Evaluation of Vibration Characteristics and Human Response to Hand Transmitted Vibration of Single Axle Tractor with Varying Key Parameters

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AUTHORS' DECLARATION

I, hereby declare that this dissertation entitles*Evaluation of Vibration Characteristics and Human Response to Hand Transmitted Vibration of Single Axle Tractor with Varying Key Parameters'* was own research work. It has not been submitted in whole or part to another university for a degree award.

Siraj K. Busse
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04/01/2021
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We, hereby declare that this dissertation entitles '*Evaluation of Vibration Characteristics and Human Response to Hand Transmitted Vibration of Single Axle Tractor with Varying Key Parameters'* was conducted under our supervision. We have confirmed that it has not been submitted in whole or part to another university for any degree award.

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ABSTRACT

Hand-Arm vibration from a 15-horsepower single-axle tractor can be very powerful and can induce operator fatigue plus various physiological disorders in the vascular, neurological and musculoskeletal systems. The transmission of vibration is determined by the dynamic response of the human body and depends on the physical characteristics of the individual hand, the contact area, the grip force, the push force and the posture. The grip force is an integral part of the spatial distribution of the touch pressure distributed over the entire hand and influences the surface of the contact. This research aimed to test a single-axle tractor operator's vibration characteristics and human response to hand-transmitted vibrations. The research was conducted at the Melkasa Agricultural Research Center in Ethiopia in Oromia Regional State, East Shoa District. Anthropometric data measurement, a physiological response and hand vibration of single-axle tractor operators and single-axle tractor handle vibration were performed. For biodynamic reaction, grip strength and vibration transmissibility measurements were assessed using 2, 3 and 4-DOF models. The demand for expenditure capacity, physical workload, and daily vibration exposure of operators were calculated from measured data. To dampen the vibration of the single axle tractor, mechanical dampers made of a rubber compound were fabricated and tested.

Without any damping mechanism, the mean measured resting heart rate, working heart rate and heart rate estimated after operation of single axle tractor were 71±7, 162 ± 4 and 126 ± 24 beats per minute, respectively; however, the maximum acceptable working heart rate for a work shift of 8 h according to international standards is only 136 ± 8 bpm. The measured values of the physiological workload or cardiovascular stress index and the ratio of work to resting heart rate were 74 ± 10 per cent and 2.3 ± 0.4 ($p < 0.0001$) respectively. The calculated cardiovascular strain and relative cardiovascular load was 131 ± 0.42 and 67 ± 17 % respectively.

Finally, the grip strength of single-axle tractor operators was measured and it was found that the operator's grip strength decreased by 11.34 and 9.5% after vibration exposure of dominant and non-dominant hands, respectively, relative to the grip strength before vibration exposure.

To improve the understanding of hand-arm vibration biodynamics, the two-, three-and four-degrees-freedom (DOF) models were used to simulate the dynamic reactions of the hand-arm

system in three orthogonal directions (vertical, forward and lateral); results indicated the highest magnitude of vibration transmission to be in the vertical direction.

Actual measurements of vibration transmitted to the tractor operators working in second and third gear were contrasted with the vibration predicted by the 2, 3 and 4-DOF models. The 4-DOF model showed the best agreement. It was observed that for all models the vibration transmitted to the forearm of the palm wrist rose with frequency up to the resonance frequency, and then decreased to zero at a frequency of 1250 Hz.

However, the 4-DOF model is the best model for the measurement of hand-arm transmitted vibration in the hand-arm system, as it can be used to quantify the vibration transmitted to fingers and upper arm-shoulder parts, unlike the 2-DOF model. The 4-DOF model also has the advantage over the 3-DOF model in accounting for the vibration transmitted to the upper arm-shoulder

Following the installation of the rubber vibration damper, the vibration measurement was carried out at the handle of the single axle tractor in the longitudinal, forward and lateral directions and these were compared with the value before. There was a reduction in vibration magnitude of 42%, 38% and 46% following installation of the damper system in the vertical, forward and lateral directions, respectively. Reductions in vibration magnitude in third gear of tractor operation were 46%, 29% and 50% in the longitudinal, forward and lateral directions, respectively following damper installation. The vibration total value after the vibration damper implementation dropped by 42% and 46% in the second and third gears, respectively. The results indicate a larger percentage decrease in vibration due to the addition of a damper while operating in a third gear than the second gear.

The latency period is defined as the time elapsed before symptoms start to appear in the exposed population. As the handle vibration total value magnitude decreases from 27 m/s^2 to 16 m/s^2 due to damper installation, the latency period for hand-arm vibration syndrome increases from 2.55 to 4.76 years duration in second gear operation (89% increase). In third gear, the vibration total value falls by 15 m/s^2 upon installation of the vibration damper, while the latency time increases

by 90%

The findings suggest a substantial reduction in the handle vibration of the single-axle tractor in all three directions due to the installation of the rubber vibration damper system. However, even with the dampers installed, vibration transmission to the tractor operator remains at a hazardous level; this can lead to adverse health impact on tractor operators according to international guidelines and directives.

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LIST OF ABBREVIATIONS AND SYMBOLS

A (8)	8-hour energy-equivalent frequency-weighted vibration total value,
AO	After Operation
BMI	Body Mass Index
BO	Before Operation
CSI	Cardiovascular stress index
CVL	Relative Cardiovascular Load
CVS	Cardiovascular Strain
CVD	Cardiovascular Disease
D	Duration of activity
DO	After Operation
DOF	Degree of Freedom
EAV	Exposure Action Value
ELV	Exposure Limit Value
Dy	Latency period
EMG	electromyography
FFT	Fast Fourier Transform
FR	Fatigue Resistance
Fs	The sampling frequency
FS	Final Grip Strength
GS	Grip Strength
HAVS	Hand-Arm Vibration Syndrome
HP	Horse power
HR	Heart Rate
HRc	Average Recovery Heart Rate
HRmax (8h)	Maximum Acceptable Heart Rate for a work shift of 8hr
HRmax	Maximum Heart Rate
HRr	Resting Heart Rate
HRw	Working Heart rate
IS	Initial Grip Strength
ISO	International Standard Organization

LGP	Length of Growth Period
MARC	Melkasa Agricultural Research Center
MC	Moisture contents
PE	Number of exposure points
RMS	Root Mean Square
S	Tractor forward speed
SD	Standard Deviation
SDI	Strength Decrement Index
SMR	Standard Malaysian Rubber
SRMS	Sum of Root Mean Square
T	the total daily duration of exposure to the vibration
T_0	the reference duration of 8 hours
UNU	United Nation University
V.T.	Vibration Transmissibility
VWF	Vibration-Induced White Finger
V	Handle vibration
Wd	Dry weight
Wh	Frequency weighting
WHO	World Health Organization
Ww	Wet weight

CHAPTER ONE: INTRODUCTION

1.1. BACKGROUND OF THE STUDY

Currently, the Government of Ethiopia is funding both agricultural machinery importers and domestic agricultural machinery producers to encourage food security by increasing agricultural production. Because of the rise in secondary and tertiary sectors, the percentage of the country's population working in agriculture continues to decline with the progress of national economic growth. To accomplish this goal, the government has established and implemented a national mechanization policy. The strategy's goal is to ‘increase national food production and security via increased and sustainable use of agricultural mechanization technology to support Ethiopia's middle-income position by 2025’ (Amare Dagninet & Endalew Wolelaw, 2016).

The Agricultural Mechanization Strategy was created to increase Ethiopian agricultural mechanization from 0.1 kW/ha to 1 kW/ha, with at least 50% produced from mechanical/electrical power, and to minimize the usage of animal power for agricultural activities by 50% (MoANR and ATA, 2014).

The Agricultural Mechanization Strategy also encourages the use of agricultural mechanization technologies that can be used by female farmers, who account for at least 30% of the user population, and that reduce environmental degradation while meeting at least 50% of the needs of pastoralists and agro-pastoralists for mechanization inputs (MoANR and ATA, 2014). According to the Agricultural Mechanization Strategy, 90% of Ethiopian farmers operate on less than 2 hectars, sometimes known as smallholder farmers, and have limited access to credit, as indicated in the figure (1.1).

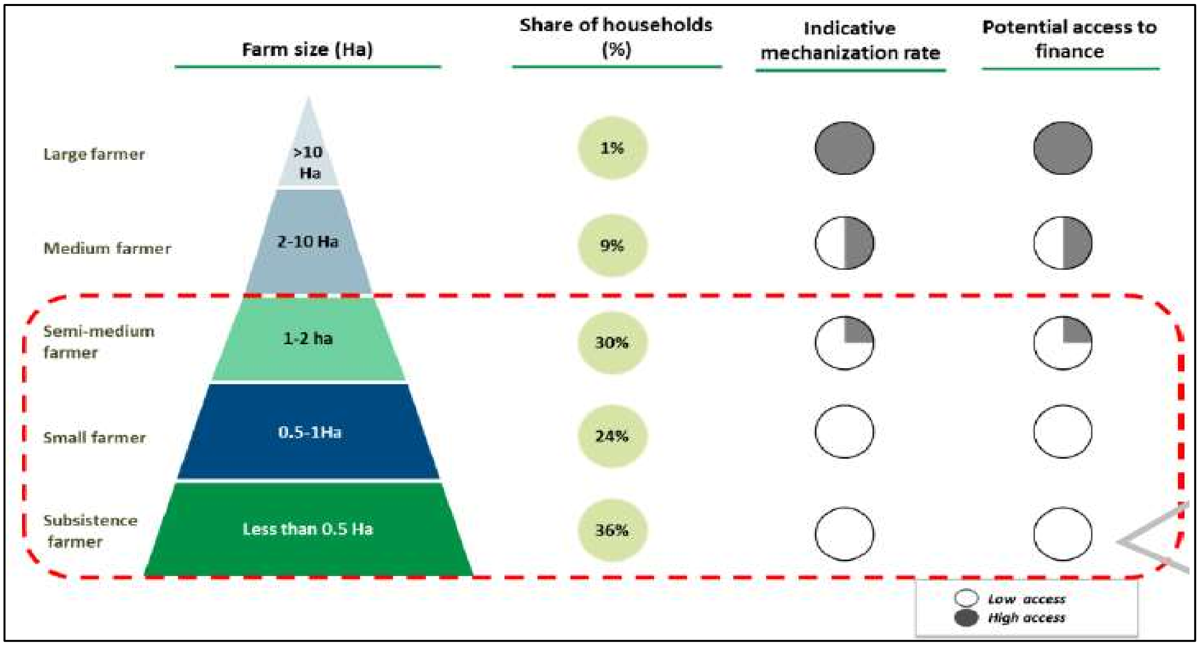


Figure 1- 1 Segmentation of Ethiopian farmers (MoANR and ATA, 2014)

Despite smallholders' best efforts to boost agricultural production, the advantages pale in contrast to plowed crop acreage, population expansion, and input consumption. Food insecurity persists in all regions of the country. Enhancing technological efficiency, a method of increasing output via proper management, might be beneficial in the future. Furthermore, the adoption of medium or low-level mechanized implements and technologies helps to relieve the load on Ethiopian women, who provide the majority of the work for agricultural output(Amare Dagninet & Endalew Wolelaw, 2016).

The mechanization progression is supported by increased utilization of large-, medium- and small-scale farm machinery that promotes increased agricultural productivity (Bill A. Stout B and ernard Cheze, 1999). Therefore, single-axle tractors are very important for small-scale farmers in the drive to shift from animal-powered farming to engine-powered farming systems.

Single-axle tractors are multi-purpose vehicles designed mainly for rotary tilling and other agricultural operations. A single-axle tractor is also known as a hand tractor, a walking tractor, a traction tractor, etc., (Bill A. Stout B and ernard Cheze, 1999). If the work piece is connected to a single axle truck, the machine is called a power-tiller.

However, the operators of single-axle tractors are subject to high degrees of vibration transferred from the handles to the wrists, arms and shoulders. The detrimental effects of the hand-arm vibrations on the operators have been known for a long time. Hand-arm vibration originating from a single axle tractor is very strong, and daily exposure to an operator over several years can cause permanent physical damage known as ‘white finger syndrome’.

Mechanical vibration is the result of a wide variety of processes and practices in the fields of manufacturing, mining, construction, forestry, agriculture and public services. Whole-body shaking occurs when the human body is supported on a vibrating surface, e.g. in most modes of transport and proximity to certain forms of heavy machinery. Hand-transmitted vibration happens as the vibration reaches the body by the fingertips, usually in diverse work procedures where spinning or percussive power tools or vibrating work pieces are carried by the hands. Human response to vibration depends primarily on the amplitude, frequency and direction of the vibration signal (M.J. Griffin, 2001). Biologically, the response of each person is different, especially when psychological effects are included. Clearly, in considering the response of man to vibration and shock, it is necessary to take in to account both mechanical and psychological effects. Knowledge about comfort and fatigue-decreased proficiency is based on statistical data collected under both field and laboratory conditions.

The human body is a very complex structure from a physical and biological point of view. When viewed as a mechanical unit, it consists of many linear and non-linear components whose mechanical properties differ considerably from person to person.

The biodynamic of the human hand-arm system is a branch of biomechanics that uses the laws of physics and engineering principles to explain the actions and forces of the system as well as their relationships. Developments and standardization of hand-borne vibration exposure estimation, evaluation and assessment can be grouped into the following four groups of biodynamic of the hand-arm system; psychophysical studies of subjective perception or discomfort; physiological and pathological mechanisms of the vibration-induced injuries and disorders and epidemiological studies of hand-arm vibration syndrome.

The man-machine environment system of single axle tractor operation indicates that the operator of a single axle tractor has to endure various environments and stresses. Among these factors, the environment is more important because it significantly accelerates fatigue and affects the sensitivity and reaction heart rates of the operator. Therefore, the performance of the single-axle tractor depends not only on the machine but also on the operator, because an operator has to walk behind the machine during work.

The reliability of the man-machine system will be weak and efficient working time will be decreased due to frequent or long rest periods, resulting in lower work productivity because of machine induced vibration. On the other hand, due to heavy strain on the operator's biological systems, machine operation can cause psychological or physiological complications which can in the long term impair the operator's health. Occupational exposure to vibration arises in many different ways, reaching the subject at levels that may disturb the comfort, health, safety, and efficiency (El-Said et al., 2009).

Exposure to hand-arm vibrations higher than permissible standard rates can have destructing effects on workers’ health(Mahdisoozani et al., 2019). The physiological reaction of the human body to vibration exposure can be assessed by various measures such as muscle activity (EMG), heart rate, and oxygen absorption and muscle metabolism via lactate development.

Lowering the levels of hand-arm transmitted vibration will result in reduced noise, an improved work environment, higher production efficiency, reduction in operator’s discomfort, and extension of the useful life of single-axle tractors. Rubber materials are commonly used to control machine noise and vibration due to their favorable tensile strength, tearing strength, wear-resistance and large loss factor (tanδ). Recent research focuses on the loss factors to improve rubber’s damping properties(Choi et al., 2012; Yong et al., 2006).

Natural rubber (NR) is a recycled polymeric material with many advantages for vibration suppression, such as excellent tensile strength and tear strength, excellent resilience and abrasion resistance, and excellent mechanical properties (Fernandes et al., 2011). Natural Rubber has a range of useful industrial applications, such as tires, caps, shock mounts and bridge and seismic insulation bearings.

Natural Rubber has the characteristic properties of undergoing very high deformations, up to several 100% in simple tension. Typical stress-strain plots are highly nonlinear and the material appears as (nearly) incompressible. However, NR has low solvent resistance, oil and ozone resistance, and poor wet grip. Chemical alteration of NR is commonly used to boost these properties (Fernandes et al., 2011). Weak tensile properties of Natural Rubber (NR) latex derived from unsaturated organic hydrocarbons can be enhanced by vulcanization techniques (Balaji et al., 2015) and this increases the physical and mechanical properties of Natural Rubber.

1.2. STATEMENT OF THE PROBLEM OF THE STUDY

The primary activity carried out in a farmer's field with mechanical power is tillage. Agricultural tillage entails soil cutting, soil turning and soil pulverization and thus consumes high energy, not just because of the vast volume of soil mass that needs to be transferred, but also because of the inefficient methods of energy transfer to the soil. The most commonly used method of energy conversion is to pull the tilling tool into the soil. This is primarily done by the use of various types of tractors with a variety of capacities and mechanical control configurations to replace human power. Words such as Tractorization, Partial Mechanization or purely Mechanization have been used to mark this replacement of human power(Kormawa et al., 2018).

Ethiopia imports a significant number of single-axle tractors for small-scale farmers to improve agricultural production and ensure food stability, under the slogan of agricultural revolution focused on agricultural mechanization. Both single-axle tractors (2 wheeled) and tractors (4 wheeled) are commonly used by both private importers (agencies) directly and government agencies through independent dealers.

Single axle tractors, on the other hand, appear to be better suited to highlands, which are characterized by small, fragmented farms and hilly terrain (which account for 90 % of farmers), than four-wheel tractors, which are only well-suited to large- and medium-scale farmers, who account for about 10% of the country's estimated 14.7 million farmers (MoANR and ATA, 2014).

The country is projected to have about 4,132 single axle tractors owned by the public and private sectors (Tefera et al., 2020) METEC, a government organization that purchased 3,000 Dongfeng brand tractors from China, imports the majority of single axle tractors, with the balance imported by private sectors(FACASI, 2016).

According to the Agricultural Mechanization Strategy, the barriers for agricultural mechanization transformation are restricted access to research and technology development; production and import; distribution; marketing, purchasing and usage; and after-sales support(MoANR and ATA, 2014). On the other hand, the majority of tractors imported by the government and commercial sectors, are not sold owing to a lack of marketing, demonstration, and affordability, and demand is low. Since of the aforementioned reasons, many users formed negative attitudes against the operation of such tractors because the single axle tractor requires a lot of human force and has a high vibration level(Fabbri et al., 2017). Also, the machine doesn‘t stay well-balanced on steeply sloped areas; it overturns on downslopes because of the lack of a third wheel. Also, there is a skill gap due to insufficient training.

While using this technology, there are a number of difficulties that must be addressed. Indeed, the operator must walk behind the machine, posing certain safety concerns. A 13% rise in agricultural labor injuries was linked to single-axle tractor accidents (Fabbri et al., 2017). However, despite the need for this technology to help smallholder farmers increase their agricultural output, the impact of single axle tractor vibration has yet to be studied in Ethiopia.

As a result, evaluating vibration characteristics and their health impact on operators is critical in order to apply this technology and enhance the livelihood of farmers with small and fragmented fields. As a consequence, this study adds to our knowledge of Ethiopian soil vibration characteristics, as well as the impacts of vibration on physiological responses and handgrip strength, as well as vibration transmissibility and vibration damping.

1.3. OBJECTIVES OF THE STUDY

1.3.1. General objectives

The general aim of this analysis was to determine the characteristics of vibration and the human response to a single axle tractor's hand-borne vibration.

1.3.2. Specific objectives

The specific objectives of this research are as follows:

- To measure and analyze the hand transmitted vibration characteristics of a 15 horsepower single-axle tractor, in terms of amplitude, the orientation of motion and safety level according to international standards.
- To measure and evaluate of physiological parameters of single axle tractor operators
- To evaluate the grip strength, fatigue tolerance, grip work and strength decrement index for operators of a 15 horsepower single-axle tractor operator,
- To attenuate the handle vibration of single axle tractor using rubber compound recipe

1.4. LIMITATION OF THE STUDY

Technical and financial constraints were also present in this dissartation. This thesis was financially limited to using less accurate instruments such as a vibration meter, a locally prepared hand vibration measurement attachment, a single test centre or area with just one type of soil texture (sandy loam soil), operating with only seven operators, and using single-axle tractor drawbar force numerical prediction instead of dynamometer measurements. Technically limited to the measurement of the acute impact on single axle tractor operators of the handle vibration.

This study may have limitations in addition to the mentioned financial and technical issues. This study does not address the history or long-term health effects of Ethiopian farmers who use single axle tractors. The damping rubber's dynamic analysis test was also omitted. The existing situation and need for single axle tractors in Ethiopia were also overlooked.

1.5. SCOPE OF THE STUDY

This study focuses on the measurement, analysis of single axle tractor handle vibration; measurement and analysis of physiological parameters of operators; measurement and analysis of handgrip strength operators; single axle tractor handle vibration isolation using natural rubber composite.

CHAPTER TWO: VIBRATION CHARACTERISTICS OF SINGLE AXLE TRACTOR

2.1. THEORETICAL BACKGROUND SINGLE AXLE TRACTOR VIBRATION

2.1.1. Key parameters

Key parameters that affect vibration characteristics are considered in this thesis. These include:

(i) Environmental parameters such as humidity and ambient temperature;

(ii) Soil parameters such as moisture content;

(iii) Machine parameters such as tractor forward speed.

1. Environmental parameters /thermal variables

Environmental factors include thermal variables (such as temperature, humidity), air quality, noise and vibration. The environment can influence the physical performance of a worker either directly or indirectly. Heat or humidity may reduce work capacity directly, while air pollution may affect physical performance by initiating an allergenic reaction which inhibits breathing. Heat could also affect work capacity indirectly through dehydration. The minimum and maximum values of relative humidity and temperature can be measured by a hygrometer and a thermometer. Measurements should be conducted with sensors that cover a wide range of temperature from 0 – 50 ^{o}C with an accuracy of ± 1.0–1.5 °C, and relative humidity in the range of 20 – 90% with an accuracy of ± 2% –5% at mid-range (Vera Zambrano et al., 2019).

2. Moisture content

In terms of both the draft and the quality of work, the soil moisture content is a significant factor. A dry soil demands excessive energy and also accelerates wear on the tilling mechanism of the cutting edges. By both direct and indirect methods, soil moisture content can be measured. A direct method involves the determination of moisture in the soil while indirect methods estimate the amount of water through the properties of water in the soil. The gravimetric method expresses the ratio of the weight of the water to the weight of the dry soil, while the volumetric method is the ratio of the volume of water to the volume of the dry soil(Tan et al., 2019; Wendroth et al., 2008).

Indirect thermo-gravimetric methods, such as oven drying or a volumetric process, are used to determine moisture content. The moisture content of the soil samples was assessed on a dry weight basis, and the wet weight of a soil sample after it was collected in a moisture container was recorded (Okoko et al., 2018):

$$MC = \frac{W_w - W_d}{W_d} * 100 \qquad 2.1$$

Where MC = soil moisture content, %
Ww = wet weight of soil sample, g
Wd = dry weight of soil sample, g

3. Tractor forward speed

Tractor forward speed (S) affects the vibration of a single axle tractor, i.e., as the tractor forward speed increases the vibration total amplitude also increases(Cuong et al., 2013; Dahham et al., 2019; Sam & Kathirvel, 2006). The vibration of the tractor handle is also strongly affected by tire inflation pressure, terrain condition, and type of tilling. For a tractor that lacks a suspension system, Cuong et al., (2013) have concluded a reduction in tractor forward speed and tire inflation pressure are very important for reducing vibration amplitude.

2.1.2. Single axle tractor

The single axle tractor (power tiller) is a prime mover (self-propelled) in which the direction of travel and its control for field operation is performed by the operator walking behind it. It is also known as a hand tractor or walking type tractor and is usually fitted with only two wheels. The operator walks behind the tractor, holding the two handles of the power tiller in his hands, although a riding seat is provided in certain designs. Single axle tractors are more economical than a draught animal for tillage operation(Nwakaire et al., 2018). The major components of the single axle tractor are the engine, transmission gears, clutch, brakes and rotary unit.

By transferring the clutch lever to the tractor handle when working in the sector, the single axle tractor is driven. As the lever moves to the spot, power from the engine is transmitted through the main clutch and the wheels through the steering clutch and the tiller link through the tiller clutch. When the lever is pushed out of place, the power of the engine is isolated from the rest of the transmission.

The single axle tractor with different attachments (implements) can accomplish many kinds of farm work such as tillage, planting, harvesting and transportation. When a tillage implement is attached to a two-wheel tractor, it is called a power-tiller as shown in figure (2.1). The single axle tractor can be classified as a) mini-type with power from 1.5 to 2.2 kW, b) traction type with power from 2.9 to 4.4 kW, c) drive type with power from 5.2 to 10.3 kW and d) Thai type with power from 5.9 to 8.8 kW (Stout and Cheze, 1999).

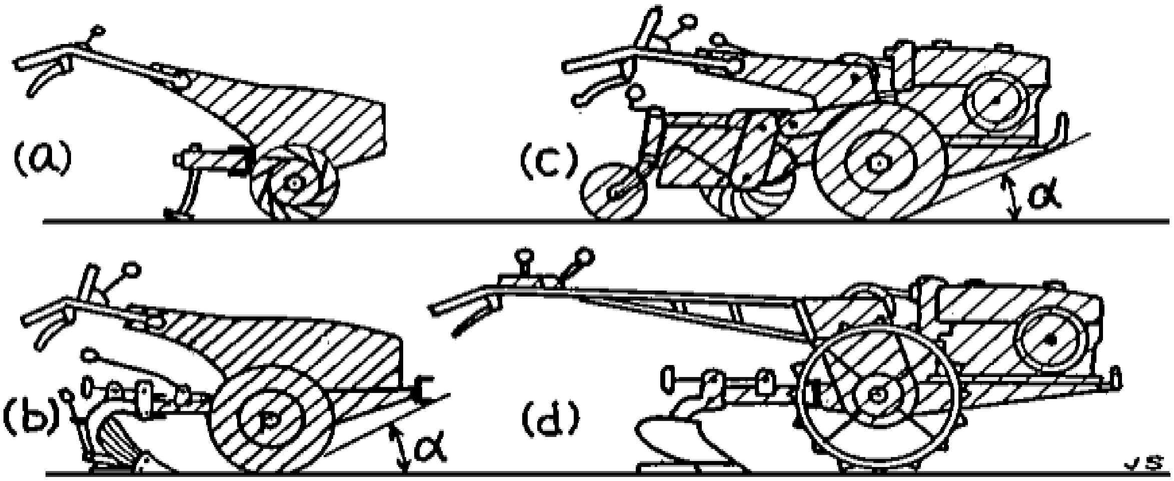


Figure 2- 1 Types of single axle tractor (Bill A. Stout B and ernard Cheze, 1999)

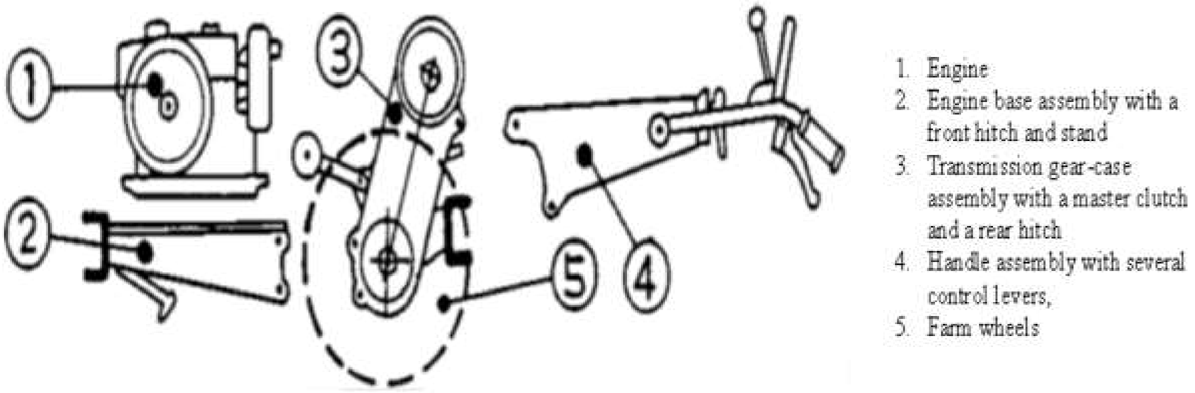


Figure 2- 2 main components parts of a single axle tractor (Bill A. Stout B and ernard Cheze, 1999)

2.1.3. Hand-Arm Vibration

In mechanical systems, mechanical vibration is a manifestation of oscillatory behaviour as a result of either the repeated exchange of kinetic and potential energies between components in the system or an oscillatory forcing excitation. These oscillatory reactions are not confined to strictly mechanical systems and are also present in electrical and fluid systems. In purely thermal systems, however, free natural oscillations are not possible, and an oscillatory excitation is needed to obtain an oscillatory response.

Mechanical vibration is the oscillatory motion of a reference location around an elastic solid or liquid) body. All bodies with mass elements and elasticity are capable of vibration; vibration can therefore be experienced by most devices and structures, including the human body. Human vibration reaction depends primarily on the magnitude, frequency, and direction of the source of excitation, according to Griffin &Erdreich(M. J. Griffin & Erdreich, 1991). In the ISO Standard (ISO 5349-1, 2001) for Calculation and Assessment of Human Exposure to Hand-Transmitted Vibration, the root-mean-square frequency-weighted acceleration expressed in m/s^2 is the most significant sum used to characterize the magnitude of the vibration transmitted to the hands of the operator.

The RMS amplitude is related to the vibration energy and thus the potential for vibration injury or destructive power over some time. The hand-transmitted vibration of a single-axle tractor is very high since the handle grip is a cantilever beam with the output of a single-cylinder diesel engine(Ying et al., 1998). The low-frequency vibrations to which the operator is subjected are the product of both the linear displacement of a single-axle tractor and the rotational oscillation of pitch and roll modes(Tiwari et al., 1997).

Regular exposure to hand-arm vibrations over a period of years can damage the joints and muscles of the wrist and elbow(Gerhardsson et al., 2020). White finger syndrome in its advanced stages is characterized by whitening of the fingertips due to damage to the arteries and nerves of the soft tissues of the hand (Griffin et al., 2003; L.P. Gite et.al., 2012). Measurements of hand-transmitted vibration were produced on representative samples of vibratory instruments used by subjects in a variety of research populations. Raw vibration magnitudes were expressed as root-mean-square acceleration values over the 6.3–1250 Hz frequency range. Amplitude data were also provided using the Wh frequency weighting method, which places a higher weight on frequencies that pose a higher biological risk (ISO-5349, 2001). For each instrument used in the research, vibration measurements were carried out at each hand position in three orthogonal directions: x, y, and z, as shown in Figure 2.3. In each case, a maximum of three magnitudes was chosen to reflect the instrument's vibration magnitude. According to ISO-5349 (ISO 5349-1, 2001) for most power tools, the hand-in-hand vibration requires inputs from all three orthogonal motion axes.

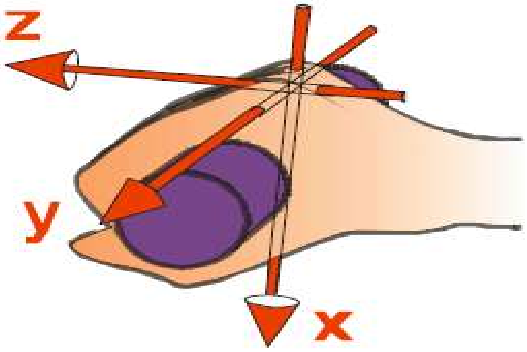


Figure 2- 3 three orthogonal directions of vibrational motion (ISO 5349-1, 2001)

According to ISO standard (ISO 5349-1, 2001) for most powertools, the vibration entering the hand contains contributions from all three orthogonal axes of motion. The frequency- weighted RMS handle acceleration values for the x-, y- and z-axes, a_{hwx}, a_{hwy}, and a_{hwz} respectively, are reported separately using the frequency weighting graph shown in figure (2.4).

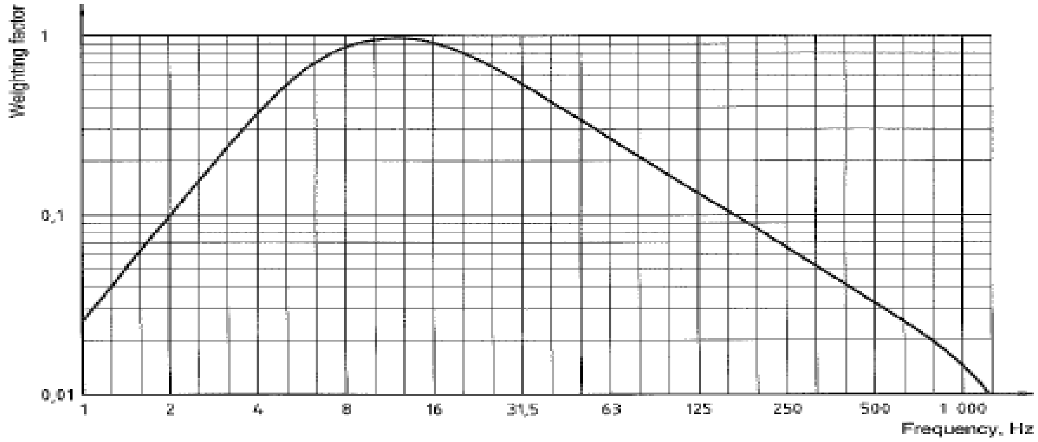


Figure 2- 4 Frequency-weighting curve Wh for hand-transmitted vibration, band-limiting included (ISO 5349-1, 2001)

The frequency weighted RMS acceleration values for the x-, y- and z-axes, a_{hwx}, $a_{hwy,}$ and a_{hwz} respectively (figure 2.5), are reported separately using the frequency weighting graph. The measurement of a_{hw} (acceleration for each axis a_{hwx}, a_{hwy} and a_{hwz}) requires the application of frequency-weighting and band-limiting filters. Frequency weighting Wh reflects the perceived value of various frequencies in causing hand injury. The range of application of the calculated values for the estimation of vibration injury is limited to the working frequency range of the octave bands from 8 Hz to 1000 Hz (i.e. the nominal frequency range from 5.6 Hz to 1400 Hz) (Appendix 2.1) (ISO-5349, 2001).

Band-limiting high-pass and low-pass filters reduce the effect on the measured value to vibration frequencies outside of this spectrum where the frequency dependency is not recognized. As a result, one-third of the octave band frequencies from 6.3 Hz to 1250 Hz constitute the primary frequency range, and the calculated ahv includes all one-third of the octave bands within this range where:

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \qquad 2.2$$

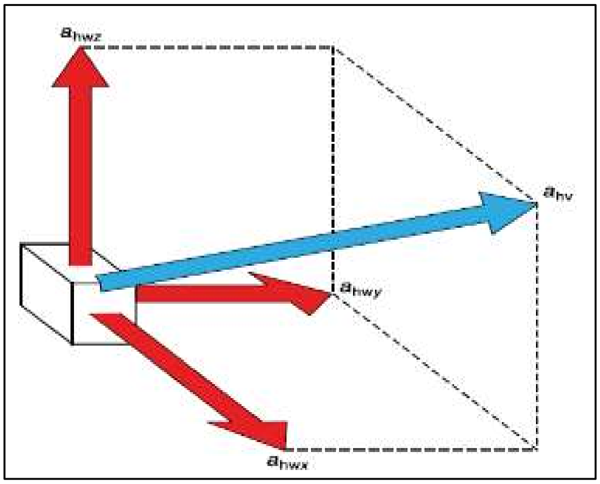


Figure 2- 5the vibration total value ahv

Frequencies outside the primary spectrum do not usually make a meaningful contribution to the importance of ahw and can be omitted from the measurement (ISO 5349-1, 2001).The estimation of daily exposure to vibration is based on the frequency of ahv vibration and the period of daily exposure. To facilitate comparisons between daily exposures of different durations, the daily vibration exposures are expressed in term of an 8-hour energy-equivalent frequency-weighted vibration total value, ahv(eq,8h), as shown in equation (2.3). For convenience ahv (eq, 8h), is given the shorthand notation of A (8) (ISO-5349, 2001):

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \qquad 2.3$$

Where T = the total daily duration of exposure to the vibration, called “trigger time”

T0 = the reference duration of 8 hours

M. D. Dong (M. D. Dong, 1996) in his study on vibration transmitted by the handles of a GN-5 type model walking tractor concluded that the main cause of vibration was the engine(Ahmadian et al., 2013). Also, he found that the vibration on the handles of the GN-5 walking tractor was very strong and seriously affected the operator’s health. Tiwari et al.,(Tiwari et al., 1997) measured ride vibrations on a single axle tractor with a seating attachment under various operating conditions and compared them with the values specified under ISO 2631 about working efficiency, health, and safety of the operator. They found that exposure time for the single axle tractor should not exceed 2 - 5 hours per day for rototilling operations.

