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Vertical Suspension Seat Transmissibility and SEAT Values for Seated Person Exposed to Whole-body Vibration in Agricultural Tractor Preliminary Study

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Abstract

Agricultural tractor drivers have been exposed to high magnitude of whole-body vibration (WBV) exposure during their daily farm work activities due to many factors (e.g. uneven road surface, posture and apparent mass of the body). High vibration magnitude exposure may also lead to detrimental health of the driver such as low-back pain. The objectives of this study are to determine the vertical suspension seat transmissibility and Seat Effective Amplitude Transmissibility (SEAT) values for a seated person exposed to WBV in agricultural tractors. A healthy male subject participated in the field measurements. Two road surface conditions were tested - (i) tarmac and (ii) field (i.e. rough off-road). In the off-road condition, data were collected during mowing. The subject was seated in an upright posture with a backrest. The vertical vibrations (z-axis) on the seat base, beneath ischial tuberosities and at the thigh (i.e. top surface of the horizontal thigh during seated position) were measured. Three vertical vibration transmissibilities were calculated- i) suspension seat transmissibility (i.e. floor to beneath ischial tuberosities), ii) upper leg transmissibility (i.e. floor to thigh) and iii) seat to thigh transmissibility. In addition, the SEAT values were also calculated. The results show resonance frequency of the seat at around 2-3 Hz and the resonance at the thigh is higher than on the seat. The calculated SEAT values were 112.6% (with weighting W_k) and 103.6 % (with weighting W_b). It is suggested that, the WBV is higher in the vertical direction when working on the off-road condition, and thus results in higher vibration energy absorbed by the operator's body.

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1. Introduction

Daily exposure to whole-body vibration (WBV) among professional drivers may lead to adverse effects of health such as musculoskeletal disorder and low back pain. WBV transmitted to the drivers upon contact with vibrating structure of the vehicle through seat, hand and foot controls. Epidemiologic studies on the exposure to WBV indicate that there is an increase of deteriorating changes of spinal system in tractor drivers, truck drivers, forklift operators and drivers of the transportation industry. Cross-sectional studies reported that the prevalence of low back pain among professional drivers for regular exposure is high - tractor drivers (81%), truck drivers (50%), bus drivers (81%) and forklift drivers (57%) [1]. European Union based on EU Directive 2002/22/EU has imposed limitations to vibration exposure for working day, and ISO 2631-1:1997 [2] set a daily WBV limit of 1.15 m/s^2 and action level of 0.5 m/s^2 for an equivalent to eight hours daily exposure period.

The primary contact point for transmission of vertical WBV to drivers is through vehicle seat (amplifies or attenuates vibration at the base). Seating system plays a vital role in isolating the vibration. Suspension seats, mostly used in off-road vehicles consist of low stiffness suspensions with low damping to attenuate vibration in some environments [3]. However, the

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efficiency of the seat is still depends on the vibration spectrum and seat dynamics. The dynamic characteristics of a seat are measured by the transmissibility. Transmissibility is a non-dimensional ratio of the vibration on the seat surface to the vibration of the seat base as a function of frequency and can be used to quantify seat performance. Various studies demonstrate a reduction in WBV exposure when using a mechanical suspension seat or pneumatic suspension seat [4]. However, this condition can only be true if the suspension system of the tractor and the seat are optimally configured. Otherwise, vibration measured at the seat can be elevated compared to the seat base.

Tractor drivers exposed to high magnitude of vibration at the frequency level range of 0.5 to 11 Hz. Conventional seats have vertical resonances at 4 Hz, which means vertical vibration amplified at this frequency and lower frequency. Only at 6 Hz of frequency and above, the seat attenuates vertical vibration. Suspension seats equipped with spring and damper mechanism, and have a vertical resonance around 2-3 Hz. Damper controls by amplifies the resonance and attenuates frequencies above the resonance frequency. However, it should be noted that, human most sensitive frequency for vertical vibration are ranges from 4-8 Hz [2]. Seat Effective Amplitude Transmissibility (SEAT) values represent the efficiency of seat isolation. A SEAT value less than 100% indicates that the seat attenuates vibration of the floor.

