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Whole Body Vibration Exposure of Haul Truck Operators – A Case Study

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Abstract: A person is exposed to Whole-body vibration (WBV) if his body is supported by a vibrating surface and the vibration is mechanically transmitted to different parts of his body. Severe health-related issues such as musculoskeletal disorder (MSD), sleep disorder, headache, may be caused due to excessive exposure to WBV for a prolonged period of time. Several studies explore almost 18% of workers in the mining industry in India are exposed to whole body vibration at work. The mining industry makes important contributions to the economic growth of a nation. It provides most of the essential raw materials for the energy and manufacturing sectors. To meet the increased demand for raw materials, the mining industry frequently uses heavy earth moving machineries (HEMM) such as haul trucks, drills, shovels, dozers, draglines, etc. HEMM operators experience WBV during operations of HEMMs.

The paper reports a study on whole body vibration (WBV) for the operators of 100 tonnes haul trucks (dumper). A host of parameters, related to the design of the machine, operating conditions and personnel, influence the whole body vibration. The parameters considered in this study are: load on dumpers, speed of empty dumpers, and speed of loaded dumpers. Triaxial piezo-electric based accelerometer sensors are used to measure WBV. The present work focuses on analysing the frequency of WBV generated for dumper operators. First Fourier Transformation (FFT) is applied to convert the signal data from the time domain to frequency domain and band power is calculated to determine the WBV exposure of a certain frequency band to which the human body is susceptible. A study on the effect of the WBV frequency considering the natural frequency of human body is also attempted in this paper. Matching of these two frequencies may create resonance and can result in severe damage to the human body parts. The frequency analysis of WBV signals is carried out for 21 dumpers and 6 cycles of operations for each dumper are considered. A cycle mainly consists of loading, loaded transportation, unloading, and empty transportation operation. Band power is positively correlated with the speed of dump trucks and also it is negatively correlated with the load on dumpers.

Keywords: Whole body Vibration, HEMM, Surface Mining, Dumper, Acceleration, Frequency, PSD, FFT

1. Introduction

For years, the contribution of the mining industry to the economic growth of a nation is irrefutable. It is a primary industry that excavates billions of tonnes of rocks. A major part of such excavation is done from the surface of the earth. This leads to the involvement of many workers operating heavy earth moving machineries, such as dumpers, shovels, dozers, etc. Good productivity of a mine demands a long working hour of a worker and a high workload. This may result in serious health damage to workers. Attention needs to be paid to the issue so that the health risk can be significantly reduced. Ergonomics is a branch of science that focuses on the health issues in such industries and helps to overcome the problems of prolonged sitting and heavy workloads (McPhee, 2004). One of the serious reasons of health risks to heavy machinery operators is due to whole body vibration (WBV). A person experiences WBV if his body is exposed to a vibrating surface and the vibration is mechanically transmitted to different parts of his body (Mansfield, 2005). Severe health related issues such as musculoskeletal disorder (MSD), sleep disorder, headache, may be caused due to excessive exposure to WBV for an prolonged period of time. Several studies explore that almost 18% of mining industry workers in India are exposed to whole body vibration at work. For the last few decades, WBV has become an important part of ergonomic study.

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The paper reports a study on WBV for the operators of 100 tonnes dumpers. A host of parameters, related to operating conditions of HEMM considered in this study, are namely load on dumpers, loaded travel speed of dumpers, and empty travel speed of dumpers. In general, WBV is measured in three perpendicular directions. Triaxial piezo-electric based accelerometer sensors are used to measure WBV. NorVibraTest software, equipped with frequency weighting as per ISO, 1997 standard, is used to analyse the measured data. A higher value of frequency weighted RMS acceleration and a certain range of frequency of WBV can severely damage human body parts. The present work focuses on analysing the frequency of WBV generated for dumper operators. First Fourier Transformation (FFT) is applied to convert the signal data from the time domain to the frequency domain. A study on the influence of different operational parameters on WBV considering the natural frequency of the human body is attempted in this paper. Matching of WBV frequencies and natural frequencies of the human body create resonance and can result in severe damage to the human body parts. The frequency analysis of WBV signals is carried out for 21 dumpers and 6 cycles of operations for each dumper are considered. A cycle mainly consists of loading, loaded transportation, unloading, and empty transportation operation. The current study considers the dumper's motion during loaded and empty phases.