Sam and Kathirvel(Sam & Kathirvel, 2006) reported that with an increase in engine speed in both stationary and transport modes, the vibration frequency of a single-axle tractor vibration increased; the vertical vibration portion differed significantly in various sections of the tractor handle and was highest at the tip of the handle. Ying et al. (Ying et al., 1998) reported that the major source of vibration excitation of Hand-Transmitted Vibration (HTV) of a walking tractor is the engine, and found that the highest amplitude of vibration was in the x (vertical) direction.

2.1.4. Hand-arm vibration exposures

The hand-arm vibration exposure calculator allows for a rapid determination of the number of exposure points for each hour of exposure time for any individual process, giving them time to reach the Exposure Action Value EAV (equal to 2.5 m/s^2 of A (8) or 100 points) and the time to reach the EAV (Exposure Limit Value) of 5 m/s^2 of A (8) or 400 points respectively. The vibration exposure calculator also calculates the Partial Exposure, which is the vibration exposure (shown in both A (8) in m/s^2 and exposure points) for the process and is calculated from the vibration magnitude and the exposure duration. The daily exposure of A (8) in m/s^2 and total exposure points can be calculated by summing the Partial Exposures(HSE, 2019). This document also offers suggestions concerning reducing risks posed by high vibration amplitudes.

A word of explanation on notation: The action value was set at a vibration magnitude of 2.5 m/s^2 and the limit value to 5 m/s^2. Both of these figures are A (8) values, meaning they are average vibration magnitudes over the course of an 8-hour workday. According to the European Commission Directives,(PGM, 2015) when the EAV is reached, a program of measures to eliminate or reduce exposures to hand-arm vibration must be implemented. When the ELV is reached, immediate action to prevent exposure above the limit value must be taken and the reasons for exceeding the ELV must be identified (PGM, 2015).

Under the European Directive 2002/44/EC (PGM, 2015) on minimum health and safety standards for employees' sensitivity to vibration, the regulation of hand-armed vibration exposure can be streamlined utilizing a point-of-exposure device. The exposure points are simply added together so that the maximum number of exposure points can be set for a person in one day.

For any process, the number of exposure points accumulated in an hour $P_{E,1h}$ can be obtained from the vibration magnitude a_{hv} expressed in m/s^2 using equation(PGM, 2015):

$$P_{E,1h} = 2a_{hv}^2 \qquad 2.4$$

The exposure scores corresponding to the exposure action and limit values are (PGM, 2015):

- Exposure action value (2.5[m/s^2]) = 100 points (maximum points for exposure action value (EAV)), and
- Exposure limit value (5 [m/s^2]) = 400 points (maximum points for exposure limit value (ELV)).

In general, the number of exposure points, PE, is defined by European Commission (EU, 2008):

$$P_E = \left(\frac{a_{hv}}{2.5m/s^2}\right)^2 \frac{T}{8hours} * 100 \qquad 2.5$$

Where ahv = the individual magnitude in m/s2 and

T = the exposure or working duration time in hours

A daily exposure A (8), can be then calculated from the exposure points using:

$$A(8) = 2.5m/s^2 * \sqrt{\frac{PE}{100}} \qquad 2.6$$

2.1.5. Latency period of Hand-Arm Vibration Syndrome

Power tools can transmit vibration to the hands and arms, and this has several effects on the body, including possible damage to the nerves and blood vessels. Vibration also tends to make the muscles tighten up; this leads to atighter grip on the tool, and increased vibration transmitted to hands and arms, making injury more likely.A relatively common occupational disorder, especially in some industrial industries, is hand-arm vibration syndrome (HAVS)(Youakim, 2012). Several studies have described 'Hand-Arm Vibration Syndrome' (HAVS) or 'Vibration-Induced White Finger' (VWF) as an occupational disorder synonymous with severe exposure to hand-borne vibrations(M. J. Griffin et al., 2003; Michael J. Griffin & Bovenzi, 2002).

The HAVS is not a single disease, but it is a collective term representing all disorders associated with vibration exposure including vascular, neurological and musculoskeletal disorders. The risk to different people who are exposed to HAVS varies depending on factors such as individual predisposition, any pre-existing disease and various personal and environmental factors (Nilsson et al., 2017). The syndrome affects the nerves, blood vessels, muscles and joints of the hand, wrist and arm(Tewari et al., 2004). The time taken for VWF to appear (latent interval) depends on the level of the exposure for the individual operator (Chaturvedi et al., 2012). In the early stage, the vibration-induced disorders appear as symptoms that if not diagnosed may develop into disorders that can result in disability of the affected person, loss of body strength reduced working capability and impairment of life quality. The ISO 5349 standard (2001) contains a method to estimate the vibration exposure that can lead to finger blanching in trial groups using tools. The equation used for the estimation of the finger blanching produced in 10% of persons exposed to vibration is (ISO-5349, 2001):

$$D_y = 31.8(A(8))^{-1.06} \qquad 2.7$$

Where D_y = latency period in years

A(8) = 8-hour energy-equivalent frequency-weighted vibration total value, m/s^2

International occupational exposure limits require average tool acceleration levels to be below 5

m/s^2 over an 8 hours shift, with an action value of 2.5 m/s^2 (the level at which additional precautions and surveillance should be instituted) (Seyed et al., 1992). Lowering the levels of hand-arm transmitted vibration will result in reduced noise, an improved work environment, higher production efficiency, reduction in an operator’s discomfort, and extension of the useful life of single-axle tractors.

2.2.MATERIALS AND METHODS

2.2.1. Experimental layout

At the Melkasa Agricultural Research Center (MARC), 117 km east of Addis Ababa, the evaluation of vibration characteristics of hand-arm transmitted vibration originating from a single-axle tractor was carried out. The region is characterized by arid to semi-arid agro-ecological zones at an altitude of 1550 meters above sea level with temperatures generally between 14 ^{o}C and 28 ^{o}C, mean annual precipitation between 750 and 800 mm, Length of Growth Period (LGP) between 3 and 6 months, and volcanic sandy soils with a pH between 7 and 8.2.

2.2.2. Measurement of key parameters

1. **Temperature and humidity measurement**

Temperature and humidity were measured with a Nicety(R) Large Digital Temperature Humidity Meter - Hygrometer and Thermometer TH-812 with the following specifications of measuring range: 10% - 95% Relative Humidity, -10 - 60°C temperature (figure 2.6).

Figure 2- 6Large Digital Temperature Humidity Meter - Hygrometer and Thermometer (© 2010 CarstanFranke)

2. **Soil moisture content**

Some criteria can be defined to characterize soil conditions before and after testing has been carried out for experiments on soil-engaging implements and machines. The site for the test should be chosen before vibration calculation and the soil samples for moisture content were taken at depths of 5, 10 and 15 cm, with five samples diagonally from the prepared field site for each depth, as shown in figure (2.7).In the laboratory, the soil moisture content of each soil sample was determined by the standard oven-drying method for 24 hours at 105°C. The dry weight and moisture content of each sample were recorded on a dry base. The dry basis of soil moisture content is a measure of how much water is in the soil, expressed as the weight of water as a percentage of the completely dry soil.

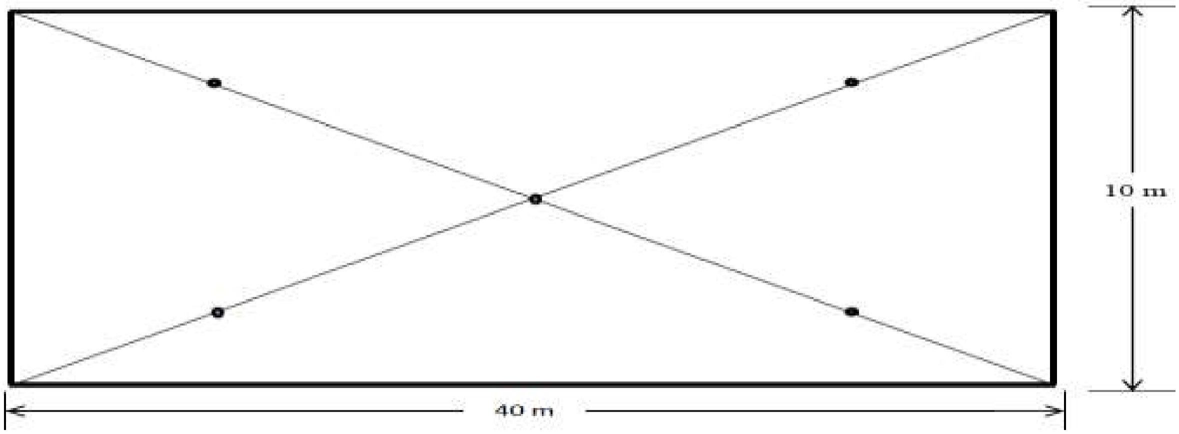


Figure 2- 7 Diagonal patterns for five soil collection sites, at depths of 5, 10 and 15 cm (total of 15 samples for moisture content tests)

The force required to push the cone into the ground is recorded as a function of depth. The force divided by the area of the base of the cone provides a "pressure" measurement and is referred to as the cone index. Common units are lb/in^2 in English units and kN/m^2 or kPa in SI units. Cone index may be measured as deep as 500 mm (50cm) when used for tillage and/or compaction measurements, but the upper 100 to 150 mm (10 to 15 cm) is commonly used for traction purposes.

3. Tractor forward speed

The gear for tractor operation was selected before the commencement of tractor forward speed. The networking time between engagement and disengagement of the implement or the machine in work was recorded. The distance travelled in each case was recorded and divided by the corresponding net time. The average of this figure is the tractor forward speed (S). In this field experiment, travel speed was measured during field trials of machines using marker poles set 20m apart to form a rectangle. An observer was then able to sight across the poles and measure the time taken for the machine to travel the known distance.

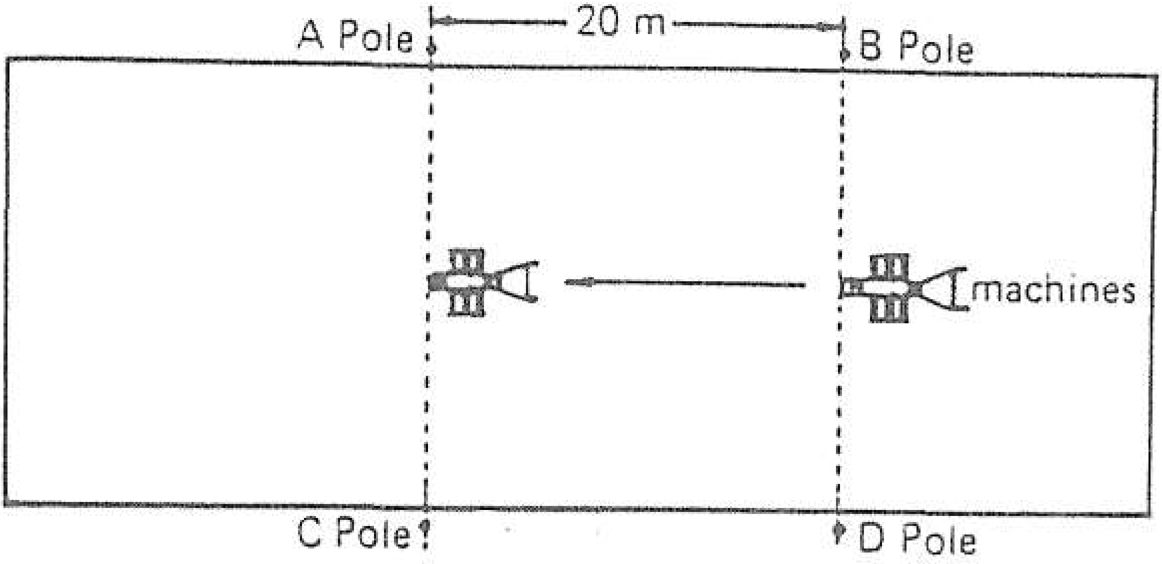


Figure 2- 8Field measurement of tractor forward speed

2.2.3. Hand-arm vibration measurement

Equipment

A single-axle 15HP Dong Feng tractor, model 2b-DF-15L with a horizontal 4-stroke diesel engine with a crankshaft turning speed of 2000 rpm with implement was used for all data collection (Figure 2.9).

Figure 2- 9 a 15 Horse Power single axle tractor

A model VM-6380 vibration meter Tester (M&A Instruments, Arcadia, CA) with a 3-axis piezoelectric accelerometer vibration sensor (figure 2.10) was used for vibration measurements. The sensor bandwidth of 10Hz – 10 kHz includes almost all of the relevant frequency range of 6.3 Hz to 1250 Hz (ISO 5349-1, 2001).

Figure 2- 10 A VM-6380 3-Axis 3D Digital Vibration Meter Tester and measurement of vibration

2.2.4. Subjects and tasks

Seven (7) male subjects participated in the operation of the 15-HP single-axle tractor. The operators performed tilling tasks with the tractor in second and third gears, while the handle vibration levels were measured at the tractor handle along the x (vertical), y (forward), and z (transverse) axes. The y- and z-directions were switched from those shown in Figure (2.3) which corresponds to the ISO 5349(ISO 5349-1, 2001) standard because the handle on this particular tractor model operator was oriented at 90 degrees from that shown in Figure (2.3).

2.3. RESULTS

2.3.1. Evaluation of key parameters

Environmental parameters

During the research work, the minimum and maximum values of the thermal variables were measured before and after the operation of the single axle tractor. The humidity levels were found to vary from 38 – 71%, and ambient temperature varied over the range 27 – 35 ^{0}C.

Soil moisture contents (MC)

The moisture content of the soil was determined using equation (2.1). The mean soil moisture content varied from 9.2 to 16 %, based on measurements at soil working depths of 5, 10 and 15 cm. The soil cone idex also found varied from 22 to 34 kPa based on the working depth of implement.

Tractor forward speed

The calculated mean tractor forward speed of the single axle tractor is presented in Table (2.1). The mean calculated tractor forward speed and working depth of the implement during the research was 1.86 km/hr and 11.73 cm respectively.

Table 2- 1 Descriptive statistics of tractor forward speed and working depth

Descriptive statistics	Working Speed (km/hr)	Working depth, [cm]
Mean	1.86	11.73
Median	1.82	11.67
Standard Deviation	0.24	1.38
Sample Variance	0.06	2.00
Range	0.92	3.33
Minimum	1.51	10.33
Maximum	2.43	14.00

2.3.2. Evaluation of single axle tractor vibration characteristics

Statistical data of measured frequency-weighted vibration at the handle of the single axle tractor in second and third gears for three axes of motion were measured and analyzed. The 3-axis piezoelectric accelerometer vibration sensor was attached at the handle of single axle tractor near to the hand of the operator. An RS-232C data cable was linked to a laptop computer to record the vibration data points from the x, y and z-axes or vertical, forward and lateral directions digital vibration meter while operating the single axle tractor. More than 1050 vibration data records were collected in the field for each axis using the laptop as a data logger for 40 – 55 minutes for each of the seven tractor operators, depending on their speed of tilling operations. The average time for data collection for all operators was 45 minutes. This yielded an average of about 15 minutes for each axis because data recording takes place individually for vertical, forward, and lateral-directions even though they are displayed at the same time on the meter.

Table (2.2) summarizes the mean reported total handle vibrations for the second and third gears. For the second gear, the mean estimated handle vibration in the vertical, forward, and lateraldirections were 18.1, 10.8 and 17.3 m/s2 respectively, while for the third gear, the equivalent values for the vertical, forward and lateral directions were 22.6, 11.4 and 20.8 m/s^2 respectively.

Piezoelectric accelerometer vibration sensor was attached at the handle of single axle tractor near to the hand of the operator. An RS-232C data cable was linked to a laptop computer to record the vibration data points from the x, y and z-axes or vertical, forward and lateral directions digital vibration meter while operating the single axle tractor. More than 1050 vibration data records were collected in the field for each axis using the laptop as a data logger for 40 – 55 minutes for each of the seven tractor operators, depending on their speed of tilling operations. The average time for data collection for all operators was 45 minutes. This yielded an average of about 15 minutes for each axis because data recording takes place individually for x, y and z-axes or vertical, forward and lateral directions even though they are displayed at the same time on the meter.

The mean measured average handle vibrations with second and third gear are summarized in table (2.2). The mean measured handle vibration in x, y and z-axes or vertical, forward and lateral directions for second gear were 18.1, 10.8 and 17.3 m/s^2 respectively whereas for third gear the corresponding values are 22.6, 11.4 and 20.8 m/s^2 for the x, y and z-axes or vertical, forward and lateral directions, respectively.

Table 2- 2 frequency weighted RMS vibration at the handle of the single axle with second and third gears

Descriptive statistics	frequency weighted RMS vibration amplitude [m/s^2]					
	Second gear			Third gear		
	Vertical	Forward	Lateral	Vertical	Forward	Lateral
Mean	18.10	10.75	17.28	22.61	11.36	20.79
Median	17.03	9.87	15.46	22.44	11.17	20.53
Mode	13.85	7.33	16.84	23.67	15.43	24.06
Standard Deviation	7.25	4.83	8.72	2.92	1.81	2.47
Sample Variance	52.58	23.34	76.00	8.50	3.29	6.08
Range	37.34	44.00	75.64	25.31	10.65	19.95
Minimum	7.08	2.91	4.26	10.88	6.59	8.35
Maximum	44.42	46.91	79.90	36.19	17.25	28.30

The measured vibration data on the handle of the tractor were processed in the time and frequency domains using the Matlab software. The mean vibration RMS values for each direction, vibration total value a_{hv} and vibration daily exposure A (8) in m/s^2 (calculated using equations (2.2 & 2.3)) at the handle of the single axle tractor are shown in Table (2.3). The daily exposure of A (8) vibrations for the handle of the single axle tractor with second and third gears were 10.8 and 12.6 m/s^2 respectively.

Table 2- 3 Frequency weighted average, vibration total value and Daily exposure at the handle with second and third gear

Process of vibration measurement	Frequency weighted RMS vibration amplitude [m/s^2]				
	Vertical	Forward	Lateral	Vibration total value [m/s^2]	Daily exposure A (8) [m/s^2]
Second gear at handle	18.1	10.8	17.3	28.3	10.8
Third gear at handle	22.7	11.4	20.9	32.9	12.6

2.3.3. Evaluation of latency period of Hand-Arm Vibration Syndrome

The latency periods for the single axle tractor handle vibration were evaluated using equation (2.7) for the estimation of the finger blanching produced in 10% of single axle tractor operators is presented in Table (2.4). From the table, it can be seen that the latency period for the third gear with daily exposure of 12.6 m/s^2 is less than that of the second gear operation with daily exposure of 10.8 m/s^2. These were found to be 2.6 and 2.2 years respectively.

Table 2- 4 second and third gears handle vibration total and latency period

Process of vibration measurement	Vibration total value $[m/s^2]$	Daily exposure A (8) $[m/s^2]$	The latency period (years)
Second gear at handle	28.3	10.8	2.6
Third gear at handle	32.9	12.6	2.2

2.4. DISCUSSION

2.4.1. Effect of soil moisture content and soil cone index on vibration

Correlation analysis is a term used to denote the association or relationship between two (or more) quantitative variables. This analysis is fundamentally based on the assumption of a straight –line (linear) relationship between the two variables. Correlation coefficients are statistical parameters whose values range from -1 to +1. A correlation coefficient "r" of +1 indicates that the two variables are perfectly related in a positive (linear) manner, a correlation coefficient of -1 indicates that two variables are perfectly related in a negative (linear) manner, while a correlation coefficient of zero indicates that there is no linear relationship between the two variables under study. The magnitude of the correlation coefficient "r" determines the strength of the correlation, according to Kimon et al.,(Kimon et al., 2012) guide: r = 0.00-0.19 "very weak"; 0.20-0.39 "weak"; 0.40 - 0.59 "moderate"; 0.60 - 0.79 "strong"; 0.80-1.0 "very strong".

In regression analysis, the coefficients of determination R-sq. or Ra-sq. are often used to assess the degree of fit of a model. These coefficients indicate how much variation in the response is explained by the model. Such analysis only works as intended in a simple linear regression model with one explanatory variable, as every predictor added to a model increases R-squared and never decreases it (Akossou et al., 2013).

The adjusted Ra-squared compares the descriptive power of regression models that include diverse numbers of predictors. Thus, a model with more terms may seem to have a better only because it has more terms, while the adjusted R-squared compensates for the addition of variables by only increasing if the new term enhances the model above what would be obtained by probability and decreases when a predictor enhances the model less than what is predicted by chance.

The correlation coefficient between the mean measured moisture content and handle the vibration of single axle tractor was found to be -0.98; this figure shows that the handle vibration tends to decrease as the soil moisture content increases, in a very strong (negative) linear relationship. Using such linear regression analysis, the relationship between soil moisture content and single axle tractor handle vibration data is shown in figure (2.11). The soil moisture content and tractor handle vibration total value have a very strong negative correlation: as the soil moisture content increases, the tractor handles vibration total value decreases linearly. This negative correlation can be expressed by using the regression equation of V = 56.659 - 2.1063MC, with R-sq. = 0.96 and adjusted Ra-sq. = 0.95 with norm of residuals = 3.8198, V = vibration total value and MC = soil moisture content. Tractor vibration amplitude is significantly decreased with increasing soil moisture content in the field (Cuong, et al., 2013).

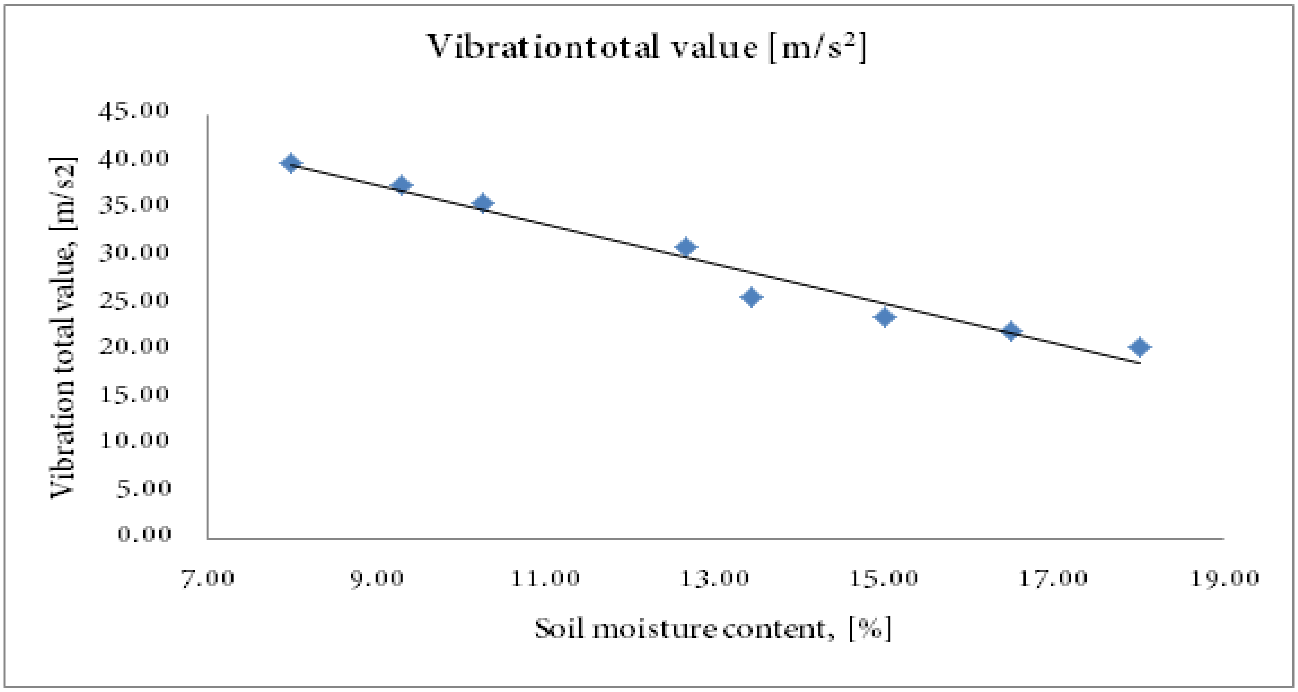


Figure 2- 11 Relationships between soil moisture content and tractor handle vibration

The relationship between the soil cone index and the vibration total value was evaluated. The relationship between the soil cone index and vibration total value is strong positive linear relationship with the relation of V = 1.4065 C -10.877, with R^2 = 0.9594, where V = vibration total value and C soil cone index.

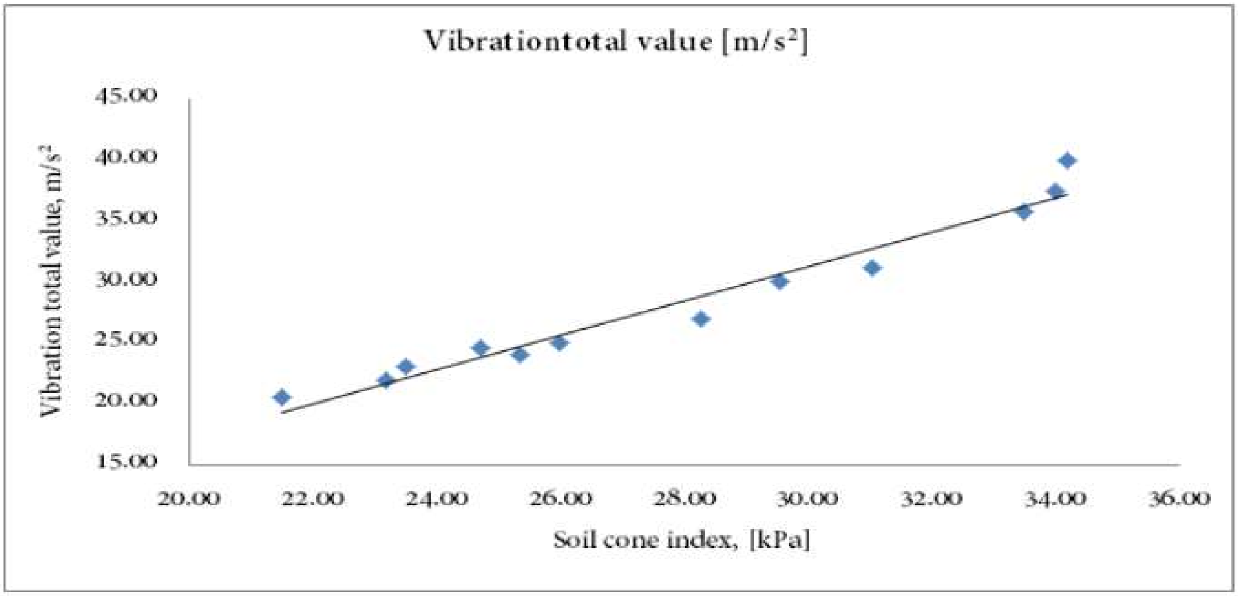


Figure 2- 12 Relationships between soil cone index and tractor handle vibration

2.4.2. Effect of tractor speed on handle vibration

From the figure (2.12) below, the tractor handles vibration total value increases as the forward speed of the tractor increases, such that they have a strong positive linear relationship given by the equation of V = 24.51+3.436S, with R-sq. = 0.97, and adjusted Ra-sq. = 0.96, with norm of residuals = 1.1043, where V = vibration total value and S = tractor forward speed(Cuong et al., 2013; Sam & Kathirvel, 2006).

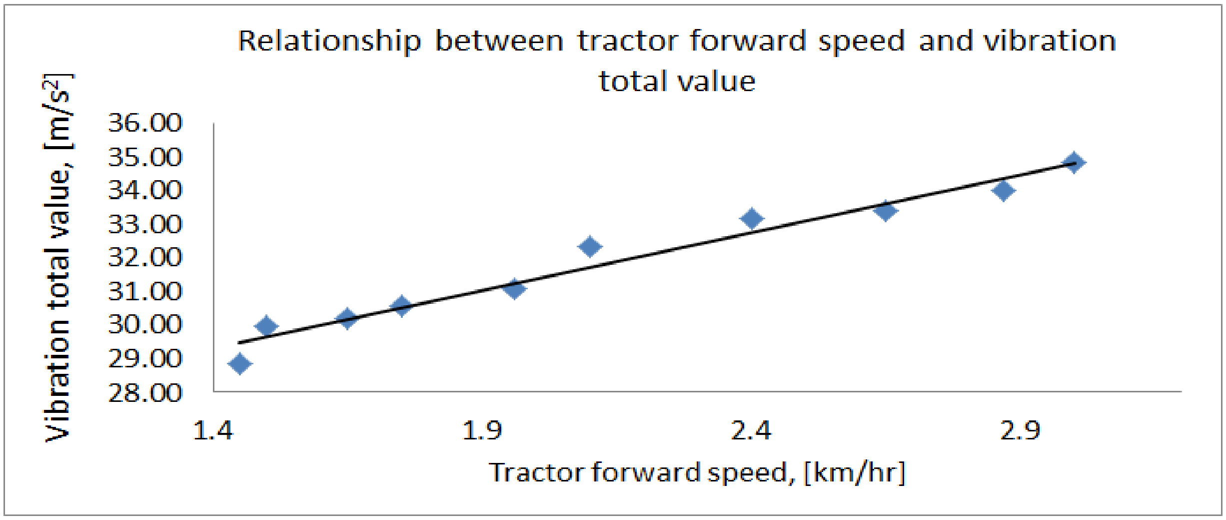


Figure 2- 13 Relationship between tractor forward speeds and vibration total value

Results of Dahham, et al., (Dahham et al., 2019) have also shown that vibration of a steering wheel tractor increases in the three directions (longitudinal, lateral and vertical) by increasing the tractor forward speed.

2.4.3. Time-domain vibration analysis

The third gear handle vibration data of the single axle tractor was low-pass filtered with a cutoff frequency of 2000 Hz to include the expected frequency range of 6.3 – 1250 Hz of hand-arm vibration. The sampling frequency (F_s) was 5000 Hz, yielding a maximum spectral frequency of 2500 Hz which is half of the sampling frequency. There were 1024 or 2^{10} data points in the Fast Fourier Transform (FFT) from field-recorded average frequency-weighted vibration data of the seven tractor operators. Representative time-domain data corresponding to vibrations at the handle of the single axle tractor in the x (vertical), y(forward), and z(lateral) directions at operating conditions of tilling are shown in figures 2.13, 2.14, and 2.15, respectively.

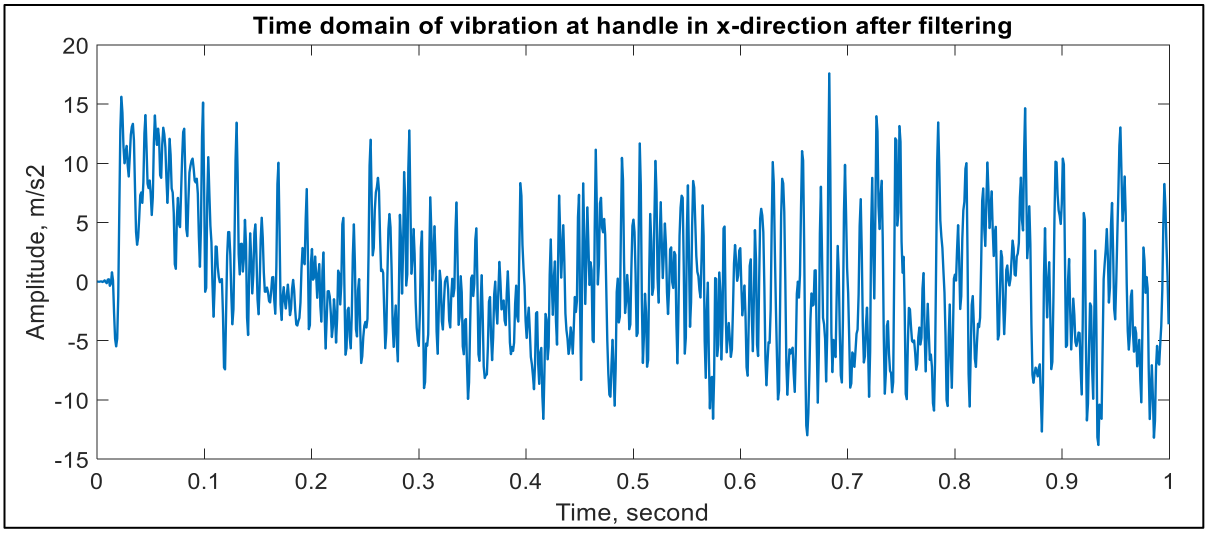


Figure 2- 14 Low-passed filtered handle vibration data in the vertical-direction

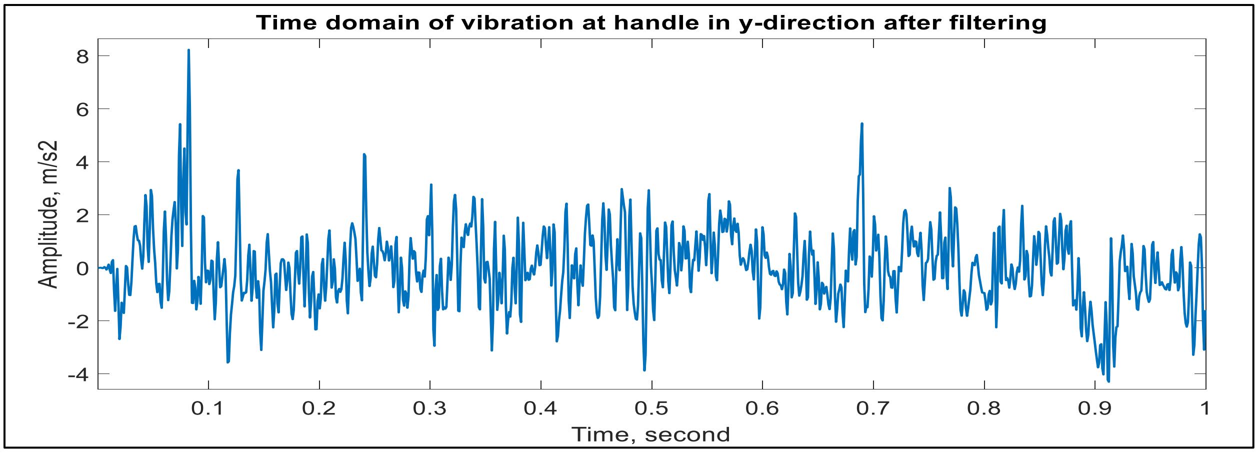


Figure 2- 15Low-passed filtered handle vibration data in the forwad-direction

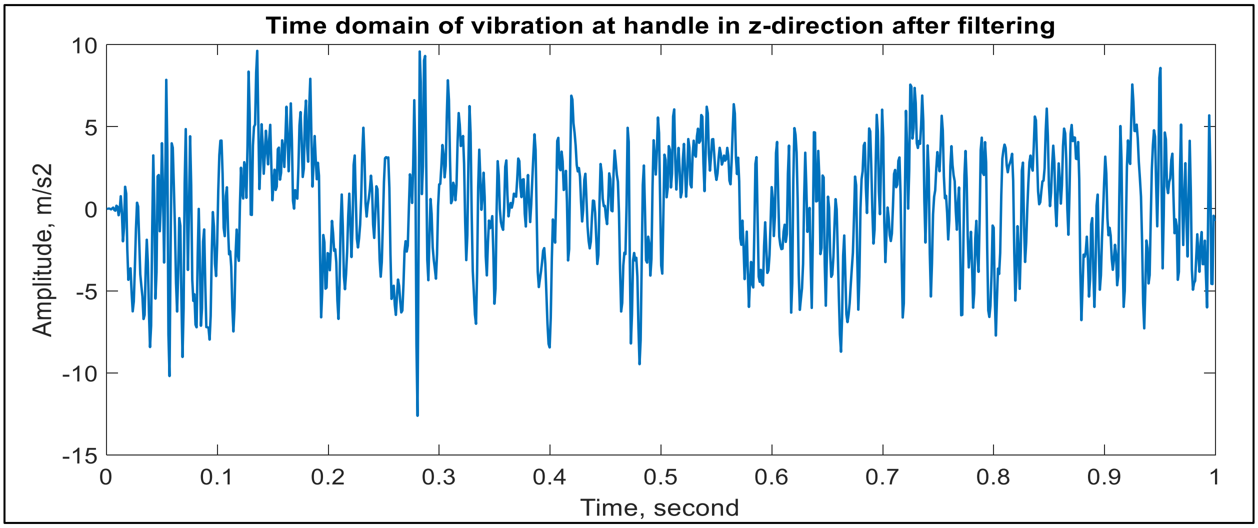


Figure 2- 16 Low-passed filtered handle vibration data in the lateral-direction

From the data of Table (2.2) and figures (2.13 and 2.14) it can be seen that the highest values of vibration in the handle of the single tractor were in the x(vertical)-direction and lowest in the y(forward)-direction for both second and third gears. The handle vibration magnitudes also show that slightly larger amplitudes were observed in third gear as compared to second gear. A similar result was noted by Nassiri et al.(Nassiri et al., 2014). Similarly,Dahham, et al., (Dahham et al., 2019) found greater hand-arm vibration intensity in the vertical direction than the lateral and longitudinal direction. It has been noted that the vibration transmitted to the operator can be increased by increasing the gripping or pushing forces; these forces are key for the support, control, and guidance of the single axle tractor; they can be adjusted to achieve higher work-rates (William Cockburn, 2008). Higher values of the root mean square (RMS) handle vibration total value will cause driver discomfort and fatigue, poorer tilling performance and decreased control of the tractor by the driver(Dahham et al., 2019).

