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Inter-cycle variation in whole-body vibration exposures of operators driving track-type loader machines

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Abstract

Whole-body vibration (WBV) measurements are an important aspect of performing risk assessments for those exposed to vibration. A large array of variables affect the outcome of a vibration measurement and its extrapolation to a daily dose measure: e.g. variability in driving style, road surface roughness, loading. The variability in vibration emission is an inherent property for most vibrating environments and there is a risk that a vibration measurement might not be representative of the long-term exposures. It is important to acknowledge the variation inherent to WBV exposure to help understand how this variation will affect health risk assessments. A field investigation was conducted in order to characterise the variation of WBV magnitudes between work cycles of track-type loaders. Six different track-type loaders were measured at four different work sites. The vibrations were measured at the operators seat in three translational axes (*x*-, *y*-, and *z*-axis) in accordance with ISO 2631-1 (1997). The findings indicate the worst axis of vibration for the track-type loaders was predominantly the fore-and-aft (*x*-axis), for most operations. The most severe emission values were measured for machine C at site 2 (1.12 ms^{-2} rms) and machine D at site 2 (1.03 ms^{-2} rms). These machines would exceed the action value of the Physical Agents (Vibration) Directive within 2 h of exposure. All of the machines measured would exceed the exposure action value of the Directive within an 8 h working period. The lateral (*y*-axis) produced the greatest amount of variability between work cycles (coefficient of variation up to 20%). It is concluded that the inherent variability between work cycles and tasks reinforces the requirement to perform a full task analysis prior to measuring WBV exposures to ensure that all tasks are measured and that adequate cycles are measured to obtain a reliable indication of the vibration emission.

1. Introduction

The physical comfort of operators is a basic ergonomic prerequisite for the safe operation of machinery. Low-frequency vibration environments such as those experienced by operators driving off-road machinery can impose a number of physical constraints. The most widely accepted impact of vibration exposure on the operator is low-back pain (e.g. Refs. [1–3]). Over long periods of exposure pathological changes could result in non-specific or diagnosable injury to the vertebrae or intervertebral discs of the back [4].

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The phasing in of the Physical Agents (Vibration) Directive [5] throughout Europe has resulted in heightened awareness of the possible risks associated with chronic exposure to whole-body vibration (WBV) and the requirement to perform risk assessments. Machine manufacturers are required to reduce vibration emissions for operators to the 'lowest level' under the EU Supply of Machinery (Safety) Directive [6], and are also required to provide purchasers with emission values. Despite the requirement for machinery suppliers to provide emission data, there is no methodology clearly defined as to how to provide such data. Currently there are no generic methods of measuring vibration for any machine type that are repeatable yet representative of site use.

Previous literature often discusses the variation that is inherent in WBV measurements. Despite this, there has been little attempt to quantify this variability from vibration measurements performed in real operating conditions. A large array of variables can alter the accuracy of a vibration measurement in its extrapolation to a daily dose measure, e.g. variability in driving style, road surface roughness, the loading of the machine [7]. It is important to acknowledge the variation inherent to WBV exposure to help understand how this variation will affect health risk assessments.

European Standard EN14253 [8] states that the number of work cycles over which measurements are made shall be sufficient to show that the average value obtained is representative of the vibration from the operation throughout the day. As it is usually not possible to measure for full days, it is important to use a sampling strategy that takes account of the likely variability in acceleration found throughout the vibration exposure. One way to determine the extent of the uncertainty in the measurement is to calculate the variation found between work cycles. The objective of this study was to investigate how much variation is typically found between work cycles of one type of earth-moving machines: track-type loaders.

2. Experimental method

Track-type loaders (sometimes known as crawler loaders) are tracked earth-moving machines that are usually fitted with a bucket and are capable of working on steeper and softer ground than equivalent wheel loaders. They are typically used for either transporting material between locations on a work site, for smoothing irregular ground surfaces or for loading tasks (e.g. loading lorries, depositing material in a crusher). The machines measured in this study weighed either 15 or 20 tonne. A typical track-type loader is illustrated in Fig. 1.

Fig. 1. A track-type loader as measured in this study.

WBV was measured in a selection of track-type loader machines at a variety of working sites. The range of sites visited ensured the sample was representative of the main working conditions found for these types of machines. Table 1 describes the four different sites where data collection took place and Table 2 presents the characteristics of the loaders and their operators tested at these four separate sites. The same operator operated machines C and D. Repeat measurements were made on two of the track-type loaders (machines A and B) over 2 day periods.

Measurement durations lasted about 1 h for most of the machines. However, in common with many types of earth moving machines, the work required some waiting time where the machine was stationary (e.g. waiting for another operator to suitably position a lorry; queuing at a site bottleneck). These stationary periods were removed from the raw acceleration data for analysis. Thus, the total vibration exposure duration was less than the total measurement duration.

The vibration measurements were conducted according to ISO 2631-1 (1997) as required by the Physical Agents (Vibration) Directive. A tri-axial accelerometer was mounted in a flexible disc and fixed to the seat beneath the ischial tuberosities. The accelerometer measured vibration in the 3 translational axes: fore-and-aft (x-axis), lateral (y-axis), and vertical (z-axis). The acceleration was sampled at 500 Hz using a Biometrics DataLogger and anti-aliasing filters, and downloaded to a PC for post-analysis using software developed in LabVIEW and compliant with ISO 8041 [9]. During the analysis process the raw acceleration signals were frequency weighted according to ISO 2631-1. Weighting W_k was used in the vertical direction and weighting W_d was used in the horizontal directions.

The analysis process used video footage and observer's written notes concerning the movement of each machine to extract acceleration data for each work cycle for each of the acquired acceleration signals. The frequency weighted rms was calculated for each axis of vibration for each cycle. In total, 369 cycles were individually analysed.

The coefficient of variation (Eq. (1)) was calculated to determine the variability found between work cycles in the three axes of vibration for the period of measurement:

$$\text{coefficient of variation} = \frac{\text{standard deviation}}{\text{mean}}. \tag{1}$$

Table 1
Identification and nature of sites used to measure whole-body vibration in track-type loaders

ID	Site type	Site Terrain
1	Road widening construction	Demolition material
2	Landfill site	Superficial material containing large rock particles
3	Landfill site	Top soil and stone mix
4	Building development area	Superficial material

Table 2
Characteristics of track-type loaders measured in this study and their operators

Ref	Site	Loader characteristics		Operator characteristics		
		Model	Weight (kg)	Age (yr)	Height (m)	Weight (kg)
A	1	953C	~15145	58	1.96	114
B	1	953	~15145	48	1.80	73
C	2	953C	~15145	62	1.88	102
D	2	963B	~19589	62	1.88	102
E	3	963B	~19589	60	1.68	102
F	4	963B	~19589	55	1.78	86

The $\mathrm{Total}_{\mathrm{rms}}$ value was calculated by combining the data obtained within each work cycle to produce an overall vibration emission value:

$$\mathrm{Total}_{\mathrm{rms}} = \sqrt{\frac{1}{T}\sum_{n=1}^{n=N} a_{wn}^2 t_n}, \tag{2}$$

where T is the sum of all of the vibration exposure times over all cycles, a_{wn} and t_n are the frequency-weighted rms and exposure time for cycle n, and N is the number of cycles. Three of the machines performed two distinct tasks (loading and levelling); in these cases the $\mathrm{Total}_{\mathrm{rms}}$ value was calculated for each task type.

