Reduction of hand transmitted and whole body vibrations experienced by tractor operators by using piezo crystal material

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Abstract: A study was proposed to investigate the effects of vibration on tractor operator's health attempting a biodynamic and physiological approach. The source vibration levels at steering wheel and seat for the hand transmitted and whole body vibration during different tractor operations were measured. Two isolators, one commercially available, made of styrene butadiene rubber (SBR) and the other custom designed, made of piezo-electric material embedded in SBR were tested for attenuation of vibration. It was observed that an average 40% reduction in vibration intensity was experienced with installation of custom-designed isolator underneath the tractor operator's seat. The measured values of vertical vibration at operator's seat were found to be within 8 h fatigue decreased proficiency boundary limit. Incorporation of custom-designed isolator reduced the muscle load to a maximum of 44.37% in erector spinae muscle during first tilling operation, while flexor carpi radialis in transport attained 23.03% reduction.

Keywords: Piezo crystal, vibration, transmissibility, accelerometer, isolators

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1 Introduction

Tractors have become the most important power source in the modern Indian agriculture. Excessive exposure to whole-body vibration (WBV) and awkward working postures are considered to be the major stressors contributing to the onset and development of musculoskeletal complaints among professional drivers (Troup, 1978). Several epidemiological studies have shown that tractor driving is associated with an increased risk for musculoskeletal disorders in the back (Boshulzen et al, 1990). Most vibration frequencies are attenuated by the body; however, frequencies between 1 and 20 Hz can cause the body, including spinal column, pelvis, internal organs and soft tissues, to resonate (Kitazaki and Griffin, 1998).

Mehta (2000) tried different combinations of cushion materials for the tractor seat since seat appeared to be the simplest, economic and best location of isolation of vibration. Accordingly, Dewangan (2007) tested and identified optimum isolator materials for reduction of vibration in a hand tractor. The vibration energy transmitted to and absorbed by the hand arm and whole body system results in relative compression and extension of muscle tissues (Reynolds, 1977). The vibration characteristics of muscles can help to quantify the influence of impinged vibrations, and provide a better insight in to the fatigue and injury mechanism of the operator's body. Therefore, it is essential to measure the hand and body muscle activities involved in various actions performed during different field operations of tractor-implement system in terms of reference voluntary electrical (RVE) activity with respect to maximum voluntary contraction (MVC) to systematically understand and quantify the muscle fatigue level leading to operator's work stress.

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Over the past 50 years piezoelectric sensors have proven to be a versatile tool for the measurement of various processes. Today, they are used for the determination of pressure, acceleration, strain or force in quality assurance, process control and development across many different industries. Piezo-ceramics are used to convert mechanical parameters, such as pressure and acceleration, into electrical parameters or, conversely, to convert electrical signals into mechanical movement or vibration. In sensors they make it possible to convert forces, pressures and accelerations into electrical signals, and in sonic and ultrasonic transducers and actuators they convert electric voltages into vibrations or deformations. Piezoelectric materials, crystals and ceramics, have the ability to generate a small electric potential when they are subjected to mechanical stress, which makes them suitable for a variety of applications, from harnessing sounds to producing electricity.

The present investigation is aimed to incorporate appropriate interventions for reduction of resulting vibration experienced by the operators during various activities with the help of piezo electric crystal materials at the operator's cushion seat. The major objective of the present investigation was to evaluate the whole body vibrations experienced by tractor operators and analyze the effect of isolators in reducing the level of vibration.

2 Piezo Crystal Material

Piezo-electricity is based on the ability of certain crystals to generate an electrical charge when mechanically loaded with pressure or tension. Conversely, these crystals undergo a controlled deformation when exposed to an electric field. The polarity of the charge depends on the orientation of the crystal relative to the direction of the pressure.

2.1 Types and properties

Since the last 20 years, new piezoelectric materials have been developed, among them, Gallium orthophosphate (GaPO4) and the Langasite family (Lanthanum Gallium Silicate La2Ga5SiO14 LGS, Lanthanum gallium tantalate, La3Ga5.5Ta0.5O14 LGT) have been studied in detail for high-performance piezoelectric resonator applications. The reasons of this interest are; the material is now available commercially in crystal sizes compatible with production machines used in the industry; GaPO4, LGS and LGT can be used at high temperatures without losing their piezoelectric properties; GaPO4, LGS and LGT exhibit temperature-compensated cuts for various modes of vibration: bulk waves, surface waves, vibrating beams and cylinders.

2.1.1 Properties of piezo crystals

Piezo crystals, also called piezoelectric crystals, are a special type of crystal formation with unique properties that help it respond easily to external stimuli. Most piezo crystals in use today are made from polycrystalline ceramics, which have better durability and flexibility than naturally occurring piezo crystals. These crystalline creations are used in circuits and timekeeping devices, among other systems.

2.1.2 Electrical response

When piezo crystals encounter a force, they respond by creating slight electrical charge. The charge is equal to the force applied--in other words, if a crystal is compressed one way, it will exhibit electric polarity in one direction; but when compressed the other way, the polarity will flip around to match the new pressure. This response to external stresses makes piezo crystals unique, according to Azomaterials, a materials research website.

2.1.3 Mechanical response

The relationship between electrical charge and mechanical force works both ways for piezo crystals. When the crystal is placed in an electrical field or when a charge is applied to the crystal, it will respond by straining, compressing based on the direction from which the current is coming. These changes happen very quickly, which allows scientists to make piezo crystals vibrate when connected to an electrical source. This vibration is steady, and helps keep time for some circuits.

2.2 Uses

Piezo-ceramics have a wide range of uses. Piezo-ceramics are used in the automotive industry in a number of applications such as in knock and oil level sensors or as actuators for precise control of injection processes in engines. In medical technology piezo-ceramic components can be found in lithotripters, devices for plaque removal and in inhalers. Common applications in mechanical engineering include ultrasonic cleaning, ultrasonic welding and active vibration damping. Pickups for musical instruments or piezo-electric gas igniters are examples for the use of piezo-electric technology in consumer applications.