2.4.4. Frequency Domain Analysis of Vibration

The spectrogram of hand vibration was obtained through a Fast Fourier Transform (FFT) of the time domain signals measured during tilling operations. An upper-frequency cut-off value of 1500 Hz was used for all frequency domain analysis. Data are presented for all three axes in figures 2.16, 2.17, and 2.18, although their relative magnitudes will depend on the grip force, the orientation of the hand and posture of the arm of an operator (Welcome et al., 2015). In the vertical-direction (figure 2-16), the peak power spectral density was 3790 (m/s^2)^2/Hz at a frequency of 19.5 Hz.

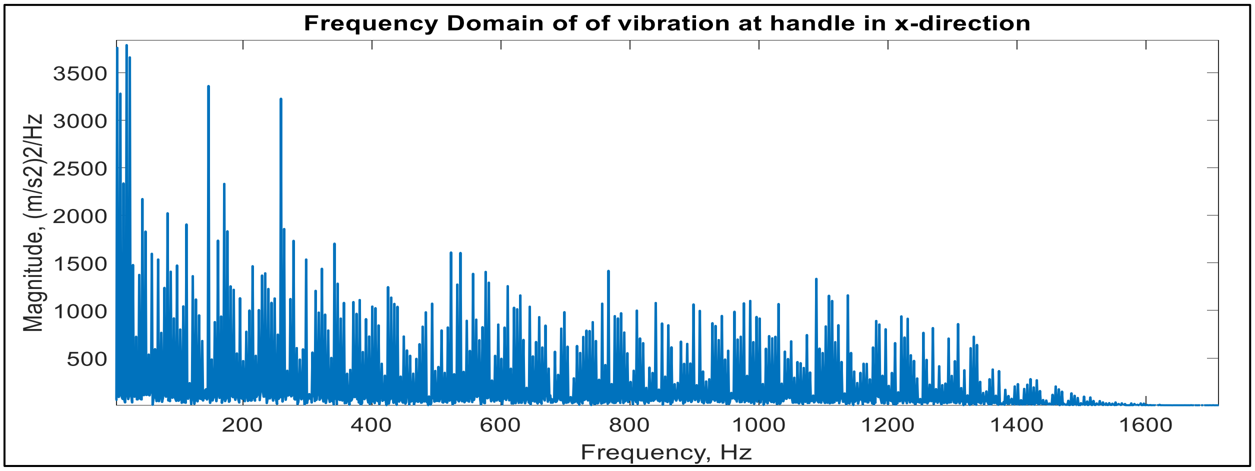


Figure 2- 17 Frequency domain of vibration at the handle in the vertical-direction

In the forward-direction shown in figure 2.17, the maximum peak of power spectral density was 845 (m/s^2)^2/Hz at a frequency of 19.5 Hz.

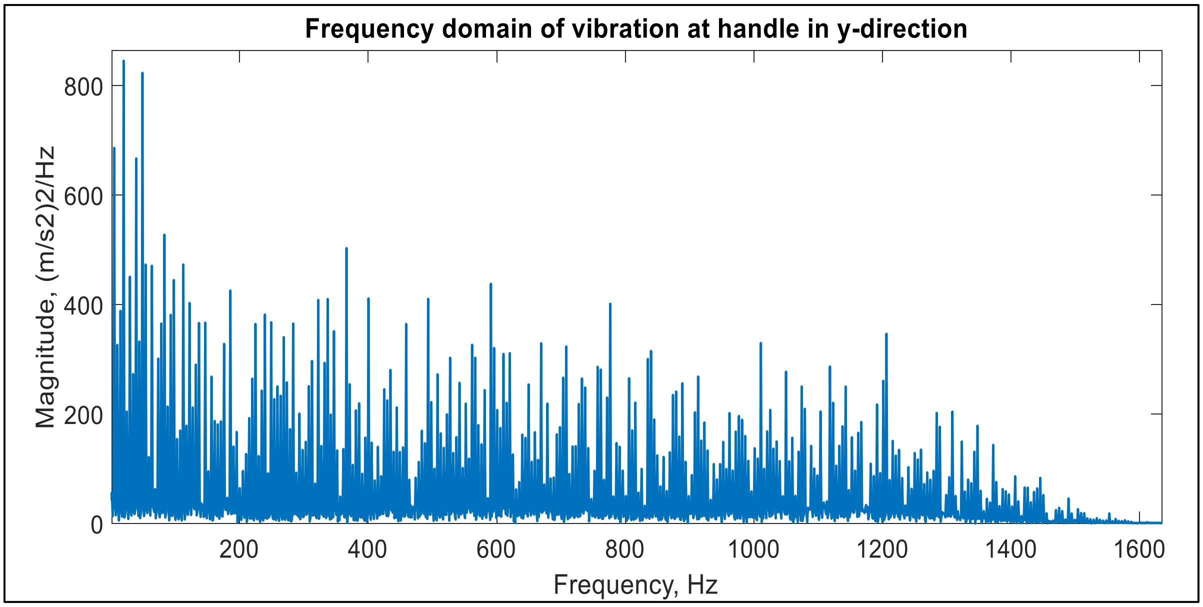


Figure 2- 18Frequency domain of vibration at the handle in the y-direction

In the lateral-direction is shown in figure 2.15, the maximum peak of power spectral density was 2485 $(m/s^2)^2$/Hz at a frequency of 24.4 Hz.

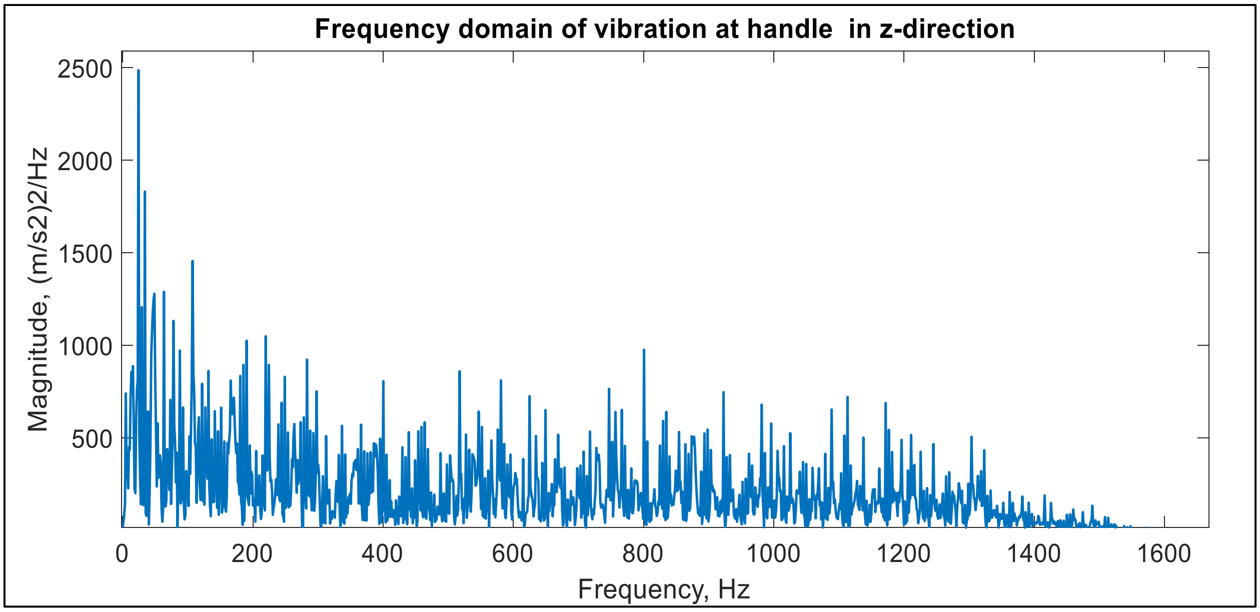


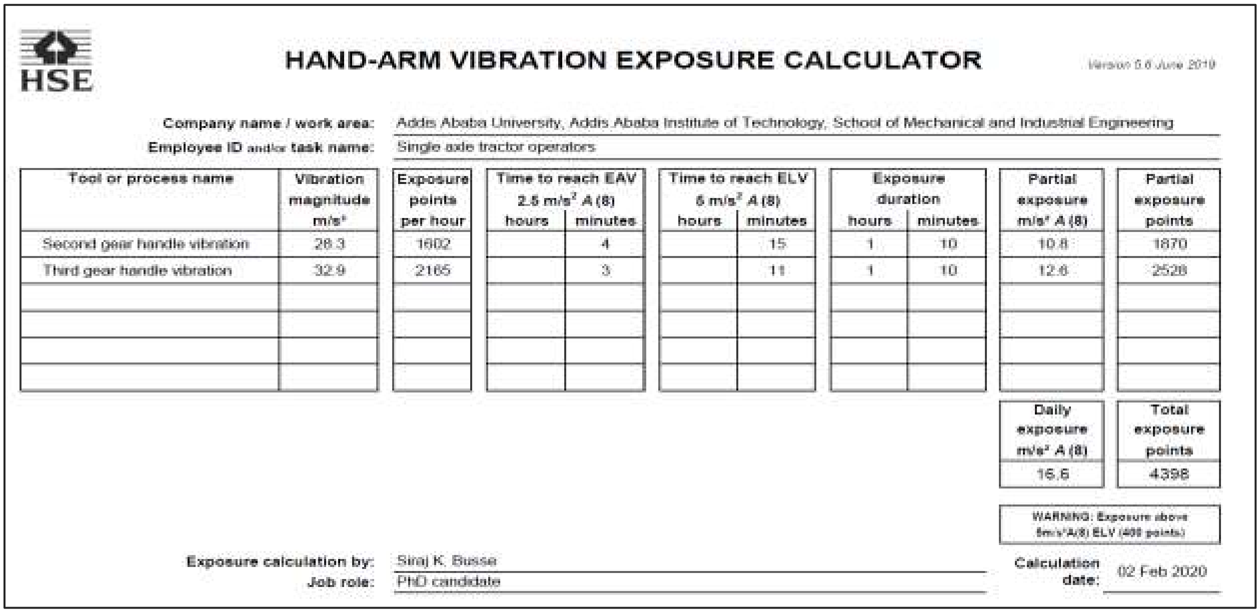
Figure 2- 19 Frequency domain of vibration at the handle in the lateral-direction

As seen from figures 2.16 and 2.17, the handle of the single axle tractor has the same frequency for the peak power spectral density in the vertical and forward-directions; however, the xvertical-direction, in general, has the larger vibration amplitudes. This type of directional dependence of the tractor handle vibrations was also observed by Griffin (M. J. Griffin, 2004).

As seen from figures (2.16 – 2.18), the maximum peak magnitudes of vibrations were in the low-frequency range (below 25 Hz) on all three axes. Vibration magnitudes in this range have a great impact on the health of operators, by transmitting effectively to the arms, shoulders, neck, and head(R. G. Dong et al., 2012). Welcome et al., (Welcome et al., 2015), also suggested that exposure to vibrations in the range of 16-500 Hz could pose a significant risk of promoting finger disorders.

2.4.5. Evaluation of vibration exposure

From the vibration total value data shown in Table (2.3), the vibration exposure was determined according to the Control of Vibration at Work Regulations that are based on the 2002 EU Physical Agents (Vibration) Directive (EU, 2008; PGM, 2015). Vibration total value and daily exposure of A(8) in m/s^2 were calculated using equations (2.5) and (2.6). The vibration daily exposure of A(8) was also calculated from vibration total value and duration of exposure data by using the Hand-Arm Vibration Exposure Calculator designed by the Health and Safety Executive according to vibration regulations 2005(HSE, 2019) (figure 2.19).



HSE

HAND-ARM VIBRATION EXPOSURE CALCULATOR

Version 5.6 June 2019

Company name / work area: Addis Ababa University, Addis Ababa Institute of Technology, School of Mechanical and Industrial Engineering

Employee ID and/or task name: Single axle tractor operators

Tool or process name	Vibration magnitude m/s²	Exposure points per hour	Time to reach EAV 2.5 m/s² A (8)		Time to reach ELV 5 m/s² A (8)		Exposure duration		Partial exposure m/s² A (8)	Partial exposure points
			hours	minutes	hours	minutes	hours	minutes		
Second gear handle vibration	28.3	1602		4		15	1	10	10.8	1870
Third gear handle vibration	32.9	2165		3		11	1	10	12.6	2528

Daily exposure m/s² A (8)	Total exposure points
16.6	4398

WARNING: Exposure above 5m/s² A(8) ELV (400 points)

Exposure calculation by: Siraj K. Busse

Job role: PhD candidate

Calculation date: 02 Feb 2020

Figure 2- 20 hand-arm vibration exposure calculator versions 5.6 and calculated results (HSE, 2019)

From figure 2.19, the vibration of the handle with the tractor in second gear will reach the EAV of 2.5m/s^2 of A(8) after only 4 minutes, and ELV of 5m/s^2 of A (8) after only 15 minutes. The

Calculated Daily exposure of 10.8 m/s^2 of A (8) is well above the Action Limit Value ($5m/s^2$); the 1870 Total Exposure points is also well above the limit of 400 points.

The vibration of the handle will reach the EAV of $2.5m/s^2$ of A (8) after only 3 minutes, and ELV of $5m/s^2$ of A (8) after only 11 minutes. The Calculated Daily exposure of 12.6 m/s^2 of A (8) is well above the Action Limit Value ($5m/s^2$); the 2528 Total Exposure points is also well above the limit of 400 points. The data indicate that safe vibration limits are routinely exceeded in a day of the normal use of a single-axle tractor, and the operators are at significant risk of developing Hand-Arm Vibration Syndrome (HAVS).

2.4.6. Latency period of Hand-Arm Vibration Syndrome

The latency period for HAVS for single axle tractor operators using second and third gear operations were 2.6 and 2.2 years with single axle tractor handle total vibration values of 28.3 and 32.9 m/s2 respectively. As seen from these data, the third gear vibration is more severe than second gear. This indicates that as the tractor forward speed increases the latency period increases. Ahmadian et al.,(Ahmadian et al., 2014) have shown that 10% of operators of the 13-HP walking tractor with vibration range of 14 – 26 m/s^2 will be affected by Hand-Arm Vibration Syndrome within 2.32 years. Similarly, Nassiri et al., (Nassiri et al., 2014)found a handle total vibration amplitude ahv of 16.95 m/s^2 for rototilling and determined the permitted working time for such machinery was only a few seconds. They suggested a risk of musculoskeletal disorders and recommended measures to reduce hand-arm vibration transmitted to the tiller user’s hands.

2.5. CONCLUSIONS

Vibration data were collected both for the hand of operators and handle of a 15-HP single-axle tractor while performing routine tilling operations with second and third gears. Handle vibration data were analyzed in both the time and frequency domain along three perpendicular axes, following international safety standards. The maximum vibration amplitude was in the x and the least value was in the y-direction. Frequency domain analysis showed that the maximum acceleration power spectral density was in the low-frequency range (< 25 Hz) for all three axes; in this frequency range, Root Mean Square handle vibrations with a total value of 33 m/s^2 are believed to be efficiently transmitted to the arms, shoulders, neck, and head of the operator. This will have adverse health effects on the operators of single-axle tractors.

The relation between soil moisture contents and handle vibration were evaluated for correlation using two-way ANOVA in MATLAB. It was found that the soil moisture content has a very strong negative linear relationship with tractor handle vibration: as soil moisture content increases, the tractor handles vibration decreases linearly with linear regression of R-sq. =0.96, and adjusted Ra-sq. 0.95.

The relation between tractor forward speed and handle vibration was also evaluated for correlation using two-way ANOVA in MATLAB. It was found that the tractor forward speed has a strong positive linear relationship with tractor handle vibration: as tractor forward speed increases, the tractor handle vibration increases linearly, with a linear regression coefficient of R-sq. =0.97, and adjusted Ra-sq. = 0.96.

The Daily Exposure in m/s^2 A(8) of vibration at the tractor handle with third gear was 12.6 m/s^2 and Total Exposure points were 2520. In both cases, the exposure limit value of 5 m/s^2 and Total Exposure points of 400 were exceeded. From frequency-domain vibration analysis and calculated results of operator daily vibration exposure, an operator of this type of single axle-tractor is at significant risk of developing Hand-Arm Vibration Syndrome (HAVS). The latency period for HAVS for single axle tractor operators using second and third gear operations were 2.2 and 2.6 years with total vibration value of 28.3 and 32.9 m/s^2 respectively.

CHAPTER THREE: PHYSIOLOGICAL RESPONSE *OF SINGLE AXLE TRACTOR OPERATORS TO HAND-ARM VIBRATION*

3.1. THEORETICAL BACKGROUND

3.1.1. Anthropometry

Anthropometry includes the systematic calculation of the physical properties of the human body specifically the scale and form of the body. Anthropometry is a science of calculating and quantifying different human physical features, such as height, weight, proportion, mobility, and power. Because everybody has different anthropometric values, the best way to build an ergonomically right and productive working atmosphere is to change workplaces differently.

Anthropometry, a human body measuring study, is used in engineering to achieve the full value and capability of the goods that people use. The use of anthropometric data at the early stages of engineering design will reduce the size and shape adjustments required later when improvements can be very costly. To use anthropometry information efficiently, it is often important to know the relationship between the body and the things worn or used.

Several factors could affect a user's strength potential. Such factors include (but are not limited to) age, gender, health status, body part, body-part position, the direction of exertion, whether the exertion is applied statically or dynamically, posture, and environmental issues.Individual characteristics of a worker, including anthropometry, health, sex, and age, may alter how work is performed and may affect a worker's capacity for or tolerance of exposure to physical or other risk factors.

3.1.2. Physiological responses to vibration

Vibration is the oscillatory action of the different bodies with the components of mass. All bodies with elasticity are capable of vibration; thus most machines and devices, including the human body, undergo vibration to some degree. The two different types of vibration that take place are the free vibration under which the mechanism oscillates due only to the action of the internal forces and the induced vibration caused by the action of the external forces. Large oscillations will occur within the mechanism and produce potentially dangerous stress as the frequency of excitation correlates with the normal frequency of the device so that the state of the resonance occurs.

Machinery such as farm tractors and other earth-moving equipment contribute to some of the most common, prolonged, and severe occupational exposures of vehicle vibration among equipment operators(Dahham et al., 2019). Vibration is transmitted to the body by physical contact with vibrating tools or hand-held power tools such as grinders and rotary tools, which are used in manufacturing industries; stone hammers and rock drills in construction, and chain saws in forestry. Most power tools are vibratory in nature and these vibrations are imparted to people handling them; chain saws, chipping hammers, jackhammers, and lawnmowers are a few that come to mind easily. These power tools tend to vibrate the operator's hands and arms.

Farm tractor operators can be effected either by the whole-body vibration produce through the seat or floor, or vibration produced by the hand-grip, Both forms of vibration can affect the operator and this can reduce his job performance and health(Dahham et al., 2019). Hand vibration results from the use of various types of agricultural hand tractors. Exposure to this vibration for extended periods can affect the nervous system causing damage to tendons, muscles, bones and the vascular system. This last item results in lower blood flow, which can lead to white finger syndrome (Dahham et al., 2019; Fereydooni et al., 2012).

Mechanical vibrations have both a short-term as well as a long-term effect on the human body(Scott, 2009). Human exposure to mechanical vibration may represent a significant risk factor for exposed workers in the agricultural sector, with particular reference to the operators driving tractors(Dahham et al., 2019; Vallone et al., 2016). Vibrations influence the human body in many different ways. The response to vibration exposure is primarily dependent on the frequency, amplitude, and duration of exposure. Other factors may include the direction of vibration input, location and mass of different body segments, level of fatigue and the presence of external support.

The human response to vibration can be both mechanical and psychological. Mechanical damage to human tissue is caused by resonance within various organ systems. Psychological stress reactions can also occur from vibrations. According to Dahham, et al., (2019), excessive exposure to hand-transmitted vibration can causes disturbances in finger blood flow, in neurological and motor functions of the hand and arm and the vibration entering to the operator's hand not only causes health problems but also lowers the driver working skills and sensation. Exposure of the hands and fingers to vibration can result in a complex combination of signs and symptoms of a physiological disorder.

Prolonged and regular exposure of the fingers or the hands to vibration or repeated shock can give rise to various signs and symptoms of a physiological disorder. These include impeded blood circulation to the fingers and 'attacks' of blanching on one or more digit (Shen, 2017). The precise extent and interrelation between the signs and symptoms are not fully understood, but five types of the disorder may be identified as shown in Table (3.1)(Salvendy, 2012).

The various disorders may be interconnected: more than one disorder can affect a person at the same time and the presence of one disorder may facilitate the appearance of another. The onset of each disorder is dependent on several variables, such as the vibration characteristics, the dynamic response of the fingers or hand, individual susceptibility to damage, and other aspects of the environment. The terms *vibration syndrome* and *hand-arm vibration syndrome* (HAVS) is sometimes used to refer to one or more of the effects listed in Table (3.1) and the development of these risks depends on many factors including vibration levels, feed force, vibration frequency, exposure duration, and others(Salvendy, 2012).

Table 3 - 1five types of disorder associated with hand-arm vibration exposures (Salvendy, 2012)

Type	**Disorder**
Type A	Circulatory disorders
Type B	Bone and joint disorders
Type C	Neurological disorders
Type D	Muscle disorders
Type E	Other general disorders (eg. Central nervous system)

In studies of (M. J. Griffin et al., 2003; Michael J. Griffin, 2008; Lindsell & Griffin, 2002; Shiralkar et al., 2011) “Hand-Arm Vibration Syndrome” or “Vibration-induced White Finger” (VWF) have been defined as the occupational disorder associated with prolonged to hand-transmitted vibration. The HAVS is not a single disease, but it is a collective term representing all disorders associated with vibration exposure including vascular, neurological and musculoskeletal disorders. The risk to different people who are exposed to HAVS varies depending on other factors such as individual predisposition, any pre-existing disease and various personal and environmental factors(M. J. Griffin et al., 2003).

The syndrome affects the nerves, blood vessels, muscles and joints of the hand, wrist and arm (Tewari et al., 2004). The time taken for VWF to appear (latent interval) depends on the level of the exposure for the individual operator(Chaturvedi et al., 2012). In the early stage, the vibration-induced disorders appear as symptoms that if not diagnosed may develop into disorders that can result in disability of the affected person, in loss of body strength, working capability and impairment of life quality. The severity of the effects of vibration is sometimes recorded by reference to the *stage* of the disorder. The staging of the vibration-induced white finger is often based on verbal statements made by the affected person recalling an attack of finger blanching, but it may be influenced by evidence in photographs taken during an attack. In the Stockholm Workshop staging system, the staging is influenced by both the frequency of attacks of blanching and the areas of the digits affected by blanching as shown in Table (3.2)(Salvendy, 2012; Shen, 2017).

Table 3 - 2 Stockholm Workshop Scale for Classification of Vibration-Induced White Finger (Salvendy, 2012; Shen, 2017)

Stage	Grade	Description
0	-	No attacks
1	Mild	Occupational attacks affecting only the tips of one or more fingers
2.	Moderate	Occupational attacks affecting distal and middle (rarely also proximal) phalanges of one or more fingers
3	Severe	Frequent attacks affecting all phalanges of fingers
4	Very severe	As in stage 3, with trophic skin changes in the fingertips

Vibratory tools operating technique, grip and feed force, posture, temperature, humidity condition and the exposure to vibration are all factors that affect HAVS or VWF. It is important to analyze significant factors that contribute to HAVS and adjust the procedures or tasks to reduce the symptoms. Occupational Safety and Health stated that hand-arm vibration has become a significant issue. This issue can be very serious and contribute to human health as well as the efficiency of production. Therefore, to quantify and assess safe levels of human exposure to vibration, it is necessary to measure and analyze the characteristics of vibrations and their effect of blood pressure, oxygen saturation and heart rate.

Different techniques and methods have been developed to determine the physiological workload or physiological strain such as the Rating of Perceived Exertion method (RPE)(Anondho & Suparman, 2020; Gatti et al., 2010), the measurement of oxygen consumption and Heart Rate (HR) monitoring (Gatti et al., 2010). Heart rate is a valuable measure of physiological strain. The level strain measured by heart rate per minute is strongly related to the physical workload and the physical work capacity of the subject and several researchers (Bláfoss et al., 2019; Eroglu & Rahmi Yilmaz and Yildirim Kayacan, 2015; Gatti et al., 2010; Granzow et al., 2019; Hwang et al., 2016; Hwang & Lee, 2017; Ismaila et al., 2013a, 2013b; Lee et al., 2020) have used heart rate (HR) to determine physiological workload in different studies.

Resting heart is measured under the condition of no physical effort. It is best measured in the morning before any stress, caffeine or much movement. Maximum heart rate (HRmax), on the other hand, is an estimate of heart rate that someone could (not should) achieve during maximum physical exertion. A rough estimate of a person's HR_{max} can be obtained by subtracting the person's age from 220 (Wright, 2009).

$$HR_{\max} = 220 - age \text{ (in years)} \qquad 3.1$$

The Maximum Acceptable Heart Rate for a work shift of 8hr ($HR_{max(8h)}$) of the workers were determined from age-dependent maximum and resting heart (Ismaila et al., 2013a).

$$HR_{\max(8h)} = \frac{HR_{\max}}{3} + HR_r \qquad 3.2$$

Where HRr = resting heart rate, bpm

Several studies have been conducted to determine the physical workload on an operator imposed by various machines(Caliskan & Çağlar, 2010; Eroglu et al., 2015). Saraczynski(Sarzynski et al., 2013) suggested that the maximum workload is roughly indicated by achieving 85% of age-predicted maximum heart rate. The ratio of working heart rate (HRw) to resting heart rate (HRr) is obtained from (Çalişkan & Çağlar, 2010; Eroglu, Kayacan, et al., 2015; Granzow et al., 2019)

$$Ratio = \frac{HR_w}{HR_r} \qquad 3.3$$

3.1.3. Physical workload

The increase in heart rate due to work-related physical activity represents the physiological cost of work; minimizing the physical workload serves to optimize the mental workload (Broszkiewicz, 2006). The energy required to perform a specific physical workload is correlated to the Percentage Relative Heart Rate (%HRR) or Cardiovascular Stress Index (CSI) (R. Borah et al., 2010; S. Borah, 2015); this can be determined by applying the following formula that has been used by different researchers (Çalişkan & Çağlar, 2010; Hwang et al., 2016; Ismaila et al., 2013a):

$$CSI = \left(\frac{HR_w - HR_r}{HR_{\max} - HR_r} \right) \times 100 \qquad 3.4$$

Where CSI = Cardiovascular stress index, %

HRw = average working heart rate, bpm

HRmax = maximum heart rate, bpm

The Relative Cardiovascular Load (CVL) and Cardiovascular Strain (CVS) which are used to determine the physical strain of the workers were calculated using formula(Ajayeoba, 2019; S. Borah, 2015; Ismaila et al., 2013a, 2013b):

$$CVL = \left(\frac{HR_w - HR_r}{HR_{\max(8h)}} \right) \times 100 \qquad 3.5$$

$$CVS = \left(\frac{HR_w - HR_r}{HR_r} \right) \times 100 \qquad 3.6$$

Measurement of oxygen consumption or heart rate as indicators of the physical task requirements should be performed during the steady-state phase of the exercise. Under those conditions, ranges of energy and heart rate requirements allow general classifications of task "heaviness" according to physical work. The level of the work can be estimated by assuming a linear relationship between the heart rate and energy uptake. Work level can be classified as "resting" or "very light" or "light" or "moderate" or "heavy" or "very heavy" or "unduly heavy" worksummarized in Table (3.3) (Kroemer K. H.et al., 2010; Çalişkan & Çağlar, 2010).

Table 3 - 3 Classification of physical work (Kroemer K. H.et al., 2010; Çalişkan&Çağlar, 2010)

Classification	Total energy expenditure			Heart rate Beats/min	Cardiovascular stress index (%)
	kcal/min	kJ/min	8h (kcal/day)		
Resting	1.5	6	<720	50 – 60	0 – 10
Very light work	1.6 - 2.5	6.4 – 10	768 – 1200	60 – 70	10 – 20
Light work	2.5 – 5	10 – 20	1200 – 2400	70 – 90	20 – 30
Moderate work	5.0 – 7.5	20 – 30	2400 – 3600	90 – 110	30 – 40
Heavy work	7.5 – 10	30 – 40	3600 – 4800	110 – 130	40 – 50
Very heavy work	10 – 12.5	40 – 50	4800 – 6000	130 – 150	50 – 60
Unduly heavy work	>12.5	>50	> 6000	>150	>60

3.2. MATERIALS AND METHODS

A bodyweight scale was used to measure the weight of single axle tractor operators. The operators were instructed to remove their heavy outer clothing, such as jackets, coats, and shoes, for the bodyweight measurement. Because standing off-center may impact the measurement, the operator stands in the center of the weighing platform, weight distributed evenly on both feet. Each operator's height was measured using a measuring tape.

The operators' heart rates were measured by a Polar T31 Coded Heart Rate Transmitter and Belt Set via Bluetooth Heart rate sensors connected to a Polar A370 fitness tracker (manufactured by Polar Global Company) (figure 3.1). The Polar heart rate receiver wirelessly receives the heart rate signal from the Polar transmitter belt. The Polar T31 coded transmitter is slim, light and waterproof; it is worn on the chest of the operators, and electrically detects the heartbeat and transmits a pulse corresponding to each heartbeat.

Figure 3 - 1 Polar T31 Coded Heart Rate Transmitter and Belt Set with Polar A370

A Contec CMS-08A professional digital blood pressure monitor with finger pulse Oximeter manufactured by Contec Medical Systems Co., Ltd China is shown in figure (3.2). It was used to measure blood pressure and oxygen saturation of the tractor operators.

Figure 3 - 2 Finger Pulse Oximeter with a professional digital blood pressure monitors

The heart rates of the single axle tractor operators were recorded before the operation, and during operation at 5-minute intervals. Heart rate measurement data were recorded at times of 5, 10, 15, 20 and 25 minutes after the start of work, and 5 minutes after completion of work with the single axle tractor. The blood pressure and oxygen saturation of the operators were measured before work, and 5 minutes after completion of work with the single axle tractor.

Maximum age-dependent heart rate and maximum acceptable heart rate for a work shift of 8hr (HRmax (8h)) of the single axle tractor operators were calculated. The 50% level heart rate and ratio were calculated from measured and calculated data of heart rate. The ratio of working heart rate to resting heart was calculated. To determine the physical strain of the operators, the cardiovascular stress index (CSI), cardiovascular load (CVL) and cardiovascular strain (CVS) were determined from measured and calculated value heart rate. Finally, the total energy expenditure, maximum acceptable work duration and the total cardiac cost of work of operators were determined.

3.3. RESULTS

3.3.1. Anthropometric data of single tractor operators

The mean and standard deviation of anthropometric data of age, height, weight and body mass index (BMI) of seven (7) operators of single axle tractor were 25.57 ± 3 years, 1.70 m, 55.29 ± 4 and 19.15 ± 1 kg/m^2 respectively presented in Table (3.4). World Health Organization has categorized the body mass index (BMI) which is calculated as body mass in kilograms divided by the square of height in meters (kg/m^2)(Nuttall, 2015). A value of BMI less than 18.5 kg/m^2 is categorized as underweight; BMI between 18.5 and 24.9 kg/m^2 as normal body mass; BMI between 25.0 and 29.9 kg/m^2 as overweight; BMI > 30.0 kg/m^2 as obese(Elsangedy et al., 2013).

Table 3 - 4 summary data of anthropometry of single axle tractors (n = 7)

Descriptive Statistics	Age(years)	Height (m)	Weight (kg)	BMI (kg/m^2)
Mean	25.57	1.70	55.29	19.15
Standard error	1.07	0.03	1.54	0.44
Standard deviation	2.82	0.08	4.07	1.17
Sample variance	7.95	0.01	16.57	1.38
Range	8.00	0.23	10.00	3.49
Minimum	21.00	1.61	50.00	16.84
Maximum	29.00	1.84	60.00	20.32

Following the classification of body mass index, a detailed examination shows that 86 per cent of the operators fall into the “normal” class, whereas 14 per cent were in the “underweight” class.

3.3.2. Measured physiological response

1. ***Blood pressure and oxygen saturation***

The diastolic (lower) and systolic (upper) blood pressure and oxygen saturation levels of the tractor operators were measured and are summarized in table (3.5). The mean and standard deviation of measured diastolic blood pressures of the seven tractor operators, before and after operation of the tractor, was 73 ± 7 and 77 ± 9 mmHg respectively; the mean and standard deviation of measured systolic blood pressure of the seven tractor operators, before and after tractor operation were 122±12 and 119±7 mmHg, respectively.

The average measured oxygen saturation levels of the seven tractor operators decreased from 98±1 % to 96 ±1 %; these levels are within the normal range.

Table 3 - 5 Descriptive statistics of blood pressure and oxygen saturation of single axle tractor operators (n = 7)

Descriptive statistics	*Blood pressure (mmHg)*				*Oxygen saturation (%)*	
	Before operation		*After operation*			
	Diastolic	*Systolic*	*Diastolic*	*Systolic*	*Before*	*After*
Mean	73.33	121.67	76.67	119.17	97.83	95.83
Median	73.33	120.00	80.00	120.00	98.00	96.00
Standard Deviation	7.45	12.13	9.43	7.31	1.07	1.07
Sample Variance	55.56	147.22	88.89	53.47	1.14	1.14
Range	20.00	40.00	30.00	20.00	3.00	3.00
Minimum	60.00	100.00	60.00	110.00	96.00	94.00
Maximum	80.00	140.00	90.00	130.00	99.00	97.00

From table (3.5), the mean diastolic blood pressure has shown an increase of 3.34 mmHg after tractor operation; the mean systolic blood pressure has shown a decrement of 2.50 mmHg after the operation. The average measurements of oxygen saturation of single axle tractor operators were decreased [mean (±SD)] from 98 (1.07 %) to 96 (1.07 %); this is within the normal range of oxygen saturation.

2. *Heart rate*

Single axle tractor operators' heart rates were measured 5 minutes before the operation, every 5 minutes during operation for 25 minutes, and after the operation of a single axle tractor. The data are summarized in table (3.6) below.

