously. However, in contrast to its predecessor, the system could perform a weighted combination (vector sum) of the three directional components to yield a single summed level, thus fulfilling more recent requirements in revised versions of ISO 2631. Peak or RMS level results in units of m/s^2 or dB re 1 μ-m/s^2 could be read on the meter's display, or could be output through the meter's digital interface or analog (AC or DC) outputs. Output results could be fed to data storage devices such as tape recorders, strip chart or digital graphics plotters, or personal computers. As an alternative, the meter could internally store up to 99 vibration measurement results, thus allowing data collected in the field to be stored and downloaded later at the test engineer's convenience.

Laboratory Based Whole-Body Analyzers

For a more rigorous evaluation of whole-body vibration on a frequency basis, spectrum analyzers are available from a number of vendors which can properly cover the frequency range of interest[13]. Frequency analysis allows the test engineer greater insight into the mechanisms producing the vibrations, how the laborer is responding to the vibration, and aids in the identification and determination of appropriate vibration mitigation treatments. To comply with ISO 2631 and ANSI S3.18 requirements for whole-body vibration analysis, the spectrum analyzer must be a constant percentage bandwidth analyzer capable of third octave analysis (bands from 1 to 80 Hz). These types of analyzers are called "real time analyzers", or RTA's. An RTA will take in a continuous input signal and will perform frequency analysis through multiple parallel filter bands (analog or digital) with a processor and mathematical algorithm fast enough to avoid losing any input data signal[11]. Real time analysis does not simply mean that a video monitor is provided in the device, however, this is almost always the case. The resulting levels displayed on the monitor can be configured for almost any engineering unit or dB reference desired. The monitor allows the user to see how vibration levels instantaneously fluctuate on a level-vs-frequency or level-vs-time display. Peak and RMS processors are incorporated, and the user can program the analyzer to output any number of different levels (including the performance of single or double integration to compute velocity and displacement levels from an original acceleration signal). Results of the analysis can typically be seen on a large video monitor, or can be stored internally in most analyzers. All forms of data transferal and output are usually available to connect an analyzer with a tape recorder, personnel computer, or graphics plotter.

Of particular interest to this author is the Bruel & Kjaer Type 2123 (or 2133) Real Time Analyzer. This laboratory based analyzer is programmable with user application programs [*available from the author*] which have been specifically configured for whole-body (and hand-arm) vibration analysis[12]. User defined weighting functions have been developed for each third octave band from 1 to 80 Hz. With these, the analyzer is capable of measuring not only whole-body vibration levels in the X, Y or Z directions in accordance with ISO 2631 and ANSI S3.18, but is also capable of computing the allowable exposure time for a laborer exposed to such whole-body vibration levels.

Another type of spectrum analyzer deserves mention here as well: the Fast Fourier Transform (FFT) analyzer[11]. An FFT is a constant bandwidth analyzer, not constant percentage. As such, while it offers engineers much greater insight for the diagnosis of vibration sources, it does not conform with whole-body vibration standards which require third octave band analysis.

Data Recorders (Analog Tape and DAT)

Often it will be essential, or at least advantageous, to tape record the original vibration signals transduced in the field. This is particularly important when dealing with one-of-a-kind events or difficult field measurement logistics. The tape recorded data can then be replayed in the convenience of a laboratory, and the necessary data reduction and analysis can be performed. If necessary, the archived data can always be re-analyzed at a later date for comparison or confirmation of earlier results.

Two basic types of tape recorders are currently available: analog and digital. Analog tape recorders have been used for decades and are familiar to most everyone as reel-to-reel or cassette tape recorders. However, any magnetic medium can be used as well, such as VHS tape cassettes. Analog tape recorders store data by altering the magnetic field strength on a continuously moving strip of magnetic tape in proportion to the input signal's altering voltage level. To be suitable for human vibration measurements, the analog tape recorder must be specifically designed to record very low frequency signals (less than 1 Hz). This is often referred to as "FM" recording. Depending on the length of the tape and the speed at which it is played (recorded), several hours of vibration data can be stored on one tape. However, the dynamic range (the lowest to highest level recordable on tape) is often limited with analog tape recorders to 30 to 50 dB.

More recently, digital audio tape (DAT) recorders have offered engineers greater ability to reliably capture and store vibration data in the field. DAT recorders store digitized data on a magnetic tape cassette in computer based format (bits and bytes). As such, many advantages are gained when connecting and transferring data to and from DAT recorders and other digitally based instruments. Also, a DAT recorder can store many more types of data on the same piece of tape; data such as time and date, event identification, tape position, and voice annotation, can all be recorded as well. DAT recorders easily cover the frequency range of interest for human vibration (actually down to DC). As with analog tape recorders, the frequency range and recordable time can be adjusted by changing the speed at which data is recorded on the tape, however, DAT recorders offer much greater dynamic ranges (on the order of 80 dB).