Since the early 1960s, researchers have been studying the relationship between WBV and fatigue or working performance of the workers. In the case of WBV, vibration is transmitted to the human body from a vibrating surface where the body rests (for example, a driver's seat or a vibrating floor) (Kjellberg, 1990). However, this work focuses on WBV where the impact of different operational parameters on the human body is measured under some exposure conditions, like frequency. In 1977, Cohen et. al. (1977) showed that WBV causes fatigue and weakens the performance while the body is within the frequency range of 2.5 to 5 Hz. The following year, .Lewis and Graffin (1978) again studied the same for frequency range 3.15 to 5 Hz. In 2007, the authors of (Ljungberg and Neely, 2007) have examined frequency in different directions of a human body. The frequency shown in the paper is, 2 Hz in the x-direction, 3.15 Hz in the y-direction, and 4 Hz in the z-direction. Here, the magnitude of the vibration is 1.1 m/s^2. In 2014, Zamanian et. al. have studied WBV for the frequency range 3 – 7 Hz with different magnitudes, like 0.53, 0.81, 1.21 m/s^2 (Zamanian et. al., 2014). Studies show the human body is most sensitive to the frequency range 4 – 10 Hz lateral and 0.5 to 2 Hz longitudinal vibrations (ISO 2631-1:1997). A study conducted by Hassan and McManus in 2002 showed that a truck driver's body is mainly exposed in a low frequency range of 1.42 Hz to 5.7 Hz (Hassan and McManus, 2002). Several studies have been done on the performance analysis of a person due to WBV by only considering different magnitudes of the vibration, and without specifying any frequency (Abbate et.al., 2004), (Costa et.al., 2014). A higher magnitude of vibration may cause serious damage to the human body. However, the human body does not respond equally in each frequency, as every part of the body has different natural frequencies. A certain frequency range, on which resonance occurs, results in more damage to the human body. Hence, frequency also plays a major role along with magnitude, in analysing the effects of WBV. Parsons and Griffin, (1988) have observed that a seated man is 10 times more vulnerable to 5Hz frequency compared to 100 Hz. Brownjohn et. al.,(2001) have concluded that if the vibration magnitude is higher, then the detected human resonance frequency becomes lower. They have suggested if the vibration magnitude (such as earthquake, traffic etc.) is greater than 0.1 m/s^2 then the human resonant frequency can be considered in the range of 3 to 7 Hz.

2. Materials and Methods

The experiment is conducted in a surface mine located in the eastern part of India. The mine comprises 34 dumpers of 100 tones which are of the same models with the same specifications. The dumpers are used for transporting coal and overburden, especially sandstone and shale. Among the 34 dumpers used in the mine, 21 dumpers have been selected for the experiment with 34 operators. Top slicing with backfilling is a common mining practice. A WBV data logger instrument made by Norsonic is used to collect the data with the help of a piezo-electric sensor. It provides the vibration data in the form of acceleration (m/s^2) in the time domain. The data is taken in the direction of three perpendicular axes where the x-axis and y-axis are two horizontal axes, and the z-axis is the vertical one.

The raw WBV data (that is, the acceleration data in the time domain) is extracted by using NorVibraTest software and further analysed in MATLAB 2021a. Figure 1 shows how data has been exported using NorVibraTest software. Different parameters reported by NorVibraTest software in the time domain are tabulated in Table 1. The proposed work analyses the vibration data in the frequency domain. Analysis of vibration data in the time domain, which quantifies the strength of a vibration profile, is limited to RMS acceleration, vibration dose value (VDV), crest factor (CF). VDV indicates the total energy transferred in an axis over time. This study reports VDV for exposures of 8 hour shifts and is represented by VDV(8). On the other hand, CF indicates the ratio of maximum vibration to root mean square acceleration (Paty et. al., 2017). Analysis in the frequency domain is not limited to only the aforementioned parameters. It gives the most in-depth analysis of whole body vibration.

