Control of driver whole-body vibration ride comfort in agricultural tractor

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Abstract: For today vehicles, ride comfort and dynamic control, are crucial criteria for customers and also for the selection of an appropriate vehicle. Tractors as vehicles are exposed to random vibrations caused by unevenness of road or soil profile, moving elements within the tractor or implements or sitting on a rigid seat without a backrest. Whole-body vibration transmission influences comfort, performance, and long-term health of the operator. In this study, whole-body vibration was estimated for an agricultural tractor and used to evaluate tractor rid comfort efficiency. The intelligent classical and adaptive neuro-fuzzy inference system (ANFIS) controller was designed according to underlying principles which can be easily applied on this agricultural tractor. A gravel road texture was selected and used. To assess vibrations transmitted to the operator, vibration dose values, kurtosis, international road roughness index and power spectral densities of the tractor (seat and floor) recorded signals were evaluated. Seat effective amplitude teransmissibility values based on the tractor seat pan vibration dose value (controlled and uncontrolled) outputs in the three-direction lateral, longitudinal and vertical) qualified vibration comfort efficiency. Tri-axial accelerometers were usually mounted on the tractor seat pan and floor. Data are frequency weighted in order to model the human response to vibration in that location and direction.

Keywords: agricultural tractor, comfort, vibration dose value, frequency weighting, whole-body vibration, adaptive neuro fuzzy inference scheme

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1 Introduction

Nowadays, the increasing progress of the technology and the need of using more of transporting devices have made the design of vehicles an important task. The improvement and reliability of the agricultural machines provide a revolution in the human activities facilitating the production of commodities of agribusiness. Though, the efficiency of the tractor, as well as the occurrence of accidents also depends on the level of fatigue to which the operator is submitted. Whole body vibration (WBV) is one of the risk factors causing the onset of professional diseases in agricultural tractors' operators, and it is also a method for assessing vehicle’s properties in terms of vibration turns out to be fundamental for comfort and safety improvement. Moreover, the combination of vehicle speed and surface roughness induces affect the transformation of vehicle forward speed.

A pilot study was undertaken to quantify WBV emission levels upon a limited range of agricultural tractors operating in controlled conditions, but the limitations of this initial study (performed entirely upon artificial test surfaces and with a limited range of vehicle types) were shown in Scarlett et al. (2007).

The European Physical Agents (Vibration) Directive: 2002 (PA(V)D) The European Physical Agents (Vibration) Directive:2002 (PA(V)D) is not likely to restrict the operation of large, state-of-the-art tractors during an 8-h day, but will become a limitation if the working day lengthens significantly. Further ‘on-farm’

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WBV data collection was required to enable the creation of a robust, generic WBV emission database for agricultural tractor operations, to enable estimation of likely WBV exposure by employers Nelson and Brereton. (2005).

WBV has the most significant influence on the productivity, and health WBV was analyzed at the seat-operator interface using a tri-axial accelerometer in 145 forestry loading operations in Turkey (Melemez and Tunay, 2010). The mean total vibration acceleration value was found to be 1.38 m s^{-2} at loading equipment mounted tractors and 1.06 m s^{-2} at original loading machines. The regression analysis was performed in order to determine the most important factors that affect total vibration values which were machine type, ground roughness condition, ground type, wheel inflation pressure, seat conditions and operator weight.

An evaluation of the levels of vibration and noise emitted by agricultural tractors with different powers has been carried out, comparing the results with the existing regulations present in Cutini et al. (2016). The tractors studied MF 4292, MF 283, MF 297 and MF 680. As results, the structures of the seat were able to absorb the impact and creating a good working condition for the machine operator. The vibration levels, in general, were below the limits established for eight hours of work at frequencies 5-10 Hz, for the three directions for all tractors studied.

Long term exposure of tractor driver to vibrations induced by agricultural machinery operations may lead to health problems. Therefore, it was valuable to obtain the range of frequencies transmitted to the tractor driver during performing far operations. In order to record tractor driver WBV, the fabrication and evaluation of an inexpensive tractor vibration measuring system were considered. The system performance in static and dynamic conditions was tested. Furthermore, the values of the equivalent daily stress index (S_{ed}) of plowing with moldboard and rotary plows were 0.35 MPa and 0.4 MPa respectively (Ahmadi, 2013a). Based on the criterion of U.S. Army Aero-medical Research Laboratory (USAASL), since these values were lower than 0.65 MPa, the severity category of operation with the examined plows were graded in the class of 3; which means that the health hazard associated with these operations were marginal. Moreover, dominant frequencies transmitted to driver seat were in the range of 0-3 Hz.

In order to quantify tractor driver WBV induced by some of the agricultural operations, the ISO 2631 standard (1997) was utilized. Detailed methodology of the calculation of the WBV evaluating indices using the time-domain acceleration data analysis was presented. Typical weighted root mean square (WRMS) value of the Z-axis vibration was more than the WRMS value of the X and Y axes vibrations when the WBV calculations for the agricultural operations (on asphalt road, plowing and power tilling based on the equivalent daily stress index (S_{ed})), were graded in the class of 3 or 4; which means that the health hazard associated with these operations is Ahmadi, 2013b). Furthermore, all of the severity categories (SV) obtained from driving the tractor marginal. Finally among the examined machines, the locally built, tractor front mounted, hydraulic power aided loader caused vibrations that were slightly higher than the exposure limit value (ELV), with regard to the parameter of WRMS over an eight hour period (A(8)).

Ride comfort in road vehicles is related to vehicle vibration levels and the perception of passenger fatigue. Vibration in vertical direction on the vehicle seat and floor were measured to characterize the ride comfort based on standard formulae and frequency analysis. A mid-size saloon vehicle and an off-road vehicle were driven on smooth, spalled and coarse asphalt road surfaces (Abouel-Seoud, 2014). To assess the vertical vibrations transmitted to the passengers, vibration dose values, Kurtosis, frequency response functions and power spectral densities of the compartment recorded signals were evaluated. Seat effective amplitude transmissibility (SEAT) value based on vibration RMS or vibration dose value (VDV) were also evaluated. It was found that the VDV increased in proportional to the vehicle speed and road roughness.

