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DIGITAL AGRICULTURE: ANALYSIS OF VIBRATION TRANSMISSION FROM SEAT TO BACK OF TRACTOR DRIVERS UNDER MULTI-DIRECTIONAL VIBRATION CONDITIONS

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The present research examines the impact of vibrations on seat-to-back transmissibility in tractor drivers. This study utilized a smart device for real-time data transmission to improve the experimentation by eliminating potential sources of error. Data was assessed using metrics such as weighted acceleration, daily exposure, power spectral density, and seat-to-back transmissibility. The seat pan and backrest were found to have high vibration levels on the vertical axis. Daily exposure response exceeded the exposure action limit of 0.5 m/s^2, as specified in Directive 2002/44/EU. Power spectral densities at the seat pan and the backrest revealed dominant frequencies in the low-frequency range. Seat-to-back transmissibility demonstrated primary and secondary resonance within the 4.1-7.2 Hz and 8.2-11.8 Hz frequency ranges. Tractor manufacturers and designers could utilize the findings of this study to decrease the excessive vibration intensities and crucial resonating frequencies and thus enhance the operator's ride comfort.

Keywords: Tractor-Powered Rotary Tiller; Whole Body Vibration; Internet of Things; Spectral Analysis, Seat-to-Back Transmissibility

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1. INTRODUCTION

Agriculture is a labor-intensive occupation that requires farmers to spend many hours each day working, with some farmers using their tractors for up to 12-14 hours per day during their busiest days (Sorainen *et al*., 1998). Thus, farmers are exposed to hazards associated with their work, like whole-body vibrations (WBV) (Scarlett *et al*., 2007; Singh *et al*., 2019; Singh *et al*., 2021). The exposure of tractor drivers to WBV is more complex than in the agricultural sector, as various variables influence field operations (Singh *et al*., 2018). Tractor drivers experience WBV caused by the implements attached to the tractor and the tractor's interaction with the land (Kumar *et al*., 2001). Vibrations may be transmitted to the driver's body through touchpoints like the steering column, backrest, seat, control levers, and tractor's base. Humans may experience comfort-related issues and occasionally health issues due to these vibrations (Park *et al*., 2019; Village *et al*., 2012). Research studies have revealed that tractor drivers are often exposed to WBV intensities higher than the recommended exposure threshold limit (0.5m/s^2) (Loutridis *et al*., 2011; Prasad *et al*., 1995; Directive & Provisions, 2002. High levels of vibration exposure have been strongly correlated with various physical condition ailments, including muscular system risks such as

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backaches (Griffin, 2007), tiredness (e.g., muscular tissue fatigue) (Loutridis *et al*., 2011), physiological issues (concentration, drowsiness etc.) (Griffin & Erdreich, 1991), and sensory organ problems (Goglia *et al*., 2003).

In addition, Tractor operators are usually exposed to vibrations ranging from 1 to 10 Hz, which corresponds to the human body's natural resonant frequencies (Griffin, 2007). Due to the inherent frequencies of various bodily parts, the human body is particularly susceptible to low-frequency vibrations (Liang & Chiang, 2008). Prolonged exposure to such conditions may affect the driver's proficiency in operating the vehicle (Cutini *et al*., 2016; Singh *et al*., 2018). A few researchers have studied the impacts of WBV exposure throughout tillage operation in actual field conditions (Servadio *et al*., 2007; Singh *et al*., 2019; Singh *et al*., 2022). However, these studies did not consider the rotary tiller for the biodynamic analysis. Prolonged exposure to WBV may impact the biomechanical system (Rakheja *et al*., 2020; Scarlett *et al*., 2007). It is necessary to comprehend the biomechanical responses to WBV to comprehend potential effects on health and ride comfort. (Griffin & Erdreich, 1991). Extensive biomechanical research was conducted to discover the vital resonating frequencies in which larger deflections and, thus, higher muscle stress on the human body may occur (Griffin, 2007). Most research evaluated the WBV transferred toward the tractor operator’s seat (Scarlett *et al*., 2007; Servadio *et al*., 2007; Singh *et al*., 2019). The mechanics' aspects of experimental biodynamics research are frequently addressed in most research, particularly the resonating frequencies and dampening as measured by amplitude response throughout the frequency spectrum. Prior biomechanical research has primarily been done in lab simulators focused on on-road driving. The biomechanical sensitivity to WBV in multifunctional vehicles, such as tractors. In addition, there was a lack of information about how well vibrations were transmitted in real-world situations, specifically regarding how vibrations transmitted from a tractor seat to the driver's back. Seat-to-back transmissibility (STBT) is a challenging measure that relates the acceleration of the driver's back toward the vibrations at the seated body interface. The resonances present in transmissibility can sometimes indicate frequencies where injuries, discomfort, or disruptions in work are more likely to occur (Harsha *et al*., 2014).