Table 1. Time domain parameters reported by NorVibraTest Software

Parameters	Mean	Range	
		Minimum	Maximum
x-axis (a_{wx})	0.4220	0.3029	0.5505
y-axis (a_{wy})	0.3726	0.2695	0.4584
z-axis (a_{wz})	0.6869	0.4773	0.9142
x-axis (VDV_x (8))	3.3593	2.2391	4.9501
y-axis (VDV_y (8))	2.8909	2.0921	4.5207
z-axis (VDV_z (8))	5.6887	3.7923	8.1003
CFx	8.44	4.86	14.50
CFy	7.13	4.10	16.60
CFz	11.83	7.13	44.70

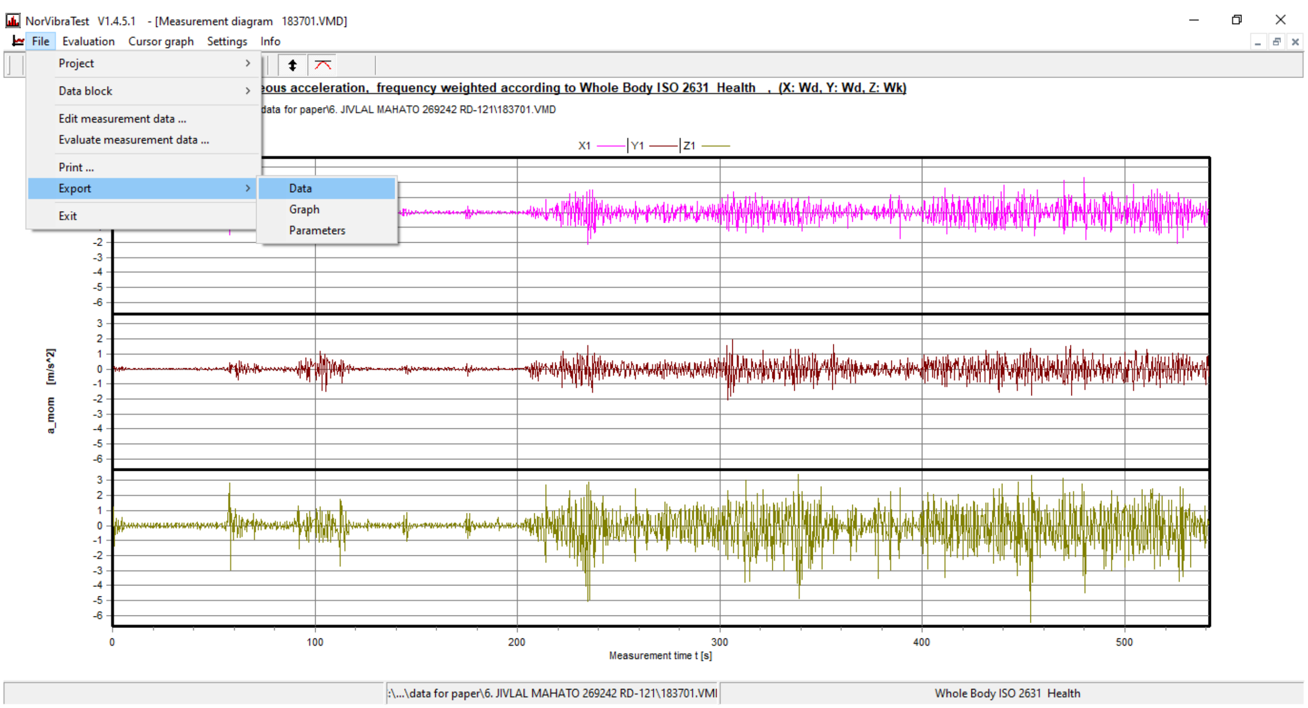

Figure 1. Raw WBV data exporting by NorvibraTest software

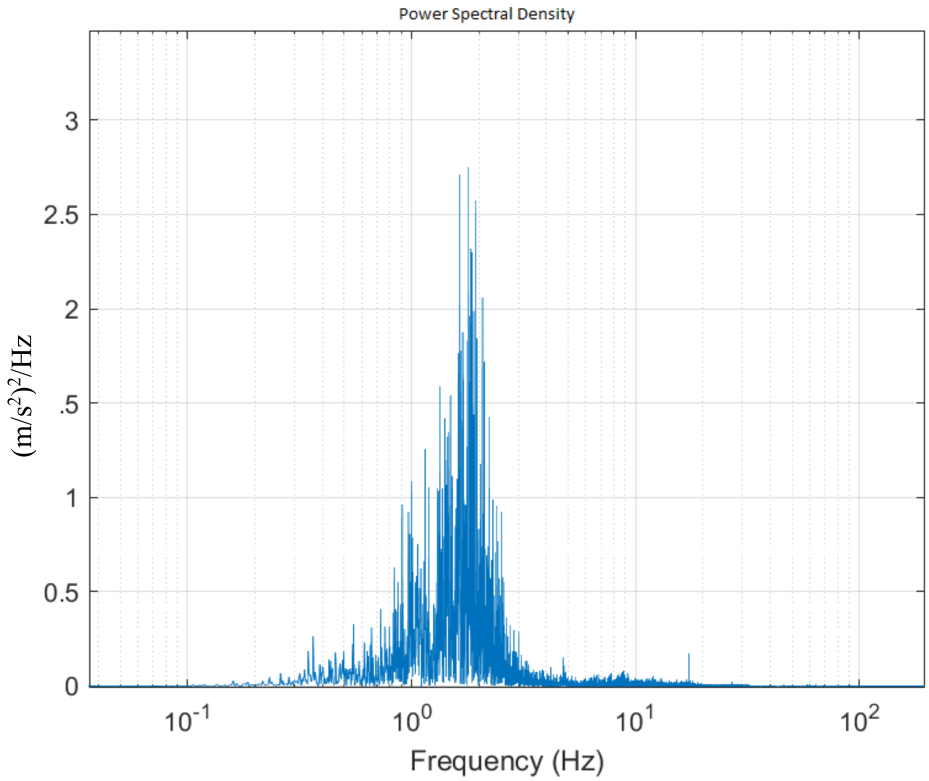

Figure 2. Power Spectral Density (PSD)

In general, vibration data is captured in the time domain and it consists of multiple simple sinusoidal signals of different frequencies. First Fourier Transformation (FFT) is an algorithm that helps in converting the time domain vibration data into the frequency domain. In the real world, vibration is random in nature and consists of waves with a large number of frequencies. Even though FFT is suitable for analysing the vibration with a finite number of dominant frequencies, it is difficult to use FFT for random vibration signals. Power spectral density (PSD) keeps only real components of signals by multiplying FFT with its complex conjugate. Also, PSD normalizes the multiplied value to frequency bin width. Frequency bin width is calculated by inversing the total measured duration. This helps to compare signals of different lengths. These are the key aspects which make PSD more useful than FFT for analysing vibrations of different lengths. Figure 2 shows the PSD of a signal using MATLAB.

A literature survey shows the human body is mostly affected by frequencies that range from 0.5 to 10 Hz. Therefore, this frequency range (or frequency band) is considered in this study for spectrum analysis. The energy of the signal within this frequency range can be calculated by integrating the PSDs. The calculated energy is basically the band power of the signals for this particular frequency band. The energy of WBV within the frequencies range from 0.5 to 10 Hz, creates resonance in the human body and is responsible for increased risk of musculoskeletal disorders (MSD). So, the power of this frequency band can be utilized as a parameter to measure WBV exposure and risk of musculoskeletal disorders (MSD) to HEMM operators. This study elaborates how band power changes with the change of different operational parameters, such as speed of dumpers during empty travel, speed of dumpers during loaded travel, load on dumpers. Correlation analyses are carried out between the operational parameters and WBV. MATLAB codes have been developed in this work for calculating different parameters like FFT, PSD, and band power. The correlation analyses and the outcomes are discussed in the next section.