Low-frequency vibrations, produced by the agricultural vehicles, can be extremely severe, depending upon the terrain that the agricultural vehicle is crossing and the forward speed of the vehicle. By comparison with the progress achieved over the past decades in improving the performance of agricultural tractors (power, transmission, electronics), the protection of the driver from vibration remains very inadequate. This is due to the fact that, in general, agricultural tractors do not have chassis suspension and the tires, which are relatively flexible and weakly damped, are the only suspension systems (Deboli et al., 2008). This explains why the tractor driver is subjected to low frequency, high amplitude vibration that is an important risk factor for low back pain disorder. In order to reduce the health risks and the discomfort to the driver and to enable the driver to work at a faster pace, it is important to isolate the driver from the machine vibration as much as possible.

The above mentioned work has shown that most of the efforts which had been done in this subject are directed towards the studying of tractor's rid comfort in the field conditions. Their contributions are limited due to the difficult existed in measurements and the equipment. Moreover, only vertical direction is considered, whereas fore-aft (longitudinal) and lateral directions have been given little considerations. Furthermore, most of the studies which have been published are largely theoretical, and relatively little data is available concerning the practical or experimental implementation. Thus, the objective of this study, was to estimate WBV for an agricultural tractor and used to evaluate tractor rid comfort efficiency. Additionally, the intelligent classical adaptive neuro-fuzzy inference system (ANFIS) controller was designed according to the underlying principles which can be easily applied on this agricultural tractor. Whole-body comfort parameters were computed in three directions (vertical, longitudinal and lateral). The tractor speeds used were 8, 10 and 12 km h^{-1} and the frequency range was up to 100 Hz.

2 BS 8641 frequency weighting filter

2.1 Field measurements

To compare the different situations in great detail, power spectral densities (PSD) are calculated from the tractor seat and floor acceleration data to describe the energy distribution over the frequency band of interest (0-100 Hz). The best methodology for comfort evaluation, giving a single number value, is looked up. A single number estimate of vibration severity requires that the motion should be weighted according to the relative importance of different physical variables: magnitude, frequency and duration. The tractor vibration accelerations are collected from three translation axes, longitudinal (x), lateral (y) and vertical (z) directions as shown in Figure 1, where (S) is seat pan surface accelerometer's mounting position and (F) is floor accelerometer mounting position. Ideally, the accelerometer's mounting position directly should be over (S) directly and actually not to be mounted further than 100 mm off-centre-line. The filters $W_i(f)$ is used for WBV evaluation (BS 6841, 1987; ISO 2631, 1997). All frequencies from the tractor vibration acceleration data with least contribution to the discomfort are lesser in value (<4 Hz). All frequencies with high contribution are higher in value (>10 Hz). The acceleration is frequency-weighted using the frequency weightings defined in the BS 6841 (1987) over the frequency range 0.5 to 80 Hz. Three frequency weightings and multiplying factors for the different axes are shown in Figure 2.

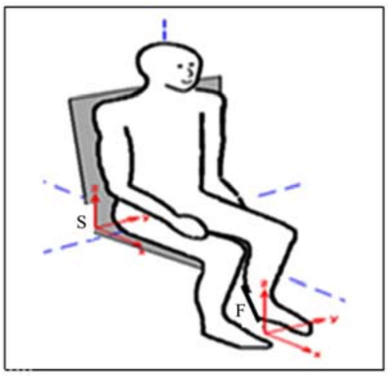


Figure 1 Direction of vibration measurements and location of accelerometers for a tractor

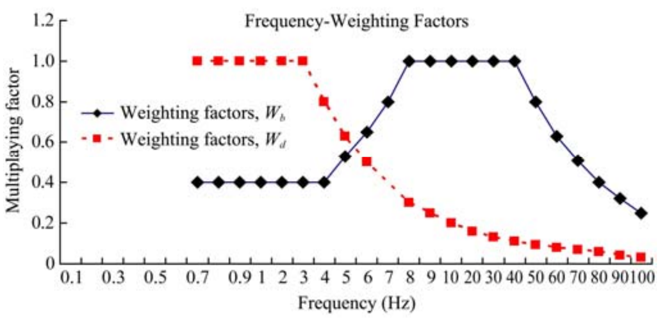


Figure 2 BS 8641 frequency weighting filter (Nahvi et al., 2009)

2.2 Vibration signal and road roughness analysis

2.2.1 Kurtosis of vibration signals

Kurtosis (Kurt) is defined as the fourth statistical moment signal, known as a global statistical parameter that is highly sensitive to the impulsiveness of the time-domain data. For discrete data sets, it can be approximated by

$$Kurtosis = \frac{(1/N)\sum_{n=1}^{N}(x(n)-\bar{x})^4}{\left[(1/N)\sum_{n=1}^{N}(x(n)-\bar{x})^2\right]^2} \qquad (1)$$

where, N is the number of data points taken in the signal; $x(n)$ is the amplitude of the signal at the n^{th} point, and $\bar{x}$ is the mean value of all amplitudes.

2.2.2 International road roughness index

In order to include the road roughness in the study, the international roughness index (IRI) was used by Ahlin et al. (2001). It is a general pavement condition indicator that summarizes the roughness qualities which affect tractor response, and is the most appropriate when a roughness measure is desired that relates to overall ride quality and overall surface condition (Nelson and Brereton, 2005). The IRI value can be defined approximately from the following equation.

$$\frac{(a)_{rms}}{IRI} = 0.16.(\frac{v}{80})^{1/2} \qquad (2)$$

where, V (km h^{-1}) is the tractor forward speed and $(a)_{rms}$ is the tractor floor root mean square (RMS) acceleration vibration (m s^{-2}).

