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Earth Moving Machine Whole-body Vibration and the Contribution of Sub-1Hz Components to ISO 2631-1 Metrics

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Abstract: Exposure to whole-body vibration (WBV) is an occupational hazard for operators of industrial vehicles, such as earth-moving machines. Quantification of WBV exposure in terms of impact on health forms one aspect of the Standard ISO 2631-1 (1997). Regarding assessment of risk to health, ISO 2631-1 (1997) states that if WBV components below 1 Hz are not 'relevant nor important' then they can be excluded from the assessment. In this paper the influence of sub-1 Hz components in WBV acquired from a sample of 46 earth moving machines is evaluated in terms of their contribution to ISO 2631-1 WBV exposure dose metrics: frequency weighted r.m.s. and the vibration dose value (VDV). For the majority of machines, a high proportion of the horizontal (x- and y-axis) WBV r.m.s. and VDV values was generated by sub-1 Hz vibration components; there was a much lower proportion of the vertical (z-axis) vibration generated by such components.

Key words: Whole-body vibration, Vibration, Frequency weighting filter, Frequency weighting curve, ISO 2631-1, Vibration dose value, Earth moving machine, Health

Introduction

Occupational exposure to whole-body vibration (WBV) is a hazard linked to several adverse health effects. The most widely reported pathogenic effects of WBV exposure include the occurrence of lower back pain[1–4] although other reported effects include increased prevalence of herniated discs and neck-shoulder disorders[5]. Vibration can also adversely affect comfort and performance[6]. In order to assist in addressing the risks to health posed by occupational exposure to WBV, the European Physical Agents (Vibration) Directive (PA(V)D)[7] specifies limits on daily occupational WBV exposure. The PA(V)D mandates application of ISO 2631-1[8] as the metrological framework for measurements of daily WBV exposure severity and the application of the appropriate frequency weightings[9].

Within the context of impact on health, the methods prescribed by ISO 2631-1 (1997) stipulate evaluation of WBV within the frequency range 0.5 Hz to 80 Hz. However, the standard also states that when assessing WBV in terms of impact on health "*If it has been established that the frequency range below 1 Hz is not relevant nor important, a frequency range from 1 Hz to 80 Hz can be substituted*". ISO 2631-1 does not give criteria by which in one can deem WBV components below 1 Hz as 'not relevant nor important'. One interpretation of the statement could be that if there exists negligible vibration energy below 1 Hz, then there is no need to measure vibration using instrumentation capable of measuring such low frequencies as it is 'not important' (although this would mean that the instrumentation would fail to meet requirements specified in ISO 8041[10]). Another possible interpretation could be that if the vibration is operator-induced then it is 'not relevant' to an assessment of vibration emission, as it is not caused by the machine per se, but by the driver; an example of this could be an individual driving a machine with repeated acceleration and deceleration with a short cycle time. Energy from each braking/acceleration manoeuvre would constitute part of the measured acceleration signal and, if there are a high number of such manoeuvres, these could dominate the

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low frequency components of the measured vibration. In this case, filtering out low frequency components could have a considerable impact on the reported vibration emission values.

The following presents a quantitative evaluation of sub-1 Hz components of tri-axial WBV vibration acquired from various types of earth moving machine. The aim of the paper is to provide an indication of the influence of applying the '1 Hz' filter described in ISO 2631-1 (1997), and the use of alternative high-pass filters in the measurement chain for the target machines. The contribution of sub-1 Hz components is evaluated in terms of their contribution to WBV metrics used by ISO 2631-1, namely frequency weighted root mean square (r.m.s.) and vibration dose value (VDV, a metric for the evaluation of WBV exposures that incorporate shocks and other transients).

Methodology

Whole-body vibration data was acquired from a sample of different types of earth moving machine. The sample included wheel loaders, track type loaders, track type tractors (i.e. dozers), tele-handlers and various other categories of earth-moving machine; data was acquired from 46 machines in total. Table 1 provides the following information for each machine: type of machine, measurement duration, and task executed. During the acquisition of each measurement, the machine, operated by its usual driver, executed a task typical of that carried out within the environment in which the machine was operated during data acquisition. The environments within which data was acquired included open-pit mines, construction sites, and a scrap metal yard. Vibration data for machines WL11 to WL18 and all the TH machines can be considered as having been acquired during worst case operating conditions. They were acquired during a test session at a proving ground in which the machine carried out operations designed as examples of extreme usage; these operations would not usually be representative of tasks/driving styles that would be executed/maintained on site for long durations.

The data acquired from each machine was frequency weighted with an implementation of 'ideal' W_d and W_k frequency weighting curves (as defined in ISO 8041) and a set of 19 W_d and W_k frequency weighting filters possessing a high-pass filter stage with a cutoff frequency other than the 0.4 Hz specified for 'ideal' frequency weighting filters. The cutoff frequency of the high-pass filter stage of each of the 19 modified W_k and W_d filters was within the range of 0 to 1 Hz (increments of 0.053 Hz, i.e. 1/19 Hz). In accordance with ISO 2631-1, the W_d filters were applied to the x- and y- axis of the data sets and the W_k filters applied to the z-axis. Figure 1 presents a plot of the W_d and Fig. 2 the W_k frequency weightings applied.