3. Results

The main tasks performed by the track-type loaders included levelling the ground with the bucket and loading aggregate lorries. Machines were also required to travel between site locations.

The total rms vibration magnitudes measured on the machines (i.e. the overall emission value) are presented in Table 3. For 10 of the 11 measurements the dominant axis of vibration occurred in the fore-and-aft direction. Loader F exhibited the greatest vibration magnitudes in the vertical direction during the levelling operation. Machines D and E were an identical model but did not demonstrate such a trend for an identical operation. This discrepancy could be caused by the increased amount of travel involved in the levelling operation at this site. The worst axis of vibration for all machines demonstrates that every operator would be exposed above the action value as defined in the Physical Agents (Vibration) Directive, within an 8 h working period. However, none of the operators would be exposed to vibration magnitudes above the limit value of the Directive within an 8 h working period. The most severe emission values were measured for machine C: $1.12\,\mathrm{ms}^{-2}$ rms and machine D: $1.03\,\mathrm{ms}^{-2}$ rms operating at site 2. These machines would exceed the action value of the Directive within a 2 h working period. The greatest emission value was measured for machine C: $1.12\,\mathrm{ms}^{-2}$ rms. There was only a small difference between the vibration emissions measured for the levelling and loading tasks.

The greatest vibration magnitudes were measured for machines C and D. These machines were different models and machine D was heavier than machine C, however, these machines were both measured at site 2 and they were both operated by the same operator. It was noted that the operator operated the machines more aggressively than the other operators observed in this study. However, the increase in vibration magnitude might also be due to the conditions of the site and the task operation. The track-type loaders were travelling in a small area, requiring the machine to frequently change direction over a range of gradients. Tasks requiring

Table 3
Overall frequency weighted rms vibration magnitudes measured for the track-type loaders for all cycles

Machine	Vibration magnitude						
	Task	Day	x-axis	y-axis	z-axis	Worst axis	No. of cycles
A	Levelling	1	0.79	0.57	0.72	x	6
A	Levelling	2	0.80	0.54	0.70	x	7
A	Loading	1	0.83	0.57	0.75	x	12
B	Levelling	1	0.85	0.45	0.56	x	13
B	Levelling	2	0.79	0.47	0.69	x	91
C	Levelling	1	1.12	0.76	0.97	x	29
D	Levelling	1	1.03	0.68	0.88	x	58
E	Levelling	1	0.61	0.33	0.48	x	26
E	Loading	1	0.76	0.50	0.55	x	6
F	Levelling	1	0.66	0.54	0.85	z	26
F	Loading	1	0.75	0.47	0.71	x	45

Note: Values are presented with the 1.4 multiplication factor for the horizontal axes.

Table 4
Example of individual loading cycles for a track-type loader at site 1

Loading cycle	rms Magnitude (m/s^2)				
	x-axis	y-axis	z-axis	Worst axis	Duration (s)
1a	0.88	0.53	0.72	x	55
1b	0.83	0.54	0.72	x	65
1c	0.78	0.57	0.66	x	53
1d	0.85	0.66	0.69	x	62
2a	0.81	0.52	0.78	x	59
2b	0.93	0.63	0.88	x	38
2c	0.75	0.41	0.73	x	36
2d	0.96	0.70	0.78	x	55
3a	0.72	0.47	0.74	z	38
3b	0.86	0.55	0.72	x	41
3c	0.73	0.53	0.74	z	43
3d	0.79	0.60	0.86	z	45
$\text{Total}_{\text{rms}}$	0.83	0.57	0.75	x	590
C of V (%)	9.2	14.2	8.5		

Note: The horizontal axes are presented with 1.4 multiplying factors.
Loading cycles are labelled to represent cycles required to load each of three aggregate lorries: '1', '2' and '3' represent each lorry; 'a'–'d' represent each cycle required to load the lorry.

frequent acceleration and deceleration (as occurred on this site) would be expected to have a greater magnitude of fore-and-aft vibration; similarly, machines working on rough terrain would be expected to have elevated vibration magnitudes. As aggressive driving, poor terrain and frequent acceleration and deceleration are all factors likely to increase the vibration magnitude, it is unsurprising that the machines operated on site 2 were those with the greatest vibration magnitudes.

Table 4 provides an example of the data obtained for individual loading cycles for one of the track-type loaders performing a loading task (individual cycle data for all machines are presented in the Appendix A). The ID numbers represent each separate cycle performed by the machine. Three aggregate lorries visited the site during the measurement resulting in three sets of loading cycles (e.g. 1a, 1b, 1c, 1d, represents 4 loading cycles for lorry 1). Cycles varied in duration from 36 to 65 s and tended to take longer for the first lorry than for the other two. The worst axis of vibration usually occurred in the x-direction, but for three cycles, the worst axis occurred in the z-direction whilst loading lorry 3. In these cases, the magnitudes that were measured in the x-direction were only slightly lower than those in the z-direction. The reason for the increase in dominant axis is unknown, although it is possible that it is due to the loader operating on a slightly different part of the site with a slightly increased surface roughness.

Summary data for individual work cycles are presented in Table 5. The axis with the most variability was predominantly the lateral axis with a mean coefficient of variation of 15% (range 9–20%). In the fore-and-aft direction the mean coefficient of variation was 12% (range 6–12%); in the vertical direction the mean coefficient of variation was 11% (range 6–18%). The maximum measurements obtained for working cycles for machines C and D exceeded the Physical Agents (Vibration) Directive exposure limit value for continuous exposure of 8 h within a 24 h period. The largest coefficient of variation between work cycles equalled 20% in the lateral axis for machines B and E whilst levelling. For most machines, the most severe axis did not correspond to the axis with the most variation in the data. In the most severe axis, the mean coefficient of variation was 12% (range 8–17%).

The machine with the lowest level of variability between work cycles was machine A. Repeat measurements were conducted on this machine over a 2 day period. The levelling operation on both days showed the smallest amount of variability, followed closely by the loading cycle operation. The variability may be this small during the levelling operation as the task was very consistent in terms of length travelled, number of directional changes and the terrain characteristics.