3 Data analysis methodology

3.1 Frequency analysis

The frequency weighted data is converted into a comfort value using *VDV*. The weighting for duration has received less consideration than frequency weighting. The VDV calculation performs the duration weightings as it is accumulated and so automatically incorporates a method of giving greater weight to occasional peaks (shocks) in the motion (Figure 2). Close up frequency weightings magnitude of the BS 6841 (1987) frequency weighting filters (W_b and W_d; digital filters with linear phase shift) are used when considering the effect of the three translation axes in longitudinal (X), lateral (Y) and vertical (Z) directions of vibrations on comfort and health values. Normally, the accelerations used for the calculation of *VDV* values are taken at the tractor operator's seat and floor.

3.2 Power spectral densities

PSD were calculated for all acceleration signals. Vibration evaluations were performed according to the recommendations in the BS 6841 (1987). This involved in the application of frequency weightings, multiplication of factors to allow for different sensitivity of the driver's body in different axes, calculation of the VDV, and summation of values over different axes.

3.3 Vibration dose values

As different seats are in use, the choice is made to use the vibrations as transmitted to the operator's feet. Consequently, the calculated VDV will be an overestimation but will be more general information history as the basis for averaging. Here, VDV is the measure of the total vibration exposure of which considers the magnitude, frequency and exposure duration. Thus VDV (m s$^{1.75}$) is defined as

$$VDV = \left(\int_0^T a_w(t)^4\,dt\right)^{1/4} \qquad (3)$$

where, $a_w(t)$: Frequency – weighted acceleration , (m s^{-2}); T: Total period of the measurement in second.

or

$$VDV = \sqrt[4]{\frac{1}{f_s}\sum_{n=0}^{N-1} a_w(n)^4} \qquad (4)$$

where, $x(n)$ is the current sample of the weighted acceleration, $f_s = T/N$ is the sampling frequency and N is the total number of samples in the measurement and T is the measured time period in second

$$VDV = \left[\frac{T_s}{N}\sum x^4(t)\right]^{1/4} \qquad (5)$$

where, $x(t)$ is the frequency-weighted acceleration (m s^{-2}) time history, and T_s is the period of time in second over which vibration occurs (BS 6841, 1987; ISO 2631, 1997). According to the BS 6841 (1987), vibration magnitudes and durations that produce *VDV* in the region of 15 m s$^{-1:75}$ will usually cause severe discomfort. The exposure period required for the *VDV* to reach a tentative action level of m s$^{-1.75}$ can be calculated as

$$T_{15} = t.\left(\frac{15}{VDV_t}\right)^4 \qquad (6)$$

where, T_{15} is the time (s), required to reach a *VDV* value of 15 m s$^{-1.75}$, and VDV_{total} is the *VDV* measured over the period of t (second). The value of *VDV* provides a suitable measurement of the total severity for whole-body vibration. According to BS 6841 (1987), excessive exposure to vibration may increase the risk of tissue damage in the body BS 6841 (1987). Basically, the VDV shows the total amount of vibration received by the human over a period of time. Having this value shows the T_{15} level as the severe discomfort criteria. Hence, VDV and T_{15} determined the amount and the severity of vibration over a period of time.

The VDV is defined by Equation (4) with the measured time period T_s; the number of points in one time period N and the frequency weighted vibration data $x(t)$. The BS 6841 (1987) specifies that when evaluating tri-axis vibration, the fourth root of the sum of the fourth powers of the VDV in each axis should be determined to give the total vibration dose value (VDV_{ttl}) for the environment (Nahvi et al., 2009).

$$VDV_t = (VDV_{xs}^4 + VDV_{ys}^4 + VDV_{zs}^4)^{1/4} \quad (7)$$

where, VDV_{xs}, VDV_{ys}, and VDV_{zs} are the VDV in the x, y, and z directions on the seat, respectively.

The data acquired is measured for 5-min. However, this is measured in such a way as to represent the vibration levels experienced by the passenger related to the normal 8-hour work period. The required parameters are then computed and extrapolated to cover the entire duration of exposure.

3.4 Seat effective amplitude transmissibility (SEAT)

Seat comfort is usually assessed by making vibration measurements on the surface of the tractor seat based on the BS 6841 (1987). Seat isolation performance was indicated by SEAT values, which can be calculated from frequency-weighted of the VDV on the seat surface and seat base, VDV_{seat}, and VDV_{floor} (BS 6841, 1987; ISO 2631, 1997).

$$SEAT\% = 100x\frac{VDV_{seat}}{VDV_{floor}} \quad (8)$$

The SEAT value is a measure of how well the transmissibility of a seat is suited to the spectrum of entering vibration, taking into account the sensitivity of the seat occupant to different frequencies. SEAT values less than 100% indicate isolation or attenuation of vibration. It allows for the comparison of seat performance on a variety of road surfaces (Nelson and Brereton, 2005).

4 Vehicle seat control performance parameters

4.1 ANFIS technique

The final output is the weighted average of each rule's output. ANFIS is functionally equivalent to a Takagi-Sugeno (T-S) fuzzy inference system. By using stipulated input-output training data pairs, ANFIS tunes the membership functions and other associated parameters by back propagation gradient descent and least square type method respectively. Such methodologies make the ANFIS modeling more systematic and less reliant on expert knowledge, and more objective. The corresponding equivalent ANFIS structure and learning process can be found in details in Takagi and Sugeno (1983) and Watany et al. (2015).

