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Whole Body Vibration Exposure during Rotary Soil Tillage Operation: The Relative Importance of Tractor Velocity, Draft and Soil Tillage Depth

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ABSTRACT

The present investigation attempted to study the overall daily vibration exposure A(8) in actual field rotary tillage operation at various ride conditions (i.e. average velocity, draft and average soil tillage depth). Three different levels of each ride condition were chosen to formulate an organised design of experiments by using Taguchi's approach. The concurrent root mean square (RMS) acceleration values were measured at the tractor platform, seat pan and seat backrest along the three translation axes to determine the A(8). Signal-to-noise ratios (SNRs) were computed and analysed concerning the conducted experiments. Further, the dominant frequencies at each set of experiment were determined by fast fourier transform (FFT) analysis. A linear regression model was developed to predict the output response and further, the ride conditions were optimised by using desirability approach. The overall daily vibration exposure was found between fairly uncomfortable to uncomfortable category (i.e. 0.64 and 0.84 m/s^2) as per ISO 2631-1 (1997). Moreover, the exposure levels are beyond the exposure action limit recommended by Directive2002/44/EU. The average velocity and draft effects on the A(8) response were found significant ($p \leq 0.05$) with a contribution of 78.38% and 18.54%, respectively. The FFT analysis depicted a range of dominant peaks in the frequency range of 0.8 to 3.7 Hz. However, the exact frequency of the peaks was found to depend on the experimental condition. The prediction model indicates a good correlation between predicted and actual experimental response with an average error of 1.02%. Desirability and Taguchi's approaches gave identical optimised ride conditions (i.e. 0.6 m/s, 6 kN, and 0.14 m) with the aim of reducing the A(8) value.

Keywords: Agricultural tractor, overall daily vibration exposure A(8); Taguchi's method; fast fourier transform (FFT), optimisation.

INTRODUCTION

Agricultural field requires a variety of primary and secondary soil tillage operations before sowing of any crop. In current era, the agriculturists are dedicating considerable attention to reducing the time period between consecutive crops with the aim of fulfilling the productivity demand. This makes them use mechanized tillage machineries in order to minimize the crop sowing time period. Most of the soil tillage tools are mounted with tractors to save the human energy for preparing optimum field conditions. Sometimes, it is difficult to carry out tillage operations especially after the paddy harvesting. The loss in soil moisture level and formation of rice stubbles are challenging issues for the farmers to perform tillage operations. Rotary tillers are becoming popular to overcome this issue with considerably less effort. There are several cutting blades affixed on flanges for the overturning of soil and clods. This process causes vibration due to the tractor-tiller interactions with the uneven field surface at different operating conditions [1]. The vibration is transmitted to the body of the driver via various source points like the floor, seat and steering wheel [2,3]. Tewari et al. [4] reported that tractors drivers are over-exposed to the whole-body vibrations as per the recommended exposure limits [5]. Prolonged exposure to such occupational whole-body vibration is a leading health risk among the tractor drivers [6,7]. Several researchers showed an association between vibration exposure and health issues like musculoskeletal disorders, fatigue, metabolism issues, cardiovascular and nervous system risks [8,9,10]. In addition, the vibrations transmission in tractor driving is of low frequencies that may also cause discomfort due to the existing natural frequencies of human body parts [11,12].

Most of the previous investigations were performed on simulators to study the ride influence of many factors such as the magnitude of vibration [13], sitting posture [14], seat backrest [15], etc. However, limited research has considered vibration exposure in actual driving conditions for on road vehicles [16] or off-road vehicle such as tractors [8,9] at various forward speeds and terrains. These studies used only tractor without any attached implements to investigate vibration exposure and ride comfort. The literature related to the real field soil tillage activities is limited to harrowing and ploughing operations [17,18]. Nowadays, farmers are using rotary tillage operation in place of harrowing and ploughing for being a powerful and versatile part of machinery. Although this considerably reduces the field preparation time for sowing of the next crop, it could lead to various health related issues among tractor drivers for being exposed to whole-body vibration (WBV). Therefore, the objective of the present study is to investigate the overall daily vibration exposure A(8) during rotary soil tillage operation at various real field ride conditions. The influence of the various tractor ride parameters i.e. average velocity, draft and average soil tillage depth will be studied. It was hypothesized that varying the ride conditions will significantly influence the ride comfort by affecting the overall daily vibration exposure A(8).

METHODOLOGY

Field and Machinery

This study used a 112×75 m sandy clay loam soil texture field with 24%-clay, 67.15%-sand, 8.85%-silt and 54.6% moisture content. The soil compactness was found 14, 20 and 28 kPa with up to 0 to 0.05, 0.05 to 0.10 and 0.10 to 0.15 m respective depth levels. The experiments were carried out on a 2014 model tractor ‘T’ of 55 horse power (HP). All tires were replaced by new tires just three months before the start of the experiment. Tire air pressure has been maintained as recommended by the manufacturers. Tractor was mounted by a seven feet rotavator of 450 kg with 2.137 m cutting width and 0.15 m depth. The rotavator had 48 cutting blades with C-shaped welded on 8 flanges to provide rotary motion.

Subject

A 24-year old male subject with mass of 81 kg, stature of 1.54 m, and body mass index (BMI) of 34.15 kg/m^2 was recruited to drive the tractor during the experiment. The selected subject is a farmer with approximately five years tractor driving experience. The intention of the study has been made clear to the driver earlier than starting the experiments. In addition, the subject reported no sensitiveness towards vibration exposure. The subject signed a consent form for his participation to carry out the experiments.