3 Theoretical principals

3.1 Vibration transmissibility

Vibration transmissibility is defined as the ratio of the vibration measured on the hand-arm/whole body system to the input vibration on the steering wheel/seat of the tractor. It can be represented as Equation (1):

$$\text{Vibration transmissibility} = \frac{a_{(m,w)v}}{a_{hw}} \tag{1}$$

where, $a_{(m,w)vv}$ = measured acceleration at the metacarpal and wrist for HAV respectively, m s^{-2}; = measured acceleration at the chest and forehead for WBV respectively, m s^{-2}; a_{hv} = acceleration at the steering/seat in three different axes x, y and z under the frequency range of 6.3 to 1,250 Hz, m s^{-2} for HAV and 1 to 80 Hz for WBV.

Furthermore the vibration is dependent on frequency response characteristics therefore, vibration transmissibility is also determined across the individual frequency within the 1/3 octave band at an anatomical location on the hand-arm/whole body system. The frequency response of vibration transmissibility is defined as Equation (2):

$$\text{Vibration transmissibility} = \frac{a_{(m,w)v}(\omega)}{a_{hw}(\omega)} \tag{2}$$

where, ω = excitation frequency, Hz.

3.2 Isolator stiffness

The stiffness of a material represents its ability to resist deformation. Stiffness can be used to estimate both the natural frequency and isolation effectiveness of a lightly damped isolation system. Stiffness can be represented as Equation (3):

$$K_s = \frac{AE}{L} \tag{3}$$

where, K_s = stiffness constant; A = area of isolator, m^2; E = Young's modulus, N m^{-2} and L = Length of isolator.

4 Methodology

4.1 Measurement of hand transmitted and whole body vibration

The experiments were conducted to assess the hand arm and whole body vibration from the tractor operation during selected operations.

4.1.1 Instrumentation

A handle adapter fabricated by Dewangan (2007) using aluminum alloy as per dimensions suggested by Rasmussen (1982) was used for measurement of three axes hand-arm vibration is shown in Figure 1.

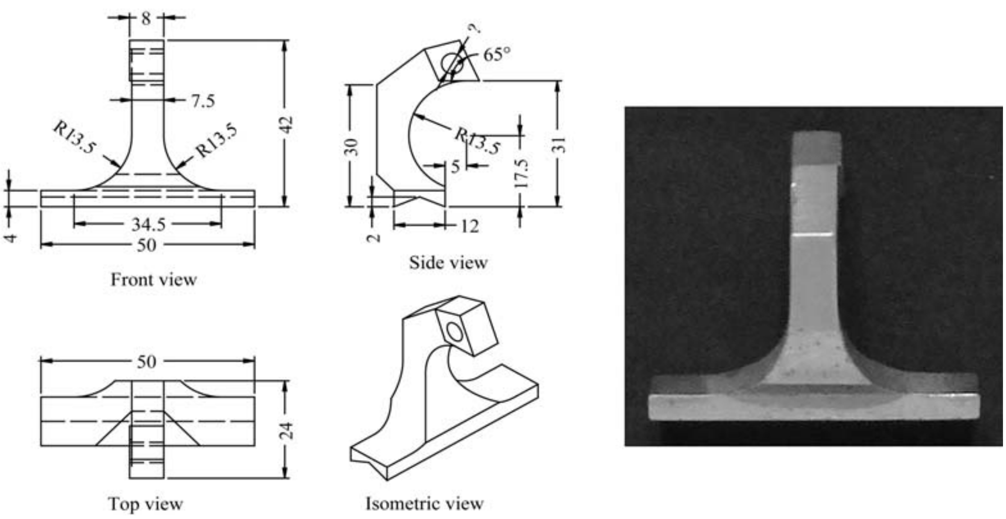


Figure 1 Handle adaptor for measurement of hand arm vibration of tractor (Rasmussen, 1982)

The measurement of vibration acceleration of the hand-arm of the subjects was done at two locations, namely, head of third metacarpal (M) and wrist (W) (Figure 2a). Two different lightweight tri-axial accelerometers (356A22 for steering, 356A24 for metacarpal and wrist, PCB, USA) were used for the hand arm vibration measurement. A strap adapter was fabricated to fix the accelerometers to selected locations. The adapter holder was of size 10 × 12 × 8 mm with press fit tightness to accommodate the accelerometer. The holder was fixed with Velcro hooks and loops on opposing sides, which when pressed together, the hooks catch in the loops and the two pieces fasten or bind temporarily. Three Velcro straps with same adapter size but varying strap length were fabricated for using at different locations of measurement. The adapter increased the contact area and stabilized the position of accelerometer. The strap enabled to tightly secure the adapter to avoid any relative vibration between the location of measurement and accelerometer. The total weight of the adapter with strap including the accelerometer was 16 g, which was within the recommended weight of 20 g by NIOSH (1989). Twelve channel real time FFT analyzer (OROS, France) was used to collect output signal from the accelerometer. A sampling frequency of 51.2 ksamples/s was used during the study. For measuring the whole body vibration form the seat, a seat pad accelerometer (356B41, PCB, USA) was used. It is installed between rider and vehicle seat, for the ride comfort studies and human vibration exposure investigations. The model contains a precision, low profile, tri-axial ICP accelerometer, which is mounted to a metal plate and screwed into a molded rubber pad. The sensor may easily be removed from the pad for calibration and verification purposes. This mechanical configuration satisfies the requirements of ISO 10326/1 (1992). This sensor supports whole body vibration studies, in accordance with ISO 2631/1 (1997) and ISO 8041 (2005) standards. It has a sensitivity of 10.2 mV (m s^{-2})$^{-1}$ with a 1.5 m integral cable and 4-pin terminating connector.