4.2 Training process for ANFIS model

The ANFIS model mainly consists of the neuro-fuzzy (NF) network placed in series with the vehicle. The training process for obtaining the model of the tractor seat pan is shown in Figure 3 where the input and output data set is used to reflect input-output characteristics of the vehicle. The training data set is used based on: $ACCx$, $ACCy$, $ACCz$, $MACC_d$, where $ACCx$ is the tractor seat pan vibration acceleration in x-direction, $ACCy$ is the tractor seat pan vibration acceleration in y-direction, $ACCz$ is the tractor seat pan vibration acceleration in z-direction, $MACC_d$, is the desired tractor seat pan acceleration. The ANFIS network can be trained by least square estimation method to minimize the error cost function E defined by:

$$E_1 = \sum_{i=1}^{N} (ACC_i - MACC_d) \quad (9)$$

ACC_i is the input signal in i-direction and $MACC_d$ the corresponding actual output of the ANFIS model of this system. The iterative learning tuner is designed to improve the tracking performance of inverse-NF control which repeats the desired task over a finite interval.

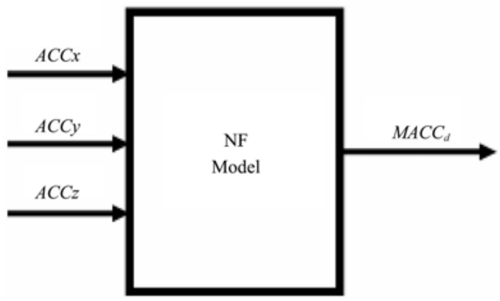


Figure 3 ANFIS friction damper model

4.3 Inputs selection

Prior to training the individual NF model, determining the number of input membership functions is very important in the initial condition. In the case of ANFIS which has n inputs and K membership functions for each input, the number of fuzzy rules R is

$$R = K^n \tag{10}$$

It is seen from Equation (8) that too many inputs and input membership functions will lead to a substantial increase of inference rules and thus increase training time and computer memory space consumption. Therefore, it is necessary to do input selection that finds the priority of each candidate inputs and uses them accordingly.

A quick and straightforward way of input selection for neuro-fuzzy modeling is to use ANFIS. The proposed input selection method is based on the assumption that the ANFIS model with the smallest RMSE after one epoch of training has a greater potential of achieving a lower RMSE when given more epochs of training. In this study, five models have been tried with different combinations of three inputs and train them with a single pass of the least square method. After several trials, the smallest training error is achieved when the inputs were the vibration acceleration of the three direction (*ACCx*, *ACCy*, *ACCz*) at the current time step and the vibration acceleration from previous time step to produce output $MACC_d$ at the current time step. Then the selected inputs are trained using the hybrid learning rule to tune the membership functions as well.

4.4 ANFIS controller design

4.4.1 Background

The engine noise and vibration remains one of the major noise and vibration sources in automotive. The vibration accelerations which recorded at the tractor seat pan in the three directions (x, y, z) are to be controlled, such vibration will lead to a reduced vibration acceleration by using ANFIS technique which is used to design a controller for this.

4.4.2 Training neuro-fuzzy friction damper controller

Given input/output data sets, ANFIS constructs fuzzy inference system (FIS) whose membership function parameters are adjusted using a back propagation algorithm. The size of input-output data must be large enough and cover all ranges to fine time the membership function. The tractor seat pan vibration acceleration in x-direction (*ACCx*), the tractor seat pan vibration acceleration in y-direction (*ACCy*) and the tractor seat pan vibration acceleration in z-direction (*ACCz*) at previous step are used as inputs and controlled (desired) tractor seat pan vibration acceleration ($CACC_d$) from current step as output as seen in Figure 4. ANFIS controller is developed using MATLAB software based on the experimental data sets. 3048 data samples were collected corresponding to vehicle speed of 12 km h^{-1}). These data were divided to 1524 points (odd number) for training and 1524 points (even number) for checking (Abouel-Seoud, 2016; Jang, 1993).

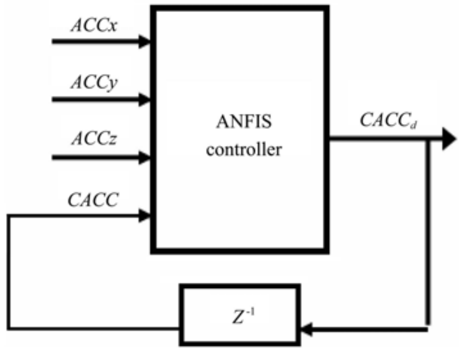


Figure 4 ANFIS controller for floor acceleration

5 Equipment and procedure

5.1 Road test

Under road conditions which unevenness of soil profile, pattern not complete, random moderately dense aggregate which are either dry or wet nutrient deficient, and slow-draining, water retention and resistance to penetration. They exhibit high permeability, acceleration data which are received from the tractor. Two tri-axial accelerometers were used for the vibration acceleration measurements. One of them was mounted on the operator (driver) seat pan surface for measuring vertical, longitudinal, and lateral accelerations. The other accelerometer was mounted on the tractor's floor beneath the front edge and centre-line of the tractor's seat pan. Measurements were taken for the values of the following variables: tractor driving speed, fully operational and profile of the driven surface. Driving speed of 8, 10 and 12 km h^{-1} and a gravel road surface were used. The gravel road surface is the agricultural worker' tend to do when coming and going to the field. Every time of 5 min, the vibration acceleration data were recorded. The goal is to analyze the vibration signals in terms of fast Fourier transform (FFT) and PSD frequency domain content in three translation directions in both tractor floor and seat for the fully operational situation.

5.2 Measurement equipment

Signals were acquired into the PULSE for analysis system as shown in Figure 5. The signal-recording period was 5-min. According to the aforementioned standards excitations up to 80 Hz should be counted for whole-body vibration analysis. Therefore, the frequency span of measurements was chosen as 100 Hz. The sampling frequency used was 2 kHz and the signals of 1.0 sec duration were recorded. B&K portable and multi-channel PULSE type 3560-B-X 05 analyzer was used. The B&K PULSE lab-shop software type 7700 was used to measure and analysis the results as shown in Figure 6. The tractor was equipped as originally furnished by manufacturers: ballast was not added and the tires were the manufacturer ones. For the purpose of measurements, two tri-axis accelerometers type B&K Type 9281B were mounted on the tractor floor and seat pan to measure the vibration of the three translation axes of longitudinal (X), lateral (Y) and vertical (Z) directions at specific speed (see Figures 7 and 8). The acceleration data measured for the tractor floor were substituted in Equations (1) and (2) to compute the kurt and IRI values at constant tractor speed. Figures 9 and 10 show photographs for this road surface and the tested tractor used respectively, where global positioning system (GPS) sensor was used for the measurement of tractor speed which provides an accurate information of the vehicle speed estimated through the Doppler's effect. The tested tractor was of "A" category (78/764/EC Directive, 2002) Deboli et al. (2008), class I (unladen mass <3600 kg). It was equipped as originally furnished by manufacturers: ballast was not added and the tires were the manufacturer ones.