Both the frequency weighted r.m.s. and VDV of the acceleration in each axis of the three measured for every WBV data set were calculated as defined by equations (1) and (2) respectively. In equations (1) and (2) a_w refers to the frequency weighted acceleration measured for the axis and T the measurement period. For each vibration axis of each data set, the percentage difference between the frequency weighted r.m.s. value measured when the corresponding 'ideal' frequency weighting filter was applied and the value measured after application of the corresponding frequency weighting filter incorporating an alternative high-pass cut-off frequency was calculated through equation (3). Equation (4) was applied in order to calculate the percentage difference between the VDV value measured when the corresponding 'ideal' frequency weighting filter was applied and the VDV value measured when the corresponding filter incorporating an alternative high-pass cut-off frequency was applied. In equations (3) and (4) r.m.s.$_{\text{diff\%}}$ and VDV$_{\text{diff\%}}$ denote the percentage difference in the metric that occurred when a frequency weighting filter incorporating an alternative high-pass cutoff frequency was applied; subscripts $_{\text{IFW}}$ and $_{\text{AHPFW}}$ respectively refer to the metric value measured after application of the 'ideal' frequency weighting and the value of the metric measured after the application of a frequency weighting filter incorporating an alternative high-pass cut-off frequency.

$$r.m.s. = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{1/2} \quad (1)$$

$$VDV = \left[\int_0^T a_w^4(t)dt\right]^{1/4} \quad (2)$$

$$r.m.s._{\text{diff\%}} = \frac{r.m.s._{\text{AHPFW}} - r.m.s._{\text{IFW}}}{r.m.s._{\text{IFW}}} \times 100 \quad (3)$$

$$VDV_{\text{diff\%}} = \frac{VDV_{\text{AHPFW}} - VDV_{\text{IFW}}}{VDV_{\text{IFW}}} \times 100 \quad (4)$$

ISO 8041[10] specifies tolerance intervals for the W_d and W_k frequency weightings with limits of +12% and –11% in the most sensitive frequency range and wider limits outside this range. Therefore, instrumentation can provide results that differ from those acquired using implementations of 'ideal' frequency weightings by 12% and still be ISO 8041 compliant. In some cases two pieces of instrumentation could both comply with ISO 8041 and produce even greater differences. For the purposes of this paper, differences of less than 12% are considered as

Table 1. Information on each element of the WBV data set

Reference	Machine Type	Action Performed During Data Acquisition	Duration (min)
WL1	Wheel Loader	Loading coal into train	146
WL2	Wheel Loader	Loading granite into aggregate lorries	189
WL3	Wheel Loader	Loading coal into crusher	127
WL4	Wheel Loader	Loading coal into crusher	80
WL5	Wheel Loader	Loading scrap metal into lorries	168
WL6	Wheel Loader	Loading scrap metal into lorries	81
WL7	Wheel Loader	Pushing shot in after blasting (quarry face)	48
WL8	Wheel Loader	Loading granite into aggregate lorries	237
WL9	Wheel Loader	Loading granite into aggregate lorries	170
WL10	Wheel Loader	Loading granite into aggregate lorries	118
WL11	Compact Wheel Loader	Rough terrain (laden)	12
WL12	Compact Wheel Loader	Stock piling	11
WL13	Compact Wheel Loader	Driving on concrete (unladen)	9
WL14	Compact Wheel Loader	Rough terrain (unladen)	12
WL15	Compact Wheel Loader	Rough terrain (laden)	11
WL16	Compact Wheel Loader	Stock piling	12
WL17	Compact Wheel Loader	Rough terrain (unladen)	11
WL18	Compact Wheel Loader	Driving on concrete (unladen)	9
TTL1	Track-Type Loader	Levelling superficial material	54
TTL2	Track-Type Loader	Levelling Six F demolition material	135
TTL3	Track-Type Loader	Levelling demolition material on steep ground	66
TTL4	Track-Type Loader	Levelling Six F demolition material	59
TTL5	Track-Type Loader	Levelling Six F demolition material	118
TTL6	Track-Type Loader	Levelling superficial material/Loading aggregate lorry	49
TTL7	Track-Type Loader	Levelling superficial material	60
TTL8	Track-Type Loader	Levelling top soil mixed with stone/Loading aggregate lorry	79
TTT1	Track-Type Tractor	Moving clay and superficials	211
TTT2	Track-Type Tractor	Smoothing ground in the superficial area	204
TTT3	Track-Type Tractor	Levelling superficial ground Six F & top soil	71
TTT4	Track-Type Tractor	Moving granite	326
TTT5	Track-Type Tractor	Moving coal	146
TTT6	Mini Track-Type Tractor	Moving superficials	123
TTT7	Mini Track-Type Tractor	Moving superficials	124
TH1	Telehandler	Rough terrain (laden 1,410 kg)	10
TH2	Telehandler	Driving on concrete (laden)	7
TH3	Telehandler	Driving on concrete (unladen)	6
TH4	Telehandler	Static/Hydrostatic functions (unladen)	8
TH5	Telehandler	Static/Hydrostatic functions (laden 1,410 kg)	4
TH6	Telehandler	Rough terrain (unladen)	10
AT	Articulated Truck	Transporting superficials	187
Cptr	Compactor	Compacting superficial material	156
MG1	Motor Grader	Smoothing ground in clay and lime area	157
MG2	Motor Grader	Smoothing track between coal mine and storage area	104
MH	Material Handler	Lifting scrap metal to be crushed	186
OHT	Off Highway Truck	Granite delivery cycle (quarry face - material process plant)	242
SSL	Skid Steer Loader	Loading sand bags	29