Evaluation of Overall Daily Vibration Exposure A(8)

To assess the ride comfort, the overall daily vibration exposure level A(8) has been evaluated after measuring the exposure levels on the seat, backrest and floor. The weighting filters and multiplication factors related to comfort were used in the evaluation as per ISO 2631-1 [5]. This is calculated from the weighted root mean square acceleration magnitude (a_w) of vibration along translational axes (i.e. x- fore-and-aft axis, y-lateral axis, z-vertical axis). It can be expressed mathematically as in Eq. (1).

$$\text{Daily Exposure } A(8)=ka_w\sqrt{\frac{T}{T_0}} \tag{1}$$

The overall daily vibration exposure can then be calculated taking into consideration the different sources of vibration as in Eq. (2).

$$\text{Overall Daily Vibration Exposure}=\sqrt{A_1(8)^2+A_2(8)^2+\ldots} \tag{2}$$

where, k is the multiplication factors with standard values for different axes [5]; a_w is root mean square frequency weighted acceleration magnitude; the axis having maximum a_w value was used in Eq. (1); T is the actual duration of exposure, T_0 is the reference time of eight hours; $A_{1, 2\ldots n}(8)^2$ is partial vibration exposure (PVE) responses at different source locations.

The severity of A (8) exposure has been decided by comparing the output response with recommended exposure limits (i.e. exposure action value (EAV): 0.5 m/s^2 and exposure limit value (ELV): 1.15 m/s^2) as per Directive2002/44/EU [31]. A(8) value exceeding the EAV indicates the need to control the risk from vibration exposure. A(8) value more than the ELV indicates high risk and should be avoided.

Measurement Locations and Apparatus

The partial vibration exposure levels at three different vibration source locations, namely floor, seat and backrest were used in order to calculate the overall daily vibration exposure as shown in Figure 1. The input vibration at the mentioned three locations was measured in the x, y, and z-directions. Two SV 84V tri-axial seat pad accelerometers were mounted at seat pan and seat backrest with a connection with SV 106A six channel vibration monitor, whereas SV151 tri-axial sensor was mounted on the floor with a connection with SV 958A four channel vibration monitor to record aw response. The duration of vibration recording was one minute at a sampling rate of 6 kHz. A band-limit (low pass) weighting filter was used as per ISO 2631-1 [5].

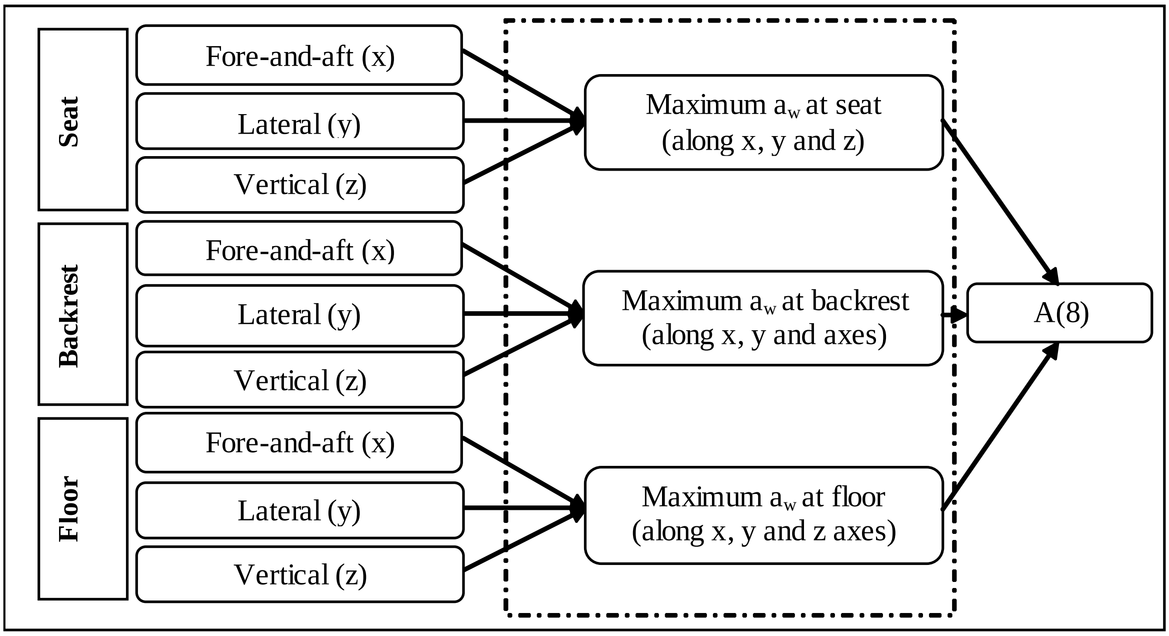


Figure 1. Hierarchy for calculating the overall daily vibration exposure A(8).