Table 5
Mean, standard deviation, minimum and maximum frequency weighted r.m.s. emission values measured over repeated cycles for track-type machines and coefficients of variation expressed in %

Machine	Task	Day	Direction	Mean	SD	Min	Max	C of V %
			x	0.78	0.06	0.67	0.83	8
A	Levelling	1	y	0.56	0.07	0.45	0.66	12
			z	0.72	0.04	0.64	0.75	6
			x	0.81	0.07	0.71	0.92	9
A	Levelling	2	y	0.55	0.05	0.50	0.66	9
			z	0.70	0.04	0.66	0.77	6
			x	0.82	0.08	0.72	0.96	9
A	Loading	1	y	0.56	0.08	0.41	0.70	14
			z	0.75	0.06	0.66	0.88	9
			x	0.82	0.14	0.53	1.03	17
B	Levelling	1	y	0.44	0.09	0.25	0.56	20
			z	0.54	0.06	0.40	0.60	11
			x	0.77	0.13	0.49	1.12	17
B	Levelling	2	y	0.47	0.07	0.32	0.65	16
			z	0.69	0.09	0.45	0.97	13
			x	1.12	0.13	0.85	1.47	12
C	Levelling	1	y	0.76	0.11	0.54	1.11	15
			z	0.96	0.08	0.79	1.14	8
			x	1.04	0.15	0.73	1.35	14
D	Levelling	1	y	0.68	0.10	0.52	0.94	14
			z	0.87	0.11	0.61	1.18	13
			x	0.65	0.11	0.45	0.84	17
E	Levelling	1	y	0.34	0.07	0.25	0.55	20
			z	0.51	0.09	0.31	0.76	18
			x	0.76	0.06	0.69	0.85	8
E	Loading	1	y	0.50	0.07	0.43	0.61	15
			z	0.55	0.06	0.45	0.62	10
			x	0.66	0.04	0.57	0.74	6
F	Levelling	1	y	0.53	0.08	0.38	0.78	16
			z	0.82	0.09	0.64	0.97	12
			x	0.77	0.09	0.60	1.05	12
F	Loading	1	y	0.46	0.07	0.32	0.62	14
			z	0.70	0.08	0.54	0.88	11

Note: Values are presented with the 1.4 multiplication factor for the horizontal axes.

Three of the track-type loaders measured during the study carried out a variety of tasks during data collection. This included loading aggregate lorries, levelling the ground and travelling on concrete or top soil/demolition material. Vibration magnitudes measured during each of these three tasks are presented in Fig. 2. For machine A, the loading tasks exposed the operator to the highest magnitudes of vibration in each axis whilst travelling exposed the operators to the lowest magnitudes of vibration. In the x-axis, trends were similar for machines E and F. Travelling exposed the operator to the greatest magnitudes of vibration; levelling exposed the operator to the lowest magnitudes of vibration. However, the highest magnitudes of vibration measured on machine F occurred in the z-direction for the levelling task. For travelling, the magnitudes measured in the x- and z-directions both equalled $0.85\,\mathrm{ms}^{-2}$ rms. The difference between the vibration magnitudes in the x-direction for machine A when compared to machines E and F could be caused by the differing terrain conditions: machine A was travelling on concrete whilst the other machines were travelling over top soil or demolition material, resulting in a less even terrain.

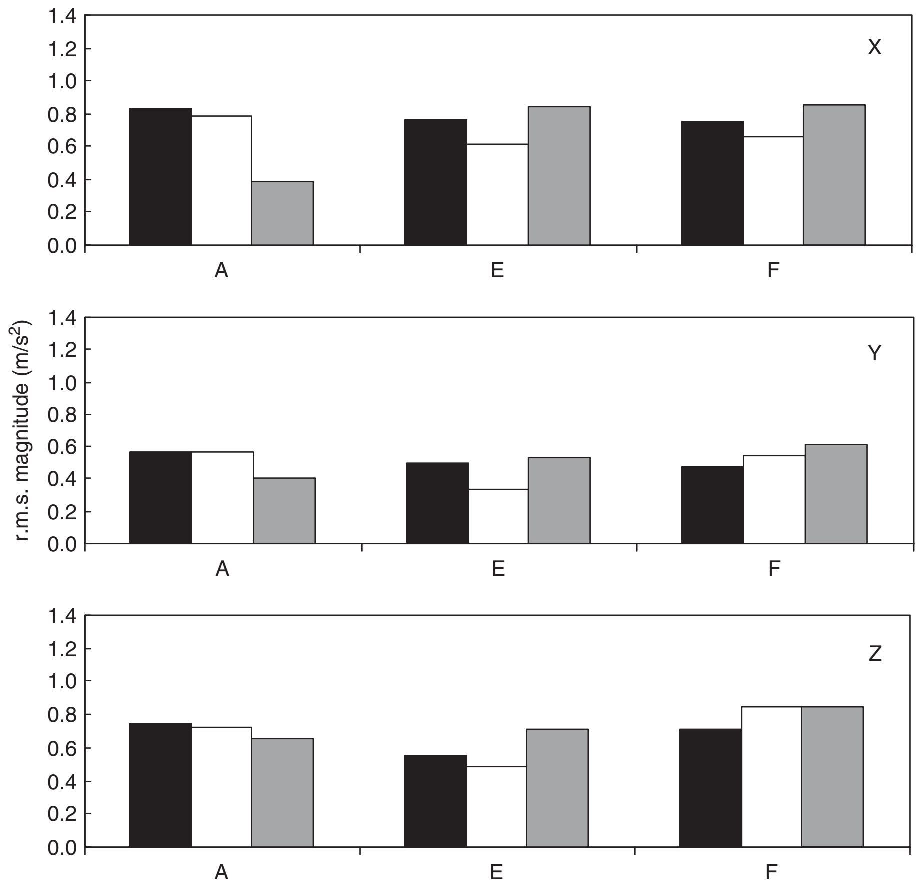

Fig. 2. Total frequency weighted acceleration for individual tasks of track-type loaders A, E and F from sites 1, 3 and 4. Tasks include; loading (black fill), levelling (white fill) and travel (grey fill). Values are presented with 1.4 multiplication factor for the horizontal axes. (*Note*: 'A' was travelling on concrete; both 'E' and 'F' were travelling on top soil.)

4. Discussion

This field study investigated the variability found between the frequency weighted accelerations of different work cycles for a range of track-type loaders operating at a variety of sites. The WBV measurements indicated that around half of the machines would expose operators to vibration that would exceed the exposure action value of the Physical Agents (Vibration) Directive in less than 4 h (corresponding to an emission value of about $0.7\,\mathrm{ms}^{-2}$ rms). As these machines are often used for extended periods of time it is likely that most operators will exceed the exposure action value and it will therefore be necessary to implement risk reduction measures, health surveillance and training, and minimisation of the vibration exposure.