The information includes element reference, type of machine data was acquired from, the action performed by the machine during data acquisition, and the duration of measurement.

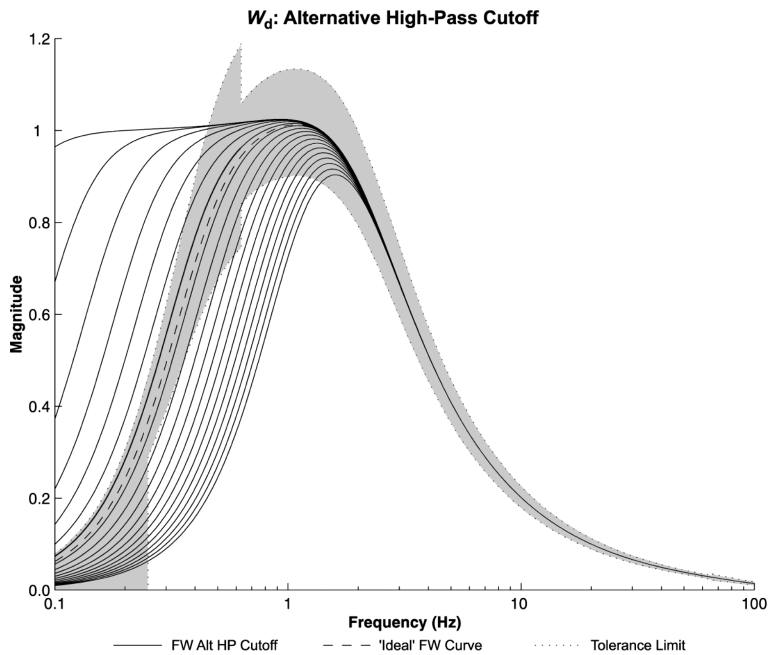

Fig. 1. ***W_d*** **frequency weighting curves incorporating high-pass Butterworth filters with alternative high-pass cutoff frequencies ranging from 0.053 Hz to 1 Hz and frequency weighting curve tolerance intervals (shaded) specified by ISO 8041.**

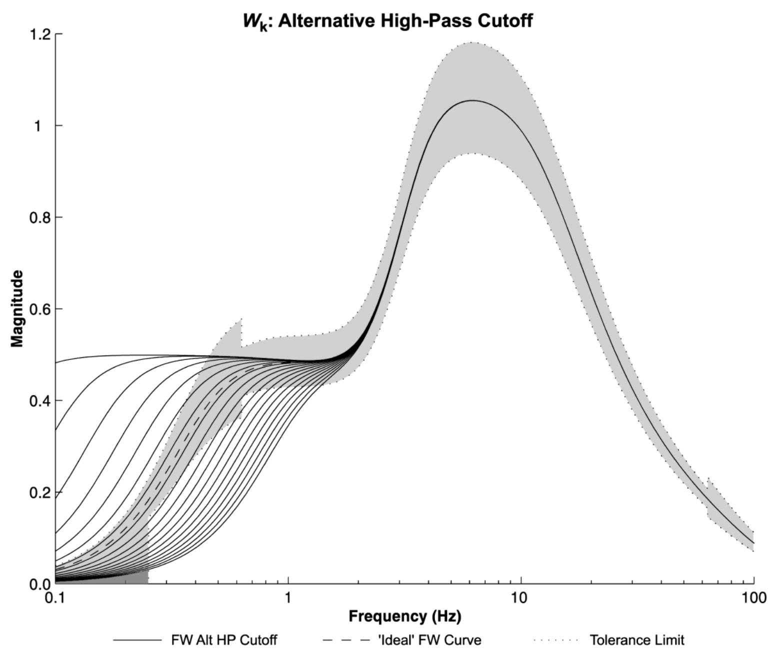

Fig. 2. ***W_k*** **frequency weighting curves incorporating high-pass Butterworth filters with alternative high-pass cutoff frequencies ranging from 0.053 Hz to 1 Hz and frequency weighting curve tolerance intervals (shaded) specified by ISO 8041.**

'unimportant', as this is equivalent to differences which are allowable due to tolerances in the frequency weighting alone.