Experimental Design

Taguchi's L9 orthogonal array was used for the design of the experiments. This orthogonal array was chosen to get the minimum number of experimental runs to understand the influence of each ride condition on A(8) response. The investigation includes three ride factors namely, average velocity, draft, and average soil tillage depth. Each factor was varied over three levels as shown in Table 1. These factors were chosen by conducting direct interviews with the farmers and carrying out free trials of the tillage operation in actual field. The average velocity was calculated by using traditional method measuring distance covered in selected gear (i.e. first low or 1-L) and time period (i.e. 60s). The draft refers to the force exerted on the draw bar to pull the mounted implement. There were two levers nearby the driver seat with standard marking points 2,4,6,8,10 and 1,3,5,7,9 to maintain the soil tillage depth. Tractor driver was asked to carry out free trials of the operation by providing no ride instructions. The operation was performed at 2, 4, 6 and 5, 7, 9 lever settings. A dynamometer was mounted with draw bar and the implement (Figure 2 (a)) to measure the draft [19]. The dynamometer provided 2, 4 and 6 kN force exerted on the draw bar at 2, 4 and 6 lever condition. The soil tillage depth was measured manually (Figure 2(b)) by using a scale ruler at respective lever setting (i.e. 5, 7 and 9) which provided an average depth of 0.10, 0.12 and 0.14m, respectively.

(a) (b)

Figure 2. (a) Representation of dynamometer mounting; (b) tillage depth measurement.

Table 1. Ride conditions and their levels.

Design factors	Levels		
	1	2	3
Average velocity (m/s)	0.6	0.7	0.8
Draft (kN)	2	4	6
Average soil tillage depth (m)	0.10	0.12	0.14

The term 'signal' (S) provides actual effect of input factors on the output while the term 'noise' (N) corresponds to the deviation in the output response due to undesirable factors [20]. The objective function of present study was to minimize the output response, therefore smaller-the-better option was chosen as per Eq. (3).

$$(\mathrm{SNR}) = -10\log\left[\frac{1}{K\left(X_1^2+X_2^2+\ldots+X_n^2\right)}\right] \tag{3}$$

where, X_1, X_2, . . ., X_n represents the A(8) with respect to each experiment replicated over K times.

Data Analysis

The raw acceleration data at three source locations was recorded and transferred into Svan PC++ software to get the root mean square frequency weighted acceleration magnitude. Further, the raw data was saved in text files (.txt files) and analyse in LabVIEW 2014 to determine Fast Fourier Transform (FFT) responses. Experimental design was prepared in Minitab 16 statistics package to get SNRs, optimum levels, analysis of variance (ANOVA), and regression modelling.

RESULTS AND DISCUSSION

Signal-to-Noise Ratio

The SNRs were computed for each experimental combination provided by Taguchi's L9 orthogonal array. Each experiment was repeated three times (T1, T2 and T3) and the mean

A(8) value of the three repetitions was calculated and tabulated in Table 2. The acceleration levels were dominant along vertical (z) axis at seat, backrest and floor locations as shown in Figure 3.

Table 2. Experimental data and SNR for daily exposure A(8).

Expt. Run	Average Velocity (m/s)	Draft (kN)	Average Soil Tillage Depth (m)	Overall Daily Vibration Exposure T1	T2	T3	Average	SNRs
1	1	1	1	0.71	0.72	0.70	0.71	2.97
2	1	2	2	0.66	0.67	0.70	0.68	3.39
3	1	3	3	0.62	0.64	0.66	0.64	3.88
4	2	1	2	0.80	0.77	0.78	0.78	2.12
5	2	2	3	0.73	0.71	0.71	0.72	2.89
6	2	3	1	0.74	0.73	0.74	0.74	2.65
7	3	1	3	0.82	0.84	0.86	0.84	1.51
8	3	2	1	0.80	0.78	0.81	0.80	1.97
9	3	3	2	0.78	0.78	0.77	0.78	2.19

Langer et al. [21] investigated the whole-body vibration exposure during tractor ride and reported similar trend of vibration response along z-axis. Therefore, a_w values along z-axis were used to calculate overall daily vibration exposure as per Equation (2). The A(8) value in all the experiments was in the range 0.64-0.84 m/s^2 which is found to vary from fairly uncomfortable to uncomfortable category as per ISO 2631-1 [5]. In addition, the exposure levels were beyond the recommended action value of 0.5 m/s^2 as per Directive2002/44/EU [31]. A previous study also reported high whole-body vibration exposure levels in tractors driven on different terrain and speeds [22]. The high levels of vibration could increase discomfort as well as the risk of health issue especially low back pain [2,12,23-24].

The mean SNR for each set of experiment was computed and plotted in Figure4. The effect of each factor on A(8) can be visualized with the change in level of respective factor. The mean SNR tends to decrease with increasing the average velocity. This means that increasing the velocity leads increasing the overall daily vibration exposure level. This is due to the increase in root mean square frequency weighted acceleration magnitude with increasing velocity levels [25, 26]. In addition, the rise in acceleration magnitudes could be the result of uneven terrain condition. These increasing acceleration levels should be monitored and controlled as it may affect the ride behavior and lower the work capacity of tractor operator [27]. Moreover, the overall daily vibration exposure found to decrease with the increase in draft and tillage depth levels as per SNRs. Therefore, the vibration transmission into the driver's body could be reduced by increasing the force in order to pull the rotavator during operation. In Figure 4, the SNRs showed a slight increase with increasing the tillage depth up to 0.12 m.