Exposure level of WBV in agricultural tractors is often measured according to IS0-5008: 2002 [5]. In the standard, acceleration levels on the seat in three axes (x, y and z-axis) are measured simultaneously when the tractor is driven over 100 m (smooth) track and 35 m (rough) track with different range of speeds. The values are then normalized, frequency weighted and derived of root mean square (r.m.s.) to obtain the frequency-weighted vibration magnitude of the tractor [2]. However, agricultural field conditions are different from the condition specified in the standard as the surface conditions are varied with different operations. Drivers use their backrest depending on the task and sitting posture. In addition, seat transmissibility measured during the actual farm work is different than the standard, as some operation involved the body movement of the drivers (e.g. during ploughing, driver needs to look back and front).

The objectives of this study were to determine the vertical suspension seat transmissibility and to investigate the isolation seat efficiency for a seated person exposed to WBV in agricultural tractor during mowing.

2. Method

The measurement was performed with a healthy male tractor driver, aged 32 years with more than five years of driving experience. The weight and height are 70 kg and 175 cm respectively. The subject was asked to sit in an ‘upright condition’ with the back leaning to the backrest so as to present the actual working condition. Tractor tested was a New Holland 55-56, had a mass of 2070 kg, a wheelbase of 2050 mm and the engine capacity is 2710 CC’s. Mower equipment that attached to the tractor has an approximate weight of 500 kg (Figure 1). Tractor seat used in the present study is equipped with a suspension system and was adjusted for the individual mass according to the operation instructions.



Fig. 1: New Holland tractor equipped with mower equipment

Vibration measurements were obtained using three accelerometers to obtain vertical vibration on the vehicle floor, at the seat-person interface (i.e. on the seat) and at the subject’s thigh. A semi rigid mounting SIT-pad, Model 5313A, was positioned on the seat surface to measure z-axis vibration on the seat (see Fig. 2(ii)). The z-axis acceleration input to the base of the seat was measured using CTC accelerometer (Fig. 2(iii)), while vertical z-axis acceleration on thigh was measured using a Bruel and

Kjaer (B&K) 55759 accelerometer (Fig. 2(iv)). All accelerometers were calibrated prior to use. The duration of the acquired signals was 60 seconds. Signals were acquired and conditioned directly using Adash VA4Pro. The acceleration waveforms were low-pass filter at 100 Hz via anti aliasing filters. The tractor was tested on-road (tarmac) and off-road with the speed of 6km/hr (Fig. 3). All the tests took place at Universiti Putra Malaysia (UPM) and Ladang 5 UPM. The magnitude of the vibrations is measured in terms of weighted acceleration root-mean square values (r.m.s).



(i) (ii)

(iii) (iv)

Fig. 2: (i) Subject seated in upright condition; (ii) Seat pad placed on the suspended seat; (iii) Accelerometer on the tractor's floor; (iv) Accelerometer on thigh



Fig. 3: Road condition: On-road (left) and Off-road (right)

3. Analysis

3.1 Transfer function and coherency

The transfer functions were calculated between the accelerations in the *z*-axis at the seat base to seat, seat base to thigh and seat to thigh using the 'cross-spectral density function method'. The transfer functions, *H(f)* was determined as the ratio of the cross-spectral density of the input and output acceleration, $G_{io}(f)$, to the power spectral density of the input acceleration, $G_{ii}(f)$:

$$H(f) = \frac{G_{io}(f)}{G_{ii}(f)} \tag{1}$$

Coherencies were determined between the tractor floor (input) and the acceleration on the seat cushion (output). The coherencies provide indication of the linear relationship between the input and the output acceleration:

$$Coherency,\ \gamma_{io}^2(f) = \frac{\left|G_{io}(f)\right|^2}{G_{ii}(f)G_{oo}(f)} \tag{2}$$

where $G_{oo}(f)$ is the power spectral density of the output acceleration.