Data collection and filter implementation

A tri-axial accelerometer (S2-10G-MF) was used for measurement of WBV as specified by ISO 2631-1; this was mounted in a seat pad and placed on the surface of the machine operator's seat. Data from each accelerometer axis was acquired using a Biometrics P3X8 data logger. The per-axis sampling rate of the data acquisition was 500 samples per second and the sampling resolution 13 bits. A filter consisting of an eighth order elliptical filter with a cut-off frequency of 100 Hz was applied as an anti-aliasing filter within the measurement system.

The frequency weighting curves were implemented as time domain filters. For both W_d and W_k, the average difference between the magnitude of the 'ideal' frequency weighting curve as defined in ISO 8041 and that of its implementation was 0.019%. The average phase response approximation error was 0.74 degrees (approximately 1%) for both frequency weightings.

Results

Figure 3 presents a plot of high-pass filter cut-off frequency versus r.m.s.$_{\text{diff\%}}$ for each of the earth-moving machine types. Nominally flat lines occurred for occasions when the worst axis was vertical (WL two data sets; TTL two data sets; TTT three data sets; TH four data sets; Misc two data sets; see also Tables 2 and 3). Although most machines showed a clear decrease in the measured worst-axis vibration magnitude as the cutoff frequency was increased from that used with an 'ideal' frequency filter (0.4 Hz) to 1 Hz this had a minimal effect for some other machines. This was due to the direction of the worst axis: if the worst axis was in the vertical direction the influence of changing the cutoff frequency was small. The positive values of r.m.s.$_{\text{diff\%}}$ in each of the plots presented in Fig. 4 occur when the high-pass filter cut-off frequency is decreased below 0.4 Hz; they result from the presence of non-negligible sub-0.4 Hz components.

Table 2 presents the r.m.s. and VDV values calculated after application of the 'ideal' W_d and W_k frequency weighting curves for individual and combined axes. In the case of the x- and y- axes a scaling factor of 1.4 was applied in accordance with ISO 2631-1. VDV values have been normalised to an eight hour dose.

Table 3 presents the contribution of frequency components below 1 Hz to the r.m.s. and VDV values presented in Table 2. In the x-axis the median of the absolute value of $r.m.s._{\text{diff\%}}$ was 21.4%, in the y-axis 15.0%, and in the z-axis 1.1%; a similar trend was observed in the case of the VDV: in the x-axis the median of absolute $VDV_{\text{diff\%}}$ was 20.4%, in the y-axis the median was 14.7%, and in the z-axis the median was 0.5%. The occurrence of positive $VDV_{\text{diff\%}}$ values in the z-axis for TTL4 and TTL6 and in the y-axis for TTL3 is due to the difference in phase response between the 'ideal' frequency weighting and filters incorporating a Butterworth high-pass filter stage with a cut-off frequency of 1 Hz.

Discussion

The purpose of the study was to quantitatively assess the result of a specific interpretation of an ambiguous element of ISO 2631-1 (1997), specifically, that which refers to the inclusion of sub-1 Hz frequency components when assessing WBV exposure in terms of impact on health. Although this paper reports vibration emission values for a range of earth moving machines, it is not recommended that these are used as a basis for risk assessments, as several of the data sets were obtained on proving grounds, where terrain and tasks were designed to be extreme and were not representative of typical working practices. The vibration profiles and factors affecting them have been discussed elsewhere[11, 12].

ISO 2631-1 (1997) allows for vibration at frequencies below 1 Hz to be neglected if the frequency range below 1 Hz is not relevant nor important. For health risk assessments, the worst axis of vibration is usually considered, and this is mandated by the EU Physical Agents (Vibration) Directive. Based on the data presented in this paper, one could deem that vertical vibration below 1 Hz in the sample of earth-moving machine WBV measurements acquired is not important: only one of the data sets was affected by more than 10% (maximum of 12.4% (r.m.s.)).

For machines within the sample in which horizontal vibration dominated the measured WBV, the effect of omitting sub-1 Hz vibration was generally greater than 20%. The low frequency component of the vibration within this sample must therefore be considered as an important element of the total vibration exposure. Although in many cases the low frequency component consists of task-induced vibration (e.g. for a cyclic loading task with short duration) and it could be argued that it represents the characteristics of the task rather than the machine; the origin of the vibration will not directly affect the biomechanical responses to it. Risk assessments (i.e. operator focused) should always be carried out using data obtained whilst the machine is carrying out typical tasks and in combination with a task analysis to ensure that measurements and durations are representative. The data presented in this paper does not support any assertion that WBV below 1 Hz is not relevant for risk assessment.

Some authors have noted that the W_d frequency weighting and multiplying factor do not represent biomechanical responses when there is backrest contact, particularly in the fore-and-aft direction[13, 14]. These show that whilst the W_d weighting peaks at 1 Hz, the biomechanical response peaks at about 3 Hz with backrest contact[15, 16]. Further work is required to directly link biomechanical responses to health risk.