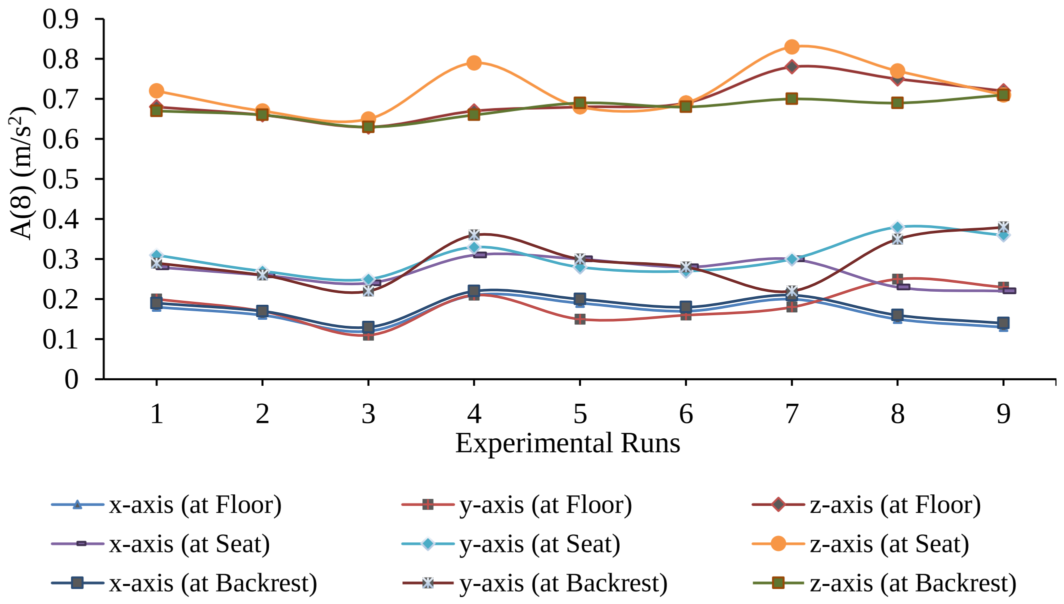


Figure 3. Daily exposure response at floor, seat and backrest locations.

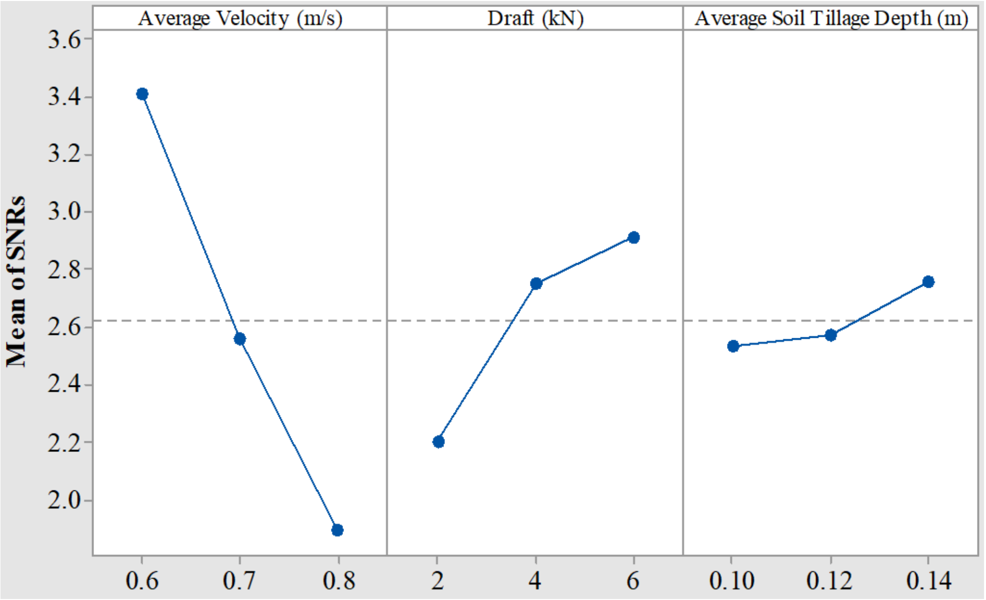


Figure 4. Main effect plot for A(8) with respect to SNRs.

This trend changes drastically when the tillage depth increased from 0.12 to 0.14 m. The cohesion and friction between soil particles and tilling tool increases which retards the flow of vibration energy [28]. Vibration energy propagates inside the ground with increase in depth which lowers the vibration transmission into the operator body due to increase in distance between the source and the operator [29]. The decay in amplitude levels may be attributed to the geometric as well as material damping.

Analysis of Variance (ANOVA)

Analysis of variance was performed to investigate the statistical significance of each input factor on the output characteristic. For this purpose, sequential sum of squares (SeqSS), adjusted mean squares (Adj MS), F-values, p-values, percentage contribution (P%), delta values and ranking of input factors were computed and recorded (Table 3). F-value was analysed at 95% (0.05) confidence levels and compared with the tabulated value i.e. $F_{0.05\ (2,\ 8)} = 4.46$, where 2 and 8 represents the degree of freedom for numerator and denominator, respectively. The average velocity and draft were found significant factors in affecting the overall daily vibration exposure at 95% level. However, the tillage depth had insignificant influence on the exposure levels. The individual contribution of each factor to the output response was calculated in terms of percentages using total sequential sum of squares (Seq SS_T) and individual sequential sum of squares (Seq SS_I). Lindman [30] stated a mathematical formula to calculate P% as:

$$P\ \% = \frac{\text{Seq } SS_I}{\text{Seq } SS_T} \times 100 \tag{4}$$

Table 3 shows that the average velocity has the highest contribution (78.38%) to influence the A(8) followed by draft (18.54%) and average tillage depth (2.01%). Delta values indicate the influencing index which has been calculated by subtraction between the upper most and the least SNR values. Delta values with respect to the average velocity, draft & average soil tillage depth were calculated as 1.520, 0.705 and 0.227, respectively. Ranking of the input factors has been performed in accordance with the calculated delta values; the maximum delta value corresponds to rank 1 for that particular factor in order to influence the output characteristic.