The worst axis of vibration was predominantly the fore-and-aft direction for these track-type loaders. Vibration spectra for this type of machine usually show substantial vibration at frequencies below 2 Hz in the x-direction. As the W_d frequency weighting is most sensitive at such low frequencies, these components are likely to form a major contribution to the frequency weighted rms vibration magnitude. It is difficult to isolate the operator from such low-frequency components as any passive isolation mechanisms would require a very low resonance frequency resulting in a large horizontal travel. Furthermore, such horizontal isolation systems for a cab or seat would also respond to other loading. For example, when the machines were operated on inclined surfaces the 'isolated' part of the system (e.g. the seat or the cab) would tend to move towards the end of the travel due to gravitational forces acting on the suspension. If the isolation were provided by a seat, then it could also prove problematic for operation of controls. For example, if an operator needed to depress the brake, the force applied would also push them back on the suspension. Finally, the suspension would also move in response to any acceleration or braking forces. Each of these constraints combine to make it impractical to use simple passive isolation systems for low-frequency horizontal vibration isolation.

The most practical methods of reducing the vibration exposure experienced in track-type loaders are to ensure that the machine operates on as smooth surfaces as possible and to ensure that operators avoid driving the machine aggressively. Such measures are practical as operators of all machines driving over a smoothed road surface will benefit from lower vibration exposures. Training of operators is a cost effective method of reducing exposures as it does not require replacement equipment to be purchased.

In many cases it might not be necessary to use a track-type loader for a particular task. Wheel loaders could have been used as an alternative to track-type loaders for many of the loading tasks observed in this study. Wheel loaders usually have a lower vibration emission than track-type loaders for simple loading tasks.

Close observation of video data showed that during some working tasks the operators driving the track-type loaders adopted poor postures in order to maintain good visibility. Although mirrors or CCTV systems were provided with most of the machines, operators were frequently observed looking over their shoulders to the rear of the machine during reversing manoeuvres. It is possible that this is a problem of non-compliance with training, failure to use visibility aids, poor matching of machine to task or a constraint in the design of the machine. These non-neutral postures adopted by the operators may subject them to additional risks whilst they are being exposed to vibration and these additional risks would need to be taken into account during a health risk assessment.

A high coefficient of variation implies a high variability in vibration magnitude from work cycle to work cycle. For the individual work cycle measurements 69% will occur within the range of the mean x $(1-$coefficient of variation) and mean x $(1+$coefficient of variation). Although most measurements occur within the range encompassed by ± 1 standard deviation of the mean, more than one quarter will occur outside this range, assuming a normal distribution of measurements. As there is a relatively high variability in the measurements of vibration emission, it is important to measure for long duration and/or over many work cycles, as highlighted previously by Mansfield et al. [7]. The amount of variation also highlights the importance of conducting a task analysis prior to performing vibration measurements, such that adequate samples can be obtained for each element of the work cycle.

5. Conclusions

Field studies have been completed with the aim of determining the amount of uncertainty inherent to WBV measurements for track-type loaders. A measure of the variation between individual work cycles of every task performed by the machines was calculated. The mean coefficient of variation for the track-type loaders in the worst axis of vibration was 12%. The greatest amount of uncertainty between work cycles was predominantly found in the lateral axis although fore-and-aft was the dominant axis of vibration. The typical variability found between work cycles reinforces the necessity of conducting a thorough task analysis prior to carrying out a vibration assessment, in addition to ensuring measurements of WBV are taken over a repeated number of work cycles.

Acknowledgement

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Appendix A

Frequency weighted rms magnitudes of individual work cycles for track-type loaders measured at 4 different sites. Values are presented with the ISO 2631-1 horizontal multiplication factors (Figs. A1–A8).

