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Occupational Whole Body Vibration Exposure of Shovel Operators: A Case Study in Mechanised Coal Mine

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Abstract: The mining industry plays a pivotal role in driving economic growth by supplying essential raw materials to energy and manufacturing sectors. As mining operations become increasingly mechanized, the prevalence of occupational hazards rises, with occupational vibration emerging as a notable concern. Whole-body vibration (WBV) occurs when an individual's body is exposed to vibrations transmitted through a supporting surface, potentially leading to various health issues such as musculoskeletal disorders, sleep disturbances, and headaches. To meet escalating demands of raw materials, heavy earth-moving machinery (HEMM) such as haul trucks, drills, and shovels are extensively utilized in mining industries. Operators of these HEMMs, particularly shovel operators in coal mines considered for this study, are subjected to WBV during routine operations, such as loading dumpers. Recent studies indicate that approximately 18% of workers in India's mining industry face exposure to WBV, underscoring a pervasive risk in this sector. The present study conducted in an Indian surface coal mine, the focus was specifically on WBV exposure among shovel operators. It utilized triaxial piezoelectric-based accelerometer sensors to measure WBV, considering parameters such as root mean square (RMS) value of vibration and vibration dose value (VDV). Additionally, the study considered the time taken to load a dumper by the shovel operator and the cycle time of a shovel as operational parameters. Frequency analysis, employing techniques like Fourier Transformation (FFT), was employed to assess the frequency of WBV generated for dumper operators. By calculating band power, the study aimed to identify the vibration amount within the frequency bands of WBV that may pose risks to the human body. Of particular interest was the resonance frequency of the human body, as matching this frequency with WBV frequencies could lead to resonance, potentially causing severe damage. The study, which involved 21 shovel operators operating four shovels. Statistical analysis indicated a negative correlation between band power in the resonance frequency band of the human body and the time taken to load a dumper by the shovel as well as the full cycle time of the shovel. This suggests that faster loading by shovels may exacerbate the effects of WBV on operators.

Keywords: Whole body Vibration, Shovel, Surface Mining, HEMM, VDV, Frequency, FFT.

1. Introduction

The contribution of the mining industry to a nation's economic growth has been undeniable for many years. As a primary industry, it involves the excavation of billions of tons of rock, with a significant portion of production coming from surface mining. This method relies heavily on large and powerful earth-moving machines that must operate in rugged conditions, leading to the use of high-power engines. These engines generate substantial vibrations, and the rugged work environment further exacerbates the vibration levels. These vibrations are transmitted to the machine operators, leading to what is known as Whole Body Vibration (WBV). WBV occurs when a person is supported by a vibrating surface, causing the vibrations to be mechanically transmitted to various parts of their body (Mansfield, 2004). Prolonged exposure to significant levels of WBV can lead to various health issues, including musculoskeletal disorders (MSD), sleep disorders, and headaches (Slota et al., 2008). Research indicates that approximately 18% of workers in the Indian mining industry are exposed to WBV at work. Consequently, over the past few decades, WBV has become a critical focus of ergonomic studies due to its impact on worker health. WBV has become a significant area of concern and an integral part of ergonomic studies over the past few

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decades. Paty et al. conducted a study demonstrating the impact of dumper operational parameters on the WBV experienced by dumper operators in a coal mine (Paty et al., 2017). The excavation process in surface mining involves numerous workers operating heavy machinery such as dumpers, shovels, and dozers. Achieving high productivity in mining demands long working hours and high workloads, which can severely impact workers' health. Addressing these health risks is essential to reduce the negative effects on workers. Ergonomics, a branch of science dedicated to improving health and safety in the workplace, addresses issues related to prolonged sitting and heavy workloads (Mcphee, 2004).