Table 3: Analysis of variance for SN ratios

Source	DF	Seq SS	Adj MS	F-value	p-value	P (%)	Delta-values	Rank
Average Velocity	2	3.48	1.74	73.06	0.01*	78.38	1.52	1
Draft	2	0.82	0.41	17.28	0.05*	18.54	0.70	2
Average Tillage Depth	2	0.09	0.04	1.88	0.34	2.01	0.23	3
Residual Error	2	0.05	0.02			1.07		
Total	8	4.44				100.00		

Significant at 95% confidence level ($F_{0.05\ (2,8)} = 4.46$), *most significant factor.

Further, the significant factors were represented in the form of interaction and contour plots to study the simultaneous effect on the mean overall daily vibration exposure as shown in Figure 5 and 6. In Figure 5, the vibration exposure levels decreased slightly with the increase in draft from 2 to 4 kN at 0.6 and 0.8 m/s. However, this trend changed while moving from 4 to 6 kN at average velocity of 0.7 m/s. In addition, the overall exposure response was minimum at 0.6 m/s followed by 0.7 and 0.8 m/s. Average velocity shows a significant effect (0.825 to 0.850 m/s^2) on the A(8) response even at a draft of 2 kN as shown in Figure 6.

Similarly, the mean overall daily exposure response A(8) can be seen at varying ride conditions with respect to different levels (Figure 6). In Figure 6, the A(8) response was found minimum in between the shaded area representing exposure level less than around 0.7 m/s^2.

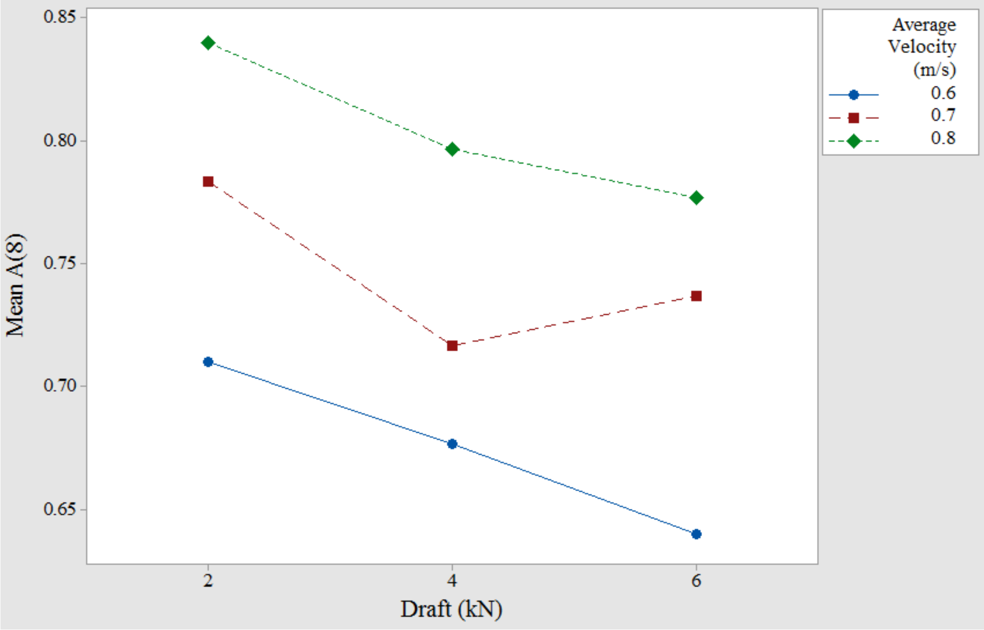


Figure 5. Interaction plot for mean A(8).