3.2 Frequency weightings

The acceleration time domains were frequency-weighted using weightings for exposure of seated persons to vertical vibration. Two weightings were used in this study: W_k as defined in International Standard ISO 2631 [2] and W_b from British Standard, BS 6841 [6].

3.3 Root-mean square (r.m.s.) vibration magnitude

The root-mean-square (r.m.s.) vibration magnitudes were determined for the vertical vibration measured on the seat base, surface of the seat and thigh.

$$Root\text{-}mean\text{-}square,\ r.m.s.\ (\mathrm{m/s^2}) = \left[\frac{1}{T}\int_0^T a^2(t)\,dt\right]^{1/2} \tag{3}$$

Where $a(t)$ is the frequency-weighted acceleration in time domain (in $\mathrm{m/s^2}$) and T is the measurement period (in seconds)

3.4 Seat Effective Amplitude Transmissibility (SEAT) values

The SEAT values was calculated as the ratio of the frequency-weighted acceleration on the seat, $r.m.s._{seat}$, to the frequency-weighted acceleration on the tractor floor, $r.m.s._{floor}$:

$$SEAT_{rms}\% = \frac{r.m.s._{seat}}{r.m.s._{floor}} \times 100\% \tag{4}$$

SEAT value below 100% implies that the seat is isolating vibration on the floor, and thus reducing discomfort from the vehicle vibration.

4. Results and Discussion

4.1 *Power Spectral Density*

Power spectral analysis was performed and found some similarity among the signals. In all road conditions, signals show the energy is concentrated at the resonance frequency of 2-3 Hz (Fig. 4). For the off-road condition, there is a second peak at around 11 Hz. However, during mowing, there are two distinctive peaks at 2-3Hz and 5 Hz.

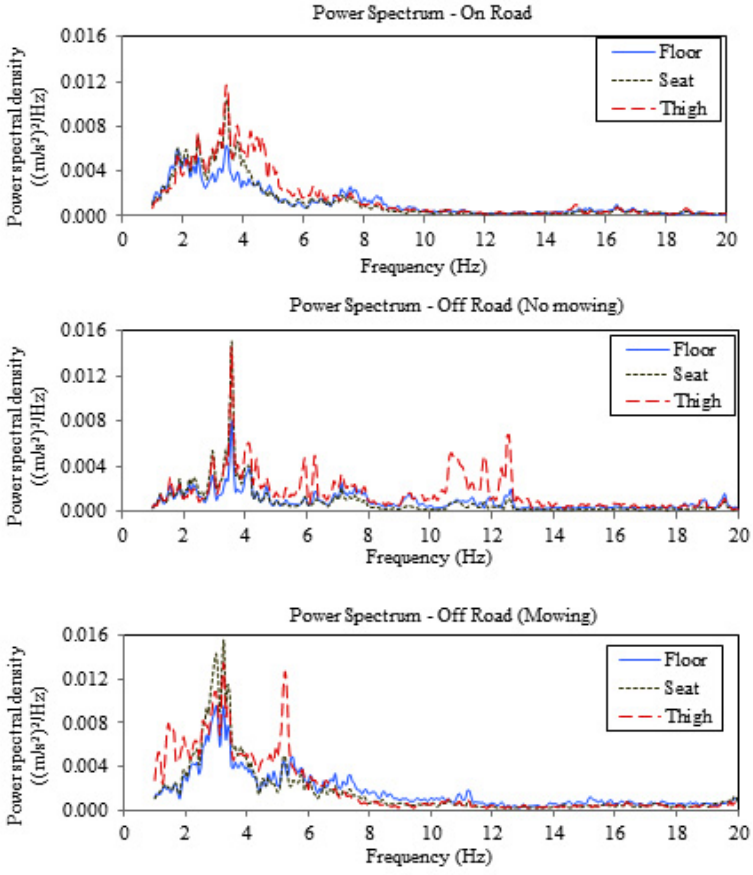


Fig. 4: Power spectrum for all road conditions (i) on-road; (ii) off-road; (iii) off-road (mowing)