3. Results and Discussions

The study examines the correlation between band power and the corresponding dumper's speed under the loaded conditions as well as empty conditions. The Pearson correlation analysis between WBV and speed of loaded dumper shows a significant positive relationship. Figure 3 shows the graphical representation of the correlation between band power vs loaded dumper speed.

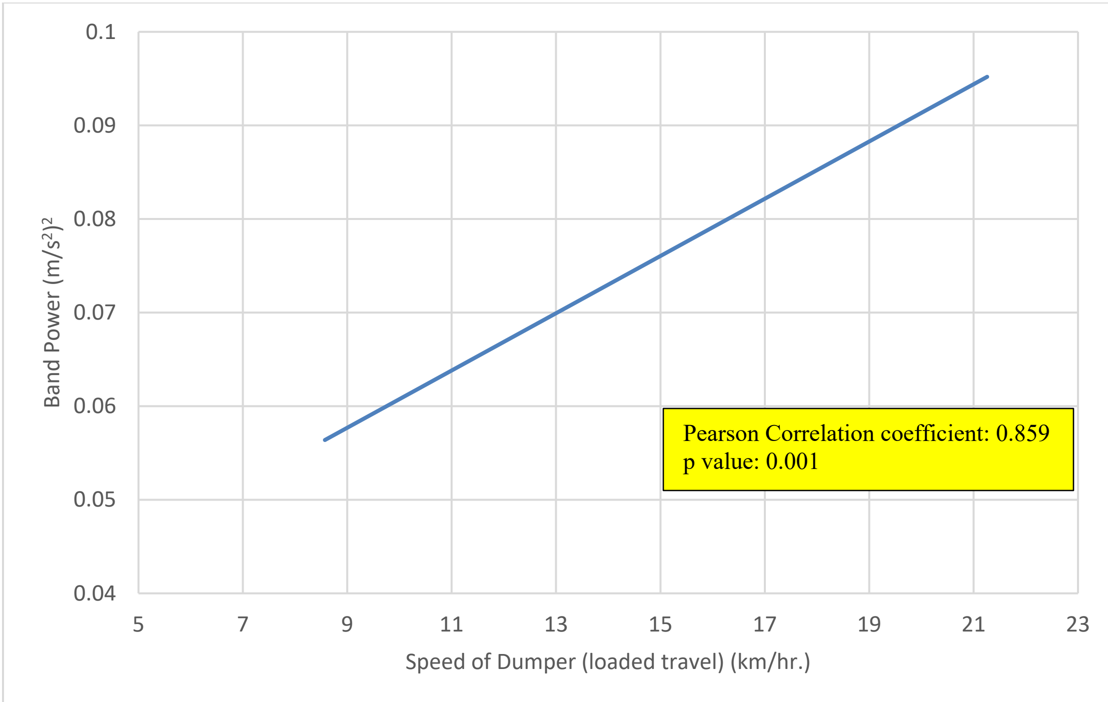

Figure 3. Positive relationship between Band Power and loaded dumper speed

A positive correlation is observed between band power and speed during loaded travel of the dumper with a Pearson correlation coefficient value of 0.859 and p-value is 0.001 which indicates that this relationship is statistically significant.