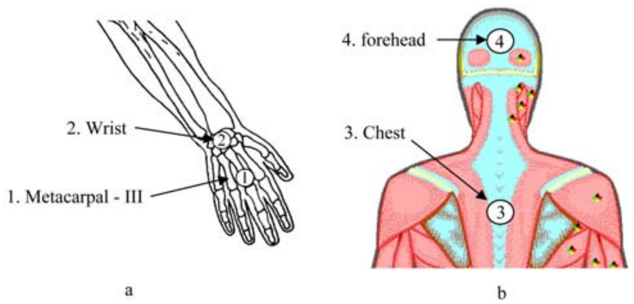


Figure 2 Location of accelerometer for transmissibility test

4.2 Experimental design

The experiment was conducted in split-split-plot design where different operations were taken as main plot, speed of operation as sub-plots and different locations of vibration measurement as the sub-sub-plots. The subjects were taken as replications. Three trials were conducted with each subject for each of the above conditions and the mean value of these trials was taken as the representative value for that replication. The treatments were given in randomized order to minimize the effects of variation in environmental and soil conditions. At a time, data from 3 locations were measured. Details of experimental variables are given in Table 1.

Table 1 Experimental plan for HAV/WBV measurement

SN	Parameter	Level	Description
Independent parameters			
1	Operations	4	First Till – Mould Board Plough Second Till – Disk Harrow Puddling - Rotavator Transport – Tarmacadem road
2	Speed of operation	5	2.22, 2.89, 4.19, 5.62 and 5.99 m s^{-1} for transport
		4	0.63, 0.95, 1.29 and 1.41 m s^{-1} for first till and second till
		3	0.63, 0.95 and 1.29 m s^{-1} for puddling
3	Subjects	12	S1, S2, S3, S4, S5, S5, S6, S7, S8, S9, S10, S11, S12
4	Locations	6	Steering, Metacarpel, Wrist for hand arm. Seat, Chest and fore head for whole body
Dependent parameter			
Vibration acceleration at X, Y and Z axes			

4.3 Experimental methodology

An adapter was rigidly fixed to the steering wheel and a light weight accelerometer was attached to the handle strap adapter (Figure 3). Acceleration measurement at the head of third metacarpal bone and the wrist were made. Other accelerometers at the seat, forehead and chest were also installed as shown in Figure 4, and data were taken at one go for a single subject under given condition so that the prevailing conditions responsible for the vibration acceleration at all measuring locations remain the same. The whole body vibration (WBV) acceleration was observed at the seat pad accelerometer in accordance with ISO 2631/1 (1986). The X–axis vibration was measured in the forward direction of motion, while Y–axis measurement was in the lateral direction (perpendicular to the direction of motion) and the Z–axis vibration acceleration was measured in the vertical direction to the seat.

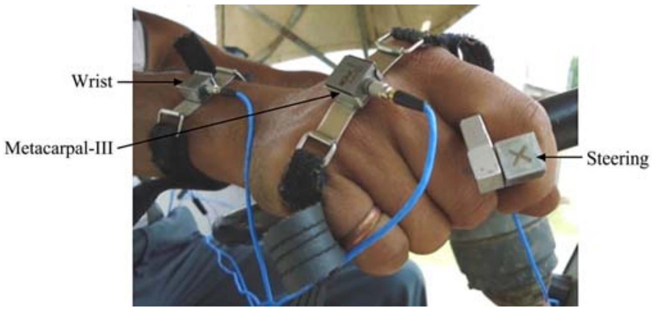


Figure 3 Accelerometers fixed using handle and strap adapter for HAV measurement

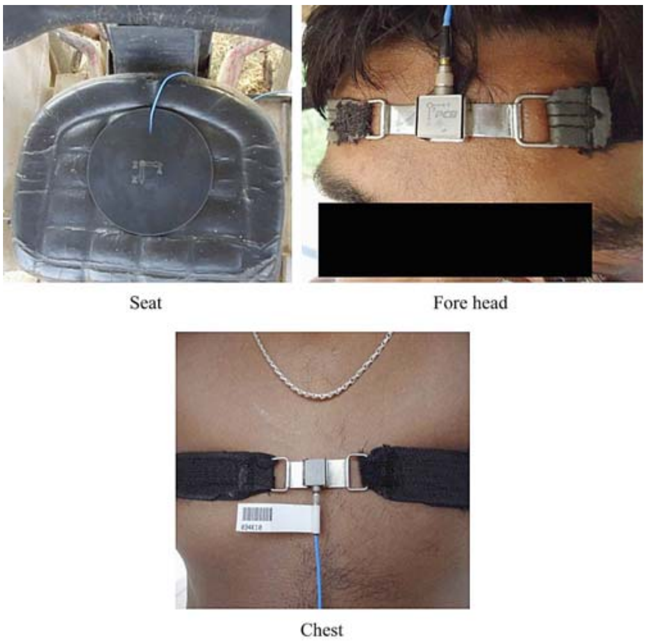


Figure 4 Accelerometers in use for WBV measurement

The subject was asked to drive the tractor at the selected mode of operation as per the experimental plan. Data were collected continuously during the selected operation. Three readings of vibration acceleration were recorded in the data acquisition system. All the trials were randomized to minimize the effects of variation in environmental conditions. Experiment was conducted for all the subjects in the same manner for all selected conditions.

4.4 Computation and data analysis

FFT analysis was performed on the observed data using the NVGate software (OROS, France). Frequency-weighted vibration acceleration (rms) for hand transmitted vibration was calculated for each axis using the filter suggested by ISO 5349 (1986). The sum of the three axes vibration was calculated according to Griffin (1990). The spectrum of vibration acceleration (rms) was obtained for each 1/3 octave band in the range between 6.3 and 1,250 Hz. The vibration transmissibility was then calculated as the ratio of the vibration acceleration at the different locations to the vibration acceleration at the steering wheel of the tractor.