Table 3 - 6 Basic statistical data analysis of the heart rate of single axle tractor operators (n=7)

Descriptive statistics	Operators heart rate [bpm]						
	Resting heart rate	*Working heart rate*					*Recovery heart rate*
	BO	DO1	DO2	DO3	DO4	DO5	AO
Mean	71.14	161.71	164.86	167.86	161.29	155.29	126.29
Median	72.00	161.00	165.00	167.00	169.00	158.00	128.00
Standard Deviation	7.95	19.55	14.93	10.32	14.03	22.53	25.98
Sample Variance	63.14	382.24	222.81	106.48	196.90	507.57	674.90
Range	24.00	57.00	45.00	24.00	39.00	62.00	84.00
Minimum	57.00	145.00	150.00	158.00	140.00	113.00	88.00
Maximum	81.00	202.00	195.00	182.00	179.00	175.00	172.00

BO = before operation, DO = during operation (1, 2, 3, 4, 5), AO = after operation of single axle tractor

From the statistical data in Table (3.6) of measured heart rate of single axle tractor operators, the mean measured resting heart rate before the operation of single axle tractor was 71 ± 8 bpm; the mean measured working heart rate were 162 ± 20, 165 ± 15, 168 ± 10, 161 ± 14 and 155 ± 23 for every five (5) minutes interval record during the operation of tractor - these yields a mean value of 162 ±4 bpm; and finally the mean measured heart rate after the operation was found to be 126 ± 26 bpm.

3.3.3. Physiological workload

The physiological workload was classified based on the working heart rate. The cardiovascular stress index (CSI) (physical workload), cardiovascular load (CVL), and cardiovascular strain (VSL) were determined in this study based on heart rate at rest, during work, and recovery heart rate.

Using equation (3.1) the age-dependent predicted maximum heart rate was found to be 194 ± 3 bpm for the seven tractor operators. From the measurement of the heart rate of the single axle tractor operators, the physiological workloads were calculated. The average estimated cardiovascular stress index determined from equation (3.2) was 74 ± 4%.

The mean calculated maximum acceptable heart rate for a work shift of 8h (*HR*max (8h)), was found to be 136 ± 8 bpm. The mean ratio of working heart rate to resting heart rate for our seven tractor operators using equation (3.5) was found to be 2.31 ± 0.42. The mean cardiovascular strain and cardiovascular load were found to 131 ± 42 and 68 ± 17 % respectively (Table 3.7).

Table 3 - 7 calculated value of physiological workload (n = 7)

Descriptive statistics	HRmax [bpm]	HRmax(8h), [bpm]	CSI, [%]	Hw/HR$_r$ ratio [%]	CVS, [%]	CVL [%]
Mean	194.43	135.95	73.52	2.31	131.26	67.57
Standard Error	1.07	3.05	3.91	0.16	15.76	6.31
Median	194.00	136.00	76.11	2.17	117.22	63.72
Standard Deviation	2.82	8.07	10.36	0.42	41.69	16.69
Sample Variance	7.95	65.07	107.26	0.17	1737.79	278.71
Range	8.00	23.00	32.31	1.25	125.01	51.85
Minimum	191.00	122.67	57.83	1.96	96.39	51.03
Maximum	199.00	145.67	90.14	3.21	221.40	102.88

HRmax = maximum heart rate, CSI = Cardiovascular Stress Index, HRw = working heart rate, HR$_r$ = resting heart rate, *HR*max (8h) = maximum acceptable heart rate for a work shift of 8h, %CVL = relative cardiovascular load, %CVS = cardiovascular strain

3.4. DISCUSSIONS

3.4.1. Anthropometry analysis

The mean Body Mass Index (BMI) which is a measure of obesity and defined as weight in kilograms divided by height in meters squared was 19.15 kg/m^2;this was in the normal category of BMI. Similar results of 19.8 kg/m^2 were obtained by Biswas & Samanta,(Biswas & Samanta, 2006) while determining the magnitude of the physiological strain of the fishermen in the actual situation of works. However, the results found in this study were very small when compared with different researchers in various works,(Çalişkan & Çağlar, 2010; Ismaila et al., 2013a; Melemez & Tunay, 2010) which their research finding value varied from 22 to 25 kg/m^2

3.4.2. Analysis of physiological response to vibration

1. ***Blood pressure***

The significance level of α was chosen at the outset of the experiment. Most often $\alpha = 0.05$ by convention. The critical values are found from the *F* table. The p-value specified as Prob>F with a confidence level of 95%, then the value of alpha (α) was found by subtracting 0.95 from one (1) that is $1 - 0.95 = 0.05$. If the p-value >α indicates that there is no substantial difference in the mean, or if the p-value <α indicates that there is a significant difference in the mean.

The analysis of diastolic blood pressure before and after tractor handle vibration exposure using two-way ANOVA was summarized in table (3.9). The column Prob>F shows the p-values of single axle tractor operators diastolic blood pressure for the vibration exposure before and after operation of single axle tractor (0.5517). The column Prob>F > α value indicates that the means of the diastolic blood pressure of single axle tractor operators before and after operations are not significantly different.

Table 3 - 8 ANOVA table of diastolic blood pressure before and after operation of single axle tractor

Source	ss	df	MS	F	P-value
Columns	28.571	1	28.5714	0.37	0.5517
Error	914.286	12	76.1906		
Total	942.857	13			

The column Prob>F shows the p-values of single axle tractor operators systolic blood pressure for the vibration exposure before and after operation of single axle tractor (0.59) as shown in

Table (3.10). The column Prob>F > α value indicates that the means of the systolic blood pressure of single axle tractor operators before and after operations are not significantly different.

Table 3 - 9 ANOVA table of systolic blood pressure before and after operation of single axle tractor

Source	ss	df	MS	F	P-value
Columns	31	1	31.002	0.31	0.59
Error	1213.69	12	101.141		
Total	1244.69	13			

2. Oxygen saturation

From ANOVA table (3.11) below the column Prob>F shows the p-values of single axle tractor operators heart rate for the vibration exposure before, during and after operation of the single axle tractor (0.0043). The column Prob>F value ($p < 0.05$) indicates that the means of the oxygen concentration of single axle tractor operators before and after operations are significantly different.

Table 3 - 10 ANOVA table of oxygen saturation before and after operation of single axle tractor

Source	ss	df	MS	F	P-value
Columns	14	1	14	12.29	0.0043
Error	13.6667	12	1.13889		
Total	27.6667	13			

The box plots are used to display the overall patterns of the operator's oxygen saturation response to the single-axle tractor handle vibration. Figure (3.3) shows that the two medians of oxygen saturation before and after handle vibration exposure of single axle tractor shown at the centre of the box and that do not overlap are significantly different at the 5% significance level.

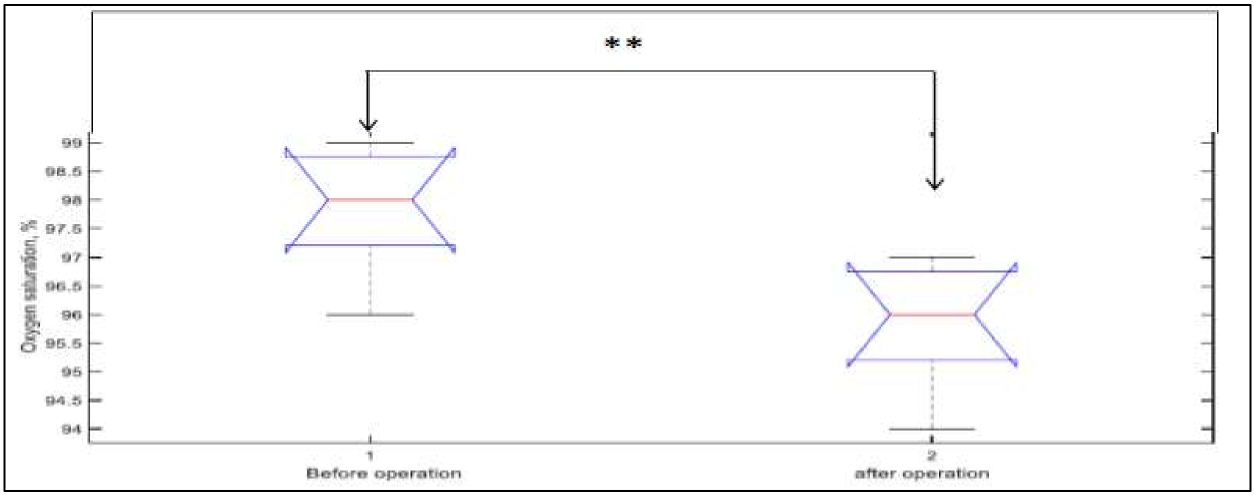


Figure 3 - 3 boxplot of the oxygen saturation of single axle tractor operators

** Significant difference, p < .005

3. Heart rate

Resting heart rate

The average measured resting heart rate for our 7 tractor operators of 71 ± 9 bpm was within the normal range of normal resting heart rates of 60 – 100 bpm (Hwang et al., 2016). Several studies have been conducted to evaluate the physiological workload of different machinery operators and similar results were found. Similar measurements by various researchers (Adeodu A. O, 2014; Çalişkan & Çağlar, 2010; Eroglu et al., 2015; Hwang et al., 2016; Ismaila et al., 2013a; Melemez & Tunay, 2010) yielded values from 60 to 79.6 bpm for operators of different machines. However, Kirk & Sullman,(Kirk & Sullman, 2001) has found the resting heart of 58 bpm of cable haulier choker setters while measuring physical strain in commercial forest harvesting operations. Abrahão, et al., (Abrahão et al., 2014) have found the resting heart rate in the range of 52 to 64 bpm during the characterization of the physical workload of the organic horticulture by determining the frequency of exposure of operators to some selected activity categories.

Maximum Acceptable Heart Rate ($HR_{max\ (8h)}$)

The Maximum Acceptable Heart Rate for a work shift of 8hr ($HR_{max\ (8h)}$) of the single axle tractor operators determined from age-dependent maximum and resting heart varied from 123 – 146 bpm and the mean value of 136 bpm were compared with different research findings. Ajayeoba, (2019) has conducted to assess the risk, the postural and physical strain of sawmill workers' found the

Maximum Acceptable Heart Rate for a work shift of 8hr (HRmax (8h)) for the classification of workers under Machine Operators (MOs), Mill Workers (MWs), Dust Parkers (DPs); and Machine Maintenance Personnel (MMPs) varies 117– 139 bpm, 115 – 135 bpm, 109 – 141 bpm and 113 – 135 bpm respectively.

Working heart rate

The average measured working heart of our seven single-axle tractor operators was 162 ± 4 bpm; and this value is very high compared to the result of 106 bpm found by Kirk &Sullman, (Kirk & Sullman, 2001). Tiwari& Gite, (Tiwari & Gite, 2002) evaluated the physiological responses during power tiller operations of rototilling and rotapuddling; they found the mean values of working heart rate were 110 and 119 bpm respectively and they have concluded that the physiological responses vary with power tiller forward speeds. Melendez & Tunay, (Melemez & Tunay, 2010) has observed the effect of vibrations on the tractor --operator; it has a direct impact on the heart rate and increases as the vibration increases. Operators complain when their heart rate increases further to more than 90 bpm. Tewari, et al.,(Tewari et al., 2004) has conducted a study to evaluate the effect of vibration on operators by comparing the new seated position with the effects of the standard design where the operator walks behind hand tractor, they have observed the higher heart rate with higher vibration in cases of walking behind the tractor.

According to Davood Afshari et al., (Davood Afshari et al., 2016) in the study of the determination of work-rest schedules based on the physical workload, they categorized the workload with working heart rate above 160 bpm as “unduly heavy work”. As seen from the result the handle vibration of single axle tractor resulted in increasing of the operators working heart rate and it was over the recommended limit of 110 bpm for an 8-h work shift (Ismaila et al., 2013a).

For further investigation of the effect of vibration on operators, heart rate before, during and after vibration exposure were compared for a significance level of difference using ANOVA analysis. Due to vibration exposure, the Prob>F column shows the p-values of the heart variance of single axle tractor operators. Heart rate resting, heart rate working and heart rate recovery were compared, and the findings showed a substantial difference in p-values (p<0.0001) and this showed that there are significantly different ways of heart rate resting, heart rate working and heart rate recovery after the operation.

Table 3 - 11 ANOVA table of the heart rate of single axle tractor operators (n=7)

Source	ss	df	MS	F	P-value
Columns	29417.4	2	14708.7	46.67	7.5457e-08
Error	5673.1	18	315.2		
Total	35090.6	20			

From the ANOVA table (3-12), the p-values of the heart rate of single-axle tractor operators were compared for vibration exposure before and after single-axle tractor operation. The results showed that there was a large difference in p-value ($p<0.0001$) when the resting heart rate was compared to the working heart rate. Between the working heart rate and recovery (heart rate after the operation), it has shown that there is a significant difference between the results with different p-values ($p < 0.0001$). Finally ($p <0.0001$) when resting heart rate compared with heart rate after operation of a single axle tractor. In all cases, the means of resting heart rate, heart rate during and after operations are significantly different.

As seen from a table (3.12), even though the p-value is very small and less α or 0.05, it does not indicate in what ways the mean is different. But the box plots are used to show overall patterns of operators' heart rate responses to the handle vibration of single axle tractor. They provide a useful way to visualize the range and other characteristics of responses for a large group. All the seven medians of heart rate before, during and after single axle tractor handle vibration exposure are significantly different at the 5% significance level and their intervals do not overlap. In general, the effect the single axle handle vibration has an impact on the operators' heart rate and made large variance between the measured mean heart rate. Figure (3.4) indicates the heart rate of operator pre-vibration exposure compared to during vibration exposure or operation and also compared to the heart rate after single-axle tractor operation, the heart rate during vibration exposure or operation compared to the heart rate after vibration exposure or single-axle tractor operation.

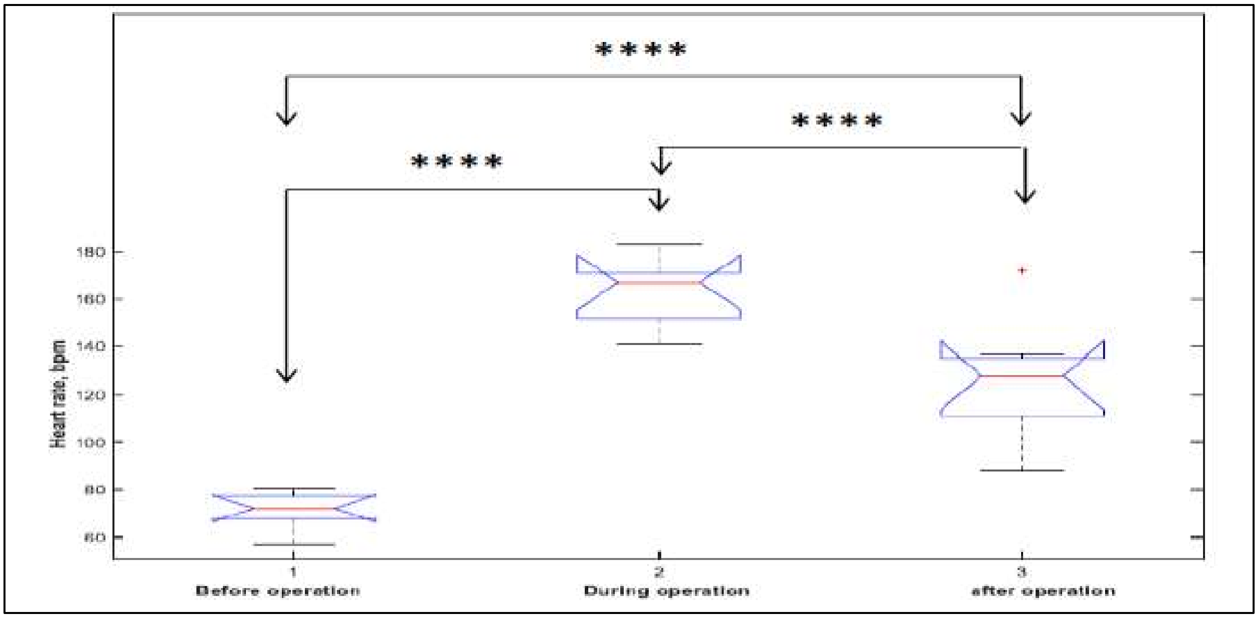


Figure 3 - 4 Box Plot result of two-way ANOVA for the averaged measurements of operators

**** Significant difference, $p < .00001$

ANOVA results have shown that the single axle tractor handle vibration has a strong statistically significant effect on operators. From the measurement of vibration, it was found that the single axle tractor handles vibration varies from person to person, and this has an effect on the difference in heart rate, and there has been a rise in heart rate as the vibration of the handle increases during the operation of the single axle tractor due to the vibration exposure of the handle. The MATLAB regression learner was used to test the relationship between the control vibration and the heart rate of the operator as shown in Figure (3.5).

The single tractor handle vibration total value and operators' heart rate have a very strong positive correlation: as the tractor handles vibration total value increases the heart rate increases linearly. This positive correlation can be expressed by using the regression equation of $HR = 2.6403V + 80.959$, with linear regression R-sq. = 0.928, where V is handle vibration.

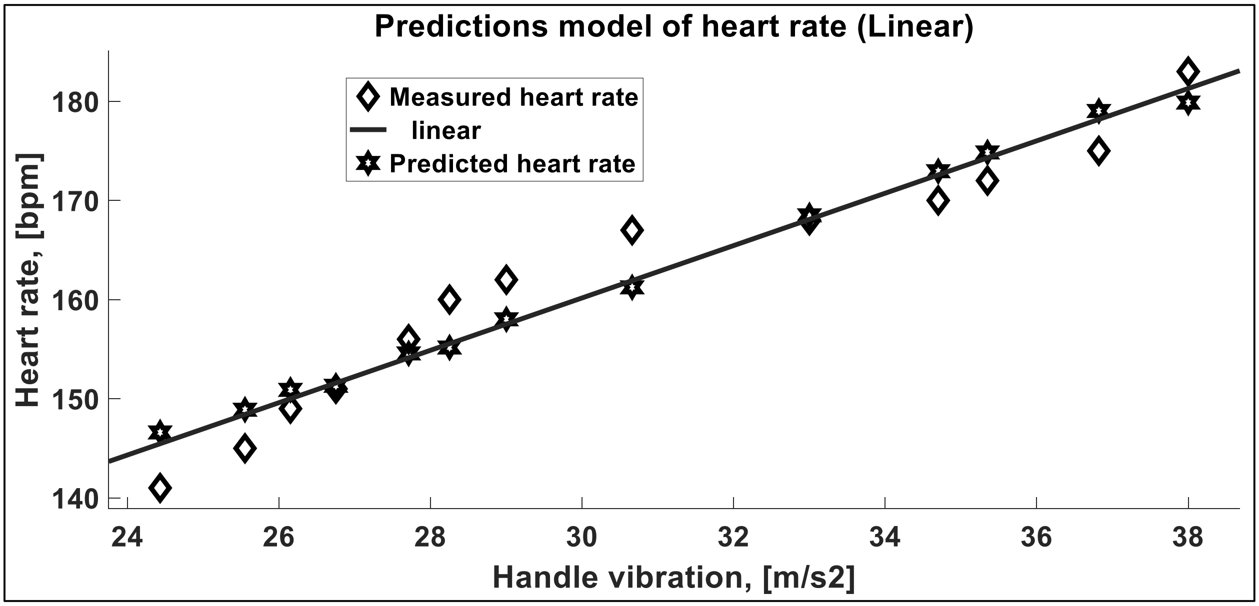


Figure 3 - 5 Relationship heart rate and single axle tractor handle vibration

Walking behind a single axle tractor controlling its operation is a tiresome task that imposes a heavy workload on the operator resulting in fatigue due to the presence of high vibrations. Statistics from the forecast model were found and presented in Table (3.13), as shown in the table; the mean heart rate measured was similar to the predicted value.

Table 3 - 12 data statistics measured and predicted heart rate of single axle tractor operators [n = 7]

Data statistics	Handle vibration [m/s^2]	Heart rate [bpm]	
		Measured	Predicted
Minimum	24.43	141	146.6
Maximum	38	183	179.9
Mean	30.49	161.5	161.7
Median	29	162	158
Mode	24.43	141	146.6
Standard deviation	4.592	15.55	11.9
Range	13.57	42	33.27

The handle vibration is above the limit and the operation of the tractor is under stressful and the muscular energy metabolism much higher and consumes much oxygen and hence the fatigue will appear in early operation. A longer period of this vibration exposure leads the operators to the physiological damage. Studies indicated that vibration has a direct effect on the heart rate of tractor operators with a positive relationship (Muzammil et al., 2004), and its exposure consistently associated with the elevated risk of cardiovascular disease (CVD) which is the main mortality cause worldwide(Dzhambov and Donka, 2016). As has indicated in a study of Rosenberger et al.,(Rosenberger et al., 2014) it was observed that there is an increment of heart rate and RMS value as an increment of hand-arm vibration levels.

As observed from measured and calculated higher heart rate the long-term single axle tractor vibration exposure may lead to increased occurrence of symptoms and sign of disorder in the muscular, neurological and musculoskeletal systems of the upper limbs since workers performing jobs in the agricultural industry, animal husbandry, and crop production and maintenance are likely to be exposed to Hand-Transmitted Vibration (Bovenzi, 2006; K. Krajnak, 2019). The performance of the operators may be reduced by affecting their motor control; the vibration may make it difficult to maintain control over the instrument or tool being used and affect tactile sensation. Both short and long term exposure to hand-arm vibration may cause a loss of sensitivity in the fingers and hand.

Resting heart rate ratio

The ratio of working heart rate to resting heart rate for our seven tractor operators was found to be 2.28 ± 0.39, compared to the value of 1.74 in a study of Çalişkan & Çağlar, (Çalişkan & Çağlar, 2010)during the examination of the physical strain experienced by chainsaw operators and the applicability of heart rate indices for measuring physical strain in forest felling operations in the northeastern region of Turkey. Eroglu, et al.,(Eroglu, et al.,2015) has found the ratio of working heart rate to resting heart rate to be 1.76 and 1.62 forForest Harvesting and Nursery-Afforestation Workers respectively. Other researchers (Borz et al., 2019; Granzow et al., 2019) have found the ratio of working heart to resting ratio varies from 1.4 to 1.56.

3.4.3. Analysis of physical workload

Heavy work is any activity that calls for great physical exertion and is characterized by high energy consumption and severe stresses on the heart and lungs. Energy consumption and cardiac effort set limits to the performance of heavy work and these two functions are often used to assess the severity of a physical task. The physiological workload is a parameter which shows the pressure that the worker encounters during working based on the heart rate frequency. Heart rate frequency is related to oxygen consumption and can be used for the determination of physical workload. Physical workload or physical load at work which causes musculoskeletal disorder either of the following categories: forceful work and manual handling, repetitive work, static load, awkward postures and vibrations(Okunribido et al., 2008). To assess the vibration effect, it is important to determine the physical workload of the single axle tractor operators, the cardiovascular stress index, the relative cardiovascular load and the cardiovascular strain were evaluated based on measured and determined heart rate results.

1. *Cardiovascular stress index (CSI)*

The average estimated cardiovascular stress index (CSI) using equation (3.3), which is an indication of physiological or level of physical activity of the tractor operators, was 74% in our study; this work level is in the category of "unduly heavy work" grade. Similar results of 72 – 83% for maximum work rate were found by Wu & Wang, (H. C. Wu & Wang, 2001) in their study of determining maximum acceptable work duration for the high intensity of work. Wu & Wang, (H. C. Wu & Wang, 2002) also found a similar result of 65% during the evaluation of the relationship between the maximum acceptable work time and physical workload; they considered that a (CSI) level over 30% during work as high physical demand.

As the result of the high amplitude of vibration-induced from the handle of single axle tractor to the hand of operators, the cardiovascular stress index exceeded the three values of threshold (24.5%)(H. C. Wu & Wang, 2002)as an acceptable level for an 8-h workday, the recommended value (30%) (Shimaoka et al., 1998)and permissible value (40%) (Nejka Potočnik et al., 2017).

The relationship between the cardiovascular stress index and single axle tractor handle vibration was compared and it has a strong positive relationship, as the single-axle handle vibration increases the cardiovascular stress index will also increase as shown in figure (3.6) with a linear relationship of equation $CSI = 1.9775V - 12.725$, with linear regression R-sq. = 0.83, where V is handle vibration.

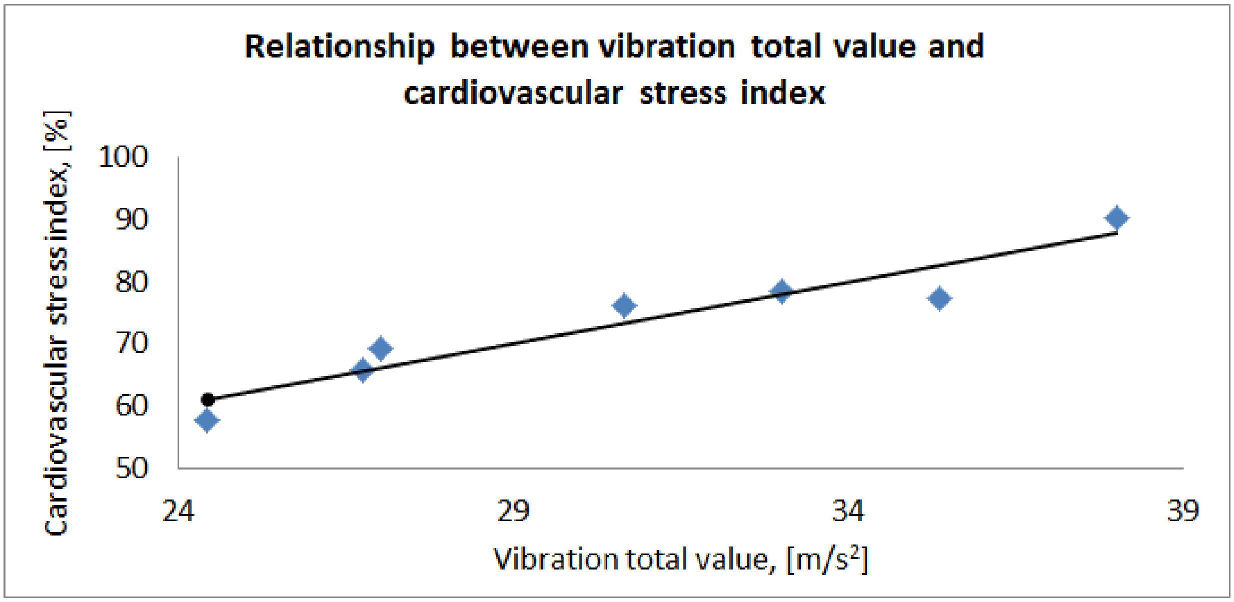


Figure 3 - 6 Relationship between cardiovascular stress and single axle tractor handle vibration

2. *Relative Cardiovascular load (CVL)*

The relative cardiovascular load determined in this study varied from 51 – 103% with the mean of 68% and this is in the range of "high level" and therefore, vibration peak load should be reduced within a few weeks. Similar results of 69% as median was found by Ismaila, et al., (Ismaila et al., 2013a) while assessing cardiovascular strain during sawmilling operations in terms of physical workload, based on heart rate. The category of relative cardiovascular load with action required was presented in several studies. The relative cardiovascular load (CVL) was categorized as CVL < 30%: acceptable level, no action required; CVL from 30% – 59%: moderate level, peak loads should be reduced within a few months; CVL from 60% – 99%: high level, peak loads should be reduced within a few weeks; CVL = 100%: intolerable high level, peak loads should be reduced immediately or work must be stopped(Ismaila, et al., 2013a; Sari, et al., 2016).

3. *Cardiovascular strain (CVS)*

The mean cardiovascular strain found in this study is "very high" that is in the range of 121-150% and "action is required within a few days"; the category of cardiovascular strain classified as CVS from 0% – 50%: acceptable, no action required; CVS from 51% – 80%: moderate, action required within a few months; CVS from 81% – 120%: high, action required within a few weeks; CVS from 121% –150%: very high, action required within a few days and CVS from151% – 180%: intolerable, action required immediately (Ismaila et al., 2013a; Sari et al., 2016). Ajayeoba, (Ajayeoba, 2019) has found the cardiovascular strain (CVL) varies from 59 – 160, 63 – 172, 47 – 168 and 48 – 160 % for the classification of workers under Machine Operators (MOs), Mill Workers (MWs), Dust Parkers (DPs); and Machine Maintenance Personnel (MMPs) respectively during the assessing the risk, postural and physical strain of sawmill workers.

3.5. CONCLUSION

The mean measured diastolic blood pressure before and after vibration exposure was increased from 73 to 77 mmHg with the value of increment of 4 mmHg. However, the p-value > α ($p > 0.05$) indicates that the means of the diastolic blood pressure of single axle tractor operators before and after operations are not significantly different.

The mean measured systolic blood pressure decreased from 122 to 119 mmHg after vibration exposure. However, the p-value > α indicates that the means of the systolic blood pressure of single axle tractor operators before and after operations are not significantly different.

The mean measured heart rate of single axle tractor operators' were measured at rest, during and after operation of single axle tractor. The mean measured resting heart rate was 71 ± 8, beat/min; the mean measured heart rate during operation with an interval of 5 minutes was 162 ± 20, 165 ± 15, 168 ± 14 and 155 ± 23 beats/min and finally the mean measured heart rate after the operation was 126 ± 26 beats/min. As seen from the results the single axle handle vibration and heart rate of operators' has a positive strong relationship, which indicated that the heart rate of operators' increase as a result of increases in handle vibration.

The calculated physiological workload such as age-dependent maximum heart rate, maximum acceptable heart rate for a work shift of 8 hours ($HR_{max\ (8h)}$), cardiovascular stress index, relative cardiovascular load, and the cardiovascular strain was found to be 194 ± 3 bpm, 136 ± 8 bpm, 74 ± 10%, 68 ± 17% and 131 ± 42% respectively.

The calculated cardiovascular stress (CSI) value 74 ± 10 % is much higher than the recommended threshold value of 24.5% which is an indicator of physical workload that is related to muscular activities due to the exposure of single axle tractor handle vibration.

From both measurements and analysis of operators' heart rates, it was concluded that the physical workload fell into the category of extremely heavy work, for which the working heart rate more than doubled compared to the resting heart rate ($p < 0.0001$). This very high physical workload has a strong impact on operators of single-axle tractors over extended periods and may lead to the risk of different musculoskeletal disorders. Results of physiological parameters in this study have indicated the operators of single axle tractor are in risk to various signs and symptoms of the physiological disorder such as impeded blood circulation to the fingers and 'attacks' of blanching on one or more digit due to prolonged and regular exposure of the fingers or the hands to single axle tractor handle vibration.

CHAPTER FOUR: EVALUATION OF BIODYNAMIC RESPONSES OF SINGLE AXLE TRACTOR OPERATORS TO HAND-ARM VIBRATION

4.1. THEORETICAL BACKGROUND

The mechanical equivalent effect due to a dynamic input such as the effect of instrument vibration on hand (R. G. Dong et al., 2008) is biodynamic responses on human segments such as tissue tension, tissue strain, apparent mass/driving point mechanical impedance, power absorption, vibration transmissibility and muscle activity (Electromyography) (EMG).Exposure to vibration can cause severe distortion or very high tissue strain that causes permanent tissue damage, and under serious circumstances, it is also known to cause muscle and nerve damage. The muscle activity or grip strength and vibration transmissibility have been considered among the presented biodynamic responses to determine the impact of hand mediated vibration (R. G. Dong et al., 2010; Kumar et al., 2018).

Knowledge of grip action between hand-tool is essential in determining the vibration transmission. Grip force, posture, contact area, hand size, etc., are significant contributors to the dynamic response of the hand. Grip type and posture of the hand-arm system affects the force transmission to the hand as well as the force-producing capacity of muscle and handling of the tool and comfort level(Widia & Dawal, 2011). Working activities that required the hand-held machine used the strength of the worker both hands able to reduce handgrip strength. Workers exposed to hand-arm transmitted vibration sometimes report difficulty with their grip, including reduced dexterity, reduced grip strength, and locked grip (Bohannon, 2019; Leong et al., 2016; Massy-Westropp et al., 2011; Meiring et al., 2013; Ranjan Pradhan et al., 2019).

4.1.1. Grip strength

Muscle activity can be of great significance to tool users because the success of the job and the secure control of the tool can require a safe grip. The presence of vibration on a handle will allow a stronger grip to be adopted than would otherwise occur and a tight grip will improve the vibration transmission to the hand. If the chronic effects of vibration result in reduced grip, this may sometimes help to protect operators from further effects of vibration, but interfere with both work and leisure activities(Merino et al., 2019; Widia & Dawal, 2011). Loss of handgrip power disability on both hands to be a significant occupational disease issue in hand-borne vibration sensitivity practices for both forms of vibrating devices. This condition causes decreased efficiency and productivity, low workplace satisfaction, higher medical costs, and compromised occupational safety and health(Ali et al., 2015).

Handgrip strength dysfunction caused by exposure to vibration is a major risk factor associated with hand-arm vibration syndrome (HAVS). The physical hazard was directly contacted by the vibration source of the system and transmitted to the staff by hand as a receiver. In general, work using vibration equipment should be removed or replaced with less exposure to vibration risk (Ali et al., 2015; Michael J. Griffin, 2008; ILO, 2011). However, the typical trend in the agriculture sector to reduce risk has been followed by management control, either by a decrease in working time or by an increase in the number of employees to complete the operation (ILO, 2011; Smith &Pillarisetti, 2017). Vibration sensitivity may be minimized by minimizing hand-borne vibration and/or the time spent carrying vibrating equipment or workpieces, and it is important to examine significant factors that lead to HAVS and modify procedures or activities to minimize symptoms. Occupational Safety and Health has reported that hand-arm vibration has become a major issue; it can be very dangerous and contribute to human health as well as production performance. Therefore, to calculate and determine safe levels of human sensitivity to vibration, it is important to assess and examine the characteristics of vibrations and their effect on muscle function, such as grip strength and vibration transmutability.

Operators of single-axle tractors are exposed to significant amounts of hand vibration over many hours of farming. The hand-tractor coupling forces from pushing and gripping are the key quantities for measurement of hand-transmitted vibration; they need to be measured continuously during the tests of physiological effects (Adewusi et al., 2010; Dewangan & Tewari, 2008; Goglia et al., 2006, 2011). According to a study(Michael J. Griffin, 2008a), the transmission of vibration is largely determined by the dynamic response of the hand; this, in turn, depends on the physical characteristics of the individual hand, the contact area, grip strength, push force, posture, etc. The effect of these variables can be quantified by calculating the energy consumed by the hand instead of the frequency of the vibration on the tool handle (Mcdowell et al., 2013).

The friction forces tangential to the surface of the handle are related to the grip strength from the usual grip touch resistance to the handle surface. (Ambike et al., 2014; Solnik et al., 2014). Measurements of vibration absorption are not only influenced by vibration intensity but also by frequency, transmission direction, grip and feed forces, and hand-arm postures. The technique normally used to determine the quantity of absorbed energy in the hand-arm system is based on measurements, made as close as possible to the surface of the hand, of vibration force, velocity, and phase between these parameters(Adewusi et al., 2010).

Long-term exposure to vibration from vibratory instruments results in muscle weakness, which affects grip strength, and the study conducted on various occupational groups such as cleaners, dental hygienists, dental technicians, dentists, drivers, metal workers, and wood product assemblers showed that numbness and loss of grip strength were the most common symptoms (Gerhardsson et al . 2013). Grip strength can be used as a quantitative measure of the quality of a user's sensorimotor ability; it also serves as an indicator of the applicability of the interface for the given task. Schlüssel et al., (Schlüssel et al., 2008) defined the grip strength as the integral of the contact pressure over the whole hand and handle contact surface; it was stated that the topic is receiving increasing attention from industrial engineers and ergonomics researchers. Research has shown that anthropometric measures such as gender, age, body weight, body mass index (BMI), dominant hand, hand length and hand width are associated on average with individual maximum handgrip strength (Hepping et al., 2015; Öcal Kaplan, 2016; Ploegmakers et al., 2013). The transfer of vibration energy to the hand is primarily impacted by the contact forces between the hand and grasping areas (R. G. Dong et al., 2014).