Since the early 1960s, researchers have studied the relationship between WBV and worker fatigue or performance. WBV is transmitted to the human body from a vibrating surface, such as a driver's seat or a vibrating floor (Kjellberg, 1990). This study focuses on WBV and measures the impact of different operational parameters on the human body under specific exposure conditions, such as frequency. In 1977, Cohen et al. demonstrated that WBV causes fatigue and weakens performance within the frequency range of 2.5 to 5 Hz (Harvey et al., 1977). In 1978, a study reported the same frequency range of 3.15 to 5 Hz (Lewis, 1978). In 2007, Ljungberg et al. examined WBV frequencies in different directions of the human body, identifying 2 Hz in the x-direction, 3.15 Hz in the y-direction, and 4 Hz in the z-direction, with a vibration magnitude of 1.1 m/s². In 2014, Zamanian et al. studied WBV within the frequency range of 3 to 7 Hz, with varying magnitudes of 0.53, 0.81, and 1.21 m/s² (Zamanian et al., 2014). The human body is most sensitive to lateral vibrations within the frequency range of 4 to 10 Hz and longitudinal vibrations within the range of 0.5 to 2 Hz (ISO 2631-1:1997). Hassan and McManus (2002) found that truck drivers are primarily exposed to low-frequency vibrations ranging from 1.42 Hz to 5.7 Hz. Several studies have analysed the performance impact of WBV by considering different magnitudes of vibration without specifying frequencies (Abbate et al., 2004; Costa et al., 2014). Higher magnitudes of vibration can cause serious damage to the human body. However, the human body does not respond equally to all frequencies, as different body parts have different natural frequencies. Resonance, which occurs within specific frequency ranges, causes more significant damage. Parsons and Griffin (1988) observed that a seated person is ten times more vulnerable to 5 Hz frequencies compared to 100 Hz. Brownjohn et al. (2001) concluded that higher vibration magnitudes result in lower detected human resonance frequencies. They suggested that when the vibration magnitude exceeds 0.1 m/s², the human resonant frequency can be considered within the range of 3 to 7 Hz. A study done by A study by Paty et al., (2021) reveals that frequencies ranging from 0.5 to 10 Hz significantly impact the WBV experienced by dumper operators.

The paper presents a study on Whole Body Vibration experienced by 21 shovel operators working with four diesel-operated hydraulic shovels, each with a gross engine power of 1400 HP and a bucket capacity of 15 m³. Conducted in an Indian surface coal mine, the study focused specifically on WBV exposure among shovel operators. Triaxial piezoelectric-based accelerometer sensors were used to measure WBV, considering parameters such as the root mean square (RMS) value of vibration and the vibration dose value (VDV). Each cycle of shovel operation includes filling the bucket, swinging with the load, dumping the load into the dumper, and returning to the starting position for the next load. In this study, the time taken by a shovel operator to load a dumper was considered as an operational parameter. This includes filling the bucket, swinging with the load, and dumping the load into the dumper. Additionally, the total cycle time was also taken into account as another operational parameter. WBV is typically measured in three perpendicular directions using triaxial piezoelectric accelerometer sensors. The data collected is analysed using NorVibraTest software, which applies frequency weighting according to the ISO 1997 standard. High values of frequency-weighted RMS acceleration and specific frequency ranges of WBV can cause severe damage to the human body. This study focuses on analysing the frequency of WBV generated for shovel operators. The data is converted from the time domain to the frequency domain using Fast Fourier Transformation (FFT). The study investigates the impact of the time taken to load a dumper and cycle time of the shovel on WBV, considering the natural frequency of the human body. Resonance occurs when the frequencies of WBV match the natural frequencies of the human body, potentially causing severe damage. The frequency analysis of WBV signals was carried out for four shovels, with six cycles of operation for each shovel. The following section provides a detailed description of the study's methodology.

2. Materials and Procedures

The experiment was conducted in a surface coal mine located in eastern India. The study focused on four shovels, each with a 15 m³ capacity, all are of the same model and specifications. These shovels are diesel engine-operated hydraulic machines with a maximum gross power of 1400 HP and a maximum swing speed of 3.8 rpm. They are utilized for loading both coal and overburden, the latter primarily consisting of sandstone and shale. The shovels load 100-tonne dumpers. A total of 21 shovel operators were selected for the experiment. The mine employs the top slicing with backfilling mining method. To collect data, a portable WBV data logger instrument made by Norsonic was used, equipped with a piezoelectric accelerometer sensor. The piezoelectric sensor is integrated into a sitting pad, which is placed on the operator's seat. During the operation of the shovel, the operator sits on this pad (as illustrated in Figure 1).

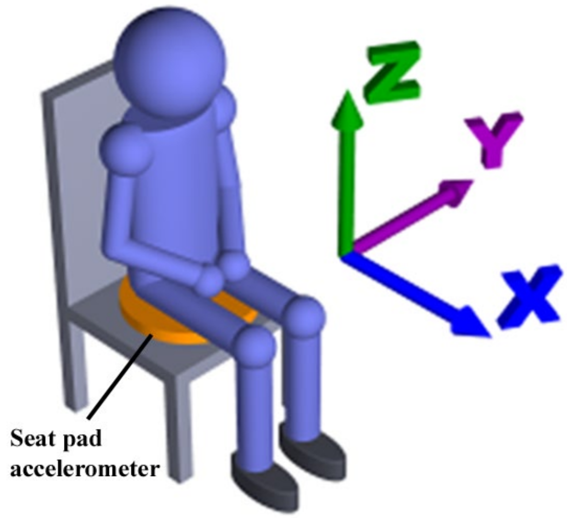

Figure 1: Operator seated with a sitting pad containing an integrated piezoelectric accelerometer.