For the whole body acceleration, frequency weighting was directly employed through the in-built filters provided in NVGate software, which are in tune with ISO 2631/1 (1997). The spectrum of vibration acceleration was thus obtained for each 1/3 octave band in the range of 1-80 Hz (Fairley, 1995; Mehta et al., 1997 and Griffin, 1998). The vibration transmissibility was also calculated from the vibration acceleration at chest and forehead and at the tractor cushion seat.

4.5 Isolators

For vibration isolation, Isolators were designed and installed beneath the seat and above the axle casing. The isomer material used is the Steryl butadiene rubber (SBR). It has a hardness of 50-55 Shore ‘A’ scale (Kalyanasundaram, 1999). The ratio of damping co-efficient to critical damping is a convenient reference for damping factor of that particular material. Two different isolators were used for the study. One was a commercially available isolator and other was designed and fabricated. The commercial one has two mild steel plates of 10 mm thickness sandwiching 12 numbers of isomer blocks of 25 mm diameter and 20 mm height arranged in a rectangular fashion. All the blocks are riveted to one mild steel flat properly in order to be secure in position while operating where as other mild steel flat is detachable, so as to enable easy fixing to the bottom of the seat. The isomer is strained in compression when the load is applied along its perpendicular direction.

4.6 Custom-designed isolator

A new vibration isolator was designed using PZT material (composite of Lead (Pb), Zirconate (Zr), and Titanate (Ti)), embedded between SBR isomer in line with the commercial isolator. The isolator consisted of isomer (39 mm diameter, 25 mm thick) which was embedded with 38 mm diameter; 6 mm thick PZT material. The isomer was separately screwed to either plate using counter sunk screws. The isolator was installed between seat and axle casing as shown in Figure 5. Stiffness of the both commercial and custom-designed isolator was determined using universal testing machine (UTM). The lightweight tri-axial hand arm accelerometer (356A22 for steering, 356A24 for metacarpal and wrist, PCB, USA) was used to measure vibration at the steering and seat pad accelerometer (356B41, PCB, USA) to measure whole body vibration of tractor operation after installation of isolator. The 12–channel pulse multi analyzer system was used to capture the signals from all combinations of the experiment. The experiment was conducted in split-split-plot design where isolator mountings were taken as main-plots and various operations as sub-plots and speed of operation as sub-sub-plot as discussed in the section 4.2.

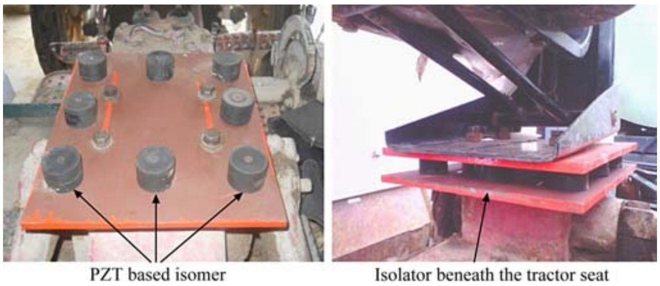


Figure 5 Custom-designed isolator installed in tractor

5 Results and discussion

5.1 Frequency response of vibration transmissibility

Spectral response of vibration transmissibility in the hand arm and whole body system of the operators experienced during field selected operations are presented in Figure 6 and Figure 7. Vibration transmissibility at metacarpal and wrist in the frequency band of 6.3 to 1,250 Hz for the hand arm system and at chest and forehead in 1 to 80 Hz for whole body system were analyzed.