In addition to the direct increase in hand vibration level with grip strength; the muscle tension causes phase shifts in the vibration(R. G. Dong et al., 2005) has shown that the operators of vibratory tools such as impact hammers, grinders, and pneumatic hammers exert high grip strengths that increase the transfer of vibration energy to the operators. According to Dong et al., (R. G. Dong et al., 2008) grip strength measurements usually depend on the orientation of the measurement axis and that the maximum value may be substantially different from the minimum value in a given gripping action. Grip strength is an indication of the overall strength capacity and muscle weakness determined by the grip strength measurement evaluation (Whitney & Peterson, 2019).

Workers who apply repeated forceful gripping and pushing forces to the handles of vibratory tools can be at risk of developing circulatory, neurological, or musculoskeletal disorders. These conditions have been grouped as hand-arm vibration syndrome (HAVS) (Shen, 2017) collectively. Liao (Liao, 2016) has determined that the strength of the handgrip is a predictor of upper extremity function deterioration and changes in muscle strength, physical movement and ability to perform daily living activities.

Of particular concern is muscular fatigue resulting from repetitive activities of the hand. After a sufficiently intense and prolonged period of exercise, the mechanical output of skeletal muscles declines. Fatigue can be described as a gradual decrease in muscle performance during exercise (Sundstrup et al ., 2016), or a decrease in the ability to exert muscle force or power induced by exercise (Law &Avin, 2010). In cases where the operator uses maximum force, or experiences high-frequency fatigue, the maximum grip strength available generally shows a rapid decline during work; however, there is generally a rapid recovery from this type of fatigue (Law & Avin, 2010). Several researchers (Alkurdi & Dweiri, 2010; Bautmans et al., 2007; Sundstrup et al., 2016)defined fatigue resistance for each hand as the time for grip strength to decrease to 50 % of its maximum value

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Bautmans et al., (Bautmans et al., 2007) defined “grip work” (GW) to be the integral of grip strength (GS) over the Fatigue Resistance time (FR), where the FR is the time for grip strength to decrease to 50% of its maximum value (Figure 4.1).

$$GW \approx 0.75 \times GS \times FR \qquad 4.1$$

Where GW = grip work

GS = maximum grip strength

FR = fatigue resistance

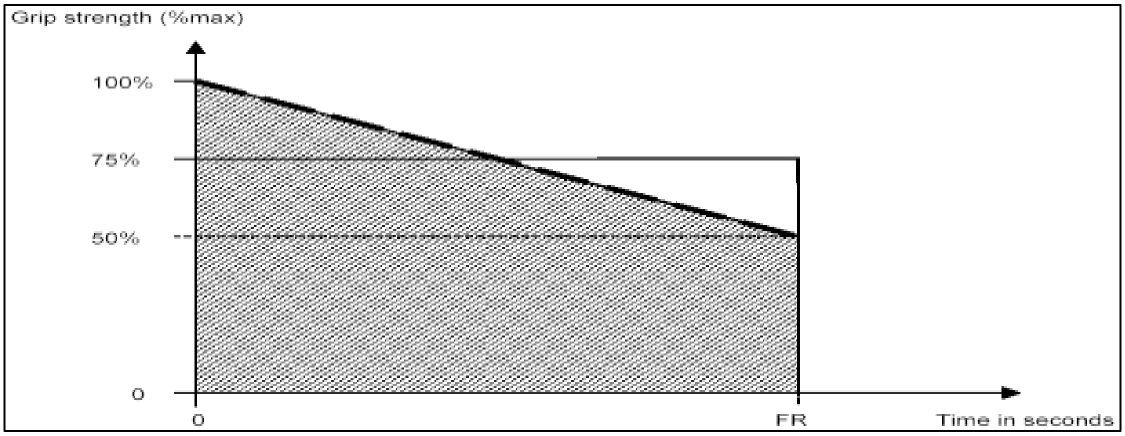


Figure 4- 1 Schematic representation of grip work (Bautmans et al., 2007)

The strength decrement index (SDI) was defined by Endurance, which is the fractional decrease in Grip Strength due to fatigue calculated with a formula proposed by Clark et al. (1955) (Figoni, 2009):

$$SDI = \frac{IS - FS}{IS} \times 100 \qquad 4.2$$

Where IS = initial grip strength

FS = final grip strength

4.1.2. Vibration transmissibility

Among other biodynamic responses, the vibration transmissibility is studied by many researchers where the vibration input vs. accelerations at various locations on the body as output is measured, using several techniques ranging from simple accelerometers to Laser Doppler Vibrometers(Picu, Mihaela and Galati, 2013). According to Tewari et al.,(Tewari et al., 2013) the vibration transmissibility (V.T.) defined as the ratio of the vibration measured on hand-arm/whole body system to the hand tool input vibration:

$$V.T. = \frac{a_h}{a_{hv}} \qquad 4.3$$

Where a_h = vibration measured at the hand (m/s^2)

a_{hv} = vibration measured at the handle (m/s^2)

Mechanical equivalent or biodynamic modelling of the hand-arm system along with tool can be a very effective way of evaluating the tool vibration effect both in analytical form as well as in conjunction with experimental work(R. G. Dong et al., 2013; Wen et al., 2019). Fingertip and rest of the hand-arm system are very complex anatomical structures, consisting of various components such as the skin layers (epidermis and dermis), subcutaneous tissue, bone, nail, tendon, muscles, joint structure with ligaments and synovial fluid, cartilage, sheath etc. Each of these components is mechanically distinct, and hence presents a challenge in creating a combined model. These parameters need estimation from invasive experiments, which vary from place, age, gender, work history, to add to the complexity. Therefore, to address specific biomechanical responses, different modelling techniques are needed. An evaluation of the models required the construction of a Human-Tool system physical models. The human models specified in the ISO 10068:2012 standard (ISO10068, 2012) were used for this purpose – model 1 (annexe B) and model 2 (annexe C) (ISO10068, 2012). Models of Human-Tool systems shown in Fig. 4.2 are the result of combining physical models in the ISO standard (ISO 10068, 2012) (Dobry & Hermann, 2015) with a model of a power tool.

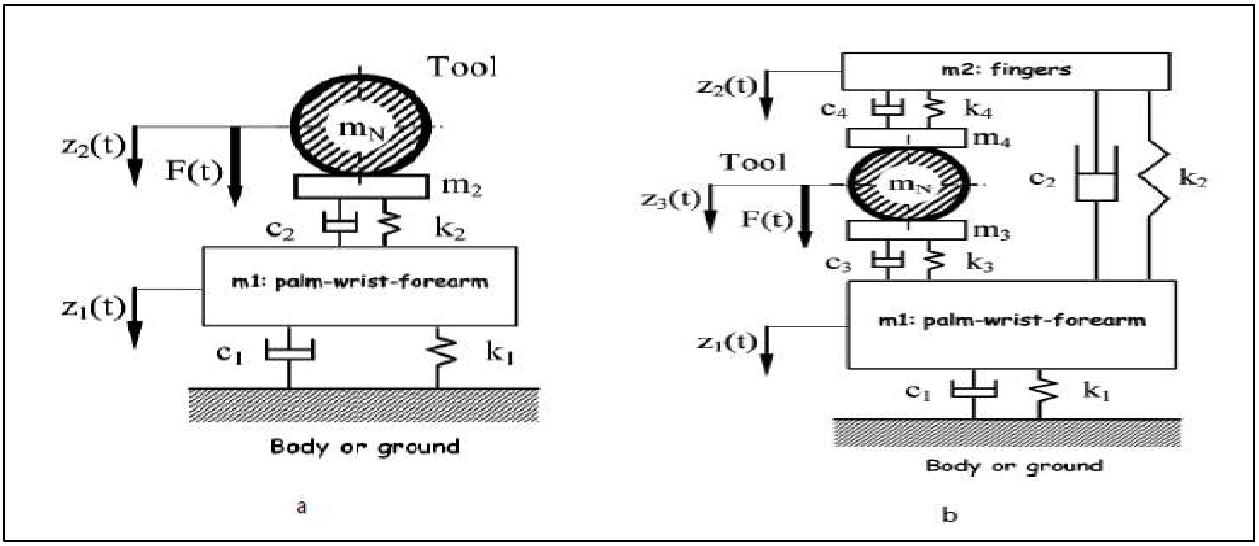


Figure 4- 2 The ISO 10068:2012-based human physical models and the tool model: a) model 1 – annexed B; b) model 2 – annexe C (ISO10068, 2012) (Dobry & Hermann, 2015)

The third model hand-arm system model used to simulate hand transmitted vibration used in this study was 4- DOF model which was recently proposed by a few researchers (R. G. Dong et al., 2007, 2008, 2013; Kamalakar & Mitra, 2018; Wu et al., 2017) and this model combines the human body with the model of the tool.

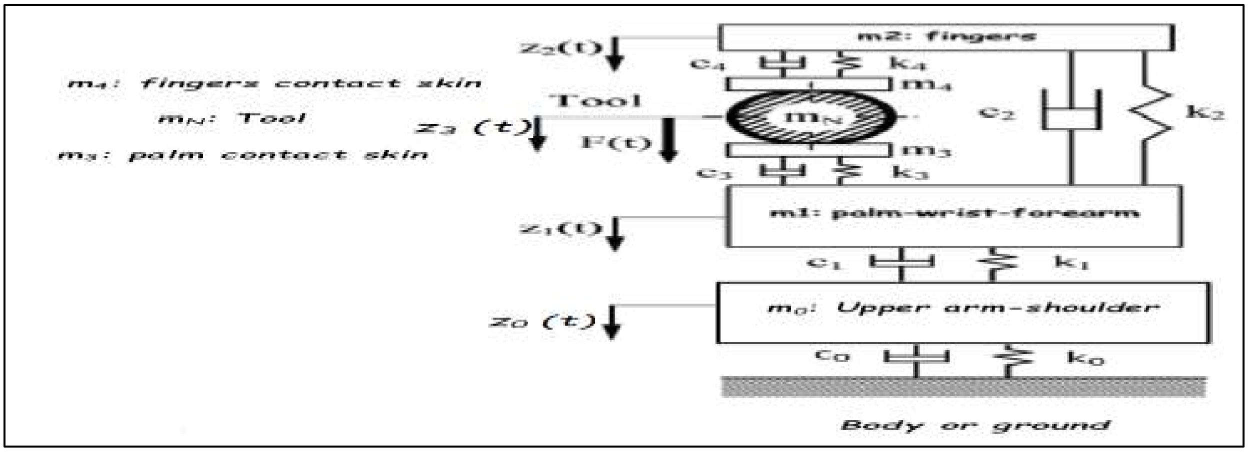


Figure 4- 3 Four Degrees of Freedom (4-DOF) physical model of the human - tool system (J. H. Dong et al., 2008; R. G. Dong et al., 2007, 2013)

As described in various research work models, which inevitably assume a single-point hand-handle coupling relationship, this model assumes a two-point coupling between the hand and the handle. The hand holding the vibrating handle is represented by a mechanical clamp-like device by dividing the hand into two main sections of the centre line of the cylindrical handle(R. G. Dong, 2013). The first component consists of fingers on one side of the handle, represented by two masses (m4 and m2) coupled by linear stiffness (k4) and viscous damping (c4). Mass m4 represents the effective mass of the fingers of the skin in contact with the handle. Mass m2 is the effective mass due to the remaining finger tissues, consisting mainly of the mass of the bones of the fingers (J. H. Dong et al . , 2008; R. G. Dong et al., 2007, 2013).

As also shown in Figure 4.3, the second part comprises the palm–wrist–forearm substructure and is represented by two masses (m_1 and m_3) coupled through k_3 and c_3. Whereas m_3 represents the effective mass of palm skin contacting the handle and m_1 is the effective mass of palm–wrist–forearm substructure. The major equivalent mass of the fingers (m_2) and the major equivalent mass of the palm–wrist–forearm (m_1) are coupled through linear spring-damping elements (k_2 and c_2) coupling. The effective palm–wrist–forearm mass m_1 is connected to the effective mass of the upper arm–shoulder structure (m_0) through another spring-damping element (k_1 and c_1). The c_1-vibration power absorption can be used to represent the power absorbed by the tissues in the forearm, upper arm, and part of the shoulder. Mass m_0 is coupled to fixed ground through another spring-damping element (k_0, and c_0) (J. H. Dong et al., 2008; R. G. Dong et al., 2007, 2013).

4.2. MATERIALS AND METHODS

4.2.1. Hand vibration measurement

The hand vibration of the single-axle tractor operator was measured by attaching the strap to the hand that was connected to the vibration meter. Seven (7) male subjects participated in the operation of a single-axle tractor of 15-HP. Operators performed tilling tasks with the tractor in the second and third gears, while the hand vibration levels were measured by the operator hand along the x (vertical), y (forward) and z (transverse) axes.

Figure 4- 4vibration measurements at the hand of single axle tractor operators

4.2.2. Grip strength measurement

Grip intensity assessment is important for determining the effect of vibration sensitivity through pre-and post-task measurement. Such awareness can help to minimize musculoskeletal issues caused by physical pain. Grip Strength is tested by holding the sensor in a vertical position, with the arms perpendicular to the body and the fingers on the pad distal to the longer proximal section where the palm is squeezed. Power can be measured by applying pressure for a sequence of brief strokes or a prolonged duration.

Equipment used for handgrip strength measurement of tractor operators included an SS25LA Hand Dynamometer, Biopac MP35 data acquisition system, and Biopac student Lab Lessons and PRO version 3.7.1 software for Win98SE, Me,2000, XP. The system is shown in Figure (4.5).

Four Channel Data acquisition Unit MP 35
(Biopac Systems Inc, USA)

Figure 4- 5Real-time standard data acquisition unit MP 35 (Biopac Systems Inc, USA) with SS25LA hand dynamometer

The MP 35 data acquisition unit (Biopac Systems Inc, USA) has four channels with sampling rates ranging from 1 to 100k samples per second and 24-bit resolution. The MP35 has an internal microprocessor to control data acquisition from the dynamometer and communication with the computer. The calibration sequence recommended by the manufacturer was used for the dynamometer before conducting the experiments

Grip strength of dominant and non-dominant hands before and after 30 minutes of tilling operations was measured and recorded. The test procedure for measuring grip strength started with the dominant forearm, with step increases of clenches in increments of 5kg until the maximum grip strength was obtained. Fatigue resistance defined as the time for maximum grip strength to decrease to 50% of its initial value was also measured. This procedure was then repeated for the non-dominant forearm for all operators.

4.2.3. Modeling of the hand-arm system

In addition to the evaluation of the vibration measured data, the simulation and modelling of the biodynamic response of the hand were used. The ISO 10068:2012-based human physical models and the tool model (Figure 4.2) and 4-DOF human physical tool model (Figure 4.3) was used in this study to investigate the biodynamic response characteristics of the hand-arm system. In the proposed model of different hand segments, joints are considered to be based on spring-mass-damper system elements. These segments are used to estimate the vibration propagation distributed in the fingertips, palm-wrist, and upper arms of the hand while holding the handle. The research demonstrated that mechanical vibrations transmitted from the excitation source to the HAS were diminished and substantially decreased from the finger to the upper arm by mounting insulators on the vibrating handle. Model HAS and simulated in the MATLAB-SIMULINK program to test RMS acceleration values in the separate hand-arm device. The HAS system has been compared through MATLAB simulation results to understand vibration transmission behaviours. The three models made it possible for three vibration directions of vertical, forward and lateral shown in Appendix (4.1) to model the effect of vibrations on the human body.

For the model from ISO 10068:2012 – model 1 (ISO10068, 2012), the following generalized coordinates with two degrees of freedom (2-DOF) were selected (Fig. 4.2a) (Dobry & Hermann, 2015):

$j_1 = 1 \;\Rightarrow\; q_1 = z_1(t)$– Displacement of mass m_1 (palm-wrist-forearm),

$j_2 = 2 \;\Rightarrow\; q_2 = z_2(t)$– Displacement of mass m_2 (mass of finger) and m_N (mass of tool),

Where: m_N– the mass of the handle.

In the case of the combined model consisting of the model ISO 10068:2012 – model 2 (ISO 10068, 2012) and the tool model (Fig. 4.2b), the following generalized coordinates with three degrees of freedom (3-DOF) were selected (Dobry & Hermann, 2015):

$j_1 = 1 \;\Rightarrow\; q_1 = z_1(t)$ - Displacement of palm-wrist-forearm (m_1)

$j_2 = 2 \;\Rightarrow\; q_2 = z_2(t)$ - Displacement of m_2 (mass of finger)

$j_3 = 3 \;\Rightarrow\; q_3 = z_3(t)$ -Displacement of the sum of the masses of palm contact skin, fingers contacts skin and tool ($m_3 + m_4 + m_N$).

The 4 - DOF human physical models (Fig. 4.3), the following generalized coordinates with four degrees of freedom (4-DOF) were selected (Dobry & Hermann, 2015):

$j_0 = 0 \;\Rightarrow\; q_0 = z_0(t)$ - Displacement of the upper arm- shoulder (m_0)

$j_1 = 1 \;\Rightarrow\; q_1 = z_1(t)$ - Displacement of palm-wrist-forearm (m_1)

$j_2 = 2 \;\Rightarrow\; q_2 = z_2(t)$ - Displacement of m_2 (mass of finger)

$j_3 = 3 \;\Rightarrow\; q_3 = z_3(t)$ -Displacement of the sum of the masses of palm contact skin, fingers contacts skin and tool ($m_3 + m_4 + m_N$).

1. *Equations of Motion (EOMs)*

After selecting the generalized coordinates, mathematical models of Human- Tool systems were formulated. In the case of the Human-Tool system (2-DOF model) the mathematical equation has the following form – Figure 4.2a:

$$j = 1,\;\; m_1\ddot{z}_1 + (c_1 + c_2)\dot{z}_1 + (k_1 + k_2)z_1 - c_2\dot{z}_2 - k_2 z_2 = 0$$

$$\ddot{z}_1 = \frac{1}{m_1}\left[-(c_1 + c_2)\dot{z}_1 - (k_1 + k_2) + c_2\dot{z}_2 + k_2 z_2\right] \tag{4.6}$$

$$j = 2,\;\; (m_2 + m_N)\ddot{z}_2 + c_2\dot{z}_2 + k_2 z_2 - c_2\dot{z}_1 - k_2 x_1 = F(t)$$

$$\ddot{z}_2 = \frac{1}{(m_2 + m_N)}\left[-c_2\dot{z}_2 - k_2 z_2 + c_2\dot{z}_1 + k_2 z_1 + F(t)\right] \tag{4.7}$$

The mathematical model for the combined model consisting of the Human-Tool system (3-DOF model)– Fig. 4.2b, the mathematical equation is given by(Dobry & Hermann, 2015):

$$j = 1,\;\; m_1\ddot{z}_1 + (c_1 + c_2 + c_3)\dot{z}_1 + (k_1 + k_2 + k_3)z_1 - c_2\dot{z}_2 - k_2 z_2 - c_3\dot{z}_3 - k_3 z_3 = 0;$$

$$\ddot{z}_1 = \frac{1}{m_1}\left[-(c_1 + c_2 + c_3)\dot{z}_1 - (k_1 + k_2 + k_3)z_1 + c_2\dot{z}_2 + k_2 z_2 + c_3\dot{z}_3 + k_3 z_3\right] \tag{4.8}$$

$$j = 2,\;\; m_2\ddot{z}_2 + (c_2 + c_4)\dot{z}_2 + (k_2 + k_4)z_2 - c_2\dot{z}_1 - k_2 z_1 - c_4\dot{z}_3 - k_4 z_3 = 0;$$

$$\ddot{z}_2 = \frac{1}{m_2}\left[-(c_2 + c_4)\dot{z}_2 - (k_2 + k_4)z_2 + c_2\dot{z}_1 + k_2 z_1 + c_4\dot{z}_3 + k_4 z_3\right] \tag{4.9}$$

$$j = 3,\;\; (m_3 + m_4 + m_N)\ddot{z}_3 + (c_3 + c_4)\dot{z}_3 + (k_3 + k_4)z_3 - c_4\dot{z}_2 - k_4 z_2 - c_3\dot{z}_1 - k_3 z_1 = F(t);$$

$$\ddot{z}_3 = \frac{1}{(m_3 + m_4 + m_N)}\left[-(c_3 + c_4)\dot{z}_3 - (k_3 + k_4)z_3 + c_4\dot{z}_2 + k_4 z_2 + c_3\dot{z}_1 + k_3 z_1 + F(t)\right] \qquad 4.10$$

The mathematical model for the 4-DOF human physical model (Figure 4.3) describing the motion of the hand-arm can be written as:

$$j = 0,\ m_0\ddot{z}_0 + (c_0 + c_1)\dot{z}_0 + (k_0 + k_1)z_0 - c_1\dot{z}_1 - k_1 z_1 = 0$$

$$\ddot{z}_0 = \frac{1}{m_1}\left[-(c_0 + c_1)\dot{z}_0 - (k_0 + k_1)z_0 + c_1\dot{z}_1 + k_1 z_1\right] \qquad 4.11$$

$$j = 1,\ m_1\ddot{z}_1 + (c_1 + c_2 + c_3)\dot{z}_1 + (k_1 + k_2 + k_3)z_1 - c_1\dot{z}_0 - k_1 z_0 - c_2\dot{z}_2 - k_2 z_2 - c_3\dot{z}_3 - k_3 z_3 = 0$$

$$\ddot{z}_1 = \frac{1}{m_1}\left[-(c_1 + c_2 + c_3)\dot{z}_1 - (k_1 + k_2 + k_3)z_1 + c_1\dot{z}_0 + k_1 z_0 + c_2\dot{z}_2 + k_2 z_2 + c_3\dot{z}_3 + k_3 z_3\right] \qquad 4.12$$

$$j = 2,\ m_2\ddot{z}_2 + (c_2 + c_4)\dot{z}_2 + (k_2 + k_4)z_2 - c_2\dot{z}_1 - k_2 z_1 - c_4\dot{z}_3 - k_4 z_3 = 0$$

$$\ddot{z}_2 = \frac{1}{m_2}\left[-(c_2 + c_4)\dot{z}_2 - (k_2 + k_4)z_2 + c_2\dot{z}_1 + k_2 z_1 + c_4\dot{z}_3 + k_4 z_3\right] \qquad 4.13$$

$$j = 3,\ (m_3 + m_4 + m_N)\ddot{z}_3 + (c_3 + c_4)\dot{z}_3 + (k_3 + k_4)z_3 - c_3\dot{z}_1 - k_3 z_1 - c_4\dot{z}_2 - k_4 z_2 = F(t)$$

$$\ddot{z}_3 = \frac{1}{(m_3 + m_4 + m_N)}\left[-(c_3 + c_4)\dot{z}_3 - (k_3 + k_4)z_3 + c_3\dot{z}_1 + k_3 z_1 + c_4\dot{z}_2 + k_4 z_2 + F(t)\right]$$

2. *Simulation for vibration effect on HAS model*

The equation-based HAS model simulation (4.6-4.14). The input sine wave signal was used and then the model was analyzed for the respective vibration behaviour of the HAS joints. The external vibration input was applied to the masses m3 and m4, and via hand-arm stiffness and damping, the other masses were connected to the masses m3 and m4. The simulation was performed using a variety of frequency inputs ranging from 6.3 to 1250 Hz. Vibration analysis has been carried out for the sinusoidal driving force F(t) with the amplitude of the mass of the tool multiplied by the acceleration of the vibration assuming that the mass of the handle tool mN is 5 kg, as described in Dobry & Hermann (Dobry & Hermann, 2015) with different frequencies (f) in Hz. The vibration transmissibility study was performed for the frequency ranges from 6.3 to 1250 Hz. Simulations in the MATLAB / Simulink program have been implemented using integration time measures ranging from a maximum of 0.001 seconds to a minimum of 0.0001 seconds. The integration protocol ode113 (Adams) with a tolerance of 0.001 was used.

4.3. RESULTS

4.3.1. Hand vibration

The mean measured vibration at hand of single tractor operators with second and third gear operations was summarized in Appendix (4.6). The mean hand vibration measured with the second gear was 10 ± 2, 7 ± 1 and 9 ± 4 m/s^2 in longitudinal, forward and lateral directions, respectively. The mean hand vibration of the third-speed single-axle operator was 12 ± 4, 7 ± 1 and 11 ± 2 m/s^2 in vertical, forward and lateral directions respectively.

With the second gear operation, the vibration transmissibility was 0.67 ± 0.33, 0.69 ± 0.26 and 0.64 ± 0.14 respectively in vertical, forward and lateral directions. The operator's third gear operation calculated vibration transmissibility was 0.54 ± 0.19, 0.62 ± 0.14 and 0.51 ± 0.12 in vertical, forward and lateral directions, respectively (Appendix 4.7). The results show that vibration transmissibility is greater in second gear than in third gear operation. This is due to the tractor's decreased speed, which increases gripping force. There is also a rise in muscular stiffness, since muscles stiffen when they contract, resulting in more vibration transferred to the hands and arms and increasing the risk of injury (Charles et al., 2018).

4.3.2. Handgrip strength

The maximum clench forces of all seven operators' dominant and non-dominant hands, as measured before and after the 30 minutes of tilling operation with the single-axle tractor, are shown in Table (4.1). The vibration of the single-axle-tractor caused a significant decrease in maximum grip strength of 30 minutes of tilling operations. The average maximal grip strength measured in the dominant hand before and after operation of the single-axle tractor was 34 ± 3 and 26 ± 3 kg force, respectively. For the non-dominant hand, the average measured maximum grip strength was 29 ± 3 and 23 ± 2 kg force before and after tilling operations, respectively as shown in table (4.1).

Table 4- 1 Grip strength of dominant and non-dominant hand before and after vibration exposure

Descriptive statistics	*Grip strength, [kg]*			
	Dominant hand		*Non-dominant hand*	
	Before exposure	After exposure	Before exposure	After exposure
Mean	33.57	26.28	28.67	23.14
Median	33.40	27.08	29.20	23.12
Standard Deviation	2.7	3.3	2.9	1.9
Sample Variance	15.51	13.24	10.03	4.08
Range	12.35	10.85	9.54	5.50
Minimum	27.35	18.46	23.25	20.75
Maximum	39.70	29.31	32.79	26.25

4.3.3. Modeling and simulation of hand-arm vibration

1. Evaluation of natural frequencies, eigenvalues and eigenvectors

The transfer of energy can be visualized as occurring at certain discrete rates depending on the stiffness and mass of the system. These rates of vibration are called natural frequencies. Associated with each of these rates of vibration is a shape of the structure called the mode shape. Every system's vibration behaviour can be characterized by computing these natural frequencies and mode shape associated with them. The total vibration of the system can be formed by summing up different amounts of vibration in each mode. The amount of vibration in each mode depends on the type of excitation. These modes and natural frequencies can be calculated using MATLAB software.

Natural frequencies and mode shapes for the four model parameter were calculated and evaluated for the equation (4.15) and the natural frequencies and eigenvectors and eigenvalues were determined using MATLAB.

$$[M]\ddot{Z}+[C]\dot{Z}+[K]Z=0 \tag{4.15}$$

Eigenvalue and eigenvectors can be determined from the equation of motion, letting by

$$z(t)=\phi_n q_n(t)$$

Where $q_n(t)=A_n\cos(\omega_n t)+B_n\sin(\omega_n t)$ and

$$\ddot{z}(t)=\phi_n\left(-\omega_n^2 A_n\cos(\omega_n t)-\omega_n^2 B_n\sin(\omega_n t)\right)$$

Substituting z(t) and $\ddot{z}(t)$ into $-\omega^2\phi_n q_n(t)$ and equation of motion and becomes

$$\left\{-\omega^2[M]\phi_n + [K]\phi_n\right\}q_n(t) = 0$$

Trivial solution $q_n(t) = 0$ the equation of motion becomes

$$\left[K - \omega^2 M\right]\phi_n = 0 \qquad 4.16$$

Where ϕ_n = eigenvector, $\omega^2 = \lambda_n$ = eigenvalue, ω = natural frequency

In several modes, most dynamic systems can be stimulated, possibly simultaneously. According to a modal variable field, each mode is characterized by one or several frequencies. For example, a single-frequency (1D axial displacement) defines a vibrating rope in 2D space, but two frequencies (2D axial displacement) define a vibrating rope in 3D space. For the given amplitude of the modal variable, each mode stores a particular amount of energy due to sinusoidal excitation. The standard or dominant mode of a multi-mode device will be the mode that stores the minimum amount of energy for the given amplitude of the modal variable, or, equivalently, for the given stored amount of energy, the dominant mode will be the mode that imposes the maximum amplitude of the modal variable. N "'eigenvalues" (i.e. ω_{12}, ω_{22}… ω_{N2}) is the solution to the problem, where N corresponds to the number of degrees of freedom. The eigenvalues give the system's natural frequencies.

The own values and the natural frequency calculated from the matrix equation determinant were obtained and this was done by MATLAB and the following frequencies were obtained. The eigenvalues (Λ) is the diagonal matrix that corresponds to the diagonal masses. The eigenvalues for two degrees of freedom (2-DOF) given in equation (4.17) corresponding to the mass of palm-wrist-forearm and hand with a combination of the tool the natural frequencies were 12.50 and 225.02 rad/s respectively.

$$[\Lambda] = \begin{bmatrix} 156 & 0.0000 \\ 0.00 & 50635 \end{bmatrix} \qquad 4.17$$

The three degrees of freedom (3-DOF) model shown with the equation (4.18) was 12.59, 245.61 and 1568.1 rad / s respectively, with the corresponding natural frequencies of the masses of the palm-wrist-forearm, fingers and hand with a combination of the instrument.

$$[\Lambda]=\begin{bmatrix}200\ 0.0000\ 0.000000\\0.00\ \ 60300\ 0.000000\\0.00\ \ 0.0000\ 2459000\end{bmatrix} \qquad 4.18$$

The eigenvalues for four degrees of freedom (4-DOF) model is represented by equation (4.19) with the corresponding natural frequencies of masses of masses of the upper arm –shoulder, palm-wrist-forearm, fingers and hand with a combination of the tool were 877.21, 259.67, 37.68 and 17.50 rad/s respectively.

$$[\Lambda]=\begin{bmatrix}769500\ 0.0000\ 0.0000\ 0.000\\0.00000\ 67430\ 0.0000\ 0.000\\0.00000\ 0.0000\ 1420.0\ \ 0.000\\0.00000\ 0.0000\ 0.0000\ 310.0\end{bmatrix} \qquad 4.19$$

The hand-arm vibration transmitted from the handle of the single axle tractor to the palm-wrist-forearm was tested using the 2, 3 and 4-DOF models to determine the natural frequency of the palm-wrist-forearm vibration. The natural frequency of palm-wrist-forearm 2 and 3-DOF models was 2 Hz, while the natural frequency of 4-DOF model was 41.33 Hz. Resonance frequencies of peak intensity vibration frequencies for the three models were observed to be 25 Hz, 8Hz and 6.3 Hz for the 2, 3 and 4-DOF models respectively.

When the eigenvalues are replaced into the original set of equations, the '''eigenvectors''' are called the values of {X} that correspond to each eigenvalue. The system's mode shapes are represented by these eigenvectors. The solution to an issue of eigenvalue can be quite cumbersome (especially for problems with many degrees of freedom), but fortunately, most math analysis programs have routines of eigenvalue.

There is a corresponding form or eigenmode mode for each eigenvalue. The shape of the deformation is that of the corresponding eigenmode when the structure is vibrating at a certain natural frequency. The first eigenmode consisting of both masses moving in the same direction is the ISO 10068:2012-based human physical model and tool model 1, while the masses travel in opposite directions in the second eigenmode.

$$First\ \text{mod}e\ shap:\phi_1=\begin{Bmatrix}z_{11}\\z_{21}\end{Bmatrix}=\begin{Bmatrix}-0.3927\\-0.3990\end{Bmatrix}\ Second\ \text{mod}e\ shape:\phi_2=\begin{Bmatrix}z_{12}\\z_{22}\end{Bmatrix}=\begin{Bmatrix}-0.8053\\0.19460\end{Bmatrix}.$$

For the ISO 10068:2012-based human physical model and tool model 2, the first eigenmode consists of masses moving in the same direction, while in the second and third eigenmodes, the masses travel in opposite directions.

$$First\ \text{mod}e\ shape:\phi_1=\begin{Bmatrix}z_{11}\\z_{21}\\z_{31}\end{Bmatrix}=\begin{Bmatrix}0.3957\\0.4013\\0.4016\end{Bmatrix}\ Second\ \text{mod}e\ shape:\phi_2=\begin{Bmatrix}z_{12}\\z_{22}\\z_{32}\end{Bmatrix}=\begin{Bmatrix}0.85550\\-0.1227\\-0.1867\end{Bmatrix}$$

$$Third\ \text{mod}e\ shape:\phi_3=\begin{Bmatrix}z_{13}\\z_{23}\\z_{33}\end{Bmatrix}=\begin{Bmatrix}-0.0150\\3.58160\\-0.0514\end{Bmatrix}$$

For the 4-DOF model, the first three eigenmode masses travel in the opposite directions, while the fourth eigenmode masses move in the same direction.

$$First\ \text{mod}e\ shape\ :\phi_1=\begin{Bmatrix}z_{11}\\z_{21}\\z_{31}\\z_{41}\end{Bmatrix}=\begin{Bmatrix}-0.000\\0.01290\\-1.0000\\0.04760\end{Bmatrix}Second\ \text{mod}e\ shape:\phi_2=\begin{Bmatrix}z_{12}\\z_{22}\\z_{32}\\z_{42}\end{Bmatrix}=\begin{Bmatrix}0.00380\\-1.0000\\0.03440\\0.31120\end{Bmatrix}$$

$$Third\ \text{mod}e\ shape:\phi_3=\begin{Bmatrix}z_{13}\\z_{23}\\z_{33}\\z_{43}\end{Bmatrix}=\begin{Bmatrix}-1.0000\\0.36970\\0.40010\\0.40730\end{Bmatrix}Forth\ \text{mod}e\ shape:\phi_4=\begin{Bmatrix}z_{14}\\z_{24}\\z_{34}\\z_{44}\end{Bmatrix}=\begin{Bmatrix}0.24210\\0.98010\\0.99620\\1.00000\end{Bmatrix}$$

2. *Evaluation of Biodynamic responses*

Three biodynamic models with equations of motion given in equations (6) to (14) are proposed to simulate handle vibration transmissibility using MATLAB Simulink and compared to the measured data. The mean vibration magnitude and transmissibility of Simulink output for 2, 3, and 4-DOF was evaluated in three directions: vertical, forward, and lateral at different frequency ranges and the results shown in Appendixes (4.8 and 4.9) in the frequency range of 2 to 25 Hz. The mean vertical, forward, and lateral vibration magnitudes with two degrees of freedom were 11, 6, and 9 m/s^2, respectively. The mean vertical, forward, and lateral directions the vibration magnitudes with three degrees of freedom were 19, 4, and 5 m/s^2, respectively. While the mean vibration magnitude in vertical, forward and lateral with 4-DOF was 12, 5, and 13 m/s^2 respectively.

The vibration mean transmissibility with third gear of two degrees of freedom, in vertical, forward, and lateral directions was 0.51, 0.53, and 0.39, respectively. With three degrees of freedom, the mean vertical, forward, and lateral vibration magnitudes were 0.83, 0.36, and 0.25, respectively. In the vertical, forward, and lateral directions, the vibration transmissibility for 4-DOF was 0.55, 0.40, and 0.61, respectively.

4.5. DISCUSSIONS

4.4.1. Analysis of grip strength

The decrease in dominant handgrip strength after vibration exposure of 7.3 kg (21.7 percent) is consistent with the findings of M Widia&Dawal (M Widia&Dawal, 2013), who carried out 5-minute grip tests on an electric drill with a mean vibration level of 10.45 m / s2 and a decrease in maximum grip strength of 24.5 percent. They then performed additional 15-minute experiments of 10.7 m / s^2 vibration levels and saw a decrease in grip strength of 29.2 percent, a substantially greater drop than seen in the 5-minute tests. Rashid et al., (Rashid et al., 2018) has found an average of 5.86 kg (10.8%) decrease in grip strength before and after 1 hour of rock drilling by stone crusher workers.