This instrument provides vibration data in the form of acceleration (m/s²) in the time domain. The data was collected along three perpendicular axes: the x-axis and y-axis representing the horizontal directions, and the z-axis representing the vertical direction. The data collected include the following measurements:

a_w: The effective acceleration value, weighted averaged arithmetically over the entire measurement duration.

$$a_w = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)dt} \tag{1}$$

In this equation,

$a_w(t)$ represents the instantaneous frequency-weighted acceleration, while T stands for the duration of the measurement.

VDV: Vibration Dose Value, indicating the total energy transferred along an axis over the entire measurement period.

$$VDV = \sqrt[4]{\int_0^T (a_w(t))^4 dt} \tag{2}$$

CF: Crest Factor, defined as the ratio of the maximum vibration to the root mean square (RMS) acceleration.

$$CF = \frac{a_{max}}{a_w} \tag{3}$$

Where, a_{max} is the maximum instantaneous acceleration value

The raw WBV data, including rms acceleration data in the time domain, VDV and CF, were initially extracted using NorVibraTest software. This data was subsequently analysed in MATLAB 2021a. Figure 2 illustrates the process of exporting data using NorVibraTest software. Various time domain parameters reported by NorVibraTest software are summarized in Table 1. In the present work, WBV acceleration data is analysed in the frequency domain to provide a more comprehensive understanding. While time domain analysis quantifies the strength of a vibration profile using metrics such as RMS acceleration, VDV, and CF, it is somewhat limited in addressing frequency-related issues, such as resonance effects, which can significantly impact the human body. In contrast, frequency domain analysis offers a more detailed examination of WBV. This method not only includes the previously mentioned parameters but also explores into the spectral characteristics of the vibration signals. By transforming the acceleration data from the time domain to the frequency domain using techniques such as Fast Fourier Transform (FFT), the analysis can identify dominant frequencies, harmonics, and resonance phenomena. This thorough approach provides deeper insights into the complex nature of WBV and its effects on operators, facilitating the development of more effective WBV management strategies and ergonomic designs.

Table 1. Summary of Different WBV Parameters for 21 Shovel Operators

Parameters	x-axis (a_{wx})	y-axis (a_{wy})	z-axis (a_{wz})	x-axis (VDV_x)	y-axis (VDV_y)	z-axis (VDV_z)	CFx	CFy	CFz
Mean	0.28	0.24	0.26	3.44	2.94	3.41	19.25	16.19	23.72
Minimum	0.14	0.11	0.18	1.53	1.29	1.89	9.69	10.40	11.20
Maximum	0.38	0.36	0.43	4.84	4.07	8.13	55.30	35.50	60.00
Standard Deviation	0.07	0.06	0.08	0.90	0.79	1.63	13.59	7.44	14.04