Tractors are widely used in India for farming activities, particularly for soil preparation. They are often utilized with a rotary tiller attachment to prepare fields for sowing by breaking up soil and making it suitable for the next crop. However, there is limited research available on tractor-rotary tiller systems. This study aimed to a) investigate WBV levels at the seat and backrest in real-world tillage situations, b) analyze the spectral response at the seat and backrest, and c) investigate how vibrations are transmitted from the tractor seat to the driver's back (seat-to-back transmissibility or STBT) in real-world situations.

2. METHOD

2.1 Participants

This research involved nine male participants who were professional tractor drivers. The participants had an average age of 27 years with a range of 21 to 36 years, a height of 1.77m with a range of 1.64m to 1.86m, and a weight of 82 kg with a range of 62-102 kg. The participants had a background in agriculture and a minimum of 6 years of experience driving tractors. Before the experiment, the participants were informed about the study's objectives and must sign a consent form. All participants were in good health and had no known sensitivities to vibration.

2.2 Test Terrain and Machinery

This study was carried out at Punjab Agriculture University (PAU), India, on a 2.073-acre post-harvested wheat field. Soil samples were collected and examined from four random locations before the experiment to determine soil texture using ISO 14688-1:2002 standards. The field was revealed to be a sandy clay loam with 27% clay, 66.25% sand, and 9.27% silt. According to ISO 17892-1:2014, the soil moisture content ranged between 48.61% and 55.43%. Using a digital soil penetrometer, the soil compactness was around 12, 22, and 29 kPa at depths of 0-0.05 m, 0.05-0.10 m, and 0.10-0.15 m, respectively. A 2014 model 55 HP two-wheel drive Farmtrac 65 EPI tractor with an original manufacturer seat was used for the investigation. The tractor's tires were changed with new ones that had no wear on the lugs, and the tire pressure was kept at the tractor catalog level. A 7-foot-long, 450-kg rotavator was fitted to the tractor to do rotary tillage tasks. The rotavator measured 1.35 2.50 0.94 meters in length and was outfitted with 48 C-shaped blades mounted on eight flanges, cutting 1.237 meters wide and 0.15 meters deep. Due to its ability to cut soil while consuming less energy than L or J-shaped blades, this type of rotavator was the most popular among farmers in Punjab, India.

2.3 Ride Conditions

Average speed (m/s), pulling force (kN), and average tool depth are the three riding variables included in this investigation (m). Participants were instructed to keep their tractor speeds between 0.6 and 0.8 m/s, as suggested by the Bureau of Indian

Standards. Following the topography, rotary tillage requires for pulling forces of 2, 4, or 6 kN. Pulling force has been determined with a dynamometer connected between the tractor and the implement. In addition, the observed tool depths were 0.10 m, 0.12 m, and 0.14 m based on the pulling force (i.e., 2, 4, and 6 kN, respectively). To familiarize themselves with the conditions, participants were requested to undergo a series of test rides at these settings. There are no test trial data included in this study.

2.4 Testing Process

Figure 1 depicts a diagrammatic representation of the assessment procedure. WBV levels were simultaneously measured at the seat and the backrest. As indicated in Figure 1, an SV 38V MEMS accelerometer was mounted at the seat, and a second SV 38V MEMS accelerometer was utilized to acquire vibration data at the seat backrest. Both accelerometers were connected to the SV 106 6-channel human vibration monitor so that vibration data along all three axes could be recorded. 6 kHz was the data sampling rate of both accelerometers. The average duration of each experiment was thirty seconds. This study utilized the mean result from three repetitions of each experiment. This work developed an Internet of Things (IoT) system to build an intelligent unit capable of interfacing with present equipment, i.e., vibration analyzers, for accessing vibration data wirelessly with minimal physical interaction throughout experiments (Singh *et al*., 2022). Typically, two or more people must sit beside the tractor operator to physically manage the equipment (Singh *et al*., 2018; Singh *et al*., 2019; Singh *et al*., 2019). This module is designed to transfer real-time data from the cloud to an Android application with a 2-second latency. Using an RJ 45 connection, an IoT module was attached to the SV 106 vibration analyzer to transmit data to the cloud.