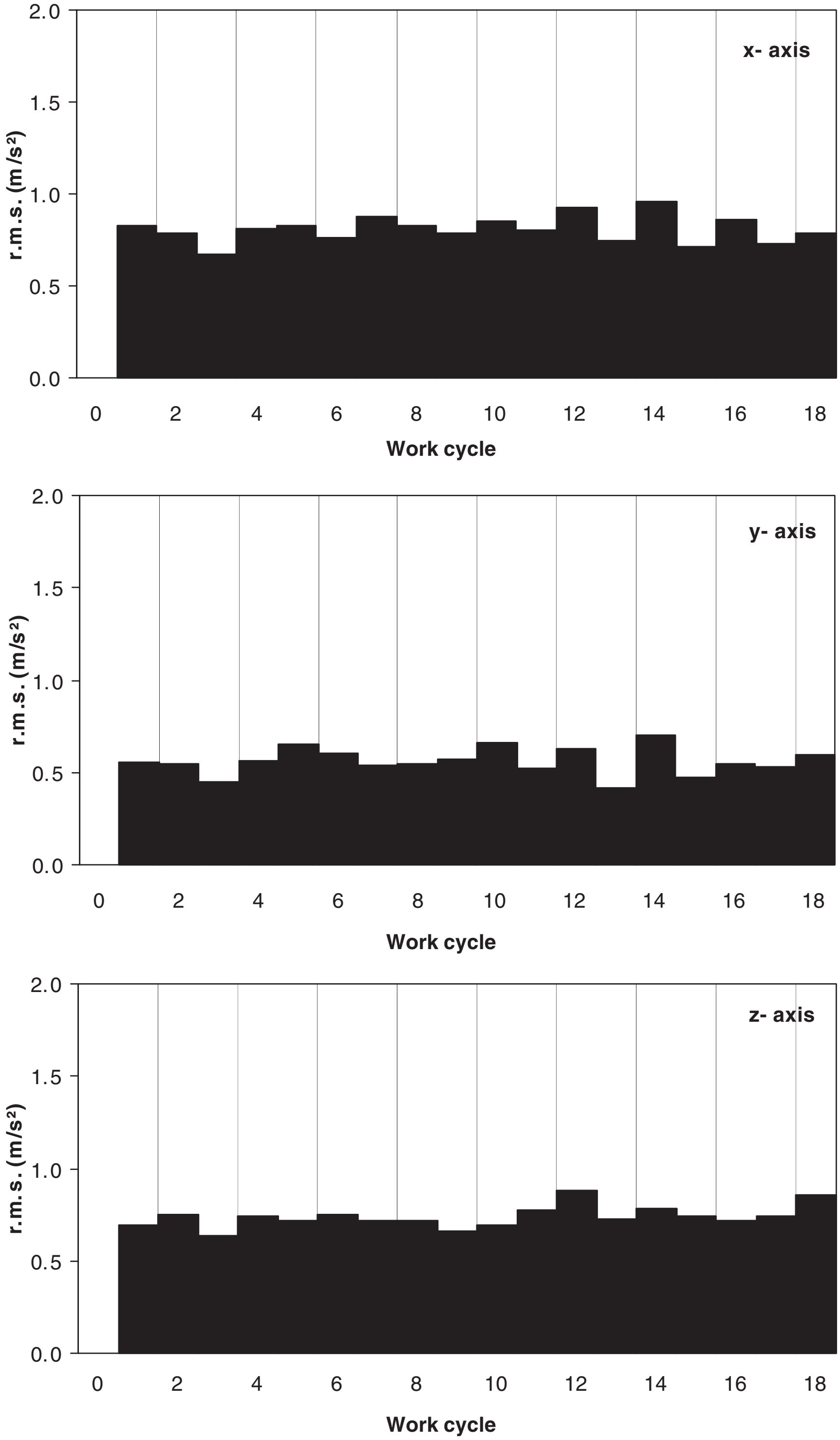

Fig. A1. Frequency weighted rms magnitude of individual work cycles for Track-Type Loader A: Day 1.

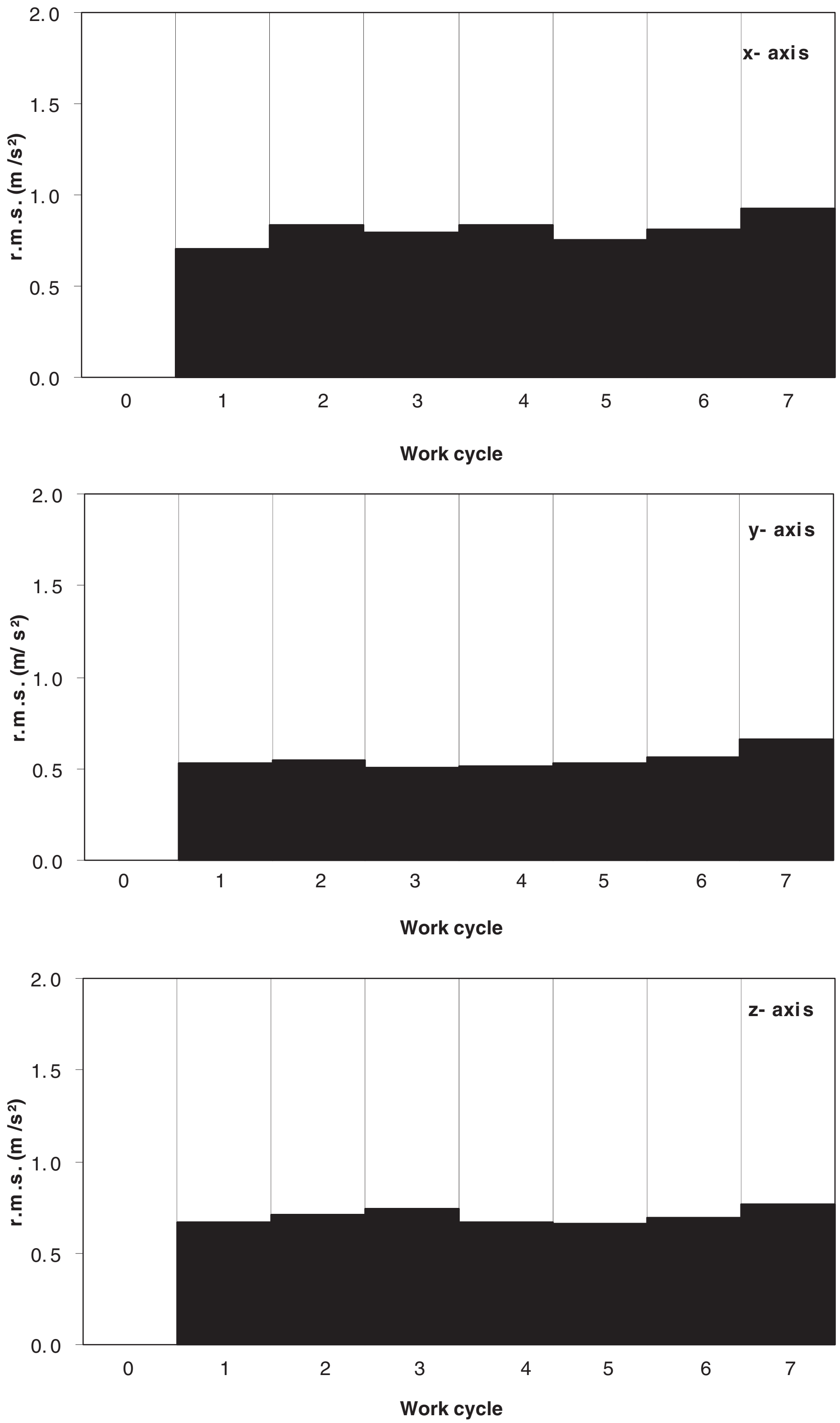

Fig. A2. Frequency weighted rms magnitude of individual work cycles for Track-Type Loader A: Day 2.