Figure 5 The PULSE for analysis system

Figure 6 The vibration Measurement system

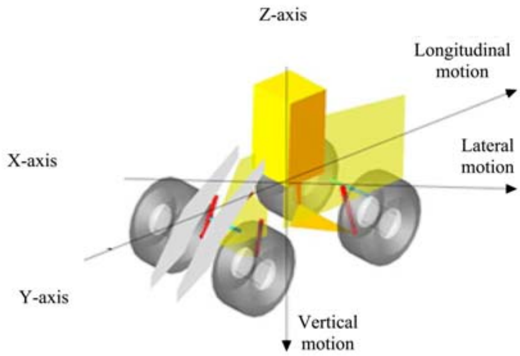


Figure 7 Tractor body-centered axis system

Figure 8 Tri-axis ace lerometers

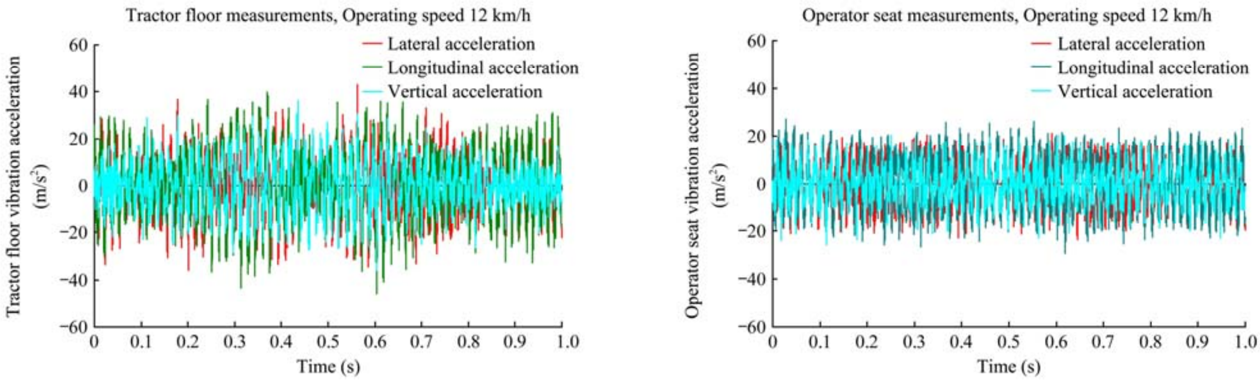
Figure 9 Gravel road surface

Figure 10 Tested tractor

6 Results and discussion

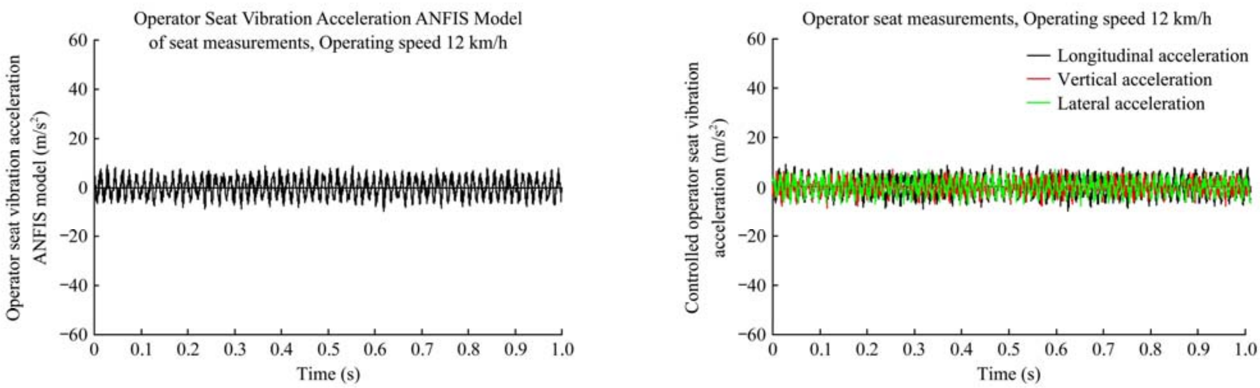
6.1 Signals time history

Figures 11 and 12 showed samples from the measurement of raw signals in terms of time history taken on the tractor floor and seat pan respectively. The measurements were recorded at three translation axes of longitudinal (x), lateral (y) and vertical (z) directions for a 5-min drive on gravel road surface at tractor speed of 12 km h^{-1}. The vibration accelerations for tractor floor are shown in Figure 11(a), while Figure 11(b) is for tractor seat pan. The vibration accelerations for tractor seat pan data model based on FANIS technique is shown in Figure 12(a), while the controlled vibration acceleration based on FANIS technique is shown in Figure 12(b). In all figures, it is observed that the vibration acceleration measured for lateral direction gives the highest level followed by the level at longitudinal direction where the lowest level is for vertical direction, where the levels are lower than those for uncontrolled signals. On the other hand, the controlled vibration accelerations shown in Figure 12(b) are lower than those present in Figure 11(b), which indicates the effectiveness of the control technique used.