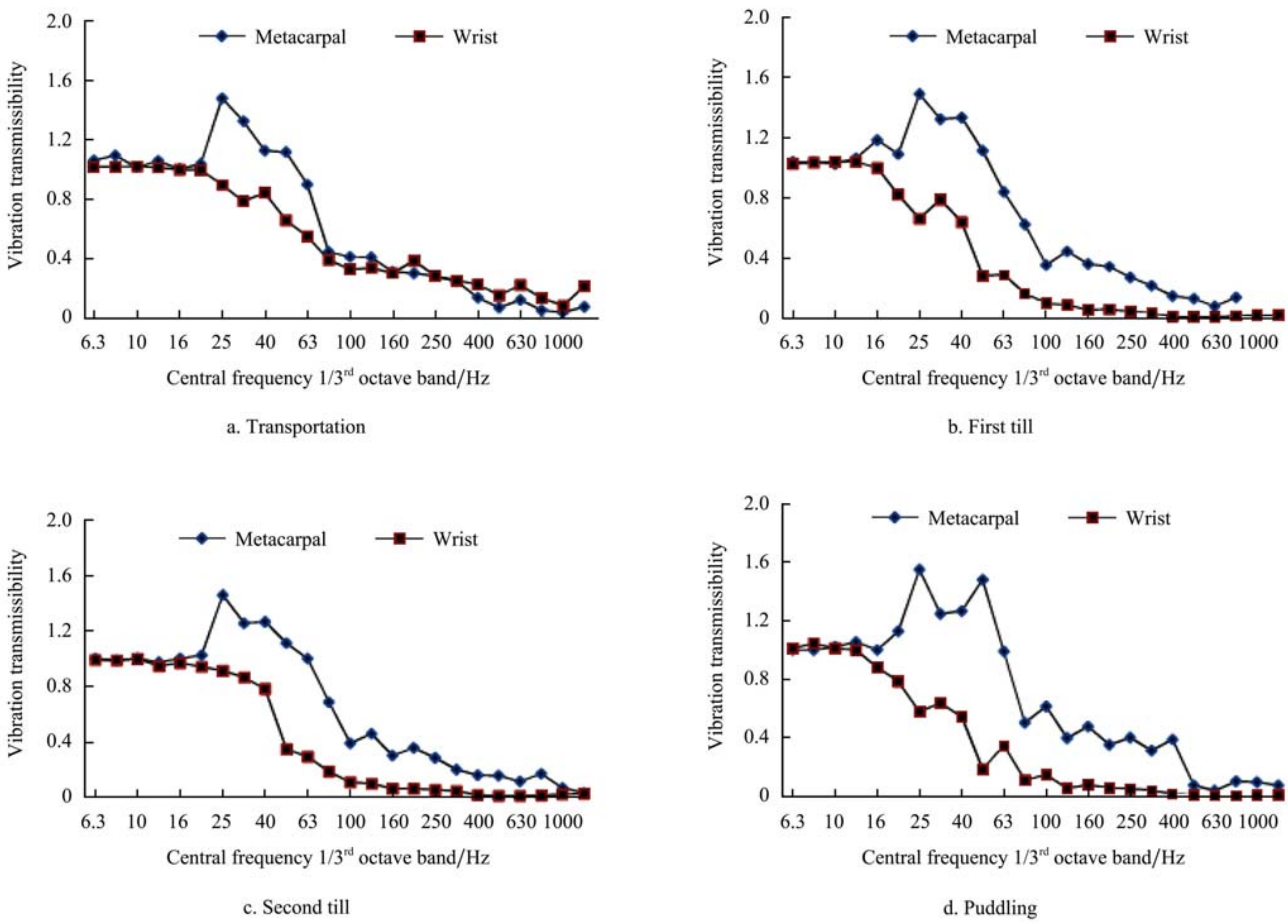


Figure 6 Spectral responses of vibration transmissibility in hand ram system for selected operations

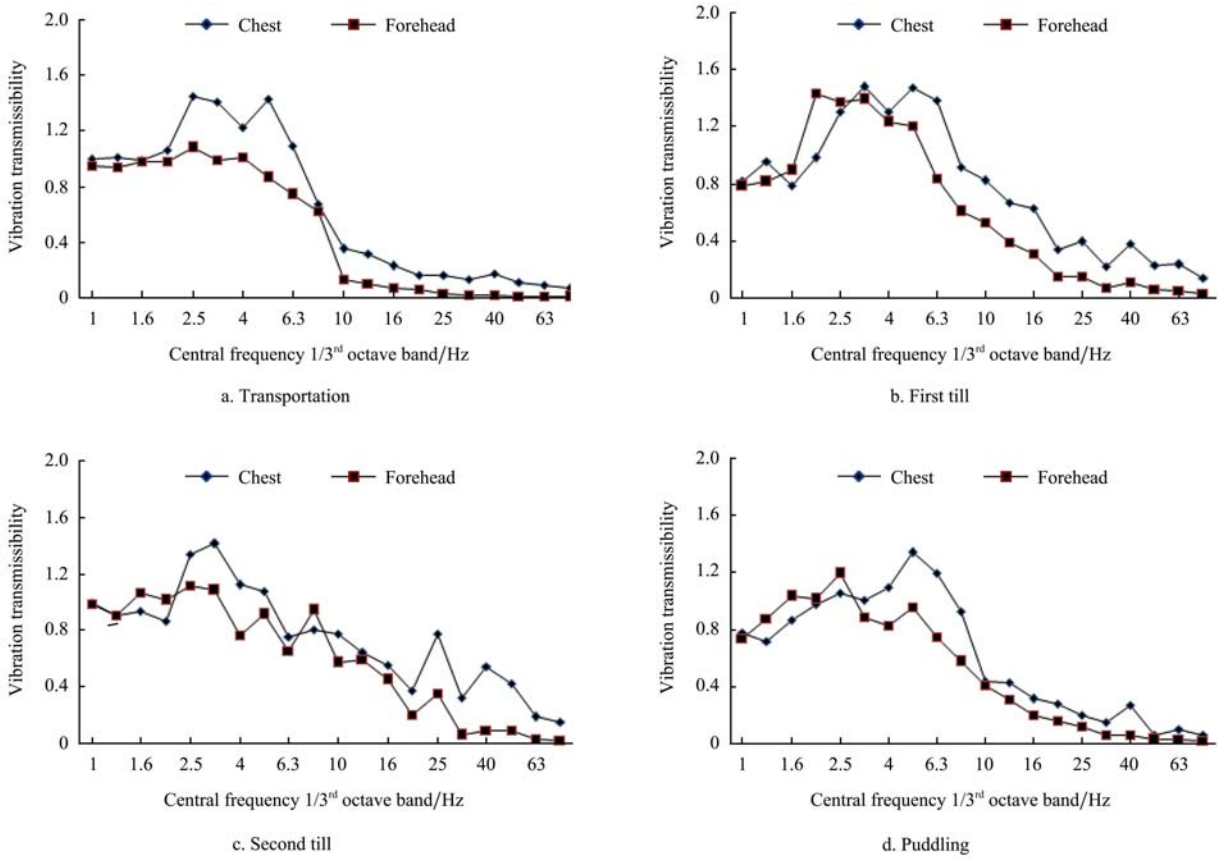


Figure 7 Spectral responses of vibration transmissibility in whole body system for selected operations

The dominant frequency in hand arm system was found as 25 Hz and hence the highest transmissibility was also obtained at this frequency. During puddling, the dominance of 50 Hz frequency was also found which resulted in a near peak transmissibility. Amplification of vibration was observed in the 25 to 63 Hz frequency range at metacarpal for all selected operations.

Peak vibration transmissibility at metacarpal was observed as 1.54, 1.49, 1.48 and 1.46 during puddling, first till, transportation and second till respectively at 25 Hz. The maximum value of transmissibility at wrist was observed to be 1.05, 1.04, 1.02 and 0.99 at 31.5 and 40 Hz during first till, puddling, transport and second till respectively (Table 2).