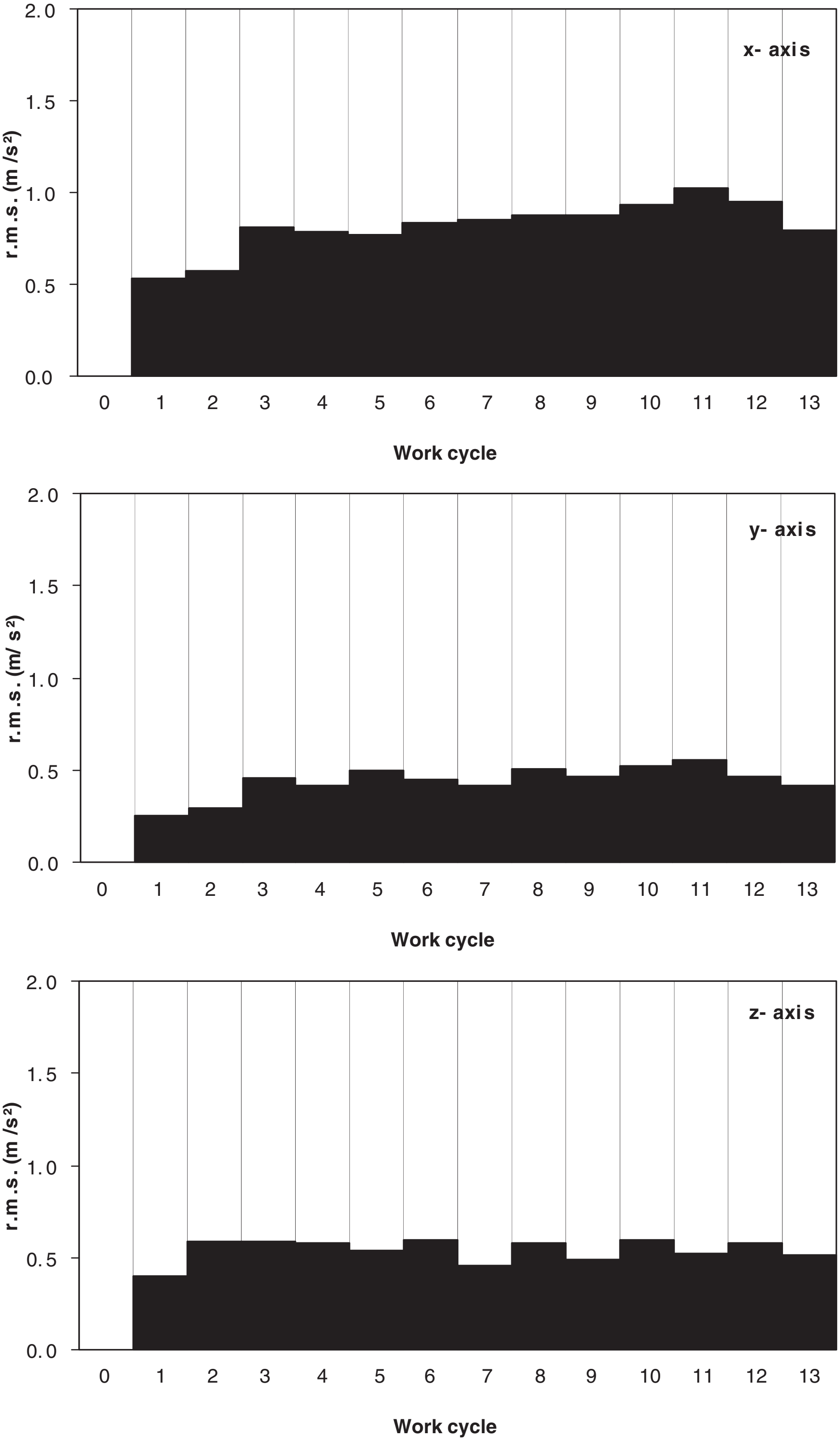

Fig. A3. Frequency weighted rms magnitude of individual work cycles for Track-Type Loader B: Day 1.

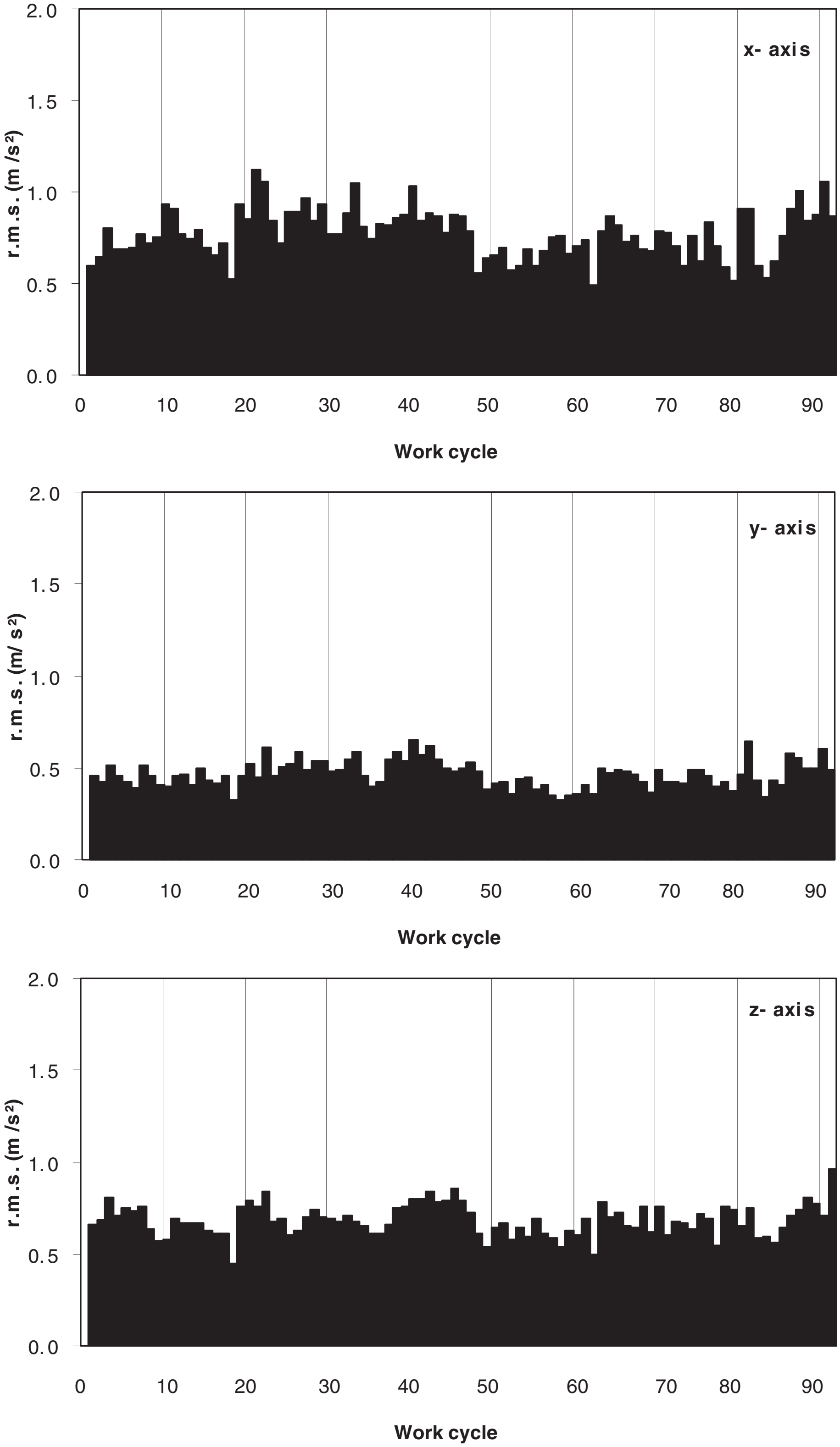

Fig. A4. Frequency weighted rms magnitude of individual work cycles for Track-Type Loader B: Day 2.