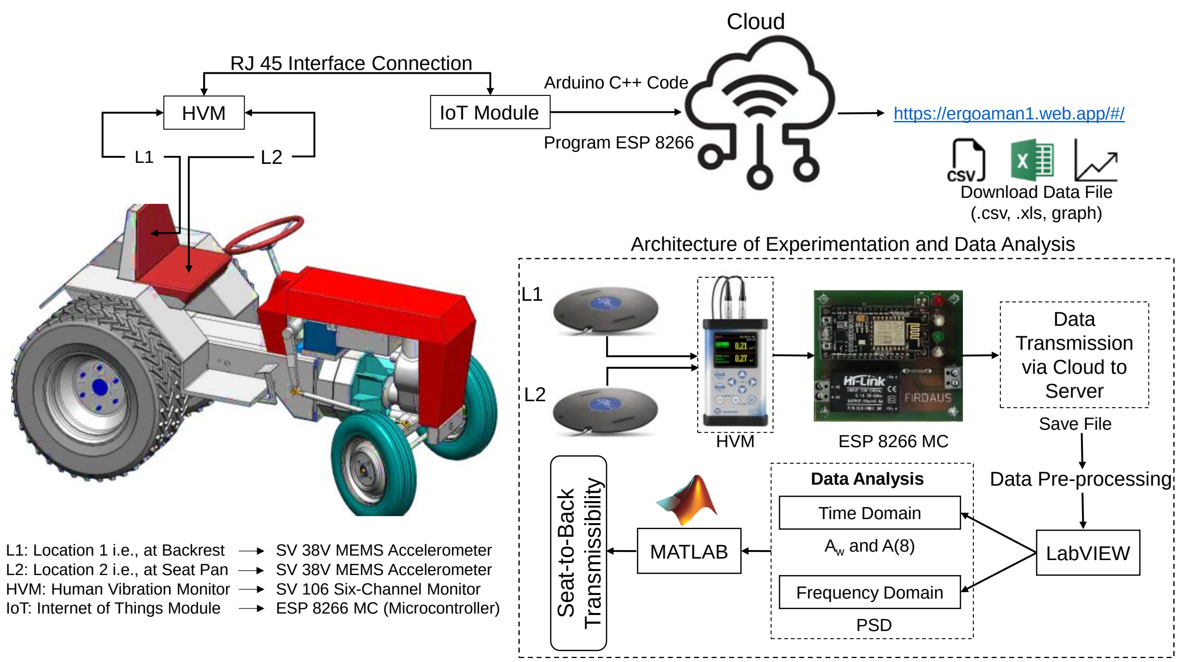

Figure 1. Schematic Diagram of Testing Procedure

2.5 Data Processing

WBV data at the seat and backrest were captured as time-domain raw acceleration values. The raw acceleration data values were treated at both measurements to get the RMS-weighted response. The daily exposure (A (8)) response at the seat was then estimated using ISO 2631-1 (Organization, 1997). The frequency component was determined by calculating power spectral response (PSDs) at the seat and backrest for the dominant directional axis. Cross-spectral density (CSD) function technique was used in this study to obtain STBT (Equation 1) (Bendat & Piersol, 1980).

$$H_C(f) = G_{xy}(f)/G_{xx}(f)\,, \tag{1}$$

where Hc(f): transfer function determined using the CSD function approach; Gxy(f): CSD at seat and backrest; and Gxx(f): PSD at seat.

2.6 Software(s)

Raw data from the measurement sites were captured and transmitted to the LabVIEW 2022 software for time-domain analysis and PSD. MATLAB 2022b was also used to evaluate the raw data to determine STBT outputs using the processed data (txt format). Variance analysis (ANOVA) was performed using Minitab 16 statistical software. The modal analysis of the human seated body was performed using COMSOL Multiphysics (version 6.1).

3. RESULTS AND DISCUSSION

The average Aw response at seat and backrest was calculated and displayed in Figure 2. Aw at seat was depicted to be 0.265 m/s^2, 0.287 m/s^2, and 0.738 m/s^2 in the longitudinal (x), lateral (y), and vertical (z) directions, respectively. The response at backrest was 0.212 m/s^2, 0.301 m/s^2, and 0.516 m/s^2 along the three translational axes. Mean A (8) at seat was exhibited 0.689 m/s^2, as shown in Figure 2. The observed WBV values fell within the Aw range described by previous tractor-based research studies (Servadio *et al*., 2007; Singh *et al*., 2018).