4.2 *Transmissibilities and coherencies*

In order to assess the effect of dynamic performance of the seat, three conditions of transmissibilities were plotted: (i) floor to seat, (ii) floor to thigh and (iii) seat surface to thigh transmissibility.

The modulus of the seat transfer function (floor to seat) shown in Fig. 5 indicates a pronounced peak at 2 to 3 Hz in response to vertical vibration. There are two peaks of floor to thigh transmissibility observed at 3 and 6 Hz (Fig. 6). For seat to thigh transfer function, there are two peaks observed at 4 and 6 Hz. The resonance at thigh is higher than on the seat. However, above 10 Hz, the transmissibility shows inconsistence trend for all conditions, possibly due to excessive noise. The coherency measured is low, (less than 0.8) at frequencies above 10 Hz, which may suggest the system is not linear correlated.

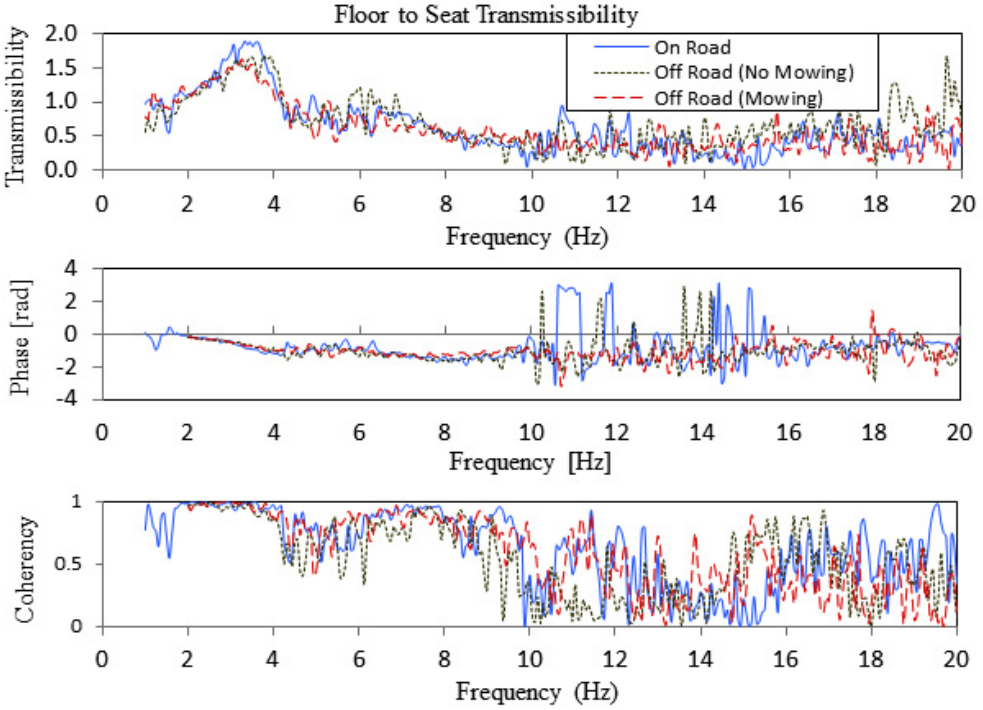


Fig. 5: Floor to seat transmissibility

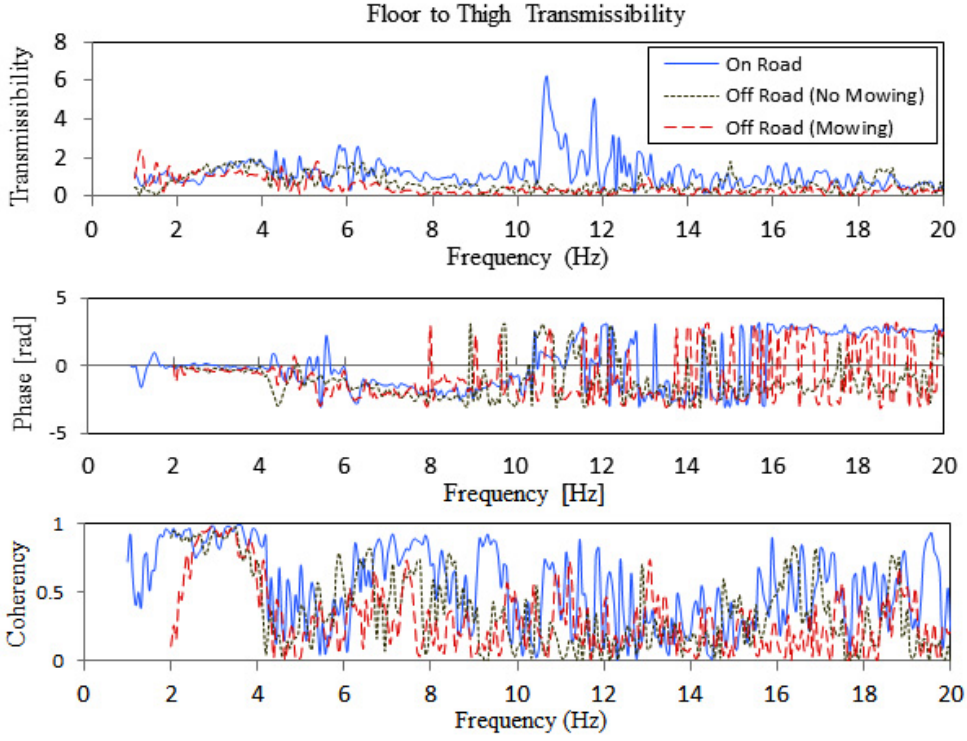


Fig. 6: Floor to thigh transmissibility

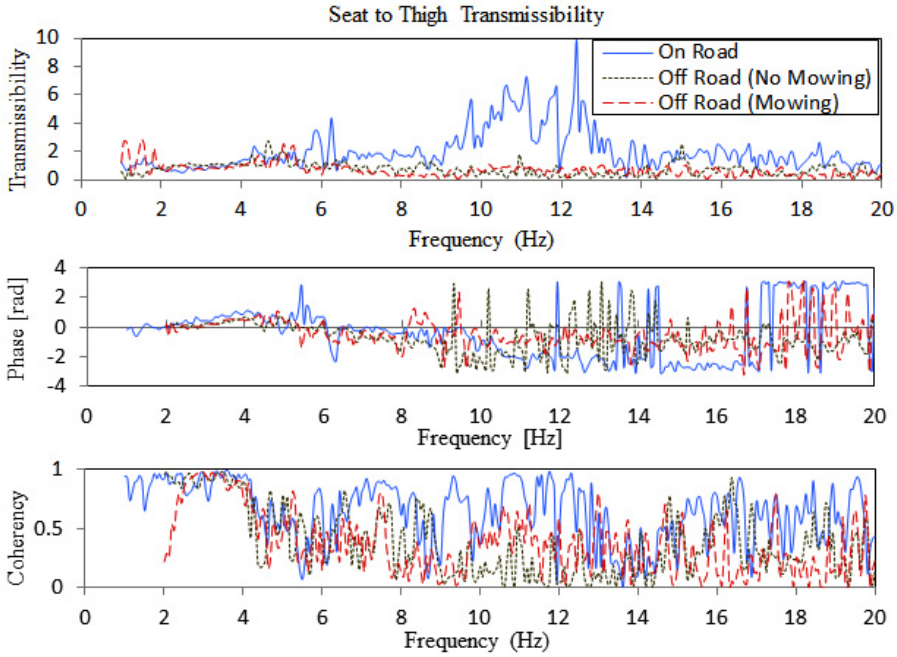


Fig. 7: Seat to thigh transmissibility

4.3 *Root-mean square (r.m.s.) vibration magnitudes*

Root-mean square (r.m.s.) vibration magnitudes were calculated for acceleration measured on the tractor's floor, seat and thigh. Table 1 presented unweighted and weighted vibration magnitudes for the tractor's vibration. Two frequency weightings were used in the analysis: W_k from ISO 2631[2] and W_b from BS 6841 [6]. The differences between these two weightings, W_k and W_b were discussed by Griffin [7]. Frequency to which human body is most sensitive are given a much heavier weighting than those at frequencies that the body is less sensitive. These weightings gives a good correlation between the measured vibration level and impact produced by the vibration.

The highest vibration magnitudes occurred at floor and seat is 0.330 m/s^2 r.m.s. and 0.353 m/s^2 r.m.s., respectively during mowing at off-road condition. As expected, the minimum vibration magnitudes occurred at on-road condition (tarmac) at all three different accelerometers positions: floor (0.233 m/s^2 r.m.s.), seat (0.266 m/s^2 r.m.s.) and thigh (0.334 m/s^2 r.m.s.). The vibration magnitudes for this study are slightly lower compared to previous study [8]. This is, possibly due to constant speed of the tractor (at 6 km/hr) regardless the road condition. For example, during on-road (tarmac), tractor can speed up to 30 km/hr, but in this case the speed was kept at 6 km/hr. It is evident that driving speed results in an increased WBV exposure especially at speed of 15 km/hr and above [4]. The speed of 6 km/hr was chosen because it is an ideal speed for mowing operation. There is a limited study of vibration magnitude on mowing operation to be compared with this study.

Table 1: Unweighted and weighted vibration magnitudes (ms^{-2} r.m.s) calculated using frequency weighting W_k and W_b

Road Condition	Unweighted r.m.s			Weighted r.m.s using W_k			Weighted r.m.s using W_b		
	Floor	Seat	Thigh	Floor	Seat	Thigh	Floor	Seat	Thigh
On-road (tarmac)	0.971	0.709	0.393	0.233	0.266	0.334	0.254	0.271	0.317