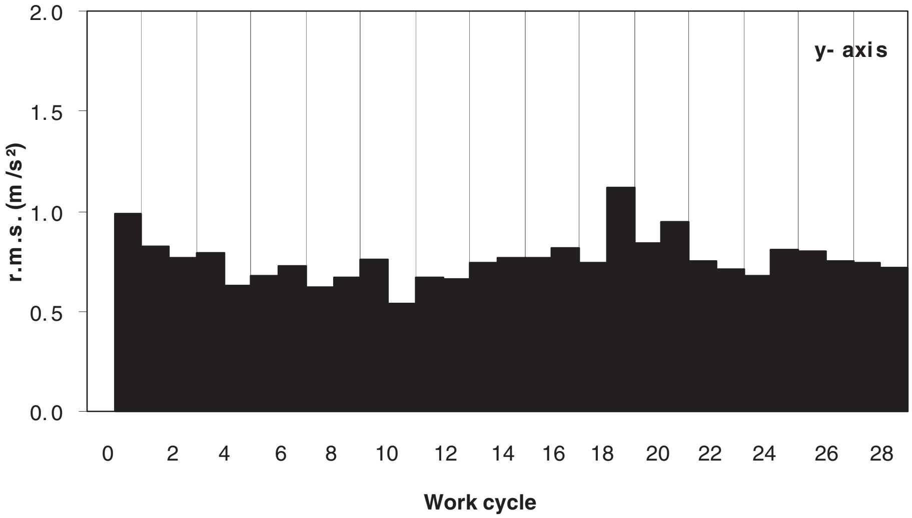

Fig. A5. Frequency weighted rms magnitude of individual work cycles for Track-Type Loader C.

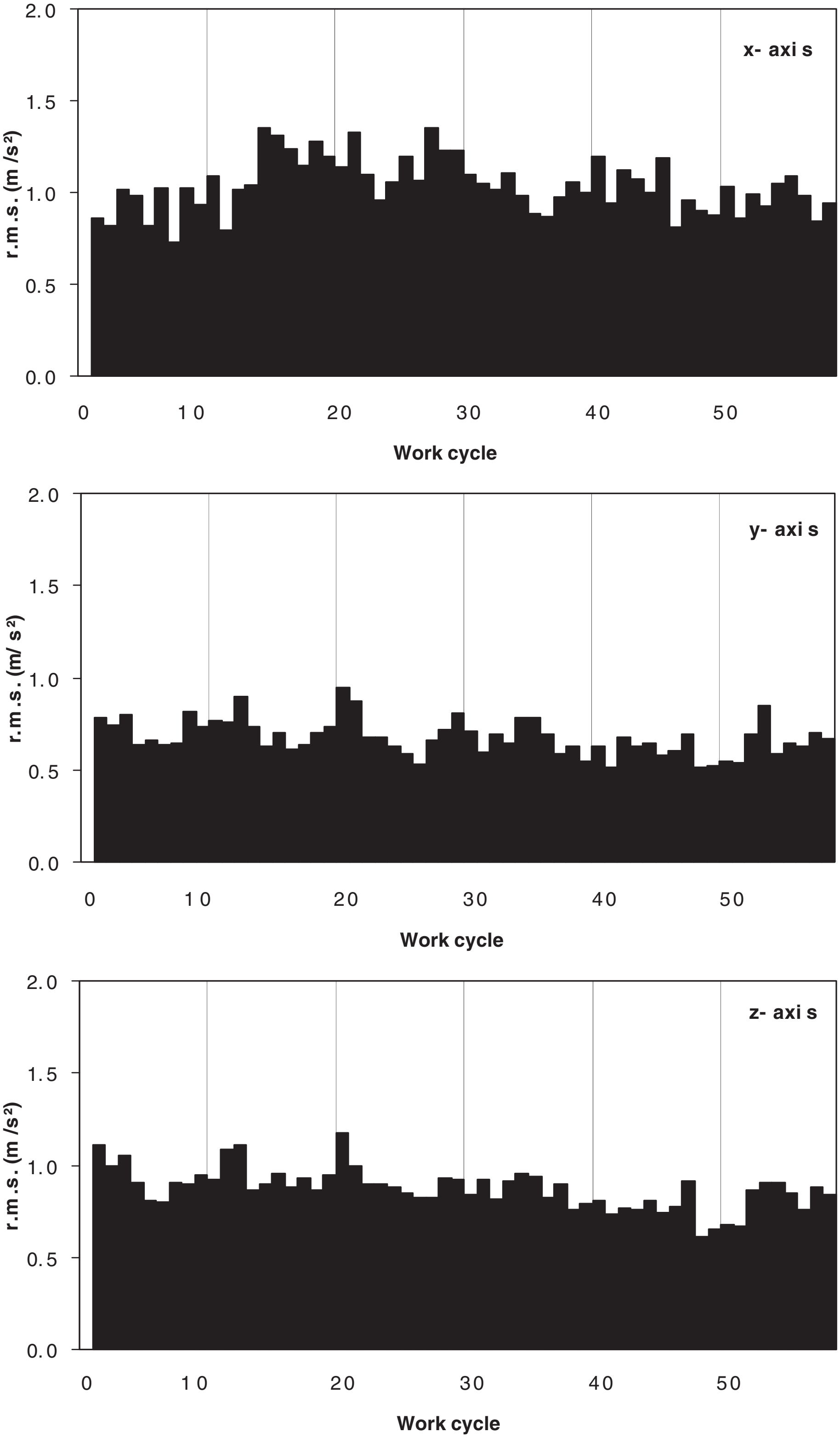

Fig. A6. Frequency weighted rms magnitude of individual work cycles for Track-Type Loader D.