Peak vibration transmissibility at chest was found to be 1.48, 1.45, 1.42 and 1.34 for first till, transportation, second till and puddling respectively at 3.15, 2.5 and 5.0 Hz. The dominant frequency range of 2–6 Hz for high vibration acceleration in whole body measurement is responsible for the high transmissibility value. The vibration amplification was found in the range of 2–6.3 Hz at chest, whereas peak at forehead was observed at 2–2.5 Hz range. The resonance frequency of trunk is 3–6 Hz which matches the transmissibility amplification found in the experiments. In HAV transmissibility, the dominant part of the frequency was localized to hands. Similarly, in WBV transmissibility, beyond 8 Hz, there was sharp decline in the transmissibility. Between 2–8 Hz, the transmissibility at chest was higher in comparison to forehead indicating that vibration intensity was highly transferred to trunk.

Table 2 Vibration transmissibility (T) peak and its corresponding frequency (f) at different pointsin the hand-arm/whole body system

Operation	Hand arm vibration transmissibility				Whole body vibration transmissibility			
	Metacarpal		Wrist		Chest		Forehead	
	T	f	T	f	T	f	T	f
Transportation	1.48	31.5	1.02	20	1.45	2.5	1.07	2.5
First till	1.49	40	1.05	20	1.48	3.15	1.44	2.0
Second till	1.46	31.5	0.99	16	1.42	3.15	1.12	2.5
Puddling	1.54	31.5	1.04	16	1.34	5.0	1.19	2.5

5.5.1 Isolator characteristics

The force-deformation characteristics of both the isolators were determined by conducting static compression test. The force deflection characteristics curves for selected isolators were obtained by interpolating the data of force-deflection plots. Figure 8 shows the force-deflection characteristics curves of the isolators.

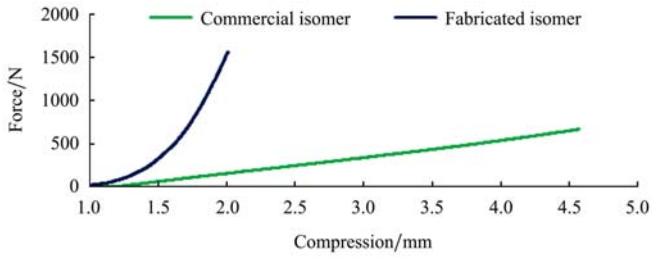


Figure 8 Static force-deformation characteristic curve of isomer during compression test

The behavior of the isomer under compression of force-deflection curve can be represented mathematically by the following Equation (4).

$$F = a + bX + cX^2 + dX^3 \quad (4)$$

where, F = applied force, N; a, b, c and d = constants, and X = deflection of cushion, mm.

The values of the constants for the isomers selected are given in Table 4. Higher values of coefficient of determination (R^2) indicated that the expression truly represented the behavior of isomer. The average stiffness of the commercial isomer was 1.912 kN mm^{-1} whereas for the custom-designed isomer it was found to be 0.369 kN mm^{-1}. The PZT plate embedded in the rubber isomer is having a Young's modulus of 63,000 MPa.

Thus the custom-designed isomer was found to have a significant higher Young's modulus of average 40.07 MPa.

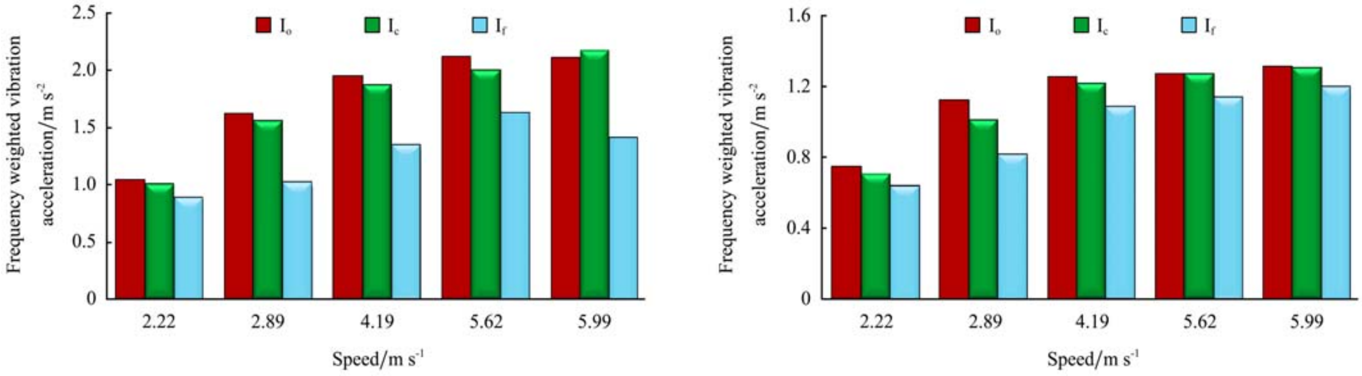
Table 4 Stiffness and values of constants of the best-fit equations for isolators

Isomer	Young' Modulus/MPa	Stiffness/kN mm^{-1}	a	b	c	d	R^2
Commercial	16.32	0.369	6.618	-70.99	87.51	-9.04	0.997
Custom-designed	40.07	1.912	-57.795	556.30	-1117.0	615.30	0.998