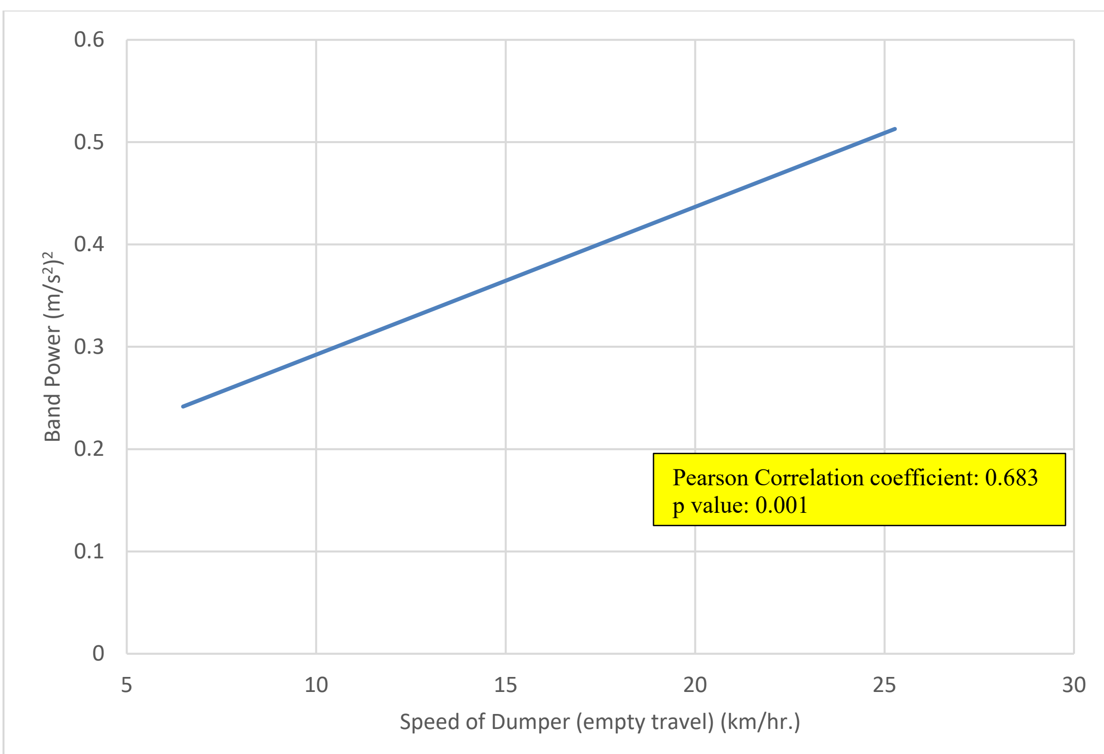

Figure 4. Positive relationship between Band Power and empty dumper speed

Also, Figure 4 represents a correlation between band power vs empty dumper. Here also, a positive correlation is observed between band power and speed during empty travel of the dumper with a Pearson correlation coefficient value of 0.683 and p-value is 0.001 which shows that this relationship is statistically significant.

Similarly, a Pearson correlation has been analysed between band power and the load of the dumpers (Figure 5). This correlation analysis shows a negative significant relationship with a correlation value of -0.527 and a p-value of 0.002.