Off-road	0.630	0.422	0.504	0.248	0.286	0.368	0.241	0.254	0.344
Off-road (mowing)	1.024	0.571	0.529	0.326	0.353	0.377	0.330	0.326	0.352

4.4 *Seat Effective Amplitude Transmissibility (SEAT) values*

Estimation of the seats in isolating the vibration from the floor can be predicted by SEAT values. SEAT values were calculated by the ratio of weighted acceleration r.m.s. measured on the seat vibration to the weighted acceleration r.m.s measured on the floor. Two frequency weightings, W_k and W_b were used to measure the SEAT values. SEAT values using W_k frequency weighting is higher than W_b, 112.6 and 103.6, respectively. However, both of the SEAT values are higher than 100%, which means the seat amplifies vibration on the floor. Suspension seat is designed to attenuate vibration on the floor. But, in the present study this is not the case. Since the resonance frequency is concentrated at 2-3 Hz, the seat failed to attenuate the floor vertical vibration. In addition, the suspension seat used in the study is used for a long period of time and poorly maintained.

5. Conclusions

Based on this preliminary study, the vertical vibration transmitted is high at off-road surface, both during mowing and no mowing activity, as compared to the seat transmissibility on on-road surface condition. A pronounced resonance frequency was observed around 2 – 3 Hz for all road conditions. The calculated SEAT values suggested that the suspension has minimal effect on attenuating the vibration transmitted to the person.

Acknowledgements

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