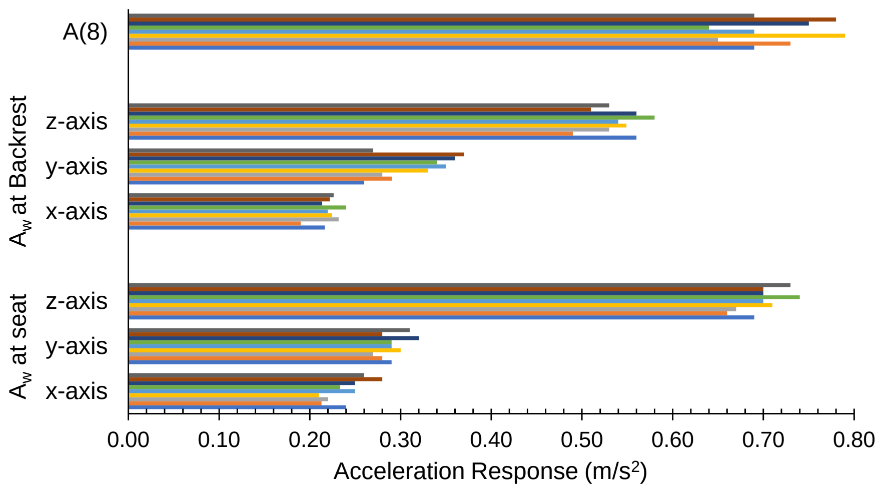

Figure 2. Representation of A_w and A(8) Response of the Participants

However, these experiments focused exclusively on WBV at seat. Among all experiments, the A (8) value was between 0.638 and 0.837 m/s^2, which ranges from fairly uncomfortable to uncomfortable according to ISO 2631-1(Organization, 1997). In addition, the exposure levels surpassed the Directive2002/44/EU threshold limit of 0.5 m/s^2 (Directive & Provisions, 2002). A prior examination also revealed excessive WBV in tractors employed at varying speeds and terrains (Cutini *et al*., 2016). High WBV may diminish ride performance and impact the muscular system, especially low back aches (Griffin, 2007; Harsha *et al*., 2014; Village *et al*., 2012). Moreover, extended WBV could harm driving conduct and decrease work capacity and performance (Village *et al*., 1989). The study's results have determined the impact of factors such as average speed, average depth, and pulling force on the A (8) exposure, as shown in Figure 2. Additionally, Figure 3 displays the combined effect of variations in these factors. As the tractor speed increases, the signal-to-noise (S/N) ratio response decreases while the mean A (8) response increases. This trend is likely due to increased acceleration at higher speed levels (Taghizadeh-Alisaraei, 2017). In addition to the increased acceleration magnitudes caused by uneven terrain conditions, it was observed that S/N ratios get increased as the tool depth increased while the A (8) response decreased. This is likely due to the dampening effect of the terrain on the measurements. Figure 3 provides a visual representation of the various A (8) levels under different conditions of tractor speed and average depth.

It has been observed that the lowest A (8) response (i.e., < 0.40 m/s^2) was recorded in a specific range of tractor speed (i.e., 0.60 to 0.64 m/s) and depth (i.e., 0.12 to 0.14 m). In contrast, the highest levels were recorded at higher speed (i.e., 0.8 m/s) and shallower depth (i.e., 0.10 m). The effect of tractor speed and pulling force on the A (8) can also be observed in Figure 3, where the lowest and highest A (8) levels were recorded under different ranges of these factors. The relative riding comfort levels can be understood by comparing the emphasized area regarding the A(8) concerning the given range (Organization, 1997) and examining exposure action and exposure limit values (Directive & Provisions, 2002).

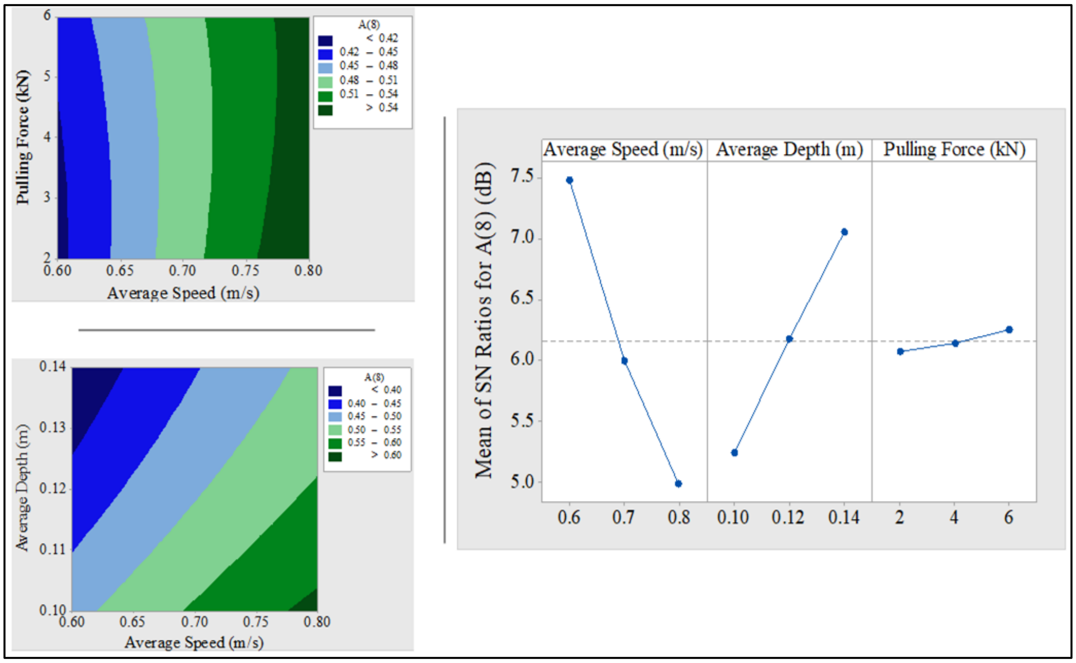

Figure 3. Representation of the Association between Ride Attributes and A (8)

The ANOVA method was applied to evaluate the effect of tractor speed, average depth, and pulling force on A (8), which are presented in Table 1. The F-value is used to determine the magnitude of the effect of ride factors on the A (8). The analysis revealed that A (8) is considerably affected by tractor speed and depth (i.e., $p \leq 0.05$). However, pulling force was found to have no significant effect on A (8). The analysis also found that average speed and depth have a 65.13% and 33.99% contribution to the influence of A (8), respectively.