(a) Tractor floor (b) Tractor seat pan

Figure 11 Time history of the raw signal-vibration acceleration



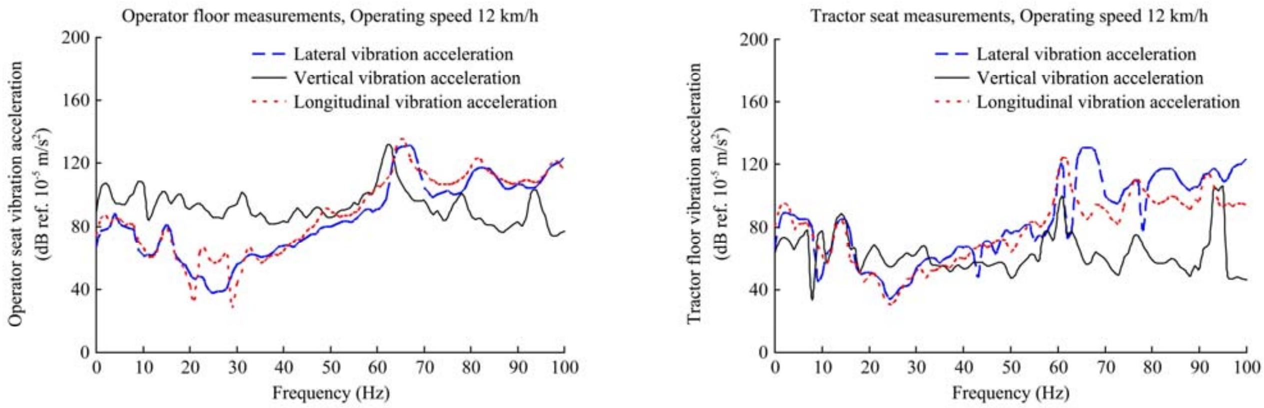
(a) Tractor seat pan ANFIS model (b) Tractor seat pan ANFIS controller

Figure 12 Time history of the controlled signal-vibration acceleration

6.2 Frequency domains characteristics

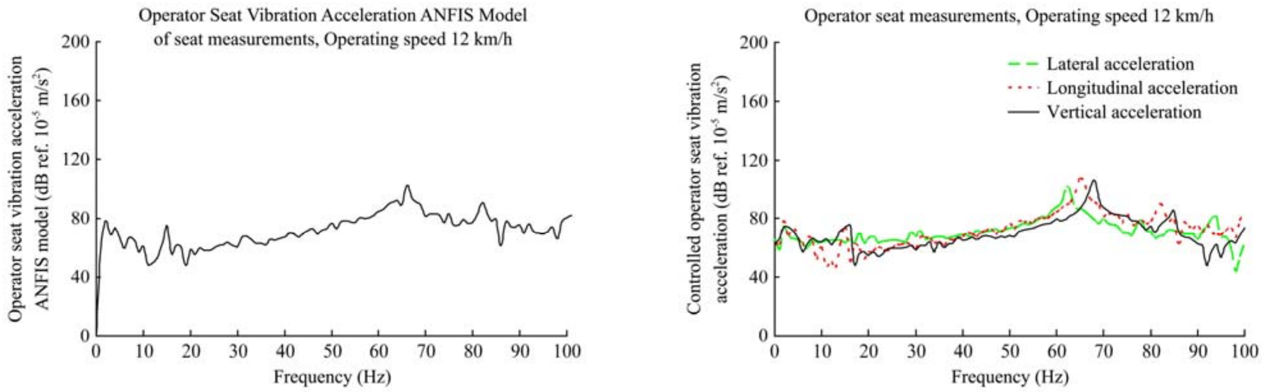
Samples from the FFT of the tractor weighted vibration acceleration measurements for a 5-min drive on gravel road surface. The tractor speed is being 12 km h^{-1} and the measurement frictions are vertical (z), lateral (x) and longitudinal (y). This is done to show the frequency range of interest up to 100 Hz and are shown in Figures 13 and 14. For example, Figure 13(a) shows that the highest peak acceleration is 133.09 dB ref. to 10^{-5} m s^{-2} at frequency of 66.0 Hz for the floor in lateral direction with the highest peak acceleration of 130.72 dB ref to 10^{-5} m s^{-2} at frequency of 66.0 Hz for the seat in lateral direction also as shown in Figure 13(b). It is noticed from the present study results that the weighted vibration acceleration which shown in Figures 13(a) and 13(b) that the highest peak frequency for the tractor seat is lower than that of the tractor floor. The vibration accelerations for tractor seat pan data model based on FANIS technique is shown in Figure 14(a), while the controlled vibration acceleration based on FANIS technique is shown in

Figure 14(b). It is observed that the controlled vibration accelerations shown in Figure 14(b) are lower than those present in Figure 13(b), which indicates the effectiveness of the control technique used. Bearing in mind that a good seat should have a highest peak frequency at least 1.4 times lower than the peak frequency of the tractor floor where the seat is mounted (Ahlin et al., 2001). In this study, the tractor seat used is no good and its suspension needs to be modified.



(a) Tractor floor (b) Tractor seat pan

Figure 13 FFT of weighted vibration acceleration



(a) Tractor seat pan ANFIS model (b) Tractor seat pan ANFIS controller

Figure 14 FFT of controlled vibration acceleration

6.3 Power spectral density

The PSD were calculated for all the weighted vibration acceleration signals measured at the .three translation axes of longitudinal (x), lateral (y) and vertical (z) directions for the FFT vibration accelerations for the tractor seat pan while driving for a 5-min on gravel road surface at speed of 12 km h^{-1}. The units in the y-axis is dB ref. 10^{-3} (m s^{-2})^2 Hz^{-1}. Figures 15 and 16 show how the uncontrolled and controlled vibration accelerations measured and computed for the tractor seat pan were distributed over the frequency range up to 100 Hz respectively. Seat pan excitations were attenuated by the seat-isolation system up to 40 Hz. Accelerations were amplified at frequencies beyond that, but the magnitudes were very low. In addition, acceleration on the floor was amplified in the longitudinal and lateral directions up to 40 Hz. On the tractor seat pan surface in the vertical direction the energy distribution tends to be concentrated toward the higher frequencies. Amplification of the lateral and longitudinal signal is achieved in low frequencies. This kind of energy observation is a powerful tool to check the capabilities of seat structures in the early stages of design, even on the test rig.