The mean measured handgrip strength of seven (7) operators' before and after operation single axle tractor for 30 minutes operation were evaluated using ANOVA and the effect of single axle tractor handle vibration were observed. From ANOVA table show below the column the p-values of single axle tractor operators handgrip strength for the vibration exposure before and after operation of single axle tractor (3.72262e-05 which is less than α or 0.05). The column p-value indicates that the means of the handgrip strength of single axle tractor operators before and after single axle tractor handle vibration exposure are significantly different.

Table 4- 2ANOVA table of grip strength before and after vibration exposure

Source	ss	df	MS	F	p-value
Columns	406.234	3	135.411	12.63	3.72E-05
Error	257.216	24	10.717		
Total	663.45	27			

As seen from the ANOVA table results shown in the table (4.2), even though the p-value is very small and less α or 0.05, it does not indicate in what ways the mean is different. But the box plots are used to show overall patterns of operators' handgrip strength change in responses to the handle vibration of single axle tractor. They provide a useful way to image the range and other response characteristics of a large group. As shown in Figure (4.6), all four (4) medians for both dominant and non-dominant handgrip intensity before and after single-axle tractor handling vibration sensitivity are substantially different at a 5 % significance level and do not overlap their intervals. Statistical analysis indicated that there was a significant difference in the mean value of the grip strength before and after tilling operations, in both the dominant and non-dominant hands (P<0.001).

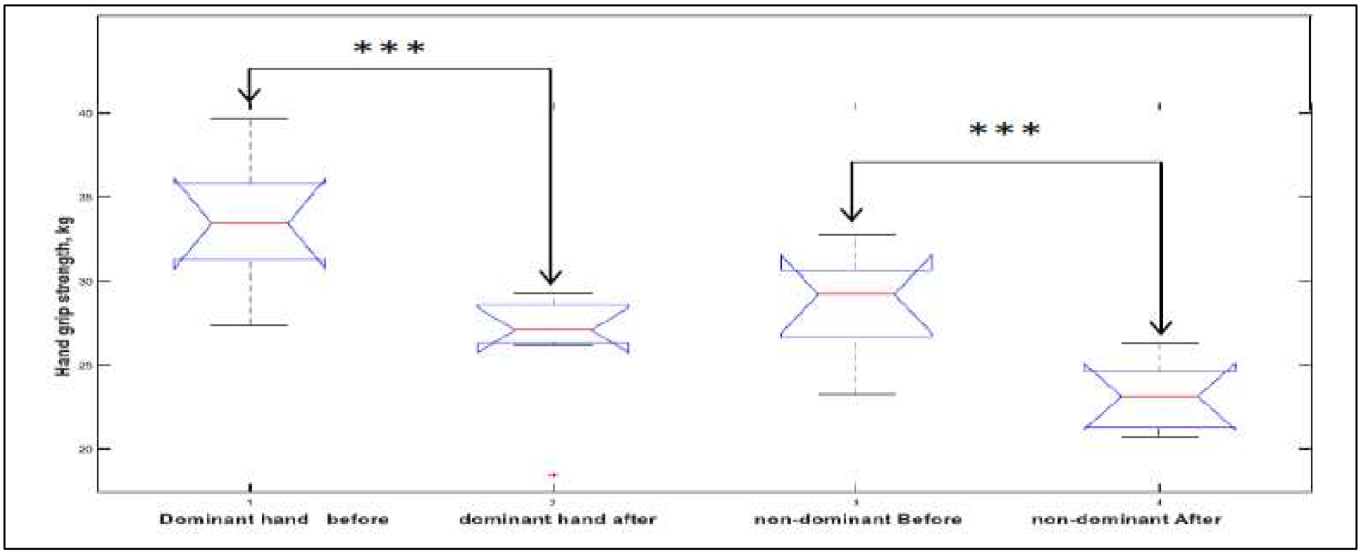


Figure 4- 6 Boxplot of dominant and non-dominant hand before after vibration exposure

*** Significant difference, ($p < 0.0001$, for $\alpha = 0.05$)

4.4.2. Grip fatigue resistance

For the dominant hand, average fatigue resistance for all seven tractor operators varied between 27.6 and 26.5 seconds before and after operation of single axle tractor respectively (figure 4.7). These results are consistent with those of Alkurdi & Dweiri,(Alkurdi & Dweiri, 2010) who examined the relationship between handgrip strength and fatigue for various anatomical configurations of operator work. They found fatigue resistance varied between 26.2 and 35.4 seconds for the right hand and from 23.2 to 40 seconds for the left hand.

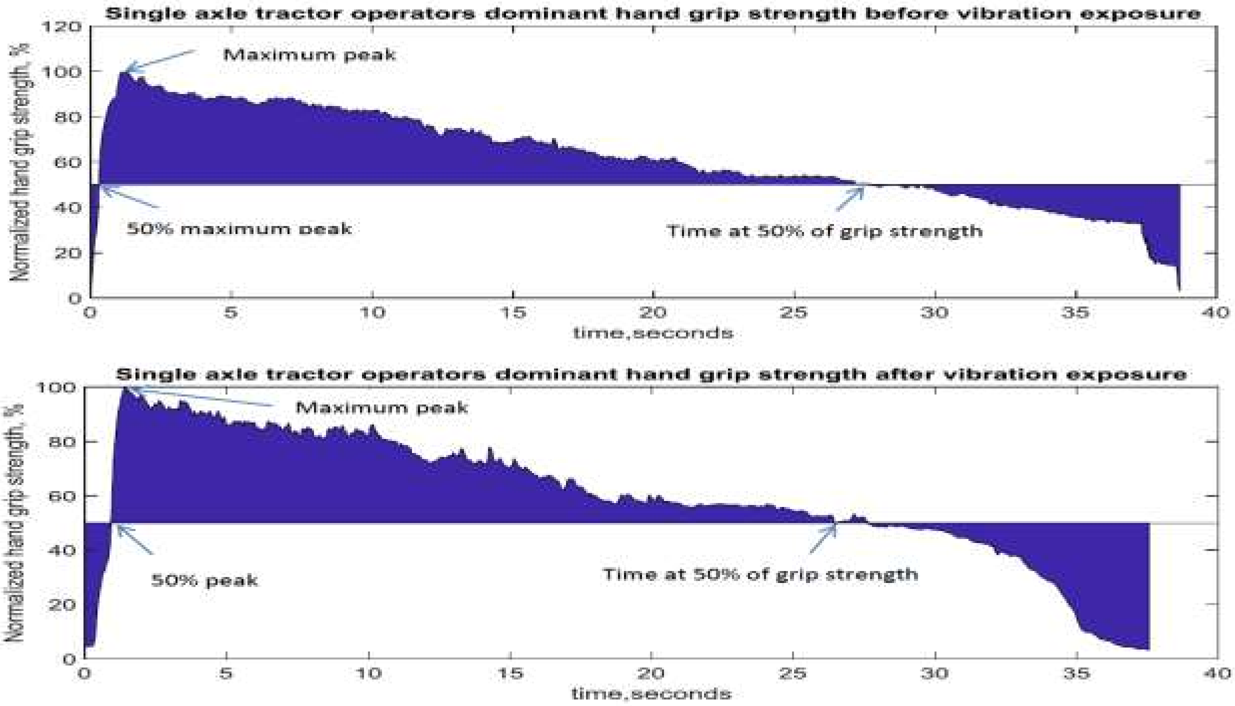


Figure 4- 7 Average maximum grip strengths for the right (dominant) hand before and after operation of the single-axle tractor for 30 minutes.

Grip work was calculated based on the equation (4.1) and was found to be 709 ± 213 and 523±208 kg-s for the dominant hand before and after 30 minutes of operation of the single-axle tractor by seven test subjects. Statistically, there is no substantial difference between the pre-and post-operative means of grip work ($p = 0.15$, i.e., $p > 0.05$). However, there was a statistical mean decrease in both grip strength and fatigue strength following tractor operation ($p < 0.005$). Endurance is an important component of the physical output that needs to be addressed when determining musculoskeletal function. Measurements were made on mean grip strength scores before and after 30 minutes of single-axle tractor operation with 7 test subjects. The average determined force decrement index (SDI) of the measured operator grip strength before and after operation of the single-axle tractor was calculated according to Equation (4.2) and was found to be 28.6 per cent. This is consistent with the SDI value of 23% measured for an operator of a power grip analyzer (Figoni, 2009). In a different test, White et al (White et al., 2013) have found a mean strength decrement index value 29.8%.

4.4.3. Modeling and simulation of hand transmitted vibration

The natural frequencies and the mode shapes of palm-wrist-forearm using three models 2, 3 and 4-DOF were evaluated for the vibration in the vertical direction of maximum vibration value (R. G. Dong, 2013; R. G. Dong et al.,2010; Xu et al., 2011). The natural frequency of palm-wrist-forearm models for 2 and 3-DOF was 2 Hz, i.e. with minimal frequency weighting, and this indicated that it had a less adverse health effect since it was below 6.3 Hz (ISO 5349-1, 2001)whereas for the 4-DOF model the natural frequency was 41.32 Hz which is corresponding to the frequency of average weight in ISO-5349-1(ISO 5349-1, 2001).

Three models were utilized in this study, and the transmissibility of each was compared to experimental or test data (Murray-Smith, 2015) . Experiments have validated and verified the vibration transmissibility generated by each of the three models. The 4-DOF model is accurate for vertical and lateral hand vibration transmissibility, producing findings that are virtually identical to actual data of both second and third gears. The 2-DOF model was validated and verified in both forward direction, according to the findings. However, the 2-DOF model was tested and verified for vibration magnitude by comparing the values of observed data in vertical, forward, and lateral directions to the models.

The vibration transmitted to the hand-arm measured with the second and third gear compared to the three models of 2, 3 and 4-DOF. The maximumvibration magnitude of the 4-DOF model was found to be similar to the maximum vibration magnitude during the second and third gears operations.

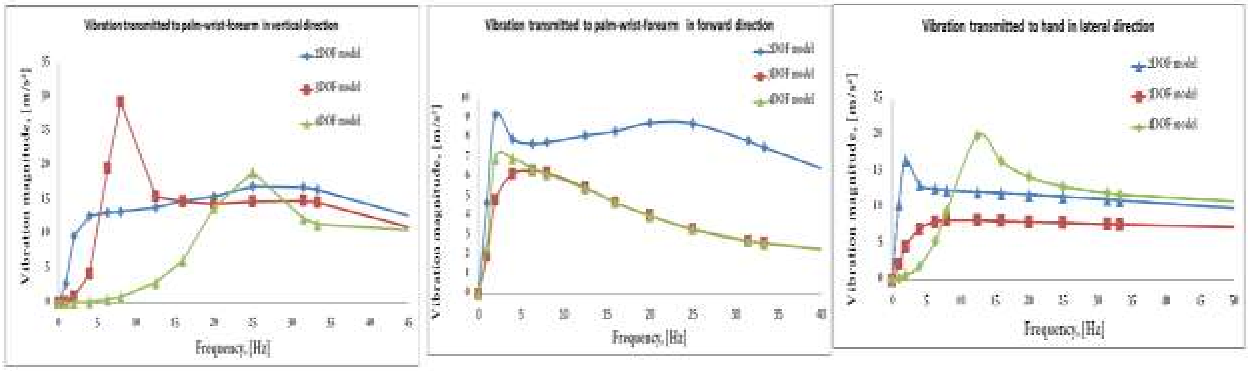


Figure 4- 8 model of handle vibration transmitted to palm-wrist-forearm with 2, 3 and 4-DOF models in three directions

As seen in figure (4.8), the vibration transmitted to the forearm of the palm wrist rose until it reached the frequency of the resonance and decreased dramatically after reaching the frequency of 31.5 Hz and gradually almost dropped to zero at a frequency of 1250 Hz. Study (Gomes &Savionek, 2014) has shown that vibrations transmitted directly to the hand-arm device at a frequency of 6.3 to 1250 Hz have undesirable health effects.

Thus the spectral power density (or simply the power spectrum) refers to the spectral energy distribution that can be observed per unit time, which corresponds to the signals that reflect the cumulative energy of such a signal overall time, or over a period that is large enough (especially concerning the length of the measurement) that may have been over an infinite time interval. The maximum spectral energy distribution or acceleration power spectral densities of the palm-wrist-forearm in the vertical direction of the models were evaluated for 2, 3 and 4-DOF models as shown in Figure (4.9). The maximum power spectral densities was observed in the frequency range of 4 to 25 Hz 2, 3and 4-DOF models.

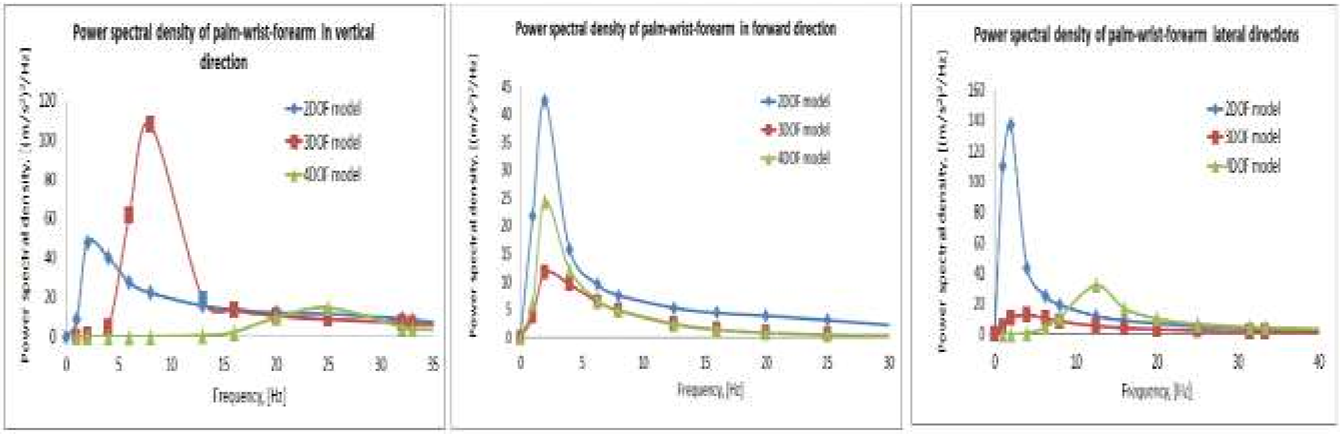


Figure 4- 9 power spectral of palm-wrist-forearm in the vertical direction

The maximum power spectral density in vertical direction was observed in 3-DOF model which was 108 $(m/s^2)^2/Hz$ at the frequency of 8 Hz, whereas the minimum power spectral density was observed the value of 15 $(m/s^2)^2/Hz$ with the model of 4-DOF at the frequency of 25 Hz. in the forward direction the maximum power spectral density was observed in 2-DOF model which was 42 $(m/s^2)^2/Hz$ at the frequency of 2 Hz, whereas the minimum power spectral density was observed the value of 12 $(m/s^2)^2/Hz$ with the model of 3-DOF at the frequency of 2 Hz. And final the maximum power spectral density in the lateral direction 137 $(m/s^2)^2/Hz$ at the frequency of 2 Hz, and the minimum was 13 $(m/s^2)^2/Hz$ at the frequency of 4 Hz with 3-DOF model.

As seen from the figures 4 - 9 above the acceleration power spectral densities in all directions were started to decrease with frequency after it passed resonance frequencies, and these have seen in different research findings (Kim et al., 2020; Supej & Ogrin, 2019; Welcome et al., 2015) in all three models and the resonance frequencies were below the frequency of 31.5 Hz.

The vibration transmissibility from the handle to the palm-wrist-forearm was calculated using 2, 3 and 4-DOF models in the MATLAB Simulink and the vertical value for further anlysis was used. The highest vibration transmissibility was achieved with the 2-DOF model, while the 4-DOF model was the smallest. The measured mean value of vibration transmissibility during the second and third gear operations was compared with the 2, 3 and 4- DOF models. The effects of vibration transmissibility in the 2-DOF model were similar to the second gear, while the value of the 3-DOF model was similar to the third gear. In contrast to the 4-DOF model that has vibration transmissibility at a nominal frequency of 60 Hz with a very limited weighting factor, the two 2 and 3-DOF versions have high vibration transmissibility.

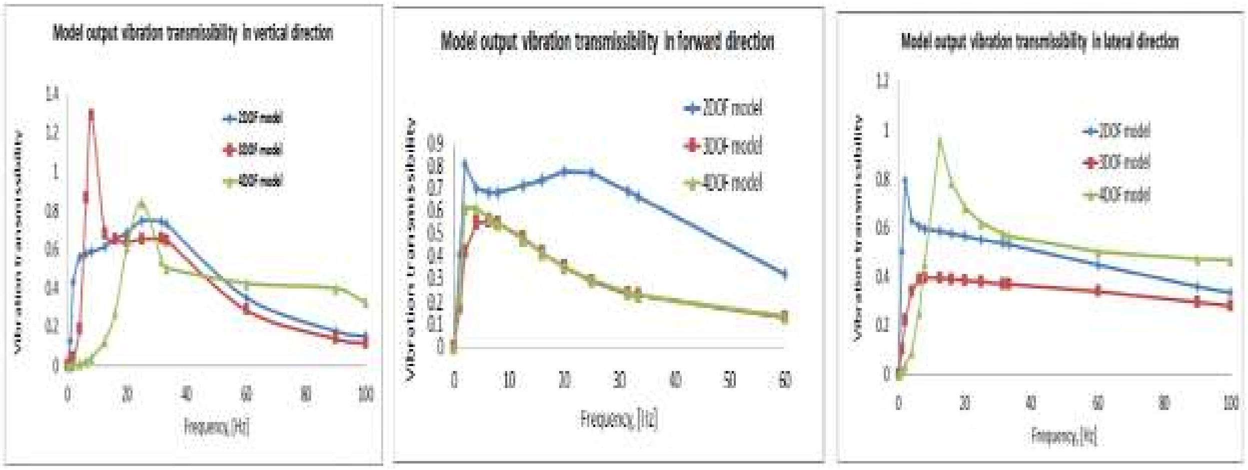


Figure 4- 10 vibration transmissibility to palm-wrist-forearm in three directions

As seen from the figures (4.10) of the three models in three directions the vibration transmissibility was started to decrease with frequency after it passed resonance frequencies, and these have seen in different research findings (Adewusi et al., 2010; Ahmadian et al., 2018; R. G. Dong et al., 2013, 2015, 2018; Supej & Ogrin, 2019; J. Z. Wu et al., 2017; Xu et al., 2017)

4.6. CONCLUSIONS

In this chapter, the biodynamic response of single-axle tractor operators was assessed in terms of the vibration transmissibility of the grip strength. For handgrip power, the calculated data for handgrip operators were evaluated and compared with other research projects. The fatigue strength, the mean grip strength and the full grip strength were calculated. For the dominant hand, the average fatigue resistance (the time to reach 50% fatigue of maximum grip strength) before and after vibration exposure for 30 minutes was 27.6 and 26.5 seconds, respectively. The average measured maximum grip strength for the dominant hand was 33.6 and 26.3 kg force before and after 30 minutes of operation by seven test subjects of a single-axle tractor, respectively. Corresponding values for the non-dominant hand were 28.7 and 23.1 kg force before and after vibration exposure, respectively. The findings indicate a substantial average difference of 7.3 and 5.6 kg of grip strength of the single-axle tractor operators, both dominant and non-dominant, and confirm that the operators greatly affected the vibration transmitted from the single-axle tractor handle. The percentage decrease in grip strength also increases as the level of vibration and period of exposure increase. The reduction in grip strength improved in quantity and magnitude as the susceptibility to the stimulus (intensity of acceleration and time of exposure) increased.

The hand vibration was measured for single axle tractor operators and the overall measured vibration was 11.95 ± 3.95 m/s^2 in the vertical direction at the palm-wrist-forearm, while the estimated vertical vibration transmissibility was 0.54 ± 0.19. Vibration transmissibility was also measured using four models, and the peak transmissibility of vibration from the handle to the palm-wrist-forearm was seen within the frequency range of 6.3 - 1250 Hz.

Palm-wrist-forearm resonance frequencies ranged from 6.3 to 25 Hz for three models and vibrations that influence and are directly transmitted to the hand-arm device at a frequency range of 6.3 to 1250 Hz. The hand vibration measured in the second and third gear tractor operations was contrasted with the vibration produced by the 2, 3 and 4-DOF models. The peak vibration magnitude of the 4-DOF model was found to be similar to the peak vibration magnitude during second and third gear operations. It was observed that for all models the vibration transmitted to the forearm of the palm wrist rose until it reached the frequency of the resonance and decreased dramatically after reaching the frequency of 31.5 Hz and gradually almost dropped to zero at a frequency of 1250 Hz.

The maximal spectral energy distribution or acceleration power of the palm-wrist-forearm spectral density was observed in the vertical direction of the 3-DOF model at the 8 Hz frequency, while the minimum power spectral density of the 4-DOF models was observed at the 25 Hz frequency.

The acceleration spectral densities of strength started to decline with frequency after passing resonance frequencies and these were seen in separate test results in all three models and the resonance frequencies of all models were observed below the 31.5 Hz nominal frequency.

The 4-DOF model accurately predicts vertical and lateral hand vibration transmissibility, yielding results that are almost comparable to actual data from second and third gears. According to the findings, the 2-DOF model was confirmed and verified in both forward and reverse directions. The 2-DOF model, on the other hand, was evaluated and confirmed for vibration magnitude by comparing observed data values in vertical, forward, and lateral directions to the models.

CHAPTER FIVE: DAMPING OF HANDLE VIBRATION OF DIESEL-FUELED SINGLE AXLE TRACTOR USING NATURAL RUBBER COMPOSITE VIBRATION ISOLATOR

5.1. THEORETICAL BACKGROUND

Recent advances in polymeric materials have greatly enhanced their application for damping treatment. Damping is a method to dissipate a viscous, viscoelastic, or structural mechanism of the energy of a vibrating structure. Damping materials are designed to reduce the effect of large vibrations on the precision and stability of the process. By converting the vibration energy of external excitation into other types of energy, they reduce the vibration magnitude.

The conversion of mechanical energy of viscoelastic materials into heat when deformed is due to their long-chain molecules; these are generally polymers that can be formulated into a wide range of different compositions that yield various material properties dependent on the frequency of operation and temperature of the surrounding environments(Dunson, 2017; Hrairi et al., 2014; Siviour & Jordan, 2016). Transmission of vibration energy from one body to another can be reduced by vibration isolation mounts by providing a resilient connection between the parts. The response of resilient mounts can be improved by adding damping materials that convert a portion of resonant vibration amplitude into low-grade heat(Alkhatib, 2013; Barale & Gawade, 2017; Guo et al., 2020).

Materials that show both viscous and elastic behaviour are called viscoelastic materials. Pure elasticity would mean a perfect transfer of energy for which all the energy contained in the material during loading is recovered when the load is removed. These elastic materials have an in-phase stress-stress relationship. On the other hand, a strictly viscous material does not recover any of the energy stored during loading after the load has been removed (Gargallo et al., 2009).

Viscoelastic material dissipates energy by shear in the form of heat or thermal energy. The maximum phase shift between stress and strain is a measure of the importance of the material attenuation; this phase shift cannot exceed 90 degrees. The larger the phase angle, the more effective a materials is at damping out vibration(Chang et al., 2019).   Elastomeric materials have become one of the most widely used engineering materials with applications including tires, engine mounts, shock-absorbing bushes, seals, etc. However, unvulcanized elastomers are generally not very strong, don't maintain their shapes after large deformation, and can be very sticky; thus, most useful elastomeric products require vulcanization. Vulcanization is a chemical process that increases elasticity and decreases the amount of permanent deformation left after the deformation force has been removed. As a result, vulcanization increases elasticity and reduces the plasticity of elastomeric materials (Mark C., et al., 2013).

Viscoelastic materials can also be used for vibration reduction in the handle grip of walking tractors. Ragni et al., (Ragni et al., 1999) applied rubber sleeves to the handles of an Italian-made walking tractor and found that the handle vibration was decreased by 35%. Tewari & Dewangan, (Tewari & Dewangan, 2009) used isolators made of elastomeric material to reduce hand-transmitted vibration in a walking tractor. Yap et al., (Yap et al., 2016) evaluated the reduction of vibration using a combination of handle grips and engine mounts rubber, and this has shown a 59.29%vibration reduction in hand tractor.Lu et al., (Lu et al., 2018) designed and developed a rubber insulation device based on a vibration transmissibility analysis, a vibration-absorption mechanism and a critical vibration management path to minimize the vibration of the power tiller handle.

Due to its strong mechanical properties of tensile strength, tear strength and wear resistance, Natural Rubber (NR) is now used in a wide range of applications, such as vibration insulators. Owing to their high loss factor (tanδ) rubber materials are widely used to control machine noise and vibration; hence, recent research focuses on rubber loss factors to enhance its damping properties (Yong et al., 2006). Installations of rubber isolators are effective vibration control mechanisms due to rubber's resistance to oxidation and weather, and good thermal stability(Yu et al., 2012). Stiffness and damping properties of rubber are generally non-linear and both frequency and temperature-dependent.

The properties of the NR compositions related to Complex Viscosity, Curing Rheometric Parameters, Payne Effect and further rheological characterizations were assessed with the aid of the RPA 2000 rubber processing analyzer(Honorato et al., 2016). This equipment is specifically designed to test the properties of cured and uncured rubber compositions which comply with international standards such as ASTM D 412. As for the torque, the measurement tolerance is 0.5% of the working range and the temperature; the test temperature is ± 0.3 ° C.

Vulcanization is a chemical process that combines long molecular chains, creating a stable and more solid molecular structure. Cross-linking is accomplished using activators, curing agents (sulfur or peroxide) and accelerators. The vulcanization process begins when the mixture is heated to a temperature of activation (120-200^{o}C) depending on the formulation of the mixture. Their viscoelastic nature gives them elasticity and also the ability to dissipate energy. Their strength is high, especially under conditions of shear and compression.

The degree of vulcanization of a rubber compound has a big influence on the properties of the final product. Therefore, precisely defining the curing process including optimum cure time is important to ensure the production of final products having high performance. Typically, vulcanization is represented using vulcanization curves. The curing characteristics of the rubber compound can be expressed in terms minimum torque (ML), maximum torque MH and torque value DM, (dNm), the optimum curing time or optimumtreatment time (t90) is the time to hit 90% of the delta torque above the minimum, scorch time (t_{s2}) used as the time to reach 2% of the delta torque above the minimum, curing rate index (CRI) of the recipe was calculated according to the following formula (Maria et al., 2016):

$$CRI = \frac{100}{\left(t_{90} - t_{s2}\right)} \tag{5.2}$$

The CRI is a measure of the rate of vulcanization based on the difference between optimum vulcanization time, t_{90}, and incipient scorch time, t_{s2}.

The minimum torque (ML) indicates the measure of the stiffness of the unvulcanized test specimen taken at the lowest point of the curve whereas the maximum torque MH and torque value DM or the maximum torque (MH) minus the minimum torque (ML) is the delta torque or the degree of cross-linking, which is a measure of stiffness or shear modulus of the fully vulcanized test specimen at vulcanization temperature(Maria et al., 2016).

5.2. MATERIALS AND METHODS

5.2.1. Rubber compound recipe materials and preparation

1. ***Materials***

Horizon Addis Tire Factory PLC manufactures all the damper materials used in this research. The materials used for the rubber compound recipe included natural rubber (SMR-20), Polybutadiene Rubber (BR-1220), Carbon black, (ISAF, N220 grade), N-cyclohexyl-2-benzothiazole sulfonamide, antioxidant (TMQ), Sulfur (Rhombic Sulfur (S_8)) and Zinc oxide (ZnO)as shown in Table (5.1).

Table 5- 1 Rubbers, fillers and other compounds are shown with their PHR

Ingredients	**A compound, [%]**	**Parts per Hundred of Rubber, [PHR)**
SMR – 20	38.05	70.00
High CIS BR – 1220	16.31	30.00
N-220/ISAF	13.59	25.00
Dutrex RA – 3	5.44	10.00
Zinc Oxide (98%)	2.72	5.00
RenacitPeptizer/Zincolet-86/Peptzola-7	0.05	0.10
Aktiplast/Zincolet-T/ACMETOL T	0.82	1.50
Rubber grade (Stearic acid 1600)	1.63	3.00
N-220/ISAF	10.87	20.00
6PPD	1.63	3.00
TMQ	0.41	0.75
Antilux/OSW	0.54	1.00
Perkasil KS 408/Active silica	6.52	12.00
TBBS	0.6	1.10
Normal sulfur	0.82	1.50
Total	**100.00**	**183.95**

2. ***Characterization of rubber compound recipe***

Rubber blends including natural rubber (SMR-20) and polybutadiene rubber (BR) filled with carbon black mixtures was explored. An optimized composition involving 70 PHR of SMR-20 and 30 PHR BR filled with mixtures of carbon blacks was proposed to be a suitable composition, as shown in Table 5.1. Swelling experiments of cured composites were performed by equilibrating them in toluene at room temperature for 48 h.

3. Sample Preparation and Vulcanization

A rubber compound formed with natural powder was taken as a reference on an open two-roll laboratory mill (L/D 320 × 360 and friction 1.27). The speed of the slow roll was 25 rpm. The rubber compound as described by Table 5.2 was formulated as follows: the raw rubber was loaded into the mill, and ZnO2 and stearic acid were added after 5min. After 3 min of homogenization, the SMR-20 was added. Following another homogenization, for 7 min the accelerator and sulfur were added, and the compound was homogenized for 4 min.

The process of preparing the rubber compound took 30 min. The temperature of the rolls did not exceed 70◦C. The ready compounds in the form of sheets stayed 24 hours before their vulcanization. The optimal vulcanization time was determined by the vulcanization isotherms taken on a moving die Rheometer (MDR)at 150^0C, according to ASTM standard ASTM 412. The vulcanization was performed on an electric hydraulic press at 10MPa. Specimens of 200 × 200 × 2mm were cut from the samples prepared for material characterization purposes. The curing characteristics were determined by the moving disk rheometer (MDR) at 150 ° C for 30 minutes in compliance with ASTM 412.

4. Measurement of Vulcanization Characteristics

Vulcanization characteristics (ML: minimal torque, dN•m; MH: maximal torque, dN•m, $\Delta M = MH - ML$, ts2: scorching time, min; T90: optimum vulcanization time, min) were evaluated based on the vulcanization isotherms used in the moving die Rheometer (MDR). The Moving Die Rheometer provides high-precision data as well as simple instrument work. All essential characteristics, such as minimum/maximum elastic torque, scorch times; treatment times and reaction speeds were precisely measured.The experiments were repeated for verifying their statistical significance

5.2.2. Vibration damper installation

Vibration dampers for the isolation of engine vibration from the handle of single axle tractor were manufactured with diameter of 80 mm, a thickness of 25 mm and inner diameter of 13 mm were made. Four (4) vibration dampers made up of rubber compound recipe were mounted on a single axle tractor at the Melkasa Agricultural Research Center laboratory. The upper and lower parts of the damper were supported by sheet metal with a thickness of 2 mm and a diameter of 80 mm (Figure 5.1).

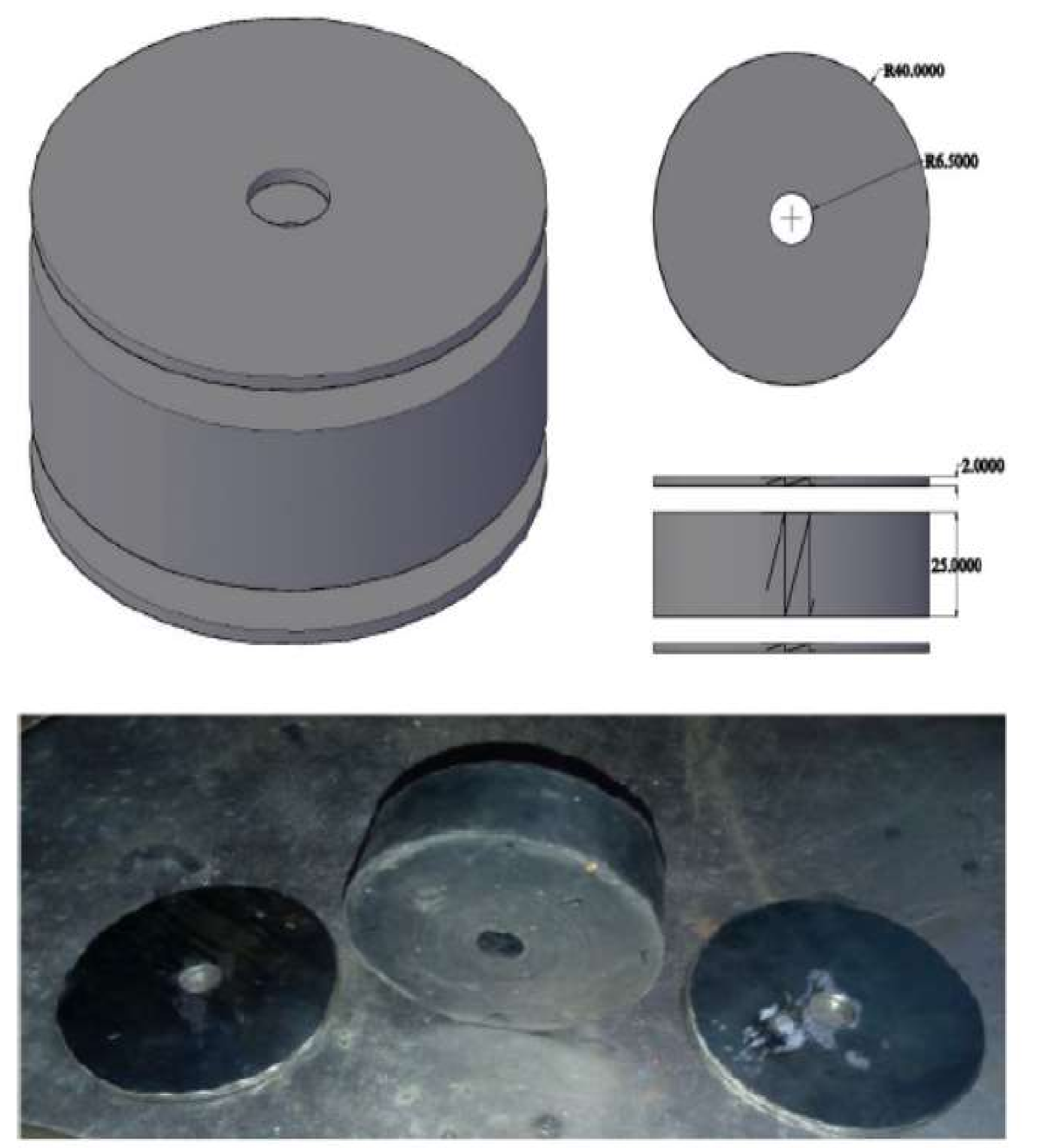


Figure 5 - 1 Rubber compound vibration damper

The handle of the single axle tractor is directly connected to the frame of the tractor and the vibration from the engine is transmitted through the chassis to the handle. As a result, to reduce the vibration from the handle, the damper was mounted at positions between the engine and the chassis as shown in Figure (5.2).