Table 1: Variance Analysis for A (8)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F-value	P-value	P (%)
Average speed (m/s)	2	9.397	9.397	4.699	124.27	0.008*	65.13
Average depth (m)	2	4.904	4.904	2.452	64.85	0.015*	33.99
Pulling force (kN)	2	0.051	0.051	0.026	0.68	0.596	0.35
Residual Error	2	0.076	0.076	0.038			0.53
Total	8	14.428					

PSDs represent the energy variation in proportion to the frequency spectrum. Most studies evaluated spectral response in a laboratory environment where the source excitation had identical power throughout the spectrum. As depicted in Figures 4 and 5, the PSD was estimated for each participant (1–9) for the dominant vertical (z) axis at the seat and backrest. PSDs of each experiment demonstrated a considerable shift in energy at various frequencies. For nine drivers, PSDs demonstrated variable intensity concerning resonating peaks at both measurement locations. The majority of drivers' primary resonance peals remained between 2.4 and 3.1 Hz. Moderately intense resonance peaks were seen within the region of 3.2 to 3.8 Hz. Multiple peaks were seen, most notably between 4 and 5,4 Hz and 8.8 Hz. Additionally, a strong peak frequency was observed near 9.7 Hz. Figure 5 displays the backrest's PSD with a strong intensity of around 2.6 Hz. Multiple frequency peaks were typically observed between 2.1 and 3.5 Hz. Peak intensity was found to be considerably reduced till 4.4 Hz before abruptly rising on or after 4.5 Hz to generate a high-intensity peak around 5.1 Hz. The intensity of the frequencies remained mild, varying from 5.1 to 7.7 Hz. The frequency spectrum exhibits peak intensities around 7.9 Hz, 8.7 Hz, and 9.7 Hz to 9.9 Hz.

Furthermore, vibration intensities measured at the backrest tend to fluctuate around the legitimate frequency range. The response of PSD revealed that low vibration frequencies are present during rotary operation. The low-frequency range (1 to 10 Hz) is crucial for the human body because of the resonant frequency of distinct body parts (Kumar *et al*., 2001). The prominently reported frequencies may reflect the resonant frequency of different body parts like the spinal, shoulders, and internal organs, resulting in discomfort, stomach problems, muscle spasms, and headaches (Jayasuriya & Sangpradit, 2014;

Matsumoto & Griffin, 2000). Tractor drivers can experience several human body ailments due to these resonances, notably muscular ailments, particularly in the low back region (Taghizadeh-Alisaraei, 2017). Resonances, such as those found in transmitting vibrations from the seat to the backrest, are thought to reveal the frequencies at which people are most at risk of experiencing injury, discomfort, or disruption of their normal activities. STBT provides thorough information on the biodynamic responses of tractor drivers.