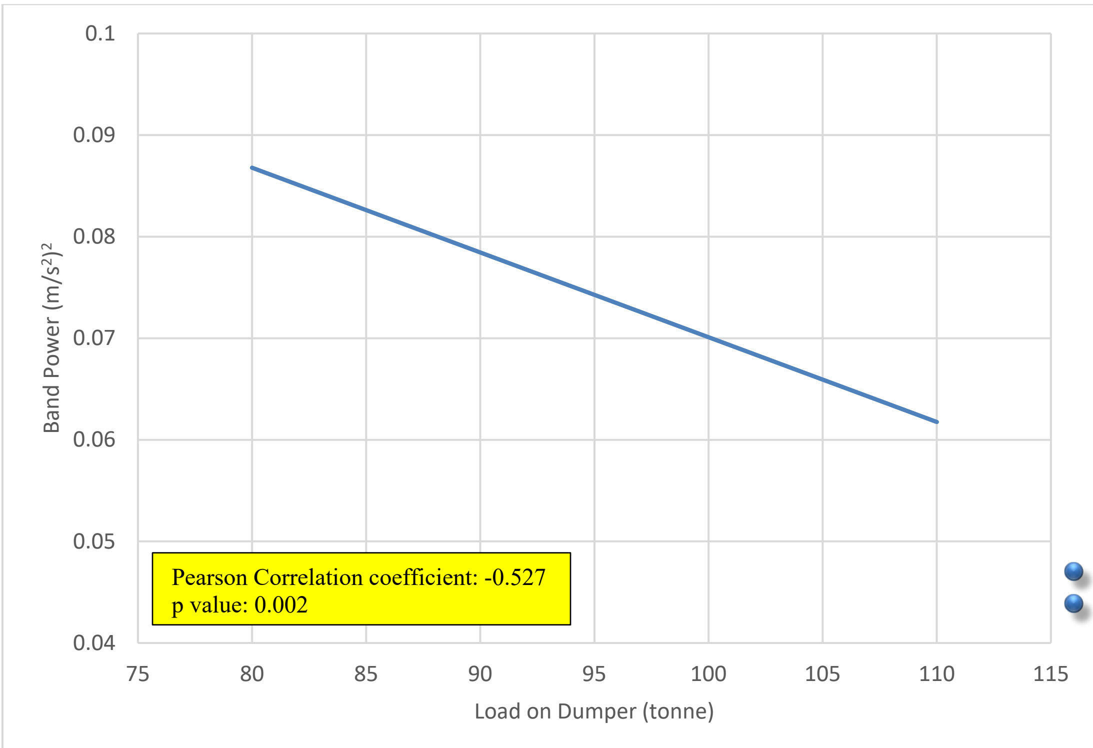

Figure 5. Negative relationship between Band Power and load on dumper

The best fit graph of band power vs. speed plot (Figure 3 & Figure 4) shows a linear trend of band power of the WBV-speed relationship which implies WVB increased monotonously with average driving speed for loaded as well as empty conditions. However, from the correlation values, it can be concluded that band power is more strongly correlated to the loaded travel speed compared to the empty travel speed.

So, it can be said that band power of 0.5 to 10 Hz frequency range increases with the increase of speed of the dumper for both loaded and empty conditions. It indicates that the higher speed of dumpers is related to more safety risks and it causes more musculoskeletal disorder (MSD) in the human body.

Figure 5 shows that higher loads on dumpers reduce the band power of the vibration within the particular frequency range, that is from 0.5 Hz to 10 Hz. Higher load dampens the vibration of the given frequency range which causes a reduction of band power in the particular band.

4. Conclusion

Dumper operators are significantly exposed to a particular frequency band of whole body vibration. This paper investigates how WBV exposure of the certain frequency band changes with changes of different operational parameters, such as speed of dumpers and load on dumpers. Band power of the frequency band, for which the human body is susceptible, is considered as a parameter of WBV exposure. Band power varies from 0.0518 $(m/s^2)^2$ to 0.0899 $(m/s^2)^2$ during loaded travel of the dumper. The correlation between band power and speed during loaded travel is positively significant. Band power varies from 0.1441 $(m/s^2)^2$ to 0.5455 $(m/s^2)^2$ during empty travel of the dumper. The correlation between band power and speed during empty travel is also positively significant. A much higher band power value is observed during empty travel compared to the loaded travel. It implies that the effects of WBV on the operators of dump trucks are higher during empty travel. Correlation analysis between band power during loaded travel and load on dumper shows a negative significant relationship which indicates underloaded dump trucks generate more vibration than properly loaded dump trucks. In conclusion, the current study demonstrates the effects of WBV exposure to the operators during loaded travel as well as empty travel phases of the haul trucks. The work has mainly concentrated on the band power calculation of WBV and the correlation between band power and speed during different running situations of haul trucks. However, there are some limitations of the study. Loading and unloading phases of a dumper cycle have not been considered in this study, which can be further investigated as future work.

5. References

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