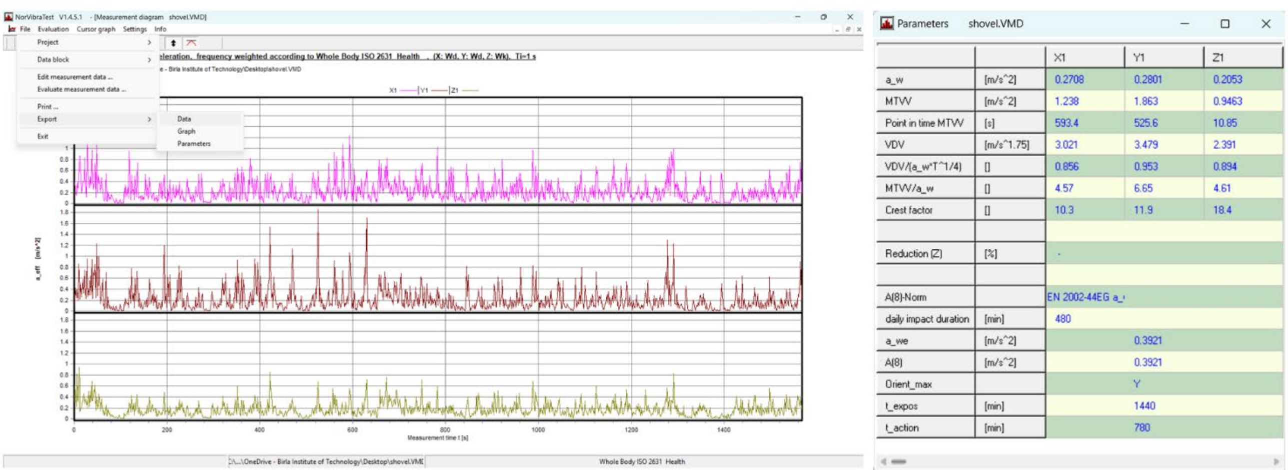

Figure 2: Data exporting and evaluation by NorVibraTest software.

In our study, vibration data is captured in the time domain, comprising multiple simple sinusoidal signals of varying frequencies. The FFT is an algorithm that converts time domain vibration data into the frequency domain. In real-world scenarios, vibrations are random in nature and consist of waves with a large number of frequencies. Although FFT is effective for analysing vibrations with a finite number of dominant frequencies, it proves challenging when applied to random vibration signals. Power Spectral Density (PSD) addresses this limitation by retaining only the real components of the signals, achieved by multiplying the FFT with its complex conjugate. Additionally, PSD normalizes the multiplied values to the frequency bin width, which is calculated as the inverse of the total measured duration. This normalization allows for the comparison of signals of different lengths. These characteristics make PSD more advantageous than FFT for analysing vibrations over varying durations. In the present work, PSD was utilized for frequency domain analysis. Figure 3 displays the PSD of a recorded WBV signal.

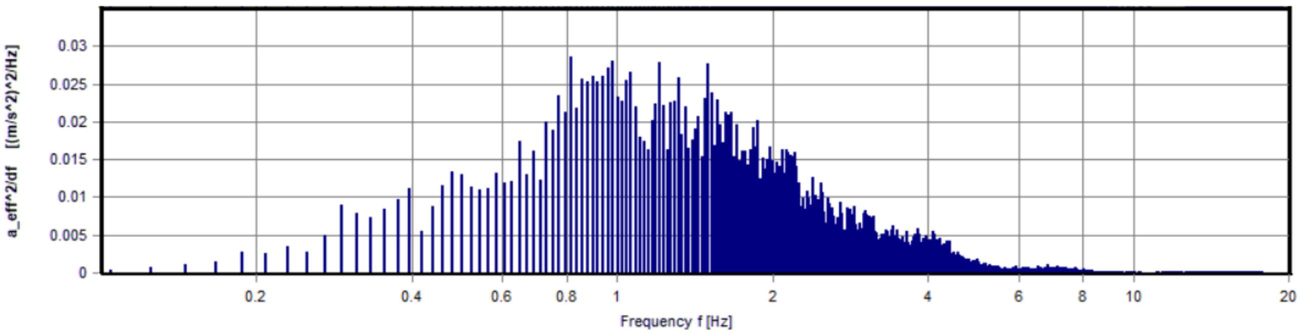

Figure 3: Power Spectral Density (PSD) of a recorded WBV signal.

Previous research has established that the human body is particularly susceptible to frequencies ranging from 0.5 to 10 Hz. Hence, this frequency range is the focus of spectrum analysis in this study. By integrating the Power Spectral Densities within this frequency band, the signal's power, known as band power, can be calculated. This band power reflects the potential impact on the human body. The study explores how the band power of WBV signals varies with changes in shovel operational parameters, such as loading time and cycle time. Correlation analyses are performed between the operational parameters and the band power of WBV. The band power is calculated from the Power Spectral Density using the following formula:

$$Band\ Power = \int_{f_1}^{f_2} PSD(f)\, df \tag{4}$$

Where,

Band Power is the total power within the frequency band from ($f_1\ Hz\ to\ \ f_2\ Hz$).

$PSD(f)$ is the power spectral density as a function of frequency (f).

($f_1 = 0.5\ Hz$) and ($f_2 = 10\ Hz$)are the lower and upper limits of the frequency band, respectively.

MATLAB codes have been developed to calculate various parameters such as FFT, PSD, and band power. The results of the correlation analyses and their implications are discussed in the subsequent section.

3. Findings and Discussions

The study investigates the relationship between the band power of the 0.5 Hz to 10 Hz frequency range of WBV and two key operational factors: the cycle time of the shovel and the loading time of a dumper by the shovel.