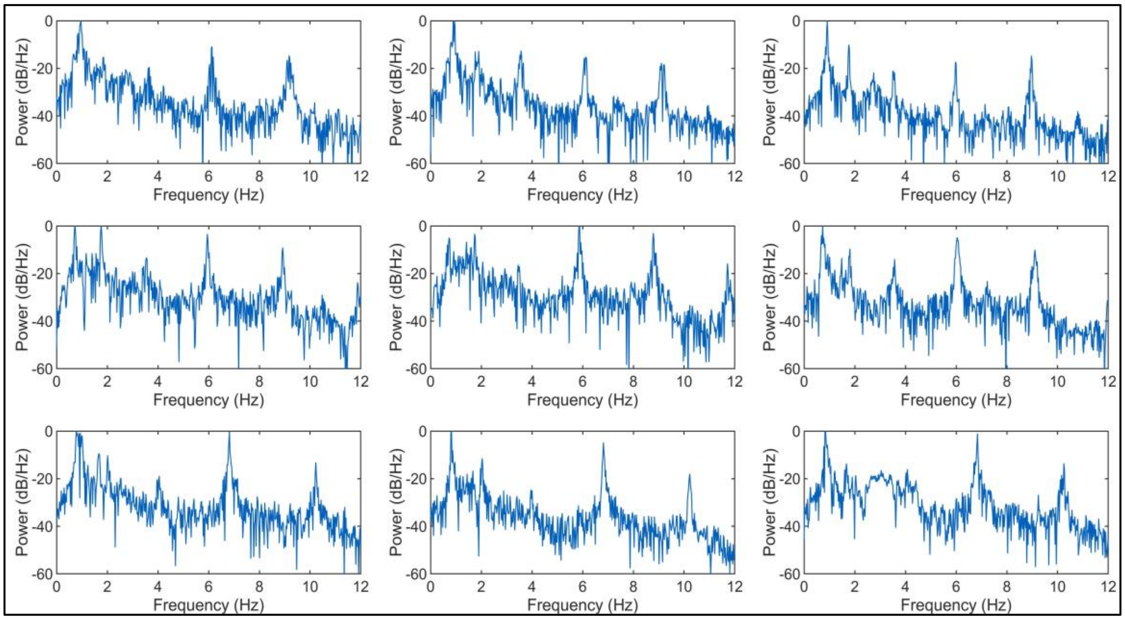

Figure 4. PSD Response at Seat for the 9 Participants

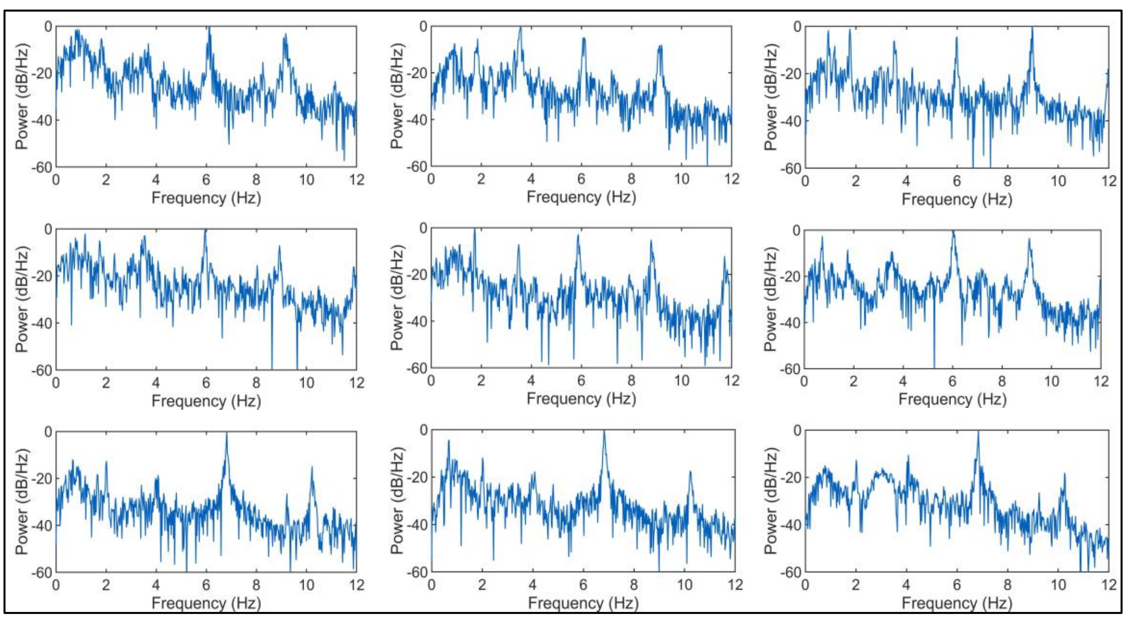

Figure 5. PSD Response at Backrest for the 9 Participants

Transmissibility characterization can be used to determine the biomechanical characteristics of the human body under WBV exposure. It has characterized by identifying the frequency ranges associated with the natural frequency of different body parts (Paddan & Griffin, 1998). Transmissibility functions have also been used to examine the nonlinear characteristics of seats to determine whether they amplify or dampen vibrations at frequencies, which impacts driving comfort (Toward &

Griffin, 2010; Zhang *et al*., 2015). The present study examined WBV responses collected at both measurement sites to establish STBT in the dominant vertical direction, as illustrated in Figure 6. Despite significant scatter in STBT responses, the absolute significant peak of STBT is located within the 4 to 7 Hz band. Vertical resonances occur at 4 Hz in typical seats, which enhances vertical vibration (Adam & Jalil, 2017). Most participants demonstrated early resonance peaks in the 1-2 Hz range but with lower amplitudes. This type of STHT peak at around 1 Hz along the vertical direction is commonly observed when a driver is seated without the support of a backrest (Hinz *et al*., 2010). Furthermore, a secondary resonance was identified in the 8-12 Hz range. The findings of the STBT in the vertical direction agreed with previous studies conducted on laboratory simulators (Bhiwapurkar *et al*., 2016; Wang *et al*., 2006). In contrast, when examining seat-to-spine transmissibility vertical WBV, the second resonant peak has been found in the range of 8 to 10 Hz (Mansfield & Griffin, 2000).