In the case of track type loaders and track type trac-

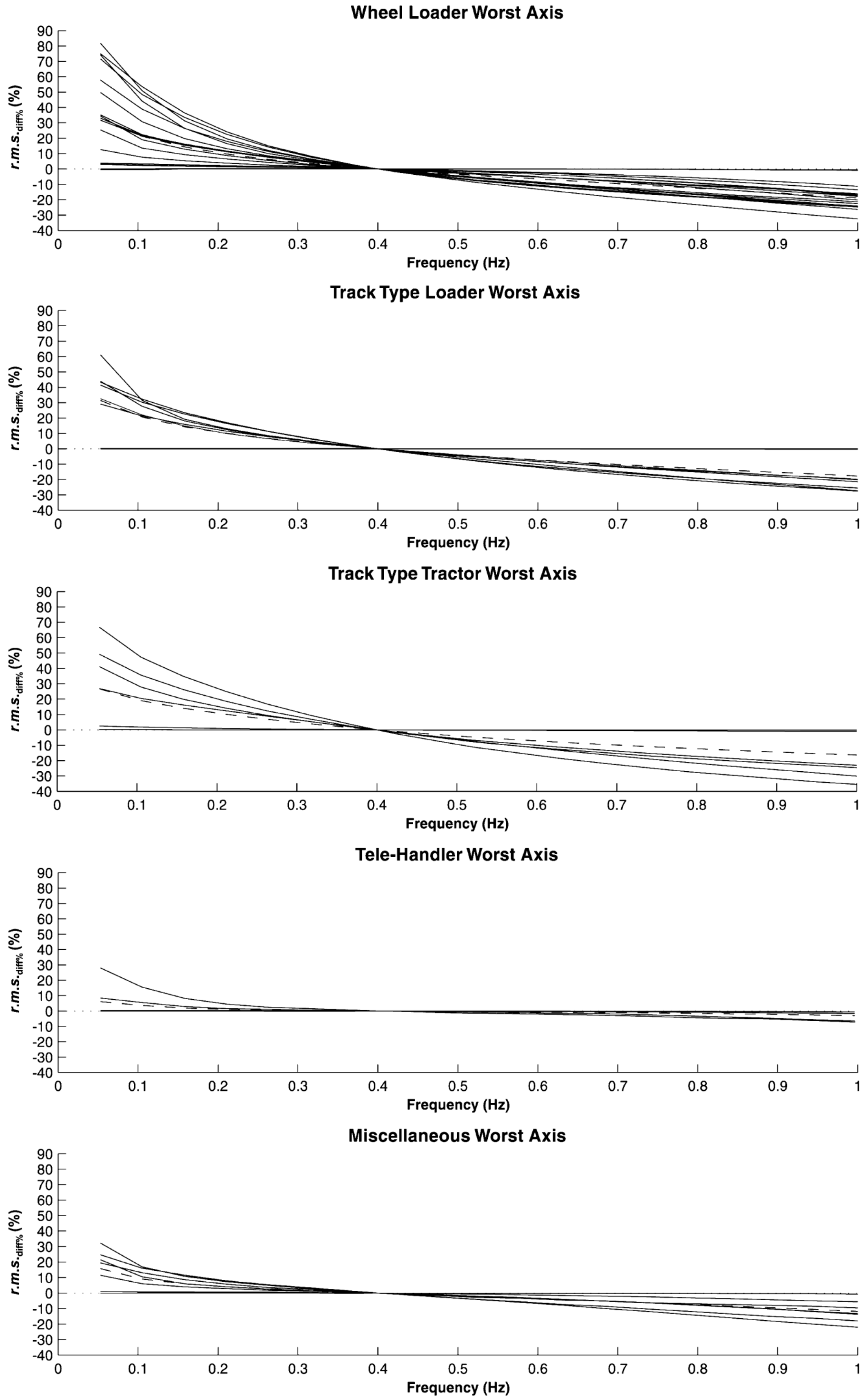

Fig. 3. Worst axis $r.m.s._{\text{diff}\%}$ versus high-pass filter cutoff frequency.
Each line represents data for one machine (- - - - - : Mean of worst axis $r.m.s._{\text{diff}\%}$).

tors, the median of the contribution of sub-1Hz vibration to y-axis (lateral) vibration was approximately 11% and 12% with maximum values of 20.9% and 21.5% respectively; y-axis vibration did not constitute the worst axis vibration for any of these machines. In the case of the tele-handlers, the median contribution of sub-1 Hz components to the frequency weighted r.m.s. of x-axis (fore-aft) vibration was 7% with a maximum value 9.3%; the x-axis constituted the worst axis in two instances of this machine type. Given the variability of operating envi-

Table 2. Values of *r.m.s.* and *VDV* measured in the x-, y- and z-axis of the data after the application of 'ideal' frequency weighting filters