With any form of tape recorder, the important application issues are to ensure: that the recorder is configured to cover the dynamic and frequency range of interest; that sufficient signal-to-noise is measured to adequately replay the signal for analysis; that sufficient tape length is available to record the event of interest; and that the user has properly recorded a calibration signal on the tape and has voice (and/or written) documentation of the recorded events for the benefit of later replay.

V. Summary

This paper has presented an overview and explanation of the history and current state-of-the-art of occupationally-induced human whole-body vibration. A recommended step-by-step approach for recognizing, measuring, evaluating, and controlling whole-body vibration, was outlined. The fundamentals of vibration physics; potential vibration sources to which laborers may be exposed; and the propagation characteristics of vibration through the human body, were presented. Currently available national and international whole-body severity criteria and standards were summarized; and the components constituting a vibration measurement instrumentation chain, including such equipment's limitations, were discussed in detail.

It is hoped that this paper will serve to raise awareness and appreciation of occupational exposure to whole-body vibration and its significance as an occupational related hazard. Whole-body vibration can be evaluated, measured, and most importantly, controlled successfully. However, misguided or inappropriate vibration control treatments can actually lead to increased vibration exposure severity and can waste valuable vibration control funds. Therefore, skilled acoustical or vibration engineers should be consulted when challenging issues involving whole-body vibration are encountered.

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Figure 1: Single-Degree-of-Freedom Vibration Transmissibility Functions[10]

Figure 2: Measured Vibration Acceleration Transmissibility Through Various Portions of the Human Body[7]