5.2 Vibration reduction through isolators

The commercial isolator (I_c) and the custom-designed isolator (I_f) were compared for their vibration reduction effectiveness with no isolator condition (I_o). The frequency unweighted vibration acceleration in transportation with different speeds of operation in all the cases showed that, with increase in speed, the vibration acceleration increased in all the three cases shown in Figure 9. The vibration acceleration recorded at 5.99 m s^{-1} with I_c was 2.17 m s^{-2} which reduced to 1.41 m s^{-2} in case of I_f. This trend was visible in most of the cases. There was a slight increase in vibration acceleration at 5.99 m s^{-1} with I_c than I_o. This may be attributed to amplification of vibration at particular frequency. It is evident from the figure that vibration acceleration drastically reduced with use of I_f at speeds of operation from 2.89 to 5.99 m s^{-1}. Marginal decrease was observed at the speed of 2.22 m s^{-1}. The frequency weighted vibration acceleration at all the cases also showed that with the increase in speed of operation, the vibration acceleration increased. It was recorded that I_c reduced the vibration acceleration in the range of 0.5 to 10% whereas I_f could reduce the level 14.3, 27.3, 13.5, 10.5 and 8.4% at 2.22, 2.89, 4.19, 5.62 and 5.99 m s^{-1} speed of operations. The high stiffness coefficient of I_f in comparison with I_c might be the reason to attenuate vibration isolation at low frequency vibration which is harmful to human body. Thus it is evident that the custom-designed isolator is effective in isolating the whole body vibration acceleration to average 10%.

In first till operation, where the vibration acceleration with no isolator was prominent among the operations, the increasing trend was visible with the speed of operation. Interestingly, at higher speeds of operation, there was an increase in vibration acceleration with I_c than I_o. At lower speeds of operation, it was found that the vibration acceleration was reduced from 1.84 to 0.79 m s^{-2} with the use of I_f. The isolator I_c reduced the vibration intensity at lower speeds, but reverse trend was visible in all other speeds. In case of I_f, the vibration intensity was decreased in comparison to I_o for all selected speeds of operation. In case of I_f, the vibration intensity was decreased in comparison to I_o for all selected speeds of operation. The vibration value was found to decrease from 1.71 to 1.49 m s^{-2} at highest selected speed of operation of 1.41 m s^{-1}. Performance of isolators was also judged in frequency-weighted vibration acceleration (rms) for the first till operation first till and second till and the same trend was observed. It is observed that the frequency weighted vibration acceleration during first till also increased with the speed of operation as observed in earlier case.

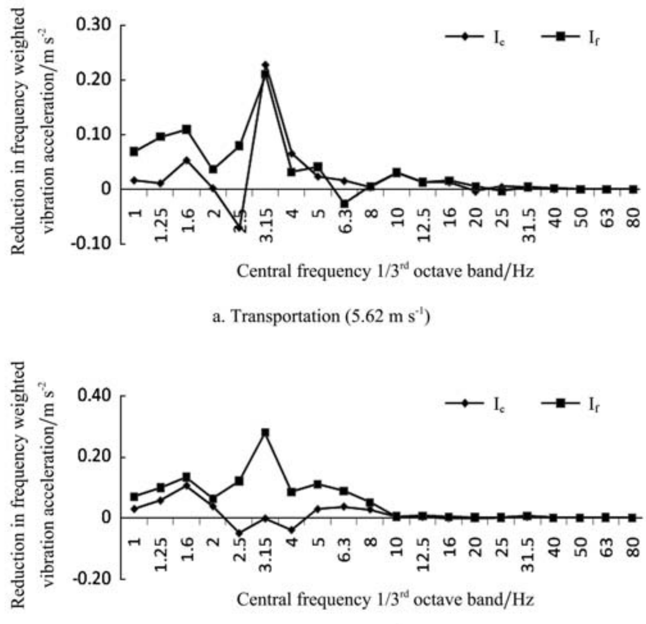


a. Frequency unweighted vibration b. Frequency weighted vibration

Figure 9 Comparison of vibration isolators in transportation

The vibration intensity was varying from 0.56 to 1.02 m s^{-2} with the use of I_f as against 0.69 to 1.3 m s^{-2} with I_c. At speed of operation of 1.29 m s^{-1}, I_c was found to amplify the vibration intensity than I_o. The percentage of reduction of vibration acceleration with the use of I_c was found to be 9.54, -0.57, -13.8 and 18.4% and with I_f, 27.2, 25.9, 9.7 and 38.1% at 0.63, 0.95, 1.29 and 1.41 m s^{-1} respectively. In second till operation also, as seen in other operations, the increasing trend in vibration acceleration was visible with the speed of operation. In puddling, the frequency unweighted vibration intensity was found to reduce with the increase of speed of operation from 0.63 to 0.95 m s^{-1} but then increased from 1.11 to 1.69 m s^{-2} with increase in speed to 1.21 m s^{-1}. Both the isolators were found to reduce the vibration intensity and their characteristics in reduction almost matched in case of frequency unweighted vibration. The frequency weighted vibration acceleration with the use of isolators during puddling increased with increase in speed of operation.

The custom-designed isolator reduced the vibration intensity to 0.62 to 0.92 m s^{-2} as against 0.69 to 1.11 m s^{-2} with I_c. The percentage reduction with the use of I_f was found to be 23.3, 5.52 and 28.1% at 0.63, 0.95 and 1.29 m s^{-1} speed of operation. The percentage reduction was minimal at speed of 1.29 m s^{-1}. The effect of isolators on vibration reduction at 1/3rd octave band having centre frequency from 1 to 80 Hz during all transportation and first till is shown in Figure 10. It shows that the performance of isolators varied considerably below 6.3 Hz and there was negligible effect of isolators on vibration reduction in the frequency range from 8 to 80 Hz.



b. First till (1.29 m s^{-1})

Figure 10 Reduction of frequency-weighted vibration in rms acceleration at 1/3rd octave band during transportation and first till operations

The effect of isolators on vibration reduction at 1/3rd octave band having centre frequency from 1 to 80 Hz during second till and puddling was also studied. A similar trend as observed in first till and transportation was observed here as custom-designed isolator could considerably reduce the vibration intensity in comparison to commercial isolator in the predominant frequency range. The vibration acceleration on vertical axis is