	X-Axis		Y-Axis		Z-Axis		Combined Axes	
	r.m.s. (m/s^2)	*VDV* ($m/s^{1.75}$)	*r.m.s.* (m/s^2)	*VDV* ($m/s^{1.75}$)	*r.m.s.* (m/s^2)	*VDV* ($m/s^{1.75}$)	*r.m.s.* (m/s^2)	*VDV* ($m/s^{1.75}$)
WL1	0.59	13.49	0.49	10.88	0.37	11.23	0.85	15.85
WL2	0.44	11.06	0.71	28.26	0.32	14.81	0.89	28.93
WL3	0.39	11.10	0.32	7.92	0.26	8.95	0.57	12.64
WL4	0.39	11.39	0.32	6.98	0.29	18.08	0.58	18.84
WL5	0.59	14.65	0.42	13.48	0.31	11.65	0.79	17.67
WL6	0.57	15.54	0.48	13.59	0.36	9.67	0.83	17.83
WL7	0.53	13.62	0.61	11.59	0.41	10.03	0.91	15.82
WL8	0.49	12.65	0.40	12.99	0.32	19.71	0.71	21.28
WL9	0.62	15.15	0.51	14.27	0.43	16.97	0.91	20.51
WL10	0.64	14.66	0.50	12.42	0.42	11.63	0.91	17.24
WL11	1.94	35.69	1.83	18.34	1.22	13.69	2.93	36.48
WL12	1.49	29.09	1.36	13.69	0.96	9.52	2.23	29.52
WL13	0.65	12.00	0.40	3.99	0.70	6.53	1.04	12.29
WL14	1.79	32.84	2.17	22.76	1.12	11.03	3.03	34.68
WL15	2.16	39.76	1.87	19.23	1.19	12.64	3.09	40.39
WL16	1.43	27.06	1.36	14.52	0.95	10.02	2.19	27.72
WL17	1.67	31.05	2.21	22.90	1.10	11.36	2.98	33.24
WL18	0.63	14.32	0.40	4.58	0.82	8.09	1.11	14.71
WL Mean	**0.95**	**19.73**	**0.91**	**14.02**	**0.64**	**11.98**	**1.48**	**23.09**
WL Median	**0.63**	**14.66**	**0.51**	**13.54**	**0.43**	**11.30**	**0.91**	**19.68**
TTL1	0.71	18.96	0.47	10.25	0.61	13.99	1.05	20.56
TTL2	0.63	14.89	0.46	9.94	0.61	17.40	0.99	19.70
TTL3	0.77	17.51	0.45	21.95	0.57	15.36	1.06	24.86
TTL4	0.49	13.65	0.33	7.24	0.44	14.45	0.74	16.87
TTL5	0.57	14.32	0.35	8.40	0.83	22.82	1.07	23.75
TTL6	0.57	14.08	0.34	6.73	0.48	9.39	0.82	14.89
TTL7	0.97	21.04	0.64	10.49	0.83	14.50	1.43	22.41
TTL8	0.62	14.71	0.44	8.67	0.69	18.26	1.03	20.11
TTL Mean	**0.67**	**16.14**	**0.44**	**10.46**	**0.63**	**15.77**	**1.02**	**20.39**
TTL Median	**0.63**	**14.80**	**0.45**	**9.31**	**0.61**	**14.93**	**1.04**	**20.34**
TTT1	0.75	19.28	0.56	15.15	0.59	14.23	1.11	21.94
TTT2	0.49	13.04	0.28	8.71	0.63	14.44	0.85	16.72
TTT3	0.54	14.06	0.33	5.98	0.66	10.52	0.91	15.14
TTT4	0.39	30.37	0.40	36.06	0.78	42.17	0.96	48.87
TTT5	0.65	18.64	0.51	12.99	0.62	17.37	1.03	22.14
TTT6	1.00	26.52	0.47	11.70	0.50	13.22	1.21	27.16
TTT7	0.72	16.38	0.44	9.83	0.50	18.87	0.98	21.36
TTT Mean	**0.65**	**19.76**	**0.43**	**14.35**	**0.61**	**18.69**	**1.01**	**21.36**
TTT Median	**0.65**	**18.64**	**0.44**	**11.7**	**0.62**	**14.44**	**0.98**	**21.94**
TH1	1.11	21.64	1.04	10.50	1.26	14.80	1.98	22.99
TH2	0.47	9.01	0.22	2.21	0.74	6.53	0.90	9.58
TH3	0.48	9.15	0.21	2.28	0.83	7.38	0.98	10.00
TH4	0.29	8.27	0.10	1.49	0.26	3.84	0.40	8.37
TH5	0.38	8.97	0.10	1.25	0.26	2.95	0.47	9.00
TH6	1.16	21.79	1.04	10.57	1.29	14.35	2.02	23.01
TH Mean	**0.65**	**13.14**	**0.45**	**4.72**	**0.77**	**8.31**	**1.13**	**13.82**
TH Median	**0.48**	**9.08**	**0.22**	**2.25**	**0.79**	**6.96**	**0.94**	**9.79**
AT	0.60	14.64	0.50	13.63	0.54	14.73	0.95	18.90
Cmptr	0.22	6.75	0.34	10.02	0.17	6.07	0.44	10.78
MG1	0.42	11.29	0.51	10.69	0.43	10.21	0.79	14.16
MG2	0.53	11.49	0.61	12.39	0.50	10.17	0.95	15.08
MH	0.25	10.56	0.21	7.68	0.17	10.14	0.37	12.76
OHT	0.35	8.69	0.36	9.94	0.44	11.57	0.67	13.52
SSL	0.42	13.78	0.27	5.97	0.46	19.57	0.68	20.71
Misc Mean	**0.40**	**11.03**	**0.40**	**10.04**	**0.39**	**11.78**	**0.69**	**15.13**
Misc Median	**0.42**	**11.29**	**0.36**	**10.02**	**0.44**	**10.21**	**0.68**	**14.16**
All Mean	**0.73**	**16.93**	**0.62**	**11.63**	**0.61**	**13.15**	**1.16**	**20.46**
All Median	**0.59**	**14.48**	**0.46**	**10.54**	**0.56**	**12.15**	**0.95**	**19.30**