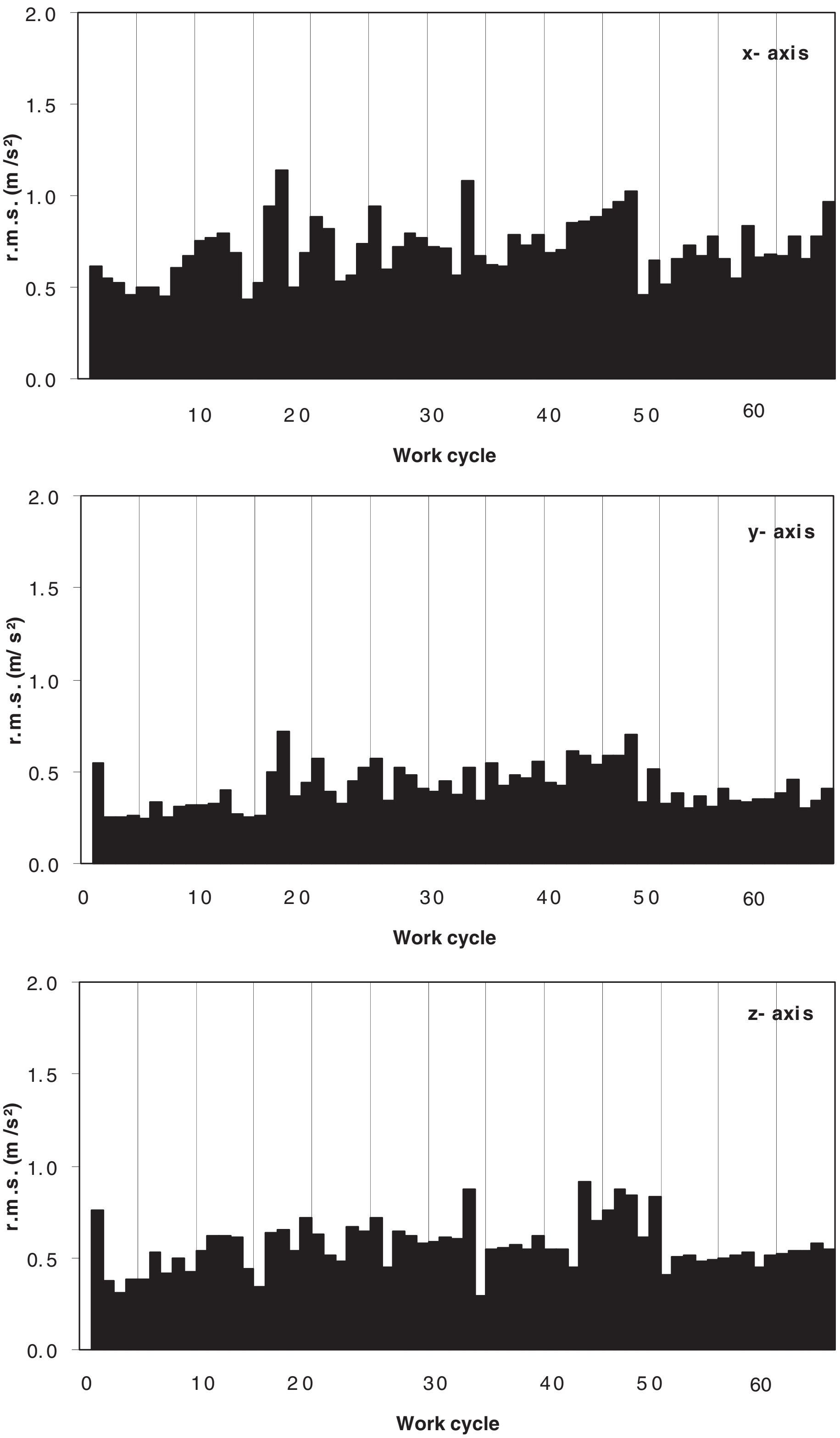

Fig. A7. Frequency weighted rms magnitude of individual work cycles for Track-Type Loader E.

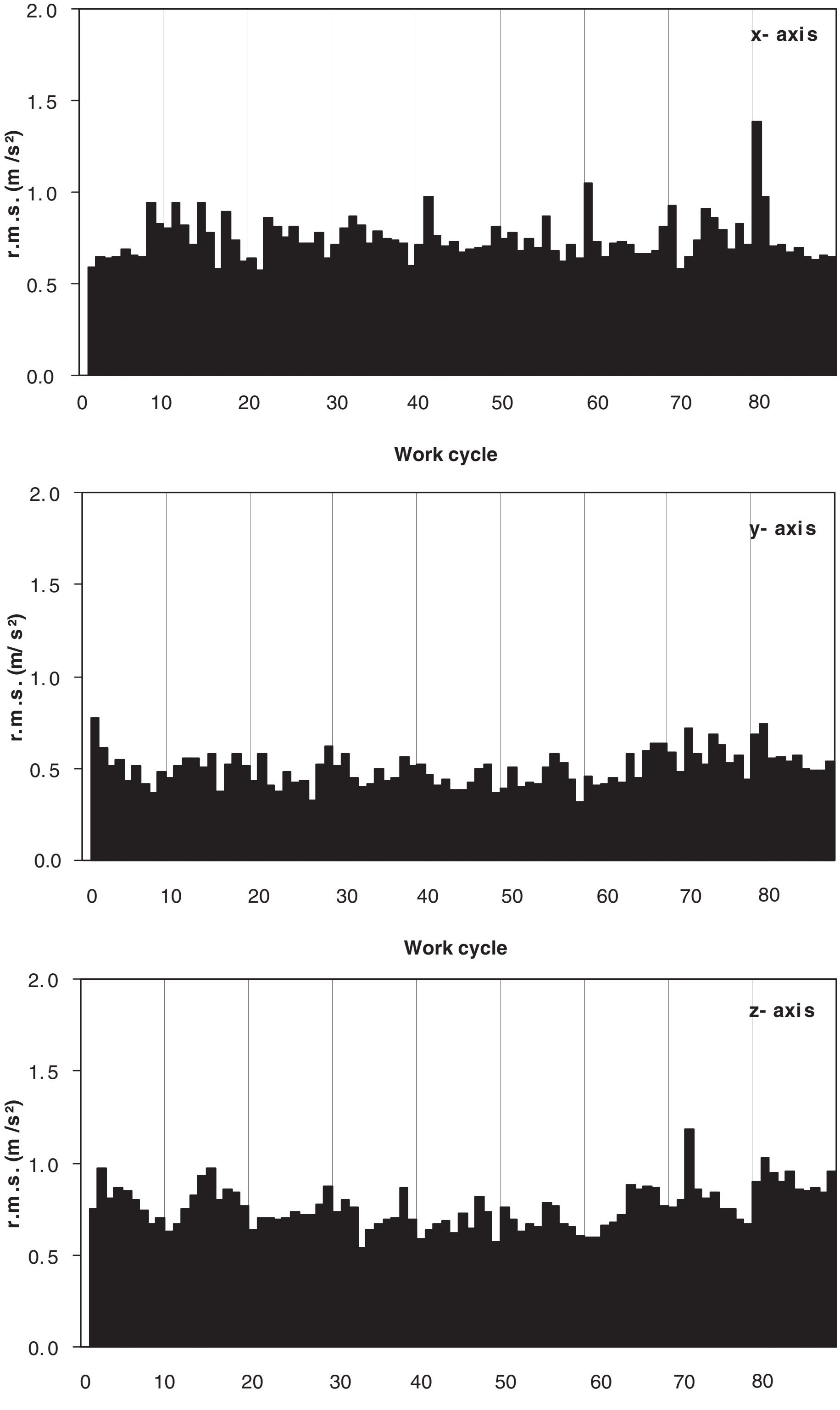

Fig. A8. Frequency weighted rms magnitude of individual work cycles for Track-Type Loader F.

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