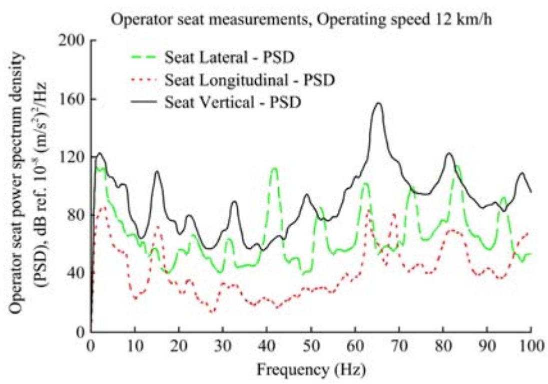


Figure 15 PSD for uncontrolled vibration accelerations measured in tractor seat pin

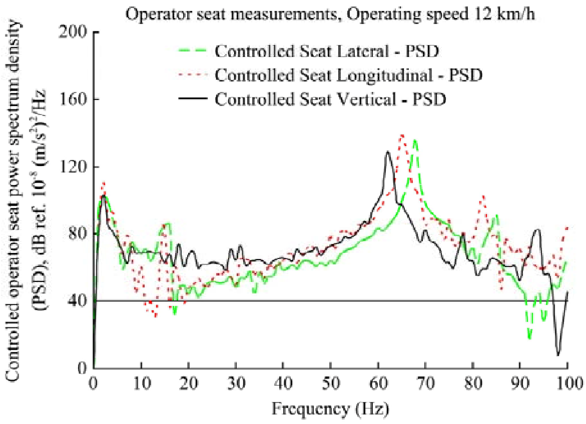


Figure 16 PSD for controlled vibration accelerations measured in tractor seat pin

6.4 Data analysis evaluation

6.4.1 Seat comfort parameters

Table 1 tabulates the data of kurtosis and international road roughness index (IRI) for all vibration acceleration signals of the vertical, lateral and longitudinal directions, while driving for a 5-min on gravel road surface at speeds of 8, 10 and 12 km h^{-1}. The kurtosis and IRI were calculated in terms of the time history of floor vibration acceleration and based on Equations 1 and 2 respectively. According to the data presented in the Table 1, it can be observed that the average kurtosis value ($Kurt_{Av}$) of 3.52 at speed of 8 km h^{-1}, the average kurtosis value ($Kurt_{Av}$) of 3.73 at speed of 10 km h^{-1} and the average kurtosis value ($Kurt_{Av}$) of 3.93 at speed of 12 km h^{-1}. This gives a single number of 3.73 which is higher than 3.0, therefore, it is not in flat distribution. Moreover, the IRI values are proportional to kurtosis values which indicate that human perceives more peaks and impulses when driving on road surface with greater roughness. The values of IRI_x, IRI_y, IRI_z and IRI_{Av} are nearly equal to 0.011. Moreover, the variations of VDV (from Table 2) with changes in IRI and kurtosis (from Table 1) are observed, where the kurtosis values increase as the IRI increases. This indicates a deviation of the acceleration signals from the Gaussian distribution as the IRI increases.

The variation of VDV is calculated based on Equations (3) and (5) over the tractor floor of three translation axes of longitudinal (x), lateral (y) and vertical (z) directions, while driving for a 5-min on gravel road surface at speeds of 8, 10 and 12 km h^{-1} are tabulated in Table 2. It may be seen that the VDV values grew as the tractor speed increased. As expected, driving on gravel road surface gives higher IRI induces kurtosis (impulses). This resulted in more kurtosis and VDV values and less objective operator comfort. Hence, the roughness of the gravel road surface could be compensated through slowing down and thereby improving the ride quality. From Table 2, the highest axis of VDV is Y-axis (lateral direction) with value of 269.7 m s$^{-1.75}$ at tractor speed of 12 km h^{-1}. Table 3 tabulates the variation of VDV and the corresponding controlled values for tractor seat pan where the VDV values are much higher than that of the controlled ones in all the tractor speeds considered.

Table 1 Summary road surfaces roughness parameters data

No.	Tractor speed (km h^{-1})	Kurtosis of Vibration Signals (Kurt)				International road roughness index (IRI)			
		$Kurt_x$	$Kurt_y$	$Kurt_z$	$Kurt_{Av}$	IRI_x	IRI_y	IRI_z	IRI_{Av}
1	8	2.95	4.61	2.99	3.52	0.01	0.01	0.04	0.010
2	10	3.06	5.03	3.10	3.73	0.01	0.01	0.01	0.011
3	12	2.25	7.34	2.20	3.93	0.01	0.01	0.01	0.012

Table 2 Summary of VDV for tractor floor data

No.	Tractor speed (km h^{-1})	Tractor floor uncontrolled VDV, m s$^{-1.75}$			
		VDVxs	VDVys	VDVzs	VDVts
1	8	82.28	41.01	3.524	83.520
2	10	92.6	53.73	11.11	95.130
3	12	193.9	269.7	150.95	291.533

The time required to reach m s$^{-1.75}$ VDV, T_{15}, calculated based on Equation 4 in the three translation axes of longitudinal (x), lateral (y) and vertical (z) directions, while driving for a 5-min on gravel road surface at speeds of 8, 10 and 12 km h^{-1} to reach the needed time which are listed in Table 4. On gravel road surface, the needed time to reach 15 m s$^{-1.75}$ VDV is so long in the relatively low speed that it is not feasible to suppose that an operator can continuously operate such a long period of time.