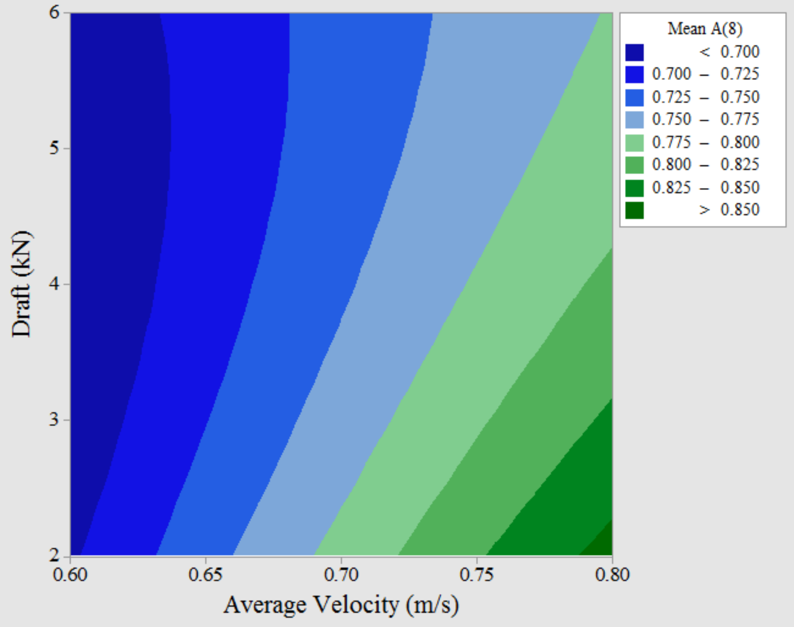
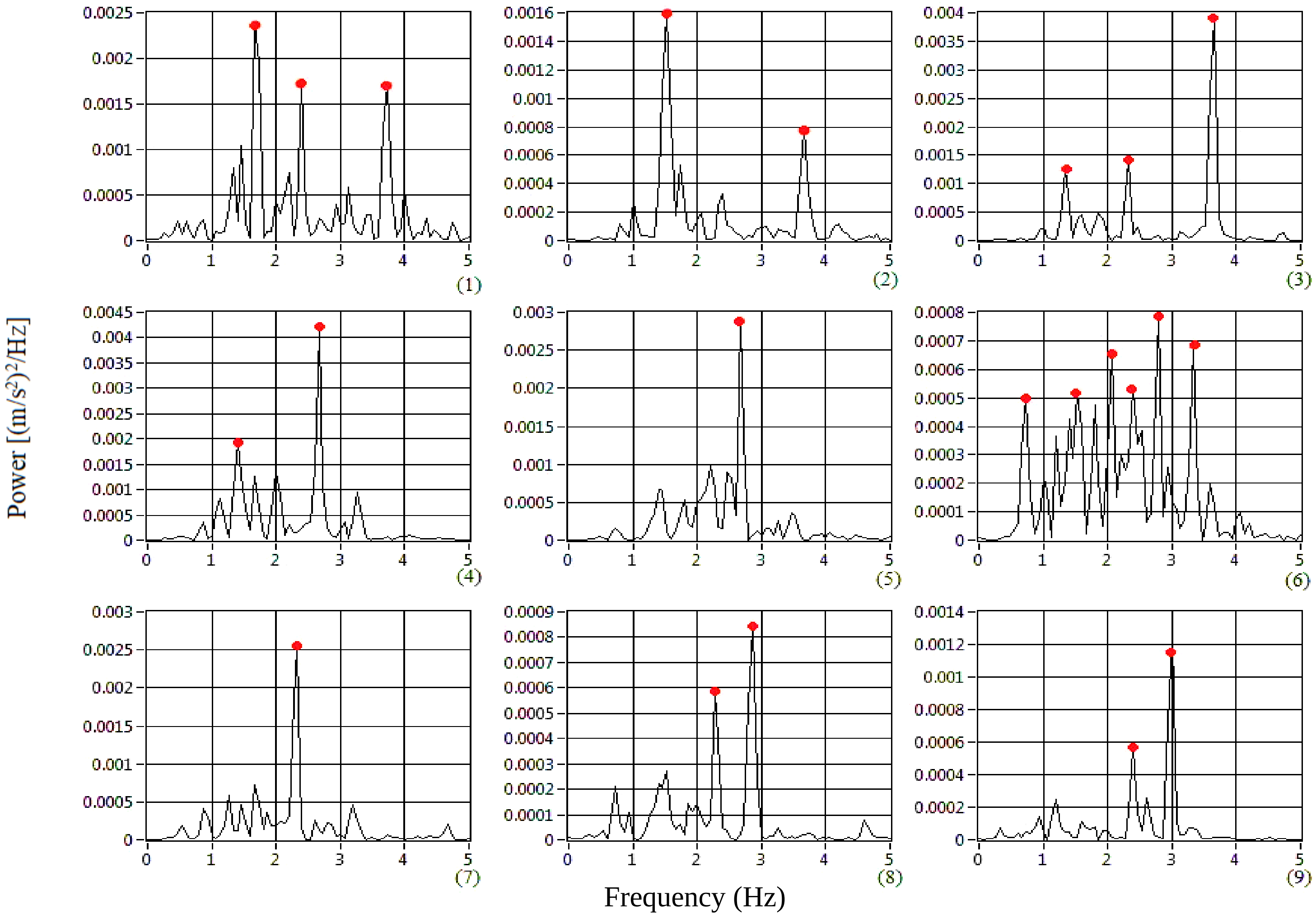


Figure 6. Contour plot of mean A(8).

Fast Fourier Transform (FFT)

The raw seat pan acceleration data at seat location was analysed along vertical (z) axis to obtain dominant frequencies for each experimental run (1-9) as shown in Figure 7. The FFT results indicated that the tillage operation causes low frequency vibration exposure between 0.8 to 3.7 Hz. The vibration energies tend to change over the selected frequency range in real field experimentation. Therefore, it can be observed that peak frequency response varies by changing the experimental conditions and each experiment showed a single or multiple frequency-peaks.

Figure 7. Fast Fourier transform (FFT) response for experiment (1) to (9) as per orthogonal array.



Experiment 5 and 7 showed a single predominant frequency peak in the range of 2 to 3 Hz. Moreover, the experiment 2,4, 8 and 9 exhibited two different peaks with a common dominant frequency range between 2 to 3 Hz and the other peak at varying frequencies such as between 1.5-2 Hz and 3-4 Hz. However, the rest of experiments (1,3 and 6) showed multiple peaks depending upon varying ride conditions. These dominant frequencies could coincide with the natural frequencies of various human body parts and may cause affect ride comfort [24].