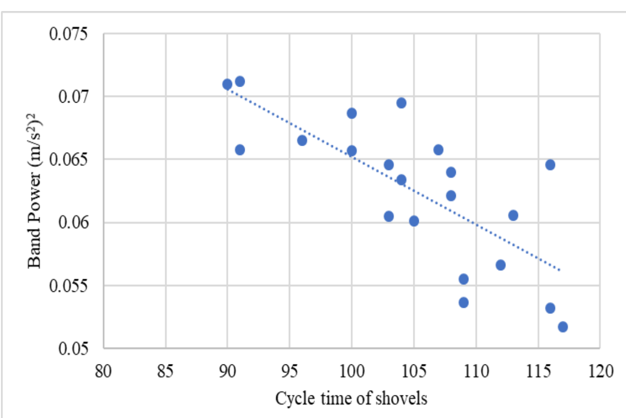

Figure SEQ Figure * ARABIC 4: Negative correlation between band power and cycle time of shovel (Pearson correlation coefficient: -0.750)

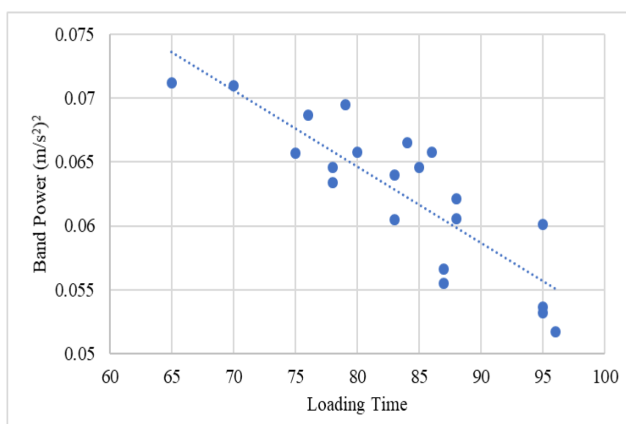

Figure SEQ Figure * ARABIC 5: Negative correlation between band power and loading time of shovel (Pearson correlation coefficient: -0.855)

A significant negative correlation is observed between the band power of WBV and both the shovel cycle time and the loading time of the dumper, as depicted in Figures 4 and 5, respectively. Figure 4 visually represents the correlation between band power and shovel cycle time, while Figure 5 illustrates the correlation between band power and loading time. Pearson correlation analysis demonstrated a negative correlation between band power within the resonance frequency range of the human body and loading time, with a Pearson correlation coefficient of -0.855. Furthermore, the analysis also showed correlation coefficient of -0.750 for the correlation between band power and full cycle time of the shovel.

The results indicate that as the cycle time of the shovel increases, and similarly, as the loading time of the dumper by the shovel extends, there is a notable decrease in the band power of the 0.5 Hz to 10 Hz frequency range. This finding suggests that quicker operation of shovels is associated with a higher occurrence of WBV-related bodily damage. Conversely, slower operation of the shovel tends to mitigate the vibration within this frequency range, resulting in a reduction of band power. The correlation coefficient between band power and loading time exceeds that between band power and shovel cycle time. This suggests that faster operation with a loaded bucket of the shovel leads to more significant damage to the operator's body compared to the correlation with shovel cycle time alone.

3. Conclusions

In this study, shovel operators in surface coal mines were found to be exposed to whole-body vibration during shovel operations. The paper investigates how WBV exposure, particularly within the frequency range of 0.5 Hz to 10 Hz, varies with different operational parameters such as the cycle time of the shovel and loading duration. The band power within the susceptible frequency range is considered a parameter of WBV exposure, ranging from 0.0578 $(m/s^2)^2$ to 0.0741 $(m/s^2)^2$ for a full cycle of the shovel. A significant negative correlation is observed between band power and speed during loaded travel. During loading operations by the shovel, band power varies from 0.0946 $(m/s^2)^2$ to 0.1025 $(m/s^2)^2$, with a similarly significant negative correlation between band power and loading time. A much higher band power value is observed during loading operation compared to the full cycle of the shovel. The correlation between band power and loading time is stronger than that with shovel cycle time alone, emphasizing the heightened risk posed by faster operations, particularly when handling material. The results highlight the importance of considering both shovel cycle time and loading time in assessing the impact of WBV on operators. Faster operations, especially when handling loaded buckets, pose a higher risk of WBV-related health issues, emphasizing the need for measures to mitigate vibration exposure during such tasks.

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