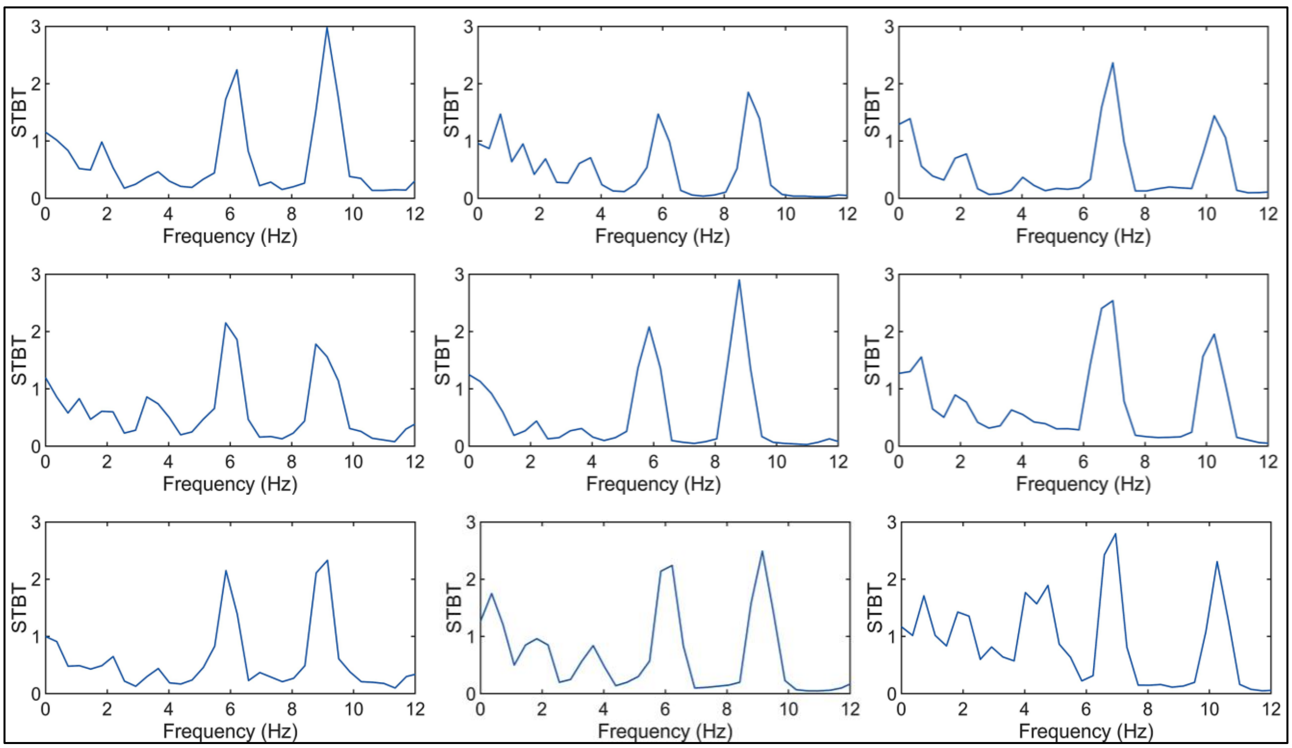

Figure 6. Variability in the STBT Response for the 9 Participants

Modal analysis of the human body using FEA is important for tractor drivers who are exposed to vibration because it allows for the identification and evaluation of the vibration modes of the body, which can be used to design machinery in such a way that reduces the exposure of operators to harmful vibration levels and critical frequencies. This study has performed an FEA analysis on the human seated model given by Kim *et al*. (2005), as shown in Figure 7. In the analysis process, the coarser element has been used to start with a mesh that is as coarse as possible, i.e., a mesh with very large elements. A coarse mesh will require minimum computational resources to obtain the required results. We applied fixed joint: seat-pelvis constraint for doing model analysis. In this model, the main influence of input frequencies and accelerations was observed legs, thighs, pelvis, viscera, torso, and head. The modal analysis has been performed to understand the influence of dominant frequencies and corresponding acceleration levels on various human body parts.

The dominant frequencies have been noted from the STBT, i.e., frequencies at which primary and secondary resonance peaks occurred. In rotary operation, the dominant frequencies were observed between 3.9 to 6.1 Hz and 8.2 to 11.3 Hz, as presented in Figure 6. For modal analysis, the minimum and maximum dominant frequencies were selected, i.e., 3.9 Hz; 6.1 Hz; 8.2 Hz; and 11.3 Hz, respectively. The mean A (8) acceleration response, i.e., 0.689≈ 0.69 $m/s^2$was used to excite the model at particular frequencies. However, the model can be investigated at any acceleration and frequency response. With these input excitations, the model was examined to check the deflection of various body parts, as shown in Figure 8.