Regression Modelling

The overall daily vibration exposure from the experiments were used to develop a regression model for predicting overall daily vibration exposure from average velocity, draft and the average soil tillage depth. Further, the purpose was to get optimum input parameters that guarantee a reduction in the overall daily vibration exposure response. The linear regression model has been formulated as shown in Eq. (5) with R^2 = 96%; R^2 (Adjusted) = 94%, R^2 (Predicted) = 88%.

$$\begin{aligned} A(8) = 0.3974 + 0.6444\ \text{Average velocity (m/s)} - 0.01500\ \text{Draft(kN)} \\ - 0.389\ \text{Average soil Tillage depth (m)} \end{aligned} \tag{5}$$

Equation (5) has been accounted to predict A(8) with respect to each experimental condition provided by Taguchi's L_9 design as shown in Table 4. The predicted responses from the model were found close to the actual experimental results as shown in Figure 8 and in the last three columns of Table 4. The percentage error shown in the last column of Table 4 was calculated for each condition using Equation (6) [30]. The mean percentage error over all conditions was found 1.02%.

$$\text{Error (\%)} = \frac{\text{Experimental value-Predicted value}}{\text{Experimental value}} \times 100 \tag{6}$$

Ride conditions were optimised by using desirability approach and the results provided the optimum levels for average velocity, draft and average soil tillage depth as 0.6 m/s, 6 kN, and 0.14 m to obtain minimum A(8).

Table 4. Comparison between experimental and predicted overall daily exposure response.

Run	Average velocity (m/s)	Draft (kN)	Average tillage depth (m)	Mean A(8) (m/s^2)	Predicted A(8) (m/s^2)	Error (%)
1	0.6	2	0.1	0.71	0.72	1.41
2	0.6	4	0.12	0.68	0.68	0.00
3	0.6	6	0.14	0.64	0.64	0.00
4	0.7	2	0.12	0.78	0.77	1.28
5	0.7	4	0.14	0.72	0.73	1.39
6	0.7	6	0.1	0.74	0.72	2.70
7	0.8	2	0.14	0.84	0.83	1.19
8	0.8	4	0.1	0.80	0.81	1.25
9	0.8	6	0.12	0.78	0.78	0.00
						Mean = 1.02

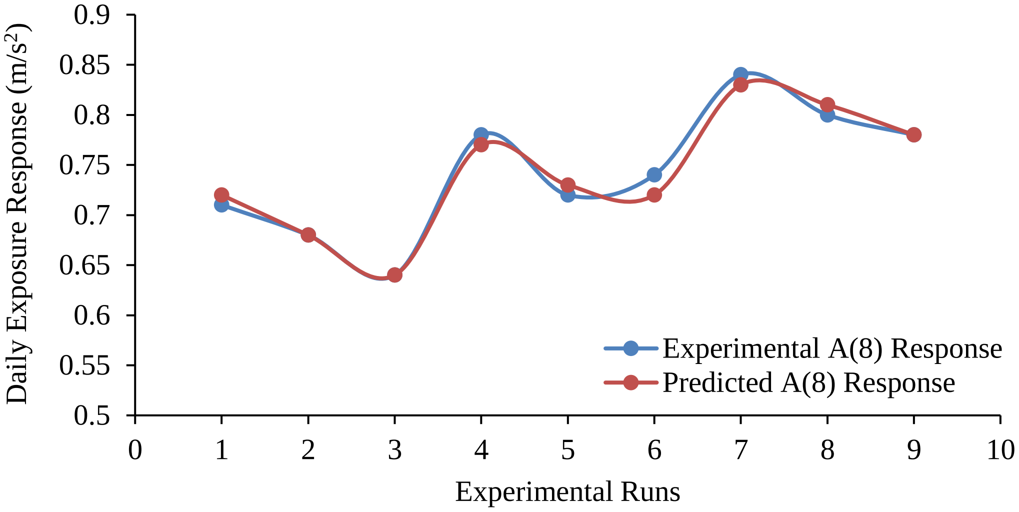


Figure 8. Correlation between experimental and predicted results.

The desirability approach is used to obtain optimum ride conditions that can provide reduced overall vibration total value. This approach refers to an objective function having values between 0 and 1 where 0 indicate that the solution is far from the target and 1 indicates that the solution reached the target. The desirability (d) value of Eq. (5) obtained was 0.93. The results provided identical optimum ride conditions (i.e. average velocity, draft and average soil tillage depth) to those obtained using Taguchi's SNR response to get minimum A(8) (Figure 4). The optimum ride conditions are tabulated with highlighted text in Table 4. Moreover, the optimum ride conditions were found within the region of minimum overall daily vibration exposure as shown in Figure 6.

CONCLUSION

The overall daily vibration exposure response was found to be exceeding the recommended action value as per ISO 2631-1 (1997). Average velocity and draft are found to be significant factors ($p \leq 0.05$) affecting the overall daily vibration exposure with a percentage contribution of 78.38 and 18.54%, respectively. The fast Fourier transform analysis depicted a range of dominant low frequencies between 0.8 to 3.7 Hz among the conducted experiments. The developed prediction model showed a good correlation between predicted and actual experimental overall daily vibration exposure A(8) with a mean error of 1.02%. The developed algorithm is valid only for the tested tractor and implement. Both Taguchi's and desirability approach provided similar optimum input levels with the aim of minimizing overall daily vibration exposure A(8).

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REFERENCES

[1] Mehta, CR, Tiwari, PS, Varshney, AC. Ride vibrations on a 7·5 kW rotary power tiller. Journal of Agricultural Engineering Research 1997;66(3):169-176.

[2] Village J, Trask C, Chow Y, Morrison JB, Koehoorn M, Teschke K. Assessing whole body vibration exposure for use in epidemiological studies of back injuries: measurements, observations and self-reports. Ergonomics 2012;55(4):415-24.

[3] Park MS, Fukuda T, Kim T, Maeda S. Health risk evaluation of whole-body vibration by ISO 2631-5 and ISO 2631-1 for operators of agricultural tractors and recreational vehicles. Industrial Health 2013;51(3):364-70.