VDVs are extrapolated to an 8-h dose.

Table 3. Values of $r.m.s._{\mathrm{diff\%}}$ and $VDV_{\mathrm{diff\%}}$ measured in the x-, y- and z-axis of the data after the application of frequency weighting filters incorporating a second order high-pass Butterworth filter with a cut-off frequency of 1 Hz

	X-Axis		Y-Axis		Z-Axis		Combined Axes	
	$r.m.s._{\mathrm{diff\%}}$ (%)	$VDV_{\mathrm{diff\%}}$ (%)	$r.m.s._{\mathrm{diff\%}}$ (%)	$VDV_{\mathrm{diff\%}}$ (%)	$r.m.s._{\mathrm{diff\%}}$ (%)	$VDV_{\mathrm{diff\%}}$ (%)	$r.m.s._{\mathrm{diff\%}}$ (%)	$VDV_{\mathrm{diff\%}}$ (%)
WL1	–22.6	–20.8	–20.6	–17.0	–2.2	–7.1	–17.5	–15.9
WL2	–30.8	–30.9	–32.5	–37.4	–12.4	–11.2	–29.1	–34.1
WL3	–21.5	–17.5	–21.7	–19.8	–1.2	–0.4	–17.3	–12.1
WL4	–24.7	–23.0	–22.0	–19.2	–1.4	–0.3	–17.6	–1.9
WL5	–24.1	–24.4	–17.3	–9.3	–1.0	–0.3	–18.5	–13.7
WL6	–24.2	–20.0	–20.6	–27.4	–2.2	–1.7	–18.2	–20.0
WL7	–23.7	–21.7	–20.2	–18.8	–1.7	–1.0	–17.8	–13.8
WL8	–26.3	–24.7	–21.3	–19.9	–1.3	–0.3	–18.8	–5.7
WL9	–24.9	–22.9	–20.7	–19.0	–1.4	–0.9	–17.4	–10.4
WL10	–24.7	–21.9	–20.4	–17.1	–1.4	–0.8	–18.1	–14.2
WL11	–16.8	–17.1	–18.2	–18.9	–2.0	–1.7	–14.6	–15.3
WL12	–17.7	–17.2	–17.5	–16.1	–1.5	–1.2	–14.2	–15.1
WL13	–5.2	–5.0	–8.7	–8.0	–0.9	–0.7	–4.1	–2.8
WL14	–12.0	–12.4	–17.4	–18.7	–1.8	–1.7	–13.4	–16.2
WL15	–11.3	–11.5	–14.6	–15.1	–1.7	–1.6	–11.1	–12.0
WL16	–16.2	–17.1	–13.8	–13.3	–1.2	–0.8	–12.3	–13.3
WL17	–11.1	–12.0	–13.6	–14.6	–1.3	–1.0	–11.1	–13.3
WL18	–3.6	–3.2	–8.5	–7.8	–0.6	–0.4	–3.0	–1.8
WL Mean	**–19.0**	**–18.0**	**–18.3**	**–17.6**	**–2.1**	**–1.8**	**–15.2**	**–12.9**
WL Median	**–22.1**	**–18.8**	**–19.2**	**–17.9**	**–1.4**	**–1.0**	**–17.4**	**–13.5**
TTL1	–27.6	–24.7	–9.8	–7.7	–0.3	–0.1	–14.2	–10.8
TTL2	–19.9	–20.7	–4.9	–5.0	–0.3	0.0	–9.4	–5.4
TTL3	–27.3	–26.3	–20.9	6.5	–0.5	–0.5	–17.8	2.6
TTL4	–25.6	–25.9	–6.3	–6.5	–0.5	0.1	–12.2	–4.6
TTL5	–16.6	–13.2	–10.8	–16.2	0.0	–0.2	–5.9	–1.6
TTL6	–21.5	–20.1	–12.3	–8.4	–0.4	2.2	–12.4	–9.7
TTL7	–20.3	–20.0	–11.4	–10.8	–0.4	-0.2	–11.2	–11.3
TTL8	–24.4	–26.0	–10.1	–11.9	–0.3	0.0	–10.2	–3.7
TTL Mean	**–22.9**	**–22.1**	**–10.8**	**–7.5**	**–0.3**	**0.2**	**–11.7**	**–5.6**
TTL Median	**–23.0**	**–22.7**	**–10.5**	**–8.1**	**–0.4**	**–0.1**	**–11.7**	**–5.0**
TTT1	–35.5	–35.9	–21.5	–24.1	–0.5	–0.3	–21.3	–25.2
TTT2	–31.8	–29.7	–7.9	–12.5	–1.0	–1.1	–11.4	–11.6
TTT3	–28.6	–29.9	–11.2	–17.2	0.0	–0.1	–10.0	–14.5
TTT4	–14.9	–7.9	–6.0	–7.9	–0.1	–1.2	–3.6	–4.6
TTT5	–23.1	–27.8	–13.3	–14.0	–0.2	0.0	–12.0	–12.7
TTT6	–30.1	–33.3	–11.9	–15.0	–1.2	–0.9	–21.3	–28.5
TTT7	–24.6	–23.4	–11.9	–12.7	–0.6	–0.2	–15.2	–6.2
TTT Mean	**–26.9**	**–26.8**	**–12.0**	**–14.8**	**–0.5**	**–0.5**	**–13.5**	**–14.8**