Table 3 Summary of VDV for tractor seat pan data

No.	Tractor speed (km h^{-1})	Tractor seat pan vibration dose value (VDV) (m s$^{-1.75}$)				Tractor seat pan controlled vibration dose value (VDV) (m s$^{-1.75}$)			
		VDVxs	VDVys	VDVzs	VDVts	VDVxs	VDVys	VDVzs	VDVts
1	8	60.8	24.7	2.662	61.21	8.53	6.968	3.328	9.390
2	10	86.27	35.37	3.702	86.87	10.113	8.53	3.351	11.23
3	12	188.1	52.53	95.93	191.5	68.118	66.93	1.65	80.30

Table 4 Summary of time required to reach m s$^{-1.75}$ VDV, T_{15}, for controlled and uncontrolled conditions

No.	Tractor speed (km h^{-1})	Time period over which vibration occurs T_s (h)	Driving time on gravel road (s)	Tractor seat pan's time required to reach M s$^{-1.75}$ VDV, T_{15}, s (uncontrolled)	Tractor seat pan's time required to reach M s$^{-1.75}$ VDV, T_{15}, s (controlled)
				T_{15t}	T_{15t}
1	8	8.0	300	1.081995	1953.547
2	10	8.0	300	0.266653	956.2823
3	12	8.0	300	0.011299	0.365278

6.4.2 SEAT values evaluation

The relationship between the tractor floor VDV and that for seat can be expressed numerically by the SEAT value. Table 5 presents the SEAT values calculated VDV and controlled VDV based on Equation 6 for the three translation axes of longitudinal (x), lateral (y) and vertical (z) directions while driving for a 5-min on gravel road surface at speeds of 8, 10 and 12 km h^{-1}, where the average values of $SEAT_{av}$ is 73.287% and 11.243% (controlled) for speed of 8 km h^{-1}, 91.32% and 11.801% (controlled) for speed of 10 km h^{-1}; and 65.679% and 27.544% (controlled) for speed of 12 km h^{-1}. Moreover, from Table 6, the values of $SEAT_{av}$ and $SEAT_{av}$ (controlled) are increased as the tractor speed increased. It can be stated that the use of the control technique for calculated the SEAT can reduce the vibration acceleration transmitted to the tractor whole body operator and consequently reduce his discomfort.

Table 5 Summary of the seat effective amplitude transmissibility data (SEAT)

No.	Tractor speed (km h^{-1})	Tractor Seat Pan's Seat Effective Amplitude Transmissibility (SEAT) (%)				Tractor Seat Pan's Controlled Seat Effective Amplitude Transmissibility (SEAT) (%)			
		$SEAT_x$	$SEAT_y$	$SEAT_z$	$SEAT_{av}$	$SEAT_x$	$SEAT_y$	$SEAT_z$	$SEAT_{av}$
1	8	73.894	60.229	75.539	73.287	10.367	16.991	94.438	11.243
2	10	93.164	65.829	33.321	91.32	16.991	15.876	30.162	11.801
3	12	97.009	19.477	63.552	65.679	35.13	24.816	1.093	27.544

7 Conclusions

On the tractor seat pan surface in the vertical direction, the energy distribution tends to be concentrated toward the higher frequencies. Amplification of the lateral and longitudinal signal is achieved in low frequencies. This kind of energy observation is a powerful tool to check the capabilities of seat structures in the early stages of design, even on the test rig. Therefore, it can be concluded that factors other than tractor seat and floor ergonomics affect operators' comfort while operating on well-maintained, smooth roads.

Generally, it can be stated that the distribution of kurtosis parameter against tractor speed variation can be noticed, where at constant tractor speed, the kurtosis parameter is greater in road surface with high roughness. Moreover, the variations of VDV with changes in IRI and kurtosis are observed, where the kurtosis values increase as the IRI increases. This indicates a deviation of the acceleration signals from the Gaussian distribution as the IRI increases.

The SEAT values indicate that injury can result from long-term driving on the gravel road surface. As seats with mechanical suspension system is the main transmission paths of vibration towards the spine of the operator, their vibration attenuating characteristics play an important role in comfort assessment. Moreover, from Table 6, the values of $SEAT_{av}$ and $SEAT_{av}$ (controlled) is increased as the tractor speed increased. It can be stated that the use of the control technique for calculated the SEAT can reduce the vibration acceleration transmitted to the tractor whole body operator and consequently reduce his discomfort.

The influence of vibration on comfort is generally known and the consequent origination or even deterioration of health. It must be kept in mind that low frequency vibration has essentially higher energy severity than a vibration of relatively middle and higher frequencies. The long-term exposition of the energy rich low frequency vibration can lead to harm to human health, and not only the health but also functionality of other organs such as the central nervous system. Therefore it is important to improve the criteria of energy rich, low frequency, vibration assessment so that the influences of energy on human health and comfort are assessed correctly.

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Nomenclature

List of acronyms

Acronyms	The meaning of acronyms
PSD	Power spectral densities
Kurt	Kurtosis of vibration signal
IRI	The international roughness index
VDV	The vibration dose value
USAASL	U.S. Army Aero-medical Research Laboratory
SEAT	Seat Effective Amplitude Transmissibility
WBV	Whole-body vibration
ANFIS	Adaptive neuro fuzzy inference scheme
ACC_i	Is the input signal in i-direction
$MACC_d$	Actual output of the ANFIS model of this system
RMSE	Root mean squared error
ACCx	The tractor seat pan vibration acceleration in x-direction
ACCy	The tractor seat pan vibration acceleration in y-direction
ACCz	The tractor seat pan vibration acceleration in z-direction
$CACC_d$	Controlled (desired) tractor seat pan vibration acceleration

List of symbols

Symbols	The symbols meaning
N	The number of data points taken in the signal
V	The tractor forward speed (km h^{-1})
S_{ed}	the equivalent daily stress index
T_{15}	The time (in seconds) required to reach a VDV value of 15 m s$^{-1.75}$
x	Longitudinal translation axis
y	Lateral translation axis
z	Vertical translation axis
E	Error
n	Number of inputs
K	Membership functions for each input
R	The number of fuzzy rules