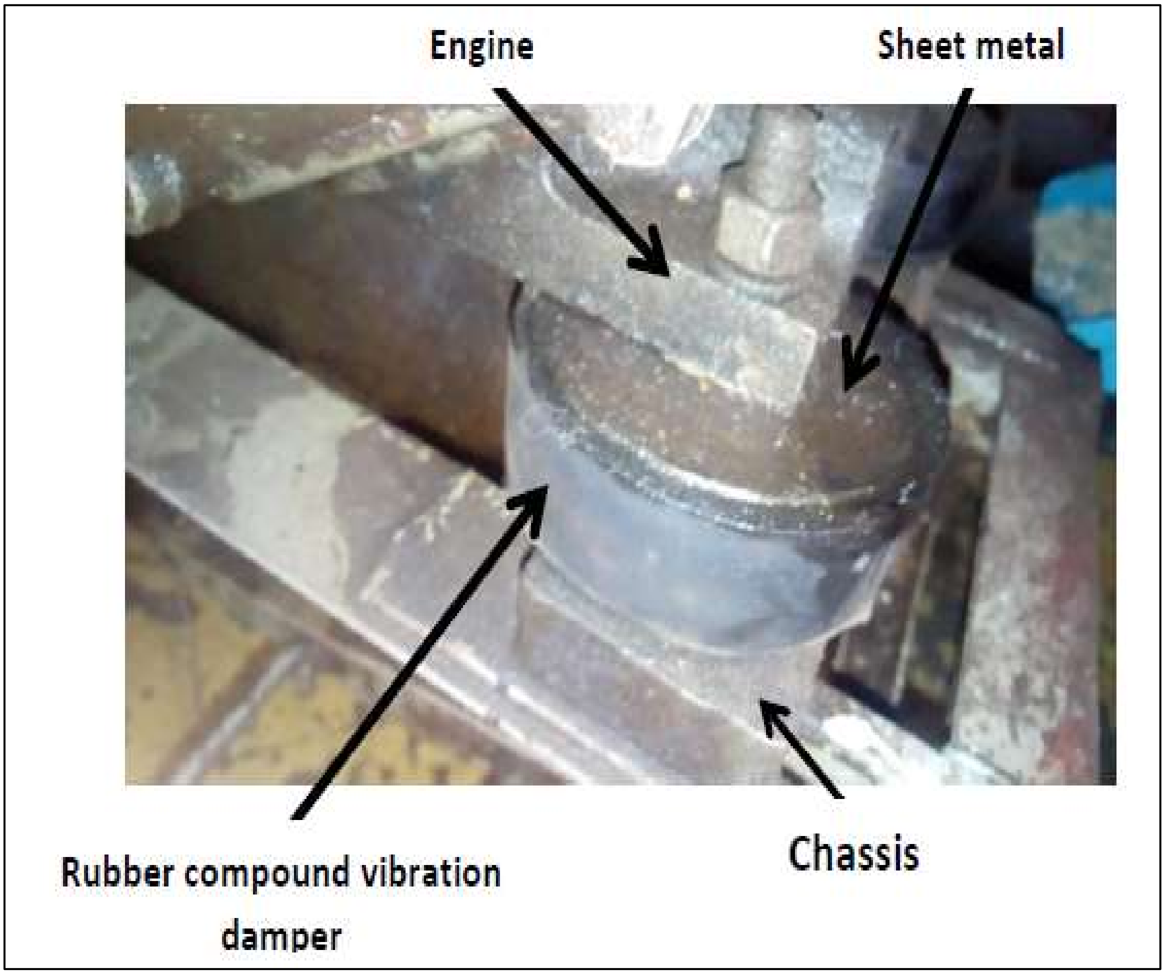


Figure 5 - 2 rubber compound vibration damper installation

The propagation of engine vibration due to the lack of engine suspension at the handle of the single axle tractor propagates as the handle is free at one end. Therefore, it is necessary to mitigate friction by installing a damper between the engine and the frame in order to decrease the vibration of the handle of a single axle tractor.

5.2.3Handle vibration measurement

Seven (7) male subjects were used to operate a single-axle tractor, while vibration measurements were conducted for approximately 15 to 20 minutes for a single operator. The operation was repeated four (4) times for each operator during the working day of the tractor, both before and after vibration damper installation. Vibration levels were measured at the tractor handle along the x (vertical), y (forward) and z (transverse) axes. The y-and z-directions were modified from those defined in ISO 5349 (ISO 5349-1, 2001) because the handle on this particular tractor model was rotated by 90 degrees compared to that used in ISO 5349 (ISO 5349-1, 2001).The measured and calculated damped vibrations were compared to the undamped vibration with identical ground conditions, tractor forward rpm, soil moisture quality, and the same tractor operators, Data were collected for both second and third gear operations. The measured details of the vibration total value, the regular exposure and the latency time of the damped vibration were also analyzed and compared with the pre-damper data used.

5.3. RESULTS

5.3.1. Vulcanization characteristics

The specific formulation in Table (5.1) has 70 parts of raw natural rubber (SMR-20) and 183.95 parts of the total material. After curing for 30 minutes at 150°C its vulcanized properties were determined to be 61^0 Shore-hardness, with a tensile strength of 27.44 MPa and elongation at break of 675.3%. The main vulcanization characteristics of the samples determined from nine (9) test samples ae presented in Table (5.3) and Table (5.4).

The initial torque (MI), minimum torque (ML), maximum torque (MH), final torque (MF) and (ΔM)which is the difference between MH and ML which reveal the hardness and density of the vulcanization crosslinks. The average approximate MI, ML, MH, MF and ΔM torque were 2.57± 0.07, 2.26 ± 0.07, 13.06 ± 0.08, 12.96 ± 0.26 and 10.80 ± 0.18 dNm, respectively.

Scorch period (TS2), optimum curing time (TS90%) and the calculated curing index (CRI) of the rubber compound formula are illustrated and shown in the table (5.4). The mean scorch time (TS2), optimal curing time (TS90%), curing index rate (CRI) is 1.28 ± 0.02 s, 3.07 ± 0.05 s and 55.85 ± 2.77 s-1, respectively.

5.3.2. Vibration evaluation of single axle tractor - 2nd gear

The average measured handle vibration with second gear operation of seven (7) operators before and after vibration damper installation is summarized in Table (5.2).The mean measured vibration at the handle of single axle tractor operators before vibration insulator mounted was 18 ± 7, 11 ± 5 and 17± 9 m/s^2 respectively in vertical, forward and lateral directions. After installation of vibration damper, measured values were reduced to11 ± 4, 7 ± 4 and 9 ± 3 m/s^2 respectively in vertical, forward and lateral directions.

The average maximum peak value of the handle vibration for the seven (7) operators before damping was 44, 47 and 80 m/s^2, whereas the minimum peak value was 7, 3 and 4 m/s^2 with second gear operations in vertical, forward and lateral directions respectively. For damped vibration, the maximum peak value for vertical, forward and lateral directions were 27, 30 and 24 m/s^2, whereas the minimum peak valueswere 4, 0 and 4 m/s^2 respectively.

Table 5- 2-Handle vibration before damper installation with second gear

	RMS Handle vibration, [m/s^2]					
	Second gear before damper installation			Second gear after damper installation		
Descriptive statistics	Vertical	Forward	Lateral	Vertical	Forward	Lateral
Mean	18.10	10.75	17.28	10.49	7.13	9.33
Standard Error	0.39	0.26	0.47	0.23	0.19	0.18
Median	17.03	9.87	15.46	9.61	6.25	8.93
Standard Deviation	7.25	4.83	8.72	4.32	3.61	3.29
Sample Variance	52.58	23.34	76.00	18.65	13.03	10.85
Range	37.34	44.00	75.64	22.65	29.71	20.28
Minimum	7.08	2.91	4.26	4.06	0.02	3.67
Maximum	44.42	46.91	79.90	26.71	29.74	23.95

The vibration total value a_{hv} and vibration daily exposure A (8) in m/s^2 (calculated using equation (2.6)) at the handle of the single axle tractor with second gear are shown in table (5.3). The mean calculated vibration total values of second gear before and after damper installation were 27 and 16 m/s^2 respectively. The mean calculated vibration daily exposure A (8) of second gear before and after damper installation was 10 and 6 m/s^2 respectively.

Table 5- 3Frequency-weighted average, vibration total value and daily exposure of A(8) at handle before and after damping damper installation in second gear

Process of vibration measurement	**Frequency-weighted RMS vibration amplitude [m/s^2]**				
	Vertical	Forward	Lateral	Vibration total value (a_{hv}) [m/s^2]	Daily exposure of A (8)[m/s^2]
Before damper installation	18.10	10.78	17.28	27.24	10.40
After damper installation	10.49	7.13	9.33	15.8	6.0

5.3.3. Vibration evaluation of single axle tractor -3rd gear

The average measured handle vibration with third gear operation of seven (7) operators before and after vibration damper installation is summarized in Table (5.4).The mean measured vibration at the handle of single axle tractor operators before vibration insulator mounted with third gear operation was 23 ±3, 11 ± 2 and 21 ±3 m/s^2 respectively in vertical, forward and lateral directions. After installation of vibration damper, measured values were reduced to12 ± 1, 8 ± 1 and 10 ± 1 m/s^2 respectively in vertical, forward and lateraldirections.

The average maximum peak value of the handle vibration with third gear operation before damping was 36, 17 and 28 m/s^2, whereas the minimum peak value was 11, 7 and 8m/s^{2}invertical, forward and lateral directions respectively. For damped vibration the maximum value for vertical, forward and lateral directions were 15, 12 and13 m/s^2, whereas the minimum value was 8, 6 and 8 m/s^2 respectively.

Table 5- 4–Third gear vibration before and after damper installation at the handle of single axle tractor

Descriptive statistics	Third gear RMShandle vibration, [m/s^2]					
	Before damper installation			After damper installation		
	Vertical	Forward	Lateral	Vertical	Forward	Lateral
Mean	22.61	11.36	20.79	12.13	8.08	10.35
Standard Error	0.16	0.10	0.13	0.07	0.07	0.06
Median	22.44	11.17	20.53	12.23	8.06	10.24
Standard Deviation	2.92	1.81	2.47	1.26	1.32	1.17
Sample Variance	8.50	3.29	6.08	1.60	1.75	1.36
Range	25.31	10.65	19.95	6.67	6.28	5.43
Minimum	10.88	6.59	8.35	8.27	5.65	7.54
Maximum	36.19	17.25	28.30	14.94	11.93	12.97

From Table (5.5), the mean calculated vibration total value a_{hv} for third gear before and after damper installation was 33 and 18 m/s^2 respectively, whereas vibration daily exposure A (8) was 13 and 7 m/s^2 respectively.

Table 5- 5 Frequency-weighted average, vibration total and daily exposure of A (8) at the handle with third gear before and after damper installation

Process of vibration measurement after damping	Frequency-weighted RMS vibration amplitude [m/s^2]				
	Vertical	Forward	Lateral	Vibration total value (a_{hv}) [m/s^2]	Daily exposure of A (8)[m/s^2]
Before damper installation	22.61	11.36	20.79	32.75	12.50
After damper installation	12.13	8.08	10.35	17.9	6.8

5.4. DISCUSSIONS

5.4.1. Evaluation of single axle tractor handle vibration

1. Evaluation of vibration with second gear operation

The vibration at the handle of a single axle tractor for second gear operation was compared before and after vibration insulator installation (Figure 5.3), under similar operating conditions.

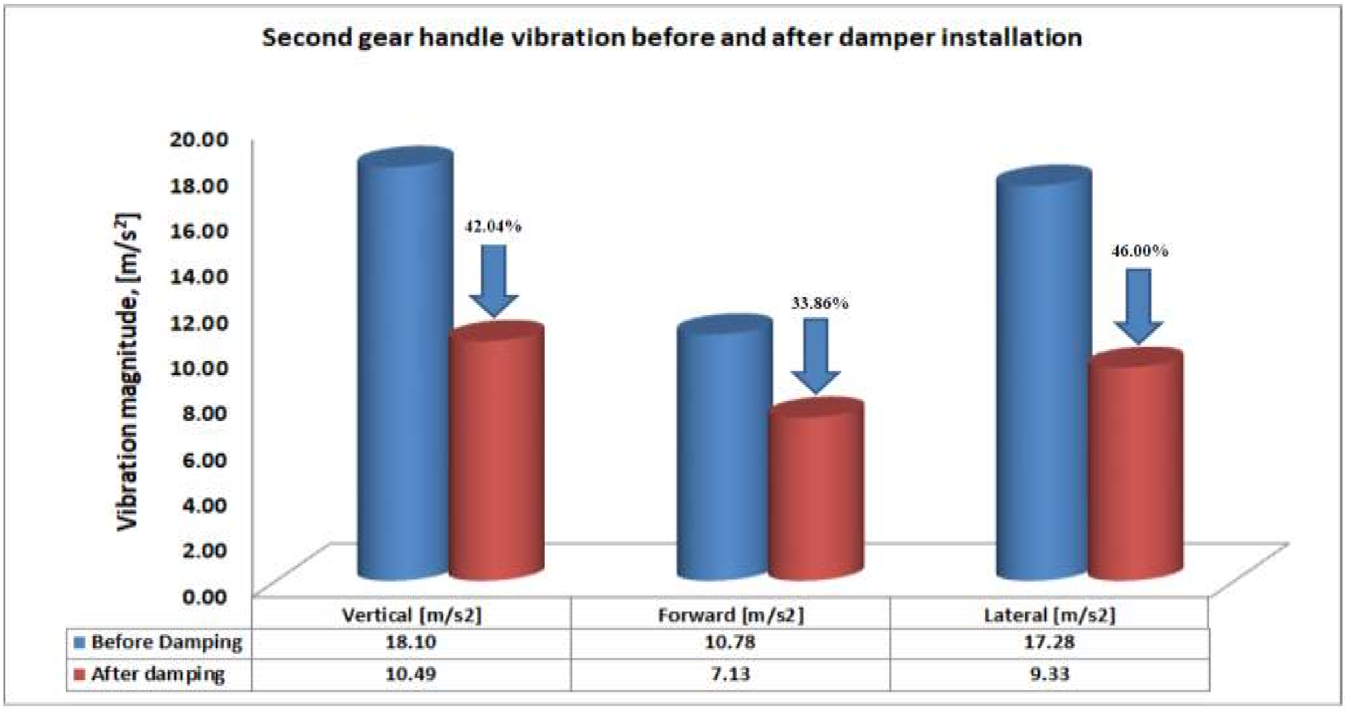


Figure 5 - 3 handle vibration of single axle tractor before and after damper installation

As seen in Figure (5-3), there is a substantial variation between the mean vibration amplitude of the handle on all three axes before and after the vibration damper installation. 42%, 39% and 46% declines were observed in the vertical, forward and lateral directions, respectively. It is evident that the largest vibration reduction is observed in the lateral direction, while the least change is observed in the forward direction.

In addition, the meanpeak (maximum) vibration amplitude showed a decrease of 40%, 37% and 70 % in the vertical, forward and lateraldirections, respectively, after installation of the damper; the maximum decrease was observed in the lateral direction. The rangeof vibration data after installation of the damper was compared with that of the vibration data prior to installation of the damper, suggesting a decrease of 39%, 33% and 73%, respectively, in the vertical, forward and lateral directions.

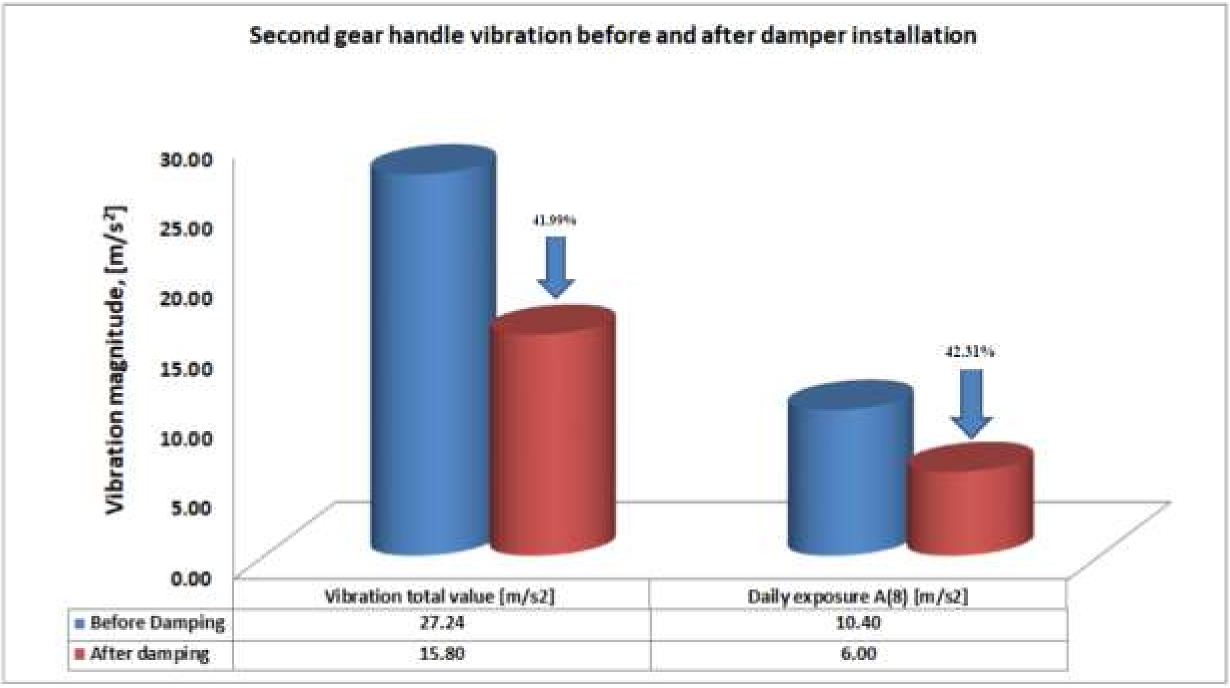


Figure 5 - 4 Vibration total value and daily exposure of single axle tractor before and after damping with the second gear

As seen in the Figure (5.4) a 42% reduction was observed in both vibration total value and A(8) daily exposure with second gear operation of the tractor. These results compare favorably with those of Chaturvedi et al., (Chaturvedi et al., 2012), who developed three intervention methods I1, I2 and I3 for vibration reduction in transport and tilling with a cultivator. In the tilling mode with a cultivator, they observed reductions in total vibration of 30.6%, 23.5% and 20.9% with intervention methods I1, I3 and I2 respectively.

2. Evaluation of vibration with third gear operation

The vibration at the handle of a single axle tractor forthird gear operation was compared before and after vibration insulator installation (Figure 5.5), under similar operating conditions.

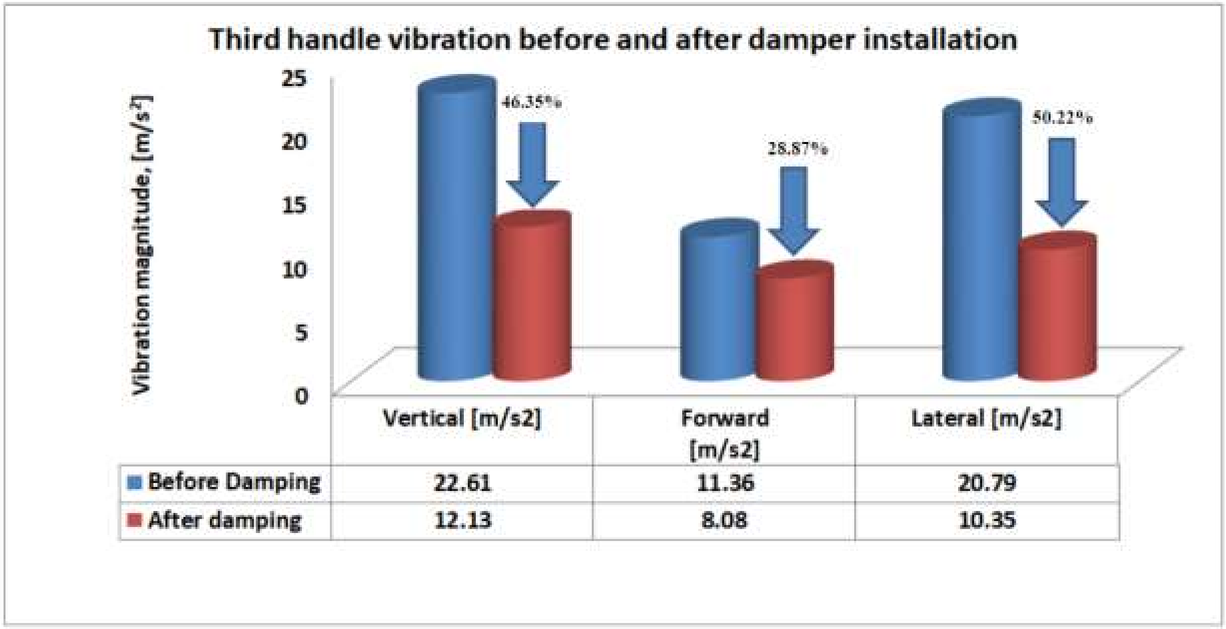


Figure 5 - 5 handle vibration of single axle tractor in third gear before and after damper installation

As seen in Figure (5-5), there is a substantial variation between the mean vibration amplitude of the handle on all three axes before and after the vibration damper installation. 46%, 29% and 50% declines were observed in the vertical, forward and lateral directions, respectively. It is evident that the largest vibration reduction is observed in the lateral direction, while the least change is observed in the forward direction.

In addition, the mean peak (maximum) vibration amplitude showed a decrease of 59%, 31% and 54% in the vertical, forward and lateraldirections, respectively, after installation of the damper for third gear operation; the maximum decrease was observed in the verticaldirection. The range of vibration data after installation of the damper was compared with that of the vibration data prior to installation of the damper, suggesting a decrease of 74%, 41% and 73%, respectively, in the vertical, forward and lateral directions.

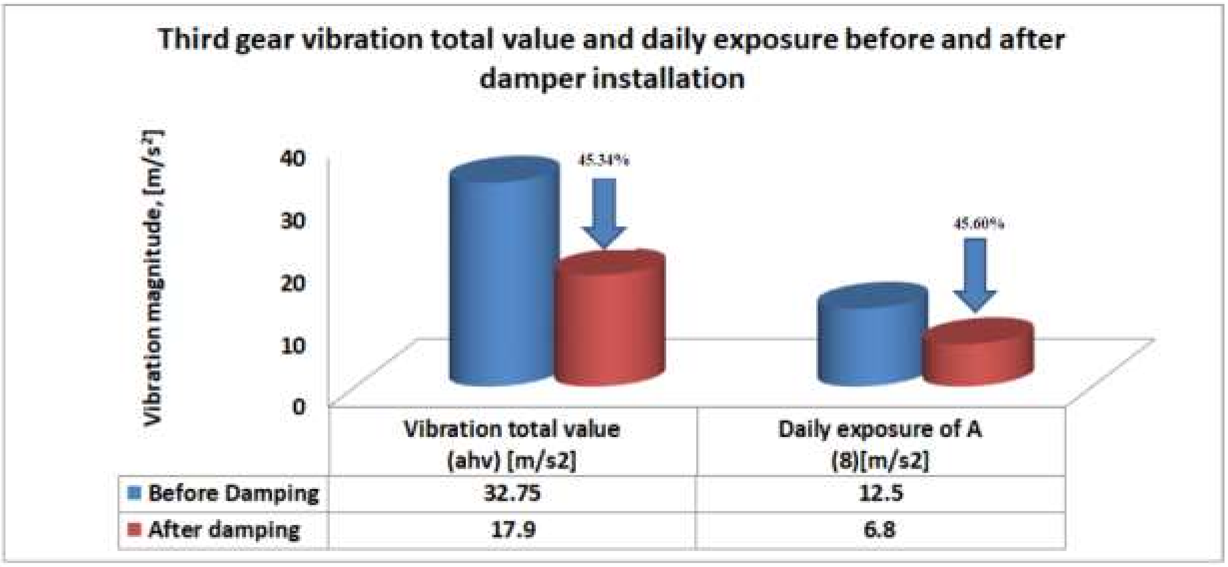


Figure 5 - 6 Vibration total value and daily exposure of single axle tractor before and after damping with third gear

As seen in the Figure (5.6) a 45% reduction was observed in the vibration total value, and a 46% reduction in A(8) daily exposure with third gear operation of the tractor. This is due to in non-linear damping system, the damping properties or force increases as the speed increases(Ghandchi-tehrani, 2015)

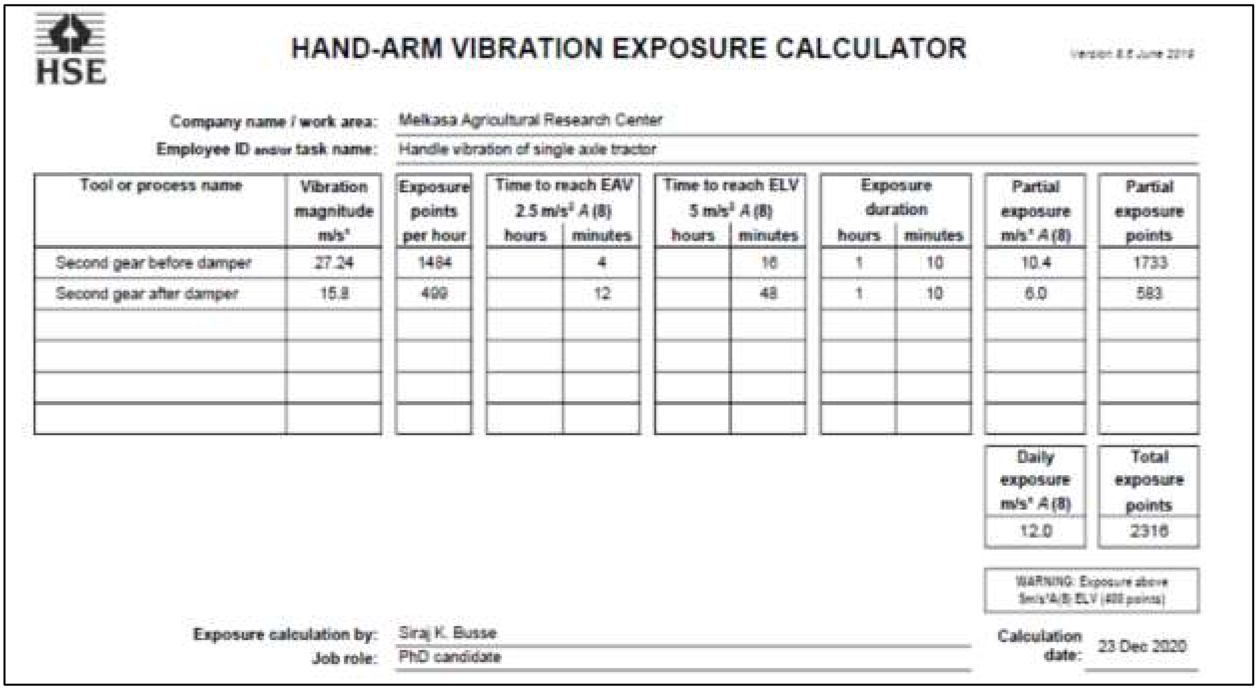
These results can be compared with those of Chaturvedi et al., (Chaturvedi et al., 2016), who focused on intervention methods to reduce vibration transmitted to power tiller operator. They achieved vibration reductions using "sheet and bush type"dampers placed between chassis and the handle bar of up to 70 %.

Yap et al., (Yap et al., 2016) measured the reduction in vibration using a combination of handle grips and rubber engine mounts. They achieved vibration reductions of 55% and 59% for gasoline and diesel engines, respectively. Lu et al. (Lu et al., 2018) engineered and prototyped rubber vibration isolation systems to decrease the vibration of the power tiller handle, and observed that the amplitude of the acceleration on the handle had been decreased by 40%.

5.4.2. Evaluation of vibration exposure of single axle tractor operators

Second gear operation

From the “vibration total value” data with second gear shown in Table 5.3 before and after damping, the vibration exposure was determined according to the Control of Vibration at Work Regulations that are based on the 2002 EU Physical Agents (Vibration) Directive (2002). Vibration total value and daily exposure of A(8) in m/s^2 were calculated using equations (2.2) and (2.3). The vibration daily exposure of A(8) was also calculated from vibration total value and duration of exposure by using the Hand-Arm Vibration Exposure Calculator designed by the Health and Safety Executive(HSE, 2019) (figure 5.7).



HSE

HAND-ARM VIBRATION EXPOSURE CALCULATOR

Company name / work area: Melkasa Agricultural Research Center
Employee ID and/or task name: Handle vibration of single axle tractor

Tool or process name	Vibration magnitude m/s²	Exposure points per hour	Time to reach EAV 2.5 m/s² A (8)		Time to reach ELV 5 m/s² A (8)		Exposure duration		Partial exposure m/s² A (8)	Partial exposure points
			hours	minutes	hours	minutes	hours	minutes		
Second gear before damper	27.24	1484		4		16	1	10	10.4	1733
Second gear after damper	15.8	499		12		48	1	10	6.0	583

Daily exposure m/s² A (8)	Total exposure points
12.0	2316

WARNING: Exposure above 5m/s² A(8) ELV (400 points)

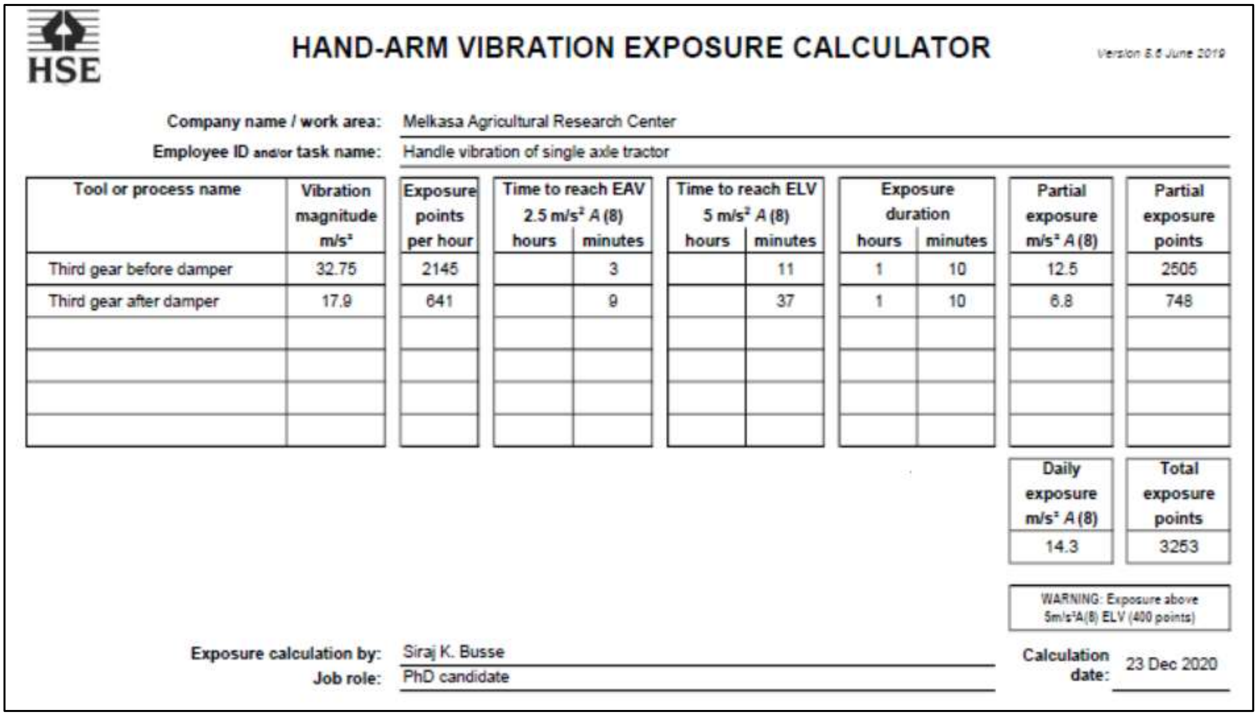
Exposure calculation by: Siraj K. Busse
Job role: PhD candidate
Calculation date: 23 Dec 2020

Figure 5 - 7 Hand-arm vibration exposure calculation for the proposed Control of Vibration at Work Regulations with the second gear

Time to reach the EAV of 2.5m/s^2 of A (8) would increase from 4 to 12 minutes, and the ELV of 5m/s^2 of A (8) would increase from 15 minutes to 48 minutes, due to installation of the damper system for second gear operation. The Measured Daily Exposure decreases from 10.8 to 6.0 m/s^2 of A (8); it is noted that this is still significantly above the Action Maximum Value of 5m/s^2. The Overall Exposure points have also decreased from 1870 to 587 Total Exposure points because of damper installation.

Third gear operation

From the "vibration total value" data with third gear shown in Table 5.5 before and after damping, the vibration exposure was determined according to the Control of Vibration at Work Regulations that are based on the 2002 EU Physical Agents (Vibration) Directive (PGM, 2015). Vibration total value and daily exposure of A(8) in m/s^2 were calculated using equations (2.2) and (2.3). The vibration daily exposure of A(8) was also calculated from vibration total value and duration of exposure by using the Hand-Arm Vibration Exposure Calculator designed by the Health and Safety Executive(HSE, 2019) (figure 5.8).



HSE

HAND-ARM VIBRATION EXPOSURE CALCULATOR

Company name / work area: Melkasa Agricultural Research Center
Employee ID and/or task name: Handle vibration of single axle tractor

Tool or process name	Vibration magnitude m/s²	Exposure points per hour	Time to reach EAV 2.5 m/s² A (8)		Time to reach ELV 5 m/s² A (8)		Exposure duration		Partial exposure m/s² A (8)	Partial exposure points
			hours	minutes	hours	minutes	hours	minutes		
Third gear before damper	32.75	2145		3		11	1	10	12.5	2505
Third gear after damper	17.9	641		9		37	1	10	6.8	748

Daily exposure m/s² A (8)	Total exposure points
14.3	3253

WARNING: Exposure above 5m/s²A(8) ELV (400 points)

Exposure calculation by: Siraj K. Busse
Job role: PhD candidate
Calculation date: 23 Dec 2020

Figure 5 - 8 Hand-arm vibration exposure calculators for proposed Control of Vibration at Work Regulations with third gear

Time to reach the EAV of 2.5m/s^2 of A (8) would increase from 3 to 9 minutes, and the ELV of 5m/s^2 of A (8) would increase from 11 minutes to 37 minutes, due to installation of the damper system for third gear operation. TheCalculated Daily Exposure decreases from 13 to 7 m/s^2 of A (8); it is noted that this is still significantly above the Action Maximum Value of 5m/s^2. The Overall Exposure points have also decreased from 2465 to 748 Total Exposure points because of damper installation; this is still well above the limit of 400 points.

5.4.3. Evaluation of latency period of single axle tractor operators

After the vibration isolator was installed, the latency period was calculated for 2nd and 3rd gear operation, and shown in figure (5.9). Installation of the damping mechanism led to a decrease in vibration at the handle of 42% and 45% in second and third gear of tractor operation, respectively. This vibration reduction led to an increase of the latency period of 89% and 90% for second and third gear operation, respectively.