[4] Tewari VK, Vidhu KP, Arudra, AK, Kumari S. Reduction of hand transmitted and whole-body vibrations experienced by tractor operators by using piezo crystal material. Agricultural Engineering International: CIGR Journal 2013;15(2):209-220.

[5] International Organization for Standardization. Mechanical vibration and shock–evaluation of human exposure to whole-body vibration–part 1: general requirements. ISO 2631-1 1997; Geneva.

[6] Hildebrand R, Keskinen E, Navarrete JAR. Vehicle vibrating on a soft compacting soil half-space: ground vibrations, terrain damage, and vehicle vibrations. Journal of Terramechanics 2008;45(4):121-36.

[7] Solecki L. Assessment of annual exposure of private farmers to whole body mechanical vibration on selected family farms of plant production profile. Annals of Agricultural and Environmental Medicine 2010;17(2):243-250.

[8] Servadio P, Marsili A, Belfiore NP. Analysis of driving seat vibrations in high forward speed tractors. Biosystems Engineering 2007;97(2):171-80.

[9] Scarlett AJ, Price JS, Stayner RM. Whole-body vibration: evaluation of emission and exposure levels arising from agricultural tractors. Journal of Terramechanics 2007;44(1):65-73.

[10] Loutridis S, Gialamas T, Gravalos I, Moshou D, Kateris D, Xyradakis P, Tsiropoulos, Z. A study on the effect of electronic engine speed regulator on agricultural tractor ride vibration behavior. Journal of Terramechanics 2011;48(2):139-47.

[11] Liang CC, Chiang CF. Modeling of a seated human body exposed to vertical vibrations in various automotive postures. Industrial Health 2008;46(2):125-37.

[12] Harsha SP, Desta M, Prashanth AS, Saran VH. Measurement and bio-dynamic model development of seated human subjects exposed to low frequency vibration environment. International Journal of Vehicle Noise and Vibration 2014;10(1-2):1-24.

[13] Ciloglu H, Alziadeh M, Mohany A, Kishawy H. Assessment of the whole-body vibration exposure and the dynamic seat comfort in passenger aircraft. International Journal of Industrial Ergonomics 2015; 45: 116-23.

[14] Rakheja, S, Dong, RG, Patra, S, Boileau, PE, Marcotte, P, Warren, C. Biodynamics of the human body under whole-body vibration: Synthesis of the reported data. International Journal of Industrial Ergonomics 2010;40(6):710-732.

[15] Nawayseh N, Griffin MJ. Tri-axial forces at the seat and backrest during whole-body vertical vibration. Journal of Sound and Vibration 2004;277(1-2):309-26.

[16] Nawayseh N. Effect of the seating condition on the transmission of vibration through the seat pan and backrest. International Journal of Industrial Ergonomics 2015; 45: 82-90.

[17] Sorainen E, Penttinen J, Kallio M, Rytkonen E, Taattola K. Whole-body vibration of tractor drivers during harrowing. American Industrial Hygiene Association Journal 1998;59(9):642-644.

[18] Muzammil M, Siddiqui SS, Hasan F. Physiological effect of vibrations on tractor drivers under variable ploughing conditions. Journal of Occupational Health. Japan Society for Occupational Health 2004;46(5):403-9.

[19] Chen Y, McLaughlin NB, Tessier S. Double extended octagonal ring (DEOR) drawbar dynamometer. Soil and Tillage Research 2007;93(2):462-71.

[20] Bagci E, Aykut S. A study of taguchi optimization method for identifying optimum surface roughness in cnc face milling of cobalt-based alloy (stellite 6). The International Journal of Advanced Manufacturing Technology 2005;29(9-10):940-47.

[21] Langer TH, Ebbesen MK, Kordestani A. Experimental analysis of occupational whole-body vibration exposure of agricultural tractor with large square baler. International Journal of Industrial 2015; 47: 79-83.

[22] Cutini M, Costa C, Bisaglia C. Development of a simplified method for evaluating agricultural tractor’s operator whole body vibration. Journal of Terramechanics 2016; 63: 23-32.

[23] Mansfield NJ. Human response to vibration. CRC press: 2004.

[24] Griffin MJ. Discomfort from feeling vehicle vibration. Vehicle System Dynamics. Informa UK Limited; 2007;45(7-8):679-98.

[25] Taghizadeh-Alisaraei A. Analysis of annoying shocks transferred from tractor seat using vibration signals and statistical methods. Computers and Electronics in Agriculture 2017; 141: 160-70.

[26] Singh A, Singh L, Singh S, Singh H, Prakash C. Investigation of occupational whole-body vibration exposure among Indian tractor driver. International Journal of Human Factor and Ergonomics 2018; 5: 151-65.

[27] Sam B, Kathirvel K. vibration characteristics of walking and riding type power tillers. Biosystems Engineering 2006;95(4):517-28.

[28] Kim DS, Lee JS. Propagation and attenuation characteristics of various ground vibrations. Soil Dynamics and Earthquake Engineering 2000;19(2):115-26.

[29] Singh A, Singh L, Singh S, Singh H, Chhuneja N, Singh M. Evaluation and analysis of occupational ride comfort in rotary soil tillage operation. Measurement 2019; 131:19-27.

[30] Lindman HR. Analysis of variance in experimental design. Springer Science & Business Media 2012; New York.

[31] Directive EU, Provisions GE. Directive 2002/44/EC of the European Parliament and the Council of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (sixteenth individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC). Official Journal of the European Communities, L. 2002; 117(13):6-7.