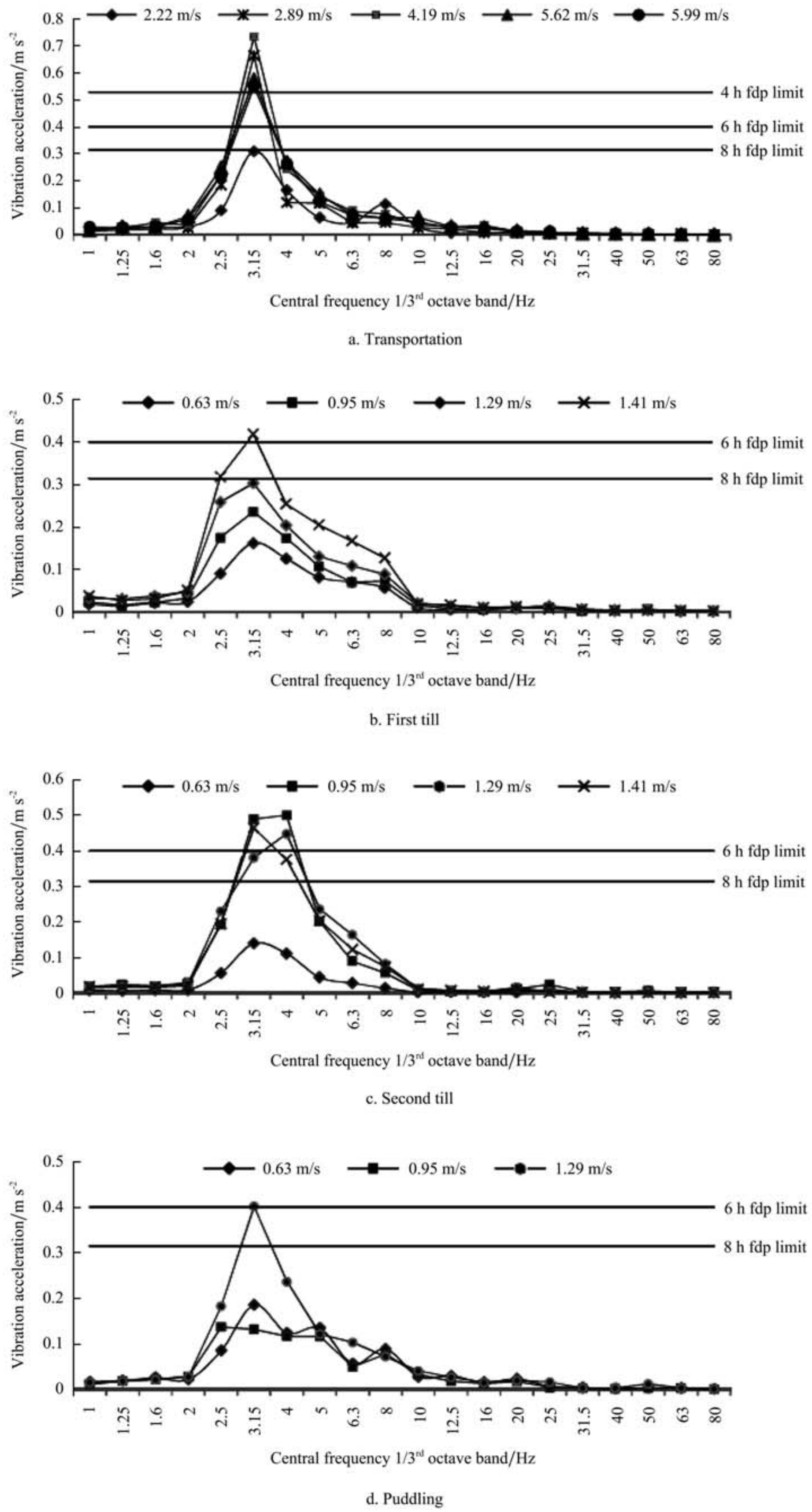


Figure 11 Vibration levels in vertical axis in relation to fdp limits for selected operations

predominant in whole body vibration. With no vibration isolator, it was seen that in all selected operations, the vertical axis vibration level exceeded the 8 h, 6 h and 4 h fdp limits. To compare the effect of custom-designed isolator in relation to fdp limits, vertical axis vibration in all selected operations were analyzed as shown in Figure 11. It was observed that, except transportation, all other operations have vertical axis vibration well within the 8 h fdp. Even for the transportation operation, at speeds of 5.62 and 5.99 m s^{-1}, the vibration acceleration was found to slightly cross the 8 h fdp. Thus, the custom-designed isolator could be a possible solution to reduce the work stress of the operator in various field tasks with tractor for a safer and comfortable operation.

6 Conclusions

1) The vibration transmissibility was found to be averaging 0.8 in all field operations at chest while, at forehead, this value was 0.5. However, the whole body vibration transmissibility did not show any increasing trend with increase in speed of operation.

2) Piezo-electric material based vibration isolator was designed and installed beneath the tractor seat. This custom-designed vibration isolator (I_f) was found to reduce the WBV values by 27% in first till at 2.89 m s^{-1} while 38% reduction was recorded at 1.41 m s^{-1}. Maximum reduction of 55% was found during second till operation at 0.95 m s^{-1}. This may be attributed to the higher stiffness of the custom-designed isolator. The isolator installed could attenuate the vibration intensity in the predominant range of 2–6.3 Hz. The isolator enhances the safe exposure time from 4 h to 6 h and hence this is recommended for use.

3) It has been found that among the different operations selected for the study, the level of hand arm vibration acceleration varied from 2.11 to 2.52 m s^{-2}. When compared with standards, it is apparent that the average value was slightly higher than the prescribed value of 2.1 m s^{-2} for an 8 h exposure limit. Further in case of whole body vibration, the vertical vibration acceleration was observed to be in the range of 0.54 to 0.82 m s^{-2}. This when compared with standards, values are found to be higher even for a 4 h exposure limit. Thus, it may therefore be recommended that the field operations may not be continued beyond 4 h per day.

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