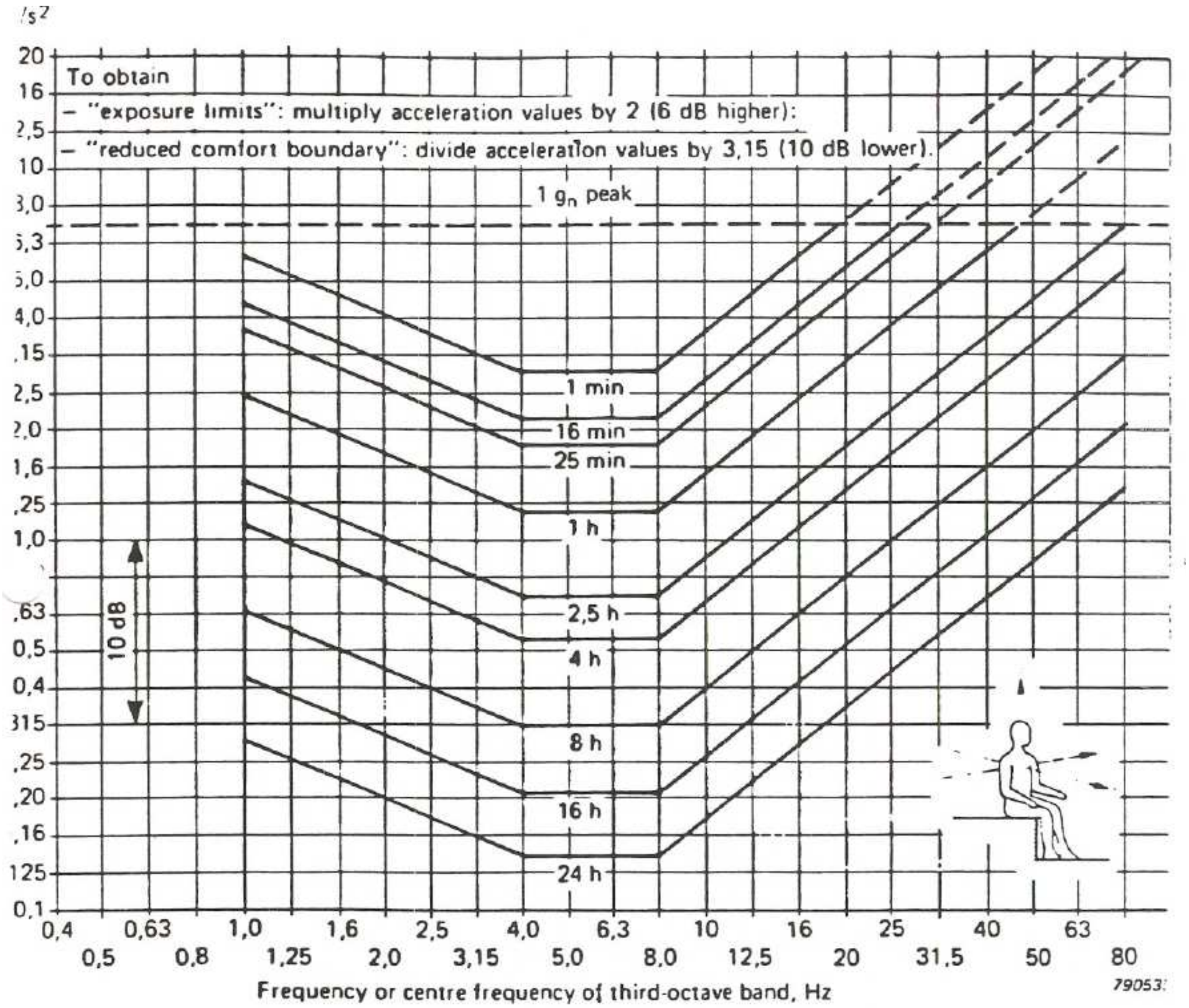

Figure 3: Whole-Body Vibration Exposure Criteria Limits in the Longitudinal (Z) Direction, per ISO 2631[1]

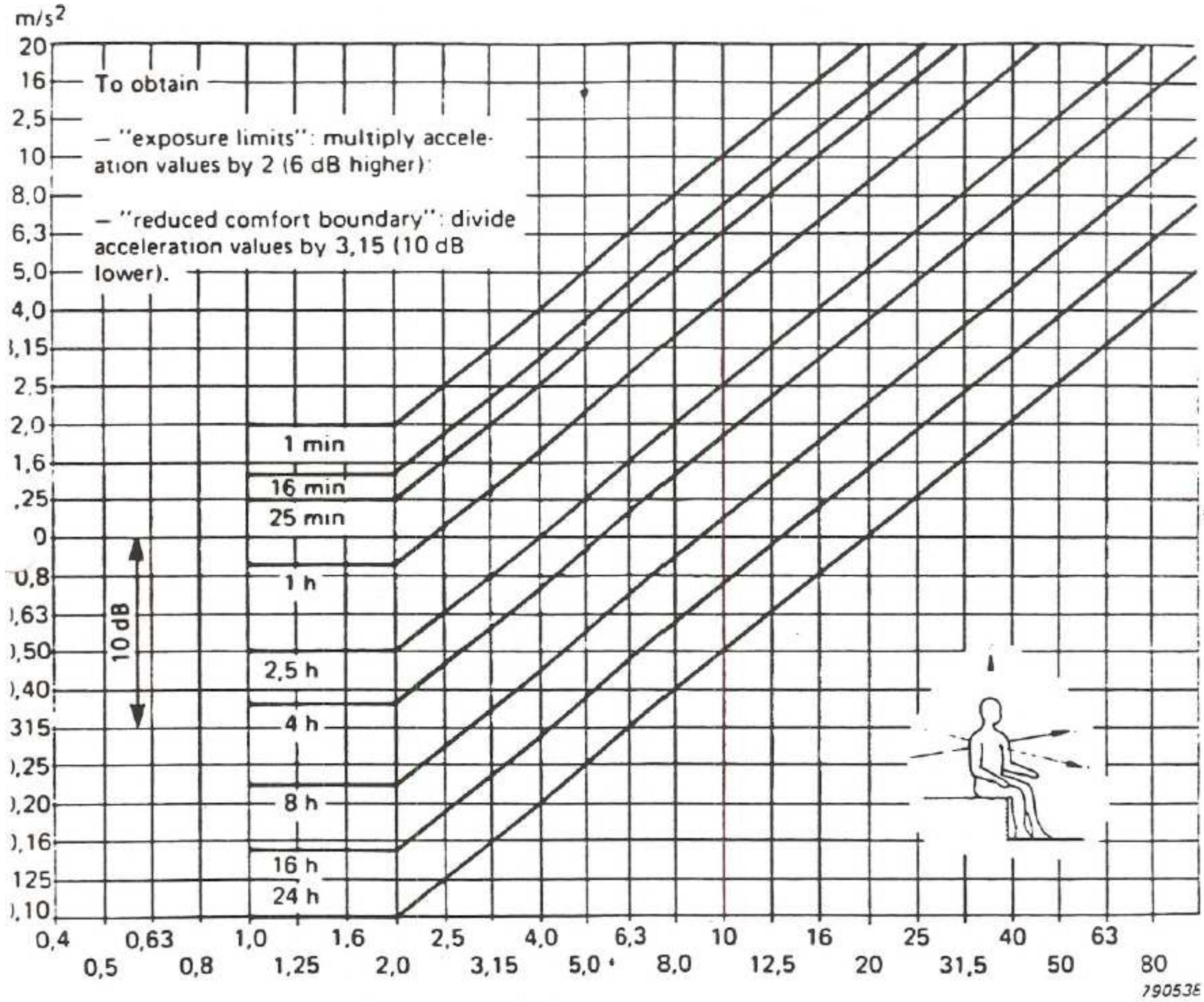

Figure 4: Whole-Body Vibration Exposure Criteria Limits in the Transverse (X, Y) Directions, per ISO 2631[1]