TTT Median	**–28.6**	**–29.7**	**–11.9**	**–14.0**	**–0.5**	**–0.3**	**–12.0**	**–12.7**
TH1	–9.3	–9.6	–17.5	–16.2	–1.7	–1.1	–8.5	–4.9
TH2	–6.5	–6.8	–15.6	–13.4	–0.5	–0.5	–2.8	–1.5
TH3	–5.3	–4.7	–18.3	–19.6	–0.6	–0.5	–2.5	–1.0
TH4	–7.2	–6.7	–18.8	-10.0	–0.4	–0.2	–5.3	–3.5
TH5	–6.6	–6.0	–14.9	–14.0	–0.4	–0.1	–4.5	–4.3
TH6	–7.1	–7.0	–20.1	–20.1	–1.6	–1.0	–7.8	–5.0
TH Mean	**–7.0**	**–6.8**	**–17.5**	**–15.6**	**–0.9**	**–0.6**	**–5.2**	**–3.4**
TH Median	**–6.9**	**–6.8**	**–17.9**	**–15.1**	**–0.6**	**–0.5**	**–4.9**	**–3.9**
AT	–22.1	–22.5	–15.0	–14.7	–5.4	–5.2	–14.8	–13.8
Cmptr	–26.6	–27.6	–18.0	–19.0	–1.8	–0.4	–17.7	–17.6
MG1	–20.5	–24.6	–13.7	–13.6	–1.4	–0.9	–12.1	–13.3
MG2	–18.7	–18.9	–13.3	–12.1	–1.6	–1.1	–11.6	–10.7
MH	–9.7	–3.9	–14.2	–3.6	–0.6	0.0	–10.7	–2.4
OHT	–21.2	–20.6	–39.2	–43.0	–5.7	–3.9	–19.3	–14.3
SSL	–17.8	–15.8	–10.5	–9.5	–0.7	–0.1	–8.8	–0.7
Misc Mean	**–19.5**	**–19.1**	**–17.7**	**–16.5**	**–2.5**	**–1.7**	**–13.6**	**–10.4**
Misc Median	**–20.5**	**–20.6**	**–14.2**	**–13.6**	**–1.6**	**–0.9**	**–12.1**	**–13.3**
All Mean	**–19.4**	**–18.8**	**–15.8**	**–15.0**	**–1.4**	**–1.1**	**–12.8**	**–10.3**
All Median	**–21.4**	**–20.4**	**–15.0**	**–14.7**	**–1.1**	**–0.5**	**–12.3**	**–11.1**

ronments and operating styles, and the task-dependency of WBV sub-1 Hz components must be incorporated within vibration assessments in order to conduct them accurately.

This paper has highlighted that sub-1 Hz components are important, are non-negligible and must be taken into account when assessing WBV exposure in terms of impact on health for the earth moving machines as sampled in this study. Alternative results could be obtained for other types of environment in which individuals might be exposed to WBV. This paper shows that for some machines considerable acceleration components occur below 0.4 Hz and it is therefore recommended that WBV measurements include these, and present results in the frequency domain.

Conclusions

A high proportion of the WBV energy measured in a sample of 46 earth-moving machines is located in the sub-1 Hz region of the frequency spectrum. In some instances more than a quarter of the vibration r.m.s. value measured in the horizontal axes was generated by components below 1 Hz. In the case of the z-axis generally less than 1% of the vibration energy was located below 1 Hz. Similar results were observed for the VDV.

It is recommended that the full frequency range is used for all WBV measurements. In order to further establish the 'relevance' of components below 1 Hz additional investigations are required.

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