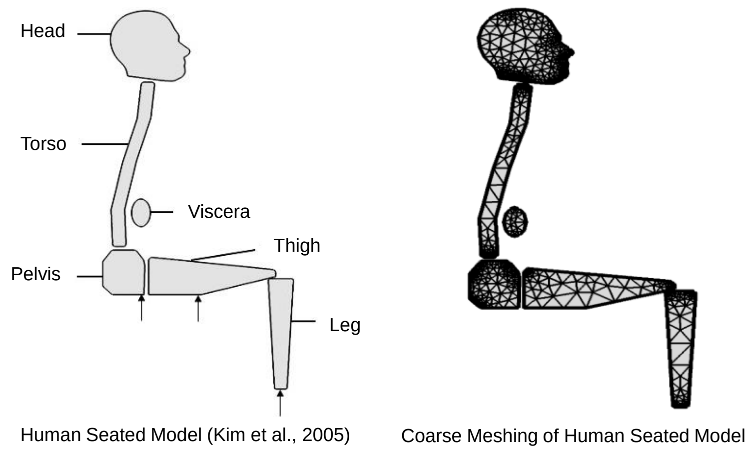

Figure 7. FEA Analysis on the Human-Seated Model

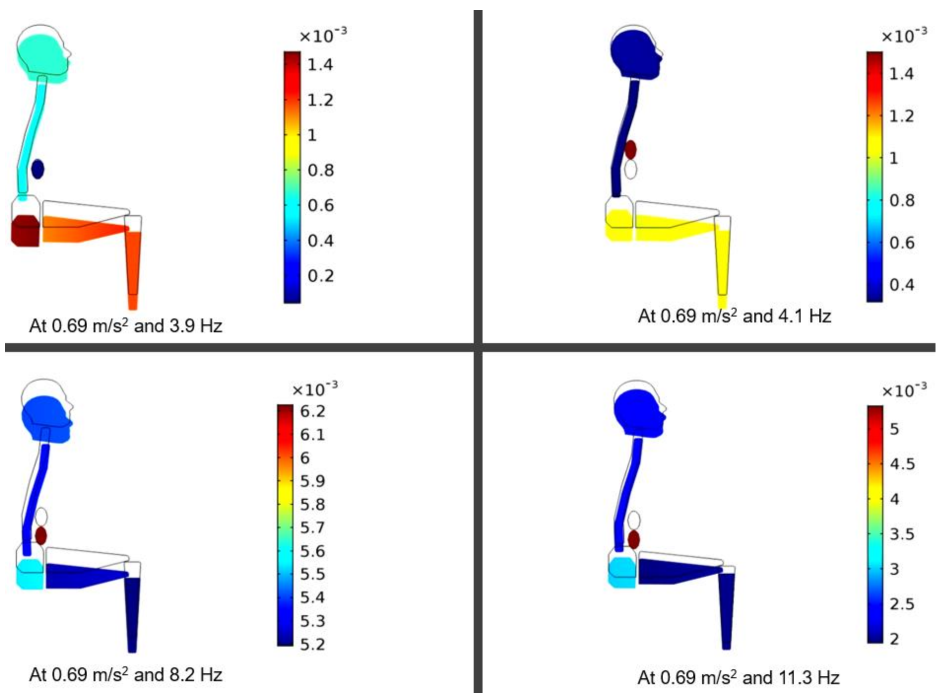

Figure 8. Modal Analysis of Human-Seated Model

At 3.9 Hz, the model showed considerable deflections for the head, pelvis, thigh, and leg region. At 4.1 Hz, the deflections along the pelvis, thigh, and leg remained similar to those found at 3.9 Hz. However, the deflection response for the head was decreased at 6.1 Hz. Additionally, the viscera were found to have noticeable deflection from the original position at 4.1 Hz. At 8.2 Hz and 11.3 Hz, the torso region showed a clear deflection compared to its original position. Moreover, the deflections corresponding to the head, viscera, pelvis, thigh, and leg remained noticeable, as observed at 3.9 Hz and 4.1 Hz. If the deflections of various body parts are observed to be more compared to the original position during a modal analysis of the human body using FEA, it could indicate that the body is experiencing high levels of vibration. When a body is excited at or near one of its natural frequencies, its response is amplified, and the deflection of the body parts is greater than it would be at other frequencies. If the body is experiencing high levels of vibration, it could lead to an increased risk of injury and discomfort for the operator.

4. CONCLUSION

Whole-body vibration intensities dominated the vertical (z) axis. Mean A_w was found to be 0.265 m/s^2, 0.287 m/s^2, and 0.734 m/s^2 at seat and 0.212 m/s^2, 0.301 m/s^2, and 0.516 m/s^2 at backrest, respectively. Furthermore, mean A (8) was greater than the threshold limit stipulated by Directive 2002/44/EU. The average speed and tillage depth levels were significant ($p \leq 0.05$). The greatest percentage of influence on A (8) was from tractor speed, at 65.13%, followed by the average depth, which contributed at 33.99%. Spectral analysis response exhibited the WBV exposure within the low-frequency zone (i.e., up to 10 Hz). Primary and secondary resonance frequencies of STBT were found to be within 3.9 to 6.1 Hz and 8.2 to 11.3 Hz. The study found that when the body is exposed to vibration at or near its natural frequencies, its response intensifies, resulting in greater deflections of various body parts. The PSDs and STBT analysis focused on the dominant directional axis, but future research could expand the analysis to include other axes. Additionally, variables such as tire pressure, seat cushions, terrain conditions, and tractor power could be investigated in future studies.

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