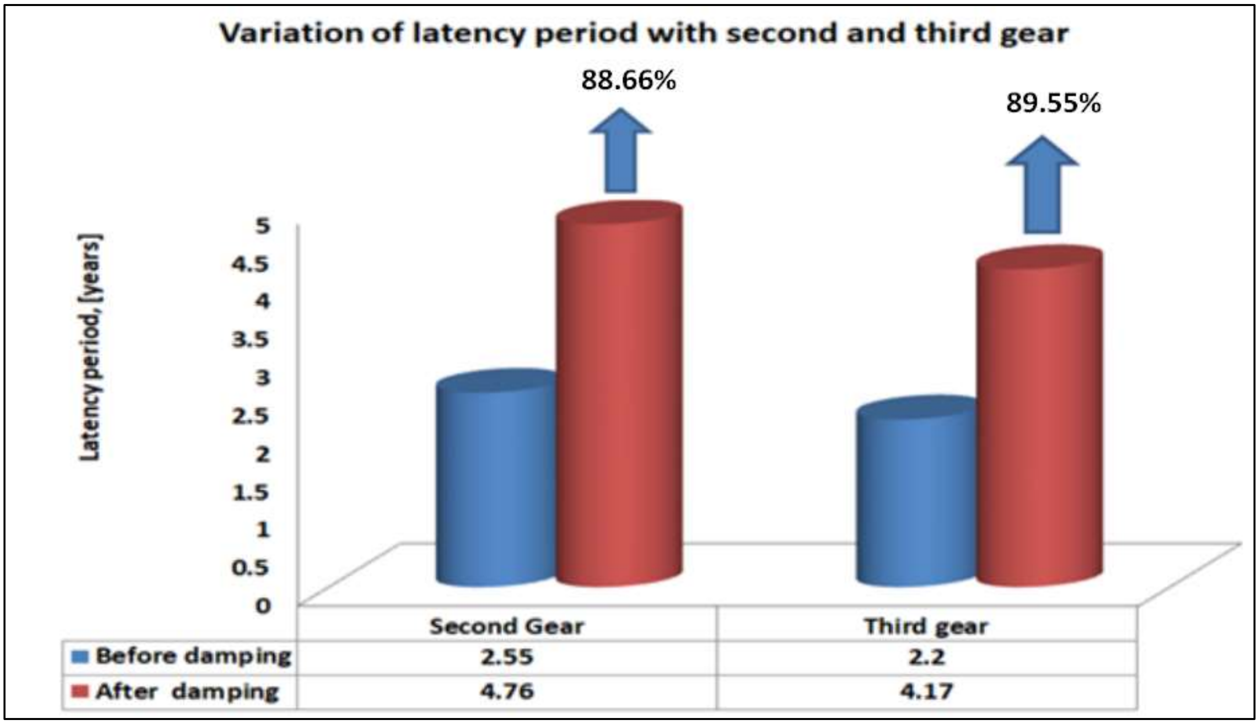


Figure 5 - 9Latency period of single axle tractor operators with second and third gears operations

The latency period is an estimate of the time for physiological symptoms to start to appear in the population of operators exposed to the tractor vibrations. For second gear of tractor operation, installation of the damper causes the vibration total value magnitude to decrease from 27 m / s^2 to 16 m / s^2, and the latency period for hand-arm vibration syndrome to appear to increase from 2.6 to 4.8 years. For third gear of tractor operation, installation of the damper causes the vibration total value magnitude to decrease from 33 m / s^2 to 18 m / s^2, and the latency period for hand-arm vibration syndrome to appear to increase from 2.2 to 4.2 years.

These results can be compared with those of other researchers. Ying et al. (Ying, et al . , 1998) tested the anti-vibration system used to regulate the grip of the walking tractor according to ISO 5349 (1986) requirements. They found that the frequency of weighted accelerations in three directions had decreased by 41%, and the latency time before neurovascular hand disorders were visible had been extended from 1,417 years to 3,309 years by installation of a damper system. Dong (Dong, 1996) evaluated the vibration absorber performance on the handles of a walking tractor following ISO 5349 (1986) and found that the weighted acceleration in the direction of most severe vibration was reduced by 56%, and the latency period of daily exposure to handling vibration was increased by 126%.

Chaturvedi et al., (Chaturvedi et al., 2012) evaluated the average exposure time(latency period) for the occurrence of white finger syndrome and observed an increased by 51%, 35% and 38% achievable with type I1, I2 and I3 interventions for vibration suppression in tilling with a cultivator for 8 h daily exposure.

Four (4) Regression Learner Models were used to test the relationship between the latency period and the total vibration value (Table 5-6). In all models it was observed that thelatency time decreasesas the vibration total value increases. Thecubic SVM regression and curve fitting modelwas found to have the best fit for relating latency period y to the total vibration value x.The relationship was found to be:

$$y = a_1x^3 + a_2x^2 + a_3x + a_4$$

Where, a_1 = -0.01244

a_2 = 0.39895

a_3 = -4.4603

a_4 =9.905

The value of y and x represents the latency period in years and daily exposure of A (8) in m/s^2. The norms of residuals of these coefficients are 0.23617 and R-sq. = 0.96. Results are graphed in Figure 5-10:the “calculated” data weredetermined from equation (2.3); the “predicted” values werecalculated by the MATLAB regression learner; the“cubic” date is from the fitted curve.

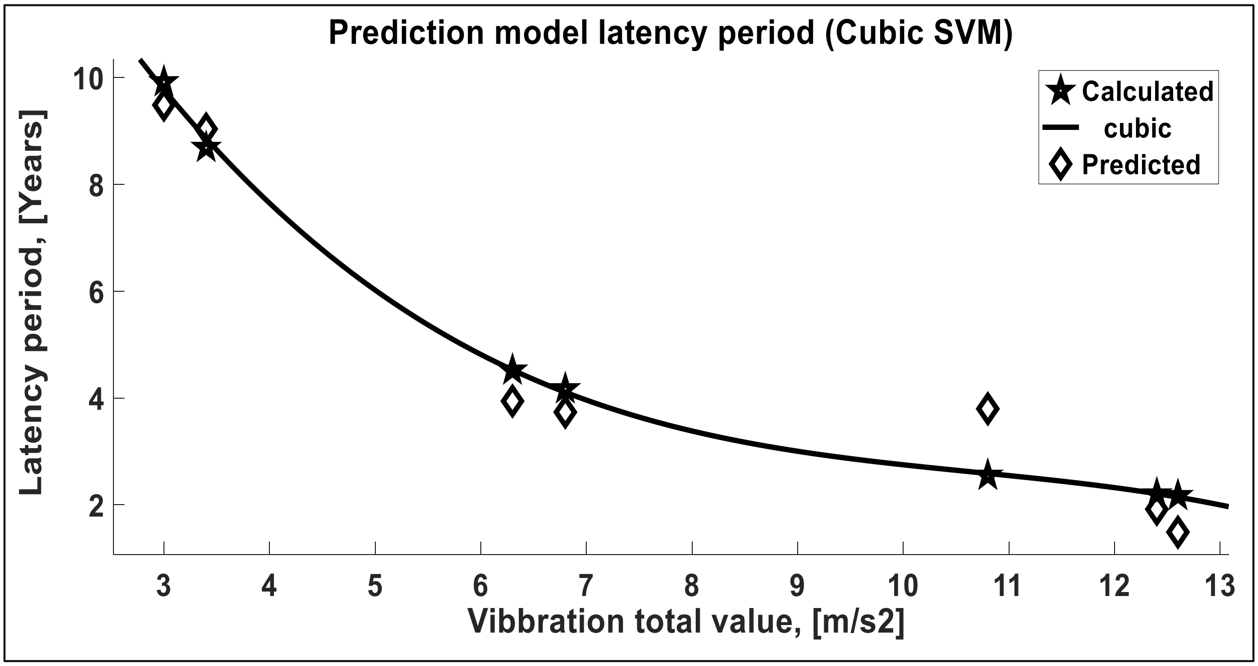


Figure 5 - 10 Relationship between latency periods and handle vibration

5.5. CONCLUSION

Vibration dampers made of a rubber compound recipe with a diameter of 80 mm, a thickness of 25 mm and an inner diameter of 13 mm were provided by Horizontal Addis Tire PLC and installed to isolate the engine vibration from the chassis as well as the handle of the single axle tractor. After the vibration damper was installed, there was a substantial reduction in vibration magnitude of single axle tractor.

After the vibration damper was installed, the measured and calculated handle vibration was evaluated for both the second and third gear of tractor operation. The vibration amplitude after damping compared with the pre-installation vibration showed a decrease of 42%, 39% and 46 % respectively in the vertical, forward and lateral directions during operation of the second gear. The mean peak (maximum) vibration after damper installation showed a decrease of 40, 37 and 70 % in the vertical, forward and lateral directions, respectively; the range of vibration data after installation of the damper was compared with that of the vibration data prior to installation of the damper, suggesting a decrease of 39%, 33% and 73%, respectively, in the vertical, forward and lateral directions. As seen from the results of mean, maximum and the range the maximum decrement in the lateral direction was observed.Reductions of 42% inboth vibration total value and A (8) daily exposure were observed with second gear operation.

With third gear operation, a decrease of 46%, 29% and 50 % in mean vibration amplitude were observed in the vertical, forward and lateral directions respectively.The mean peak (maximum) vibration after damper installation showed a decrease of 59%, 31% and 54% in the vertical, forward and lateral directions, respectively. The range of vibration data after installation of the damper decreased by 74%, 41% and 73%, respectively, in the vertical, forward and lateral directions.The average vibration total value and daily exposure A(8) after damper installation decreased by 45% and 46% respectively, after damper installation respectively.

For third gear operation, installation of the damper cause thetime to reach the EAV of 2.5m/s^2 of A (8) to increase from 3 to 9 minutes, and ELV of 5m/s^2 of A (8) to increase from 11 minutes to 37 minutes.Also, the Calculated Daily exposure decreases from 13 to 7 m/s^2 of A (8), which is still well above the Action Limit Value (5m/s^2). The Total Exposure points were also decreased from 2465 to 748, but this lower value is still well above the limit of 400 points.

As the handle vibration total value magnitude decreases from 27 m/s^2 to 16 m/s^{2}due to damper installation in second gear, the latency period at which the hand-arm vibration syndrome becomes apparent increases from 2.55 to 4.76 years duration. As the vibration total value magnitude decreases from 33 m/s^2 to 18 m/s^{2}due to damper installation in third gear, the latency period at which the hand-arm vibration syndrome becomes apparent is prolonged from 2.22 to 4.17 years.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1. CONCLUSION

A single-axle tractor is a multipurpose hand tractor mainly designed for rotary tilling and other farm operations. Recently, it has become a primary or even sole mechanical resource for small and medium-sized farms worldwide. The assessment of their vibration characteristics and their physiological effects is of great importance in the event of such widespread and continuous use. In particular, the operators of single-axle tractors are vulnerable to hand-held vibrations. These vibrations may cause complex vascular, neurological and musculoskeletal disorders, collectively referred to as hand-arm vibration syndrome. Among these, the most common condition is the vibration-induced white finger (Raynaud phenomenon).

This project studied the effects of hand-transmitted vibrations for actual Ethiopian farming conditions during the tilling/farming process, with the tractor operating in second or third gear. Seven (7) single-axle tractor operators were selected for this study. Hand-transmitted vibrations have been measured and evaluated following ISO 5349 standards and international guidelines considering key parameters. Vibration data were collected both for the hand of operators and on the handle of a 15-HP single-axle tractor while performing routine tilling operations with second and third gears. Handle vibration data were analyzed in both the time and frequency domains along three perpendicular axes, following international safety standards.

The human response to hand-arm vibration was evaluated through the consideration of physiological and biodynamic reactions. Physiological assessment involving a review of the variables associated with the functioning of the structures and subsystems in the human body of single-axle tractor operators was carried out before and after vibration exposure from tractor activity. The methods and techniques used in this approach are varied, but they are all based on empirical observation. The variables observed are derived from the measurable properties and functions of the biological systems and subsystems; phenomena such as heart rate, blood pressure, and oxygen saturation were included in this analysis.

The Health & Safety Executive (HSE) HAV Calculator (Hand-Arm Vibration Exposure Calculator) is a very useful tool for quantitative and ergonomic measurement of HAVs at the workplace and has been used in this study. The final output of the HAV Exposure Calculator is the Cumulative Exposure Points for the entire mission, which is determined by summing the partial exposure values of all components of the work assignment.

The Exposure Action Value (EAV) is equal to 100 points; this level implies increased risk to workers, and administrative or engineering controls should be considered to minimize risk. The Exposure Limit Value (ELV) is equal to 400 points; at this point, acceptable limits have been exceeded and workers are at serious risk of developing significant harm. Controls should be put in place immediately to minimize vibration exposure.The EAV action value was set at a vibration magnitude of 2.5 m/s^2, and the ELVat a value of 5 m/s^2. Both values are A(8) values, which means they are average vibration values over an 8-hour working day.

Grip strength is generally measured using a handheld dynamometer. The operator of a single axle tractor squeezes the dynamometer with maximum effort before and after the operation of a single axle tractor, usually three times with each hand. The average score is then calculated for each hand.

The vibration characteristics of a single axle tractor were assessed by measuring vibration at the handle of a single axle tractor and the hands of operators with second and third gear ratios, taking into account tractor forward speed and soil parameters such as moisture content and soil compaction. From the vibration measurements, the highest vibration amplitude was in the vertical direction, while the lowest vibration magnitude was observed in the forward direction. Frequency domain analysis found that the maximum spectral acceleration density for all three axes was in the low-frequency range (< 25 Hz); vibrations are efficiently transmitted to the operator's arms, shoulders, neck, and head from the tractor handle in this frequency range. This will have negative health effects on the operators of single-axle tractors.

The Daily Exposure in m/s^2 A (8) of vibration at the tractor handle exceeds the ELV exposure limit value of 5 m/s^2 and the Total Exposure points exceeds the limit of 400. From frequency-domain vibration analysis and calculated results of operator daily vibration exposure, an operator of this type of single axle-tractor is at significant risk of developing Hand-Arm Vibration Syndrome (HAVS). Symptoms include effects on the peripheral vascular system, the peripheral nervous system, muscles, bones, tendons and soft tissues. Episodic finger whitening (white finger) is the most commonly recognized effect, but sensory changes (loss of sensation) are now given greater significance.

The latency time for Hand Arm Vibration Syndrome (HAVS) for single-axle tractor operators in our tests ranged from 2.2 to 2.6 years. This implies a time period for the occurrence of symptoms after first exposure to vibration varying from 6 months to more than 20 years, depending on the magnitude of the exposure and personal vulnerability of the worker.

The average heart rates of single-axle tractor operatorswere measured at rest, during and after operation of the single-axle tractor. The mean resting heart rate measured was 71 ± 8 beats/min; the mean working heart rate measured every 5-minute during the operation of single axle tractor was 163 ± 18 beats/min, and the mean recovery heart rate measured after the operation was 126 ± 26 beats/min. As seen from these findings, the vibration of a single axle tractor handle and heart rate increase of the operator has a strong positive relationship. Associated physiological workload parameters such as age-dependent maximum heart rate, maximum appropriate 8-hour work shift heart rate (HRmax (8h)), cardiovascular stress index, relative cardiovascular load, and cardiovascular strain were also calculated.

The mean calculated cardiovascular stress (CSI) is a physical workload measure related to muscular activity due to the exposure of the single axle tractor to vibration regulation. For our tractor operators, the value of 74 ± 10 per cent is far higher than the prescribed threshold value of 24.5 per cent. From all of these measures of load on the heart, it was concluded that the physical workload of tractor operation falls into the category of excessively heavy work for which the working heart rate has more than doubled relative to the resting heart rate. This extremely high physical workload has a strong effect on single-axle tractor operators over prolonged periods and can contribute to the risk of various musculoskeletal disorders.

The biodynamic response of single-axle tractor operators was also assessed in terms of grip strength and vibration transmissibility. Measured handgrip data of tractor operators have been compared to values collected in other research projects. Fatigue resistance, mean grip strength and maximum grip strength have been calculated. For the dominant hand, the mean fatigue resistance (time to reduce grip strength to 50 percent of full grip strength) was 27.6 and 26.5 seconds, respectively, before and after vibration exposure by 30 minutes of tractor operation.

The mean estimated maximum grip strength for the dominant hand was 33.6 kg and 26.3 kg before and after 30 minutes of operation respectively, for seven (7) single-axle tractor test subjects. The corresponding values for the non-dominant hand were 28.7 and 23.1 kg of force before and after vibration exposure. The findings indicate a substantial average reduction of 7.3 and 5.6 kg of grip strength for dominant and non-dominant hands of the single-axle tractor operators respectively.

The 2, 3 and 4-DOF hand-arm physical model were used to analyze the propagation of vibration from the single axle tractor to the hand of operator. Models 2 and 3-DOF were models of human-tool systems used in the ISO specification for physical hand-arm system models (ISO 10068, 2012). The third model hand-arm system model used to evaluate hand-arm vibration used in this analysis was the 4-DOF model recently suggested by several researchers (R. G. Dong et al., 2007, 2008, 2013; Kamalakar & Mitra, 2018; Wu et al., 2017).

A 2-DOF model shown in figure (4.2a) is limited to evaluate the vibration transmitted to palm-wrist-forearm. The 3- DOF model shown in figure (4.2b) is used to evaluate the vibration transmitted to fingers in addition to palm-wrist-forearm, whereas the 4-DOF model shown in figure (4.3) is used to evaluate vibration transmitted to fingers, palm-wrist-forearm and upper arm-shoulder.

The 4-DOF model is the best model for the measurement of hand-arm transmitted vibration in the hand-arm system, as it can be used to quantify the vibration transmitted to fingers and upper arm-shoulder parts, unlike the 2-DOF model. The 4-DOF model also has the advantage over the 3-DOF model in accounting for the vibration transmitted to the upper arm-shoulder.

The hand vibration measured in the second and third gear tractor operations was contrasted with the vibration produced by the 2, 3 and 4-DOF models. The peak vibration magnitude of the 4-

DOF model was found to be similar to the peak vibration magnitude during second and third gear operations. It was observed that for all models the vibration transmitted to the forearm of the palm wrist rose until it reached the frequency of the resonance and decreased dramatically after reaching the frequency of 31.5 Hz and gradually almost dropped to zero at a frequency of 1250 Hz.

The acceleration spectral densities of strength started to decline with frequency after passing resonance frequencies and these were seen in separate test results in all three models and the resonance frequencies of all models were observed below the 31.5 Hz nominal frequency.

The four (4)vibration dampers made of a rubber compound with a diameter of 80 mm, a thickness of 25 mm and an inner diameter of 13 mm provided by Horizontal Addis Tire PLCwereinstalled to isolate the engine vibration from the chassis as well as the handle of the single axle tractor. After the vibration damper was installed, there is a substantial reduction in vibration magnitude of the single axle tractor when compared with the value before vibration damping.

Compared to pre-damping vibration, the mean measured vibration amplitude after damping showed a decrease of 42%, 38% and 46% respectively in the vertical, forward and lateral directions during second gear operations. In third gear, there isa decrease of 46%, 29% and 50 % respectively in the vertical, forward and lateral directions. The vibration total value after damper installation was also associated with a decrease of 42% and 46% per cent with the second and third gears respectively. It can be seen from the results that there is a stronger decrease in vibration through addition of a damper, when operating in a third gear than the second gear.

With second gear operation single axle tractor the ELV of $5 m/s^2$ of A (8) is reached in 48 minutes, compared to 16 minutes without a damper.The addition of a damper caused a decrease in the Calculated Daily exposure from 10 to 6.0 m/s^2 of A (8), but this is still above the Action Limit Value ($5 m/s^2$). The Total Exposure points were also decreased by 1733 to 583, but this is still well above the safe limit of 400 points.

The ELV of 5m/s^2 of A (8) is reached in 37 minutes, compared to 11 minutes without a damper with third gear operation. The addition of a damper caused a decrease in the Calculated Daily exposure from 13 to 7 m/s^2 of A (8), but this is still above the Action Limit Value (5m/s^2). The Total Exposure points were also decreased by 2505 to 748, but this is still well above the safe limit of 400 points.

The latency period is a measure of the time following exposure to vibration before signs of hand-arm vibration syndrome begin to occur in the exposed population. When the damper was installed during second gear operation, the average vibration total value of the handle decreased from 27 m/s^2 to 16 m/s^2, and the latency period increased from 2.55 years to 4.76 years (89% improvement).When the damper was installed during third gear operation, the average vibration total value of the handle decreased from 33 m/s^2 to 18 m/s^2, and the latency period increased from 2.22 years to 4.17 years (89% improvement).

6.2. RECOMMENDATIONS

For small-scale farmers, single-axle tractors are very important, but due to operational problems such as excessive vibration, they are not fully utilized. The vibration characteristics of a single axle tractor were addressed in this research work by introducing a rubber compound damper and measuring the physiological and biodynamic reactions of the operator. The following actions should be considered by industry and operators of single-axle tractors:

- Single-axle tractor manufacturers should consider redesigning the handles or the engine mounting on the frame by including vibration dampers to reduce the vibration that is transmitted from the handles to the operator's wrists, arms and shoulders.
- Decrease the exposure time and vibration magnitude of current single-axle tractors by operating at low forward speed, revising the working schedule, employingtask rotation (allowing rest periods) or using anti-vibration gloves.
- Proper instruction on the fundamentals of single-axle tractor handling and operation should be provided to operators before they are permitted to operate single-axle tractors.
- Single-axle tractor operatorsshould have medical check-ups after each farming season to diagnose any microscopic damage to the hand-arm system as it starts as pain and eventually progresses into a complex vibration-induced condition as the exposure to vibration continues.
- Tractor and implement matching which involves balancing implement load characteristics with tractor output characteristics to obtain the best output from the combination should be carried out.

The following topics may be suitable for further academic research:

- Application of adaptive technology to solve problems of single-axle tractor stability
- Dynamic analysis of single axle tractor implements
- Detailed evaluation of long term effect of hand-arm vibration.
- Field experiments in different agro-ecological zones to determine the magnitude of HTV and to identify the factors that contribute to the incidence of HAVS among single-axle tractor operators in Ethiopia.

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APPENDIXES

APPENDIX 2.1 Frequency weighting factors W_h for hand-transmitted vibration with band limiting

The one-third octave bands have lower and higher frequencies that can be defined using formula fn-1 = fn/$2^{1/3}$ for lower and fn+1 = $2^{1/3}$fn and the percent fractional bandwidth per 1/3-octave band is constant: $BW = 100\left[\left(f_n^{high} - f_n^{low}\right)/ f_n^{ctr}\right] \approx 23.2\%$ where f_n^{ctr} central frequency.

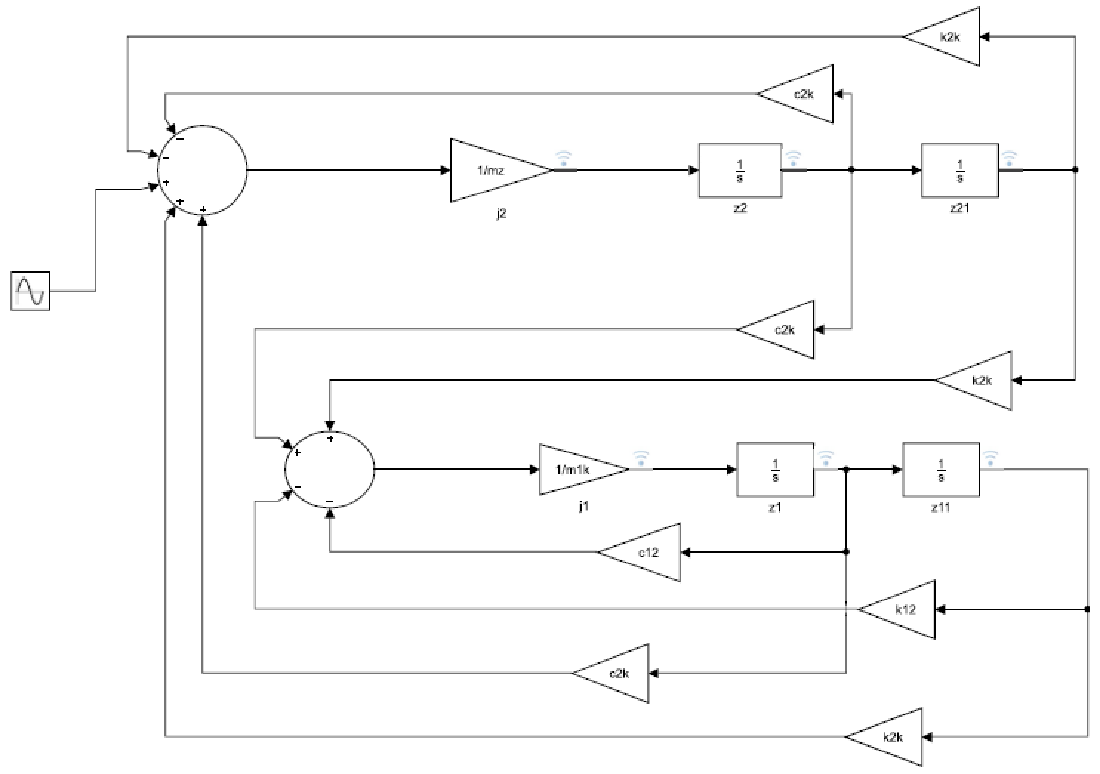
Table A.2.1 – Frequency weighting factors W_h for hand-transmitted vibration with band limiting for conversion of one-third-octave band magnitudes to frequency-weight magnitudes.

Frequency band number (i)	**Mid nominal frequency, Hz**	**Weighting factor W_h**
4	**4**	0.37500
6	**5**	0.54100
8	6.3	0.72700
9	8	0.87300
10	10	0.95100
11	12.5	0.95800
12	16	0.89600
13	20	0.78100
14	25	0.64700
15	31.5	0.51900
16	40	0.41100
17	50	0.32400
18	63	0.25600
19	80	0.20200
20	100	0.16000
21	125	0.12700
22	160	0.10300
23	200	0.07950
24	250	0.06340
25	315	0.05000
26	400	0.03980
27	500	0.03140
28	630	0.02450
29	800	0.01860
30	1000	0.01350
31	1250	0.00894
32	1600	0.00536
33	2000	0.00295

Appendix 4- 3values of dynamic parameters for ISO 10068, model 1 and 2 (Dobry & Hermann, 2015) and 4-DOF physical model (Ren G. Dong, Daniel E. Welcome, Thomas W. McDowell, 2013)

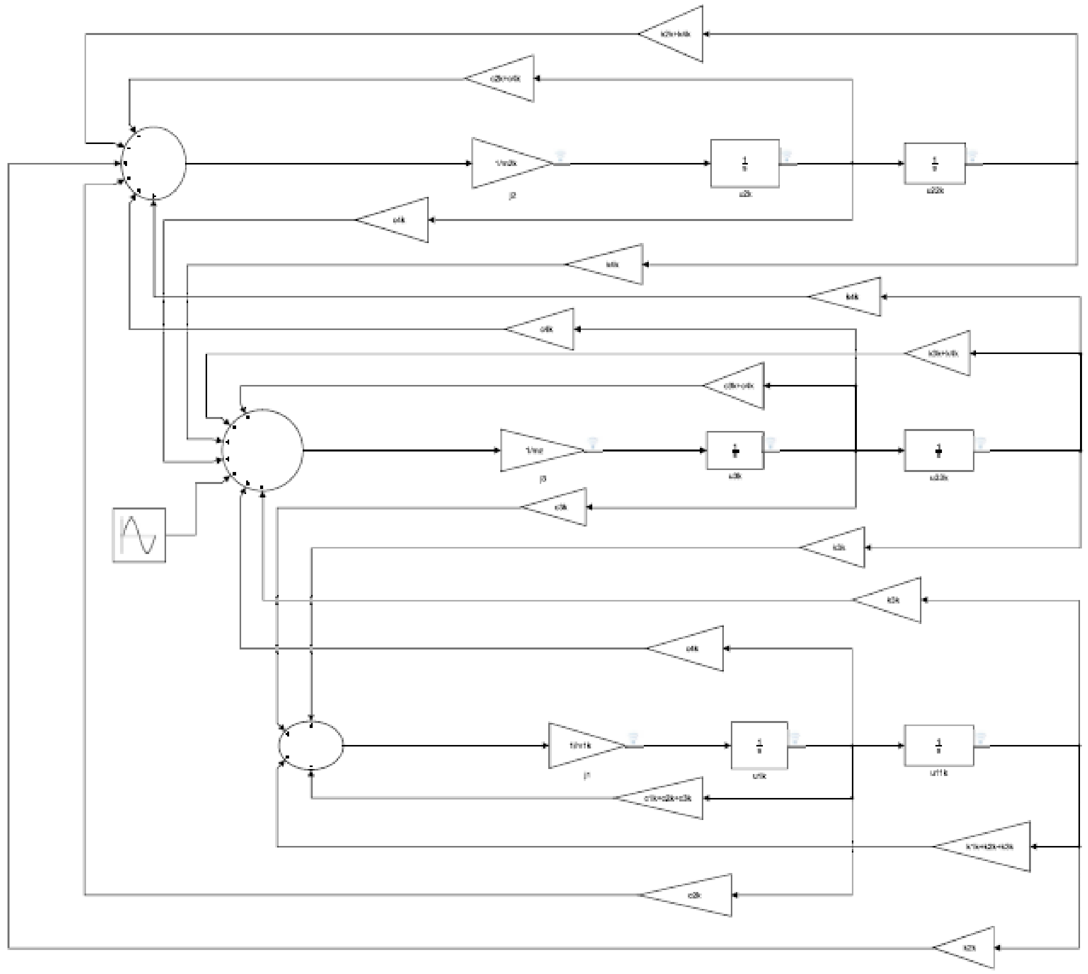
		Vibration direction								
Parameter	**Unit**	**ISO 10068 model 1**			**ISO 10068 model 2**			**4-DOF model**		
		Lateral	**Forward**	**Vertical**	**Lateral**	**Forward**	**Vertical**	**Lateral**	**Forward**	**Vertical**
m_0	Kg	-	-	-	-	-	-	0.236	0.3605	7.5
m_1	Kg	0.5479	0.5374	1.2458	0.4129	0.7600	1.1252	0.3998	0.5515	1.0721
m_2	Kg	0.0391	0.0100	0.0742	0.0736	0.0521	0.0769	0.0576	0.0725	0.076
m_3	Kg	-	-	-	0.0163	0.0060	0.0200	0.0205	0.005	0.02
m_4	Kg	-	-	-	0.0100	0.0028	0.0100	0.01	0.003	0.01
k_0	N/m	-	-	-	-	-	-	1000	1000	8059
k_1	N/m	400	400	1000	400	500	1000	6972	1000	1891
k_2	N/m	0	17648	50000	200	100	12000	100	100	12,000
k_3	N/m	-	-	-	4000	4907	43635	4000	5443	44,220
k_4	N/m	-	-	-	8000	17943	174542	65,844	15,170	176,880
c_0	N-s/m	-	-	-	-	-	-	21.8	40.5	93.1
c_1	N-s/m	22.5	38.3	108.1	20.0	28.1	111.5	22.1	95.7	112.1
c_2	N-s/m	202.6	75.5	142.4	100	39.7	39.3	69.8	37.6	39.7
c_3	N-s/m	-	-	-	144.6	50.7	86.3	128.6	51.5	83.9
c_4	N-s/m	-	-	-	79.9	14.3	121.0	81.5	11.4	116.7

Appendix 4.2 Simulink model block for ISO 10068:2012-based human physical model 1



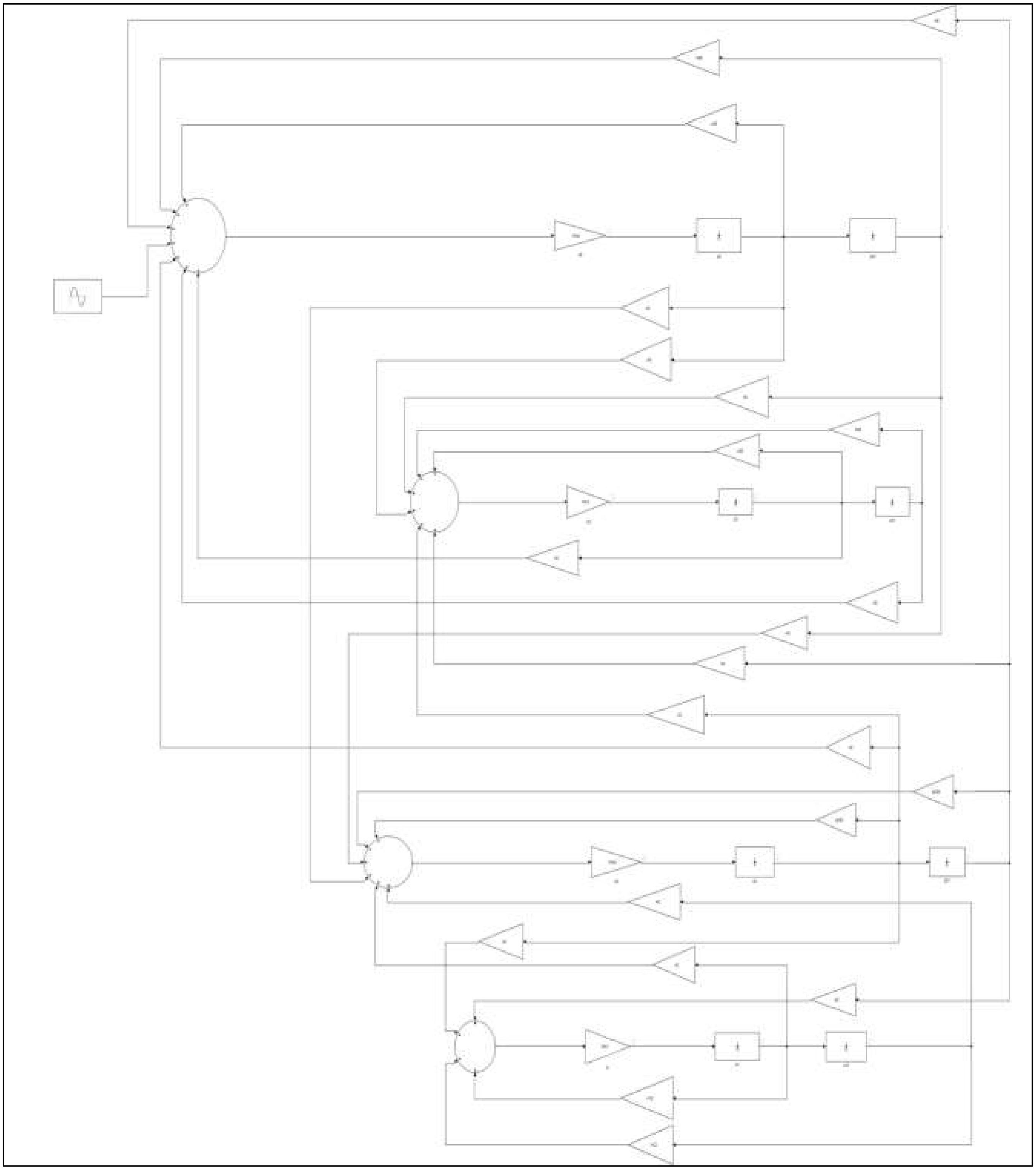
Simulink model for model 1 of ISO 10068:2012 standard

Appendix 4.3 Simulink model block for ISO 10068:2012-based human physical model 2



Simulink model for model 2 of ISO 10068:2012 standard

Appendix 4.4 Simulink model block for the 4-DOF human physical model



Appendix 4.5: Global Matrices

Mass and stiffness matrices for the three DOF model were

$$[M]=\begin{bmatrix} 1.2458 & 0.0000 \\ 0.0000 & 5.0742 \end{bmatrix} \qquad [K]=\begin{bmatrix} 51000.00 & -50000.0 \\ -50000.0 & 50000.00 \end{bmatrix} \quad [C]=\begin{bmatrix} 250.500 & -142.40 \\ -142.40 & 142.400 \end{bmatrix}$$

Mass and stiffness matrices for the four DOF model were

$$[M]=\begin{bmatrix} 1.1252 & 0.0000 & 0.0000 \\ 0.0000 & 0.0769 & 0.0000 \\ 0.0000 & 0.0000 & 5.0300 \end{bmatrix} \; [K]=\begin{bmatrix} 56635.00 & -12000.00 & -43635.00 \\ -12000.0 & 186542.00 & -174542.0 \\ -43635.0 & -174542.0 & 218177.000 \end{bmatrix}$$

$$[C]=\begin{bmatrix} 237.6000 & -39.300 & -86.8000 \\ -39.300 & 160.3000 & -121.000 \\ -86.800 & -121.000 & 207.8000 \end{bmatrix}$$

Mass and stiffness matrices for the five DOF model were

$$[M]=\begin{bmatrix} 7.5000 & 0.00000 & 0.0000 & 0.0000 \\ 0.0000 & 1.07210 & 0.0000 & 0.0000 \\ 0.0000 & 0.00000 & 0.0760 & 0.0000 \\ 0.0000 & 0.00000 & 0.0000 & 5.0960 \end{bmatrix} \; [K]=\begin{bmatrix} 9950.00 & -1891.00 & 0.00000000 & 0.00000000 \\ -1891.0 & 58111.000 & -12000.00 & -44220.00 \\ 0.000000 & -12000.0 & 56220.0000 & -44220.0 \\ 0.000000 & -44220.0 & -176880.0 & 221100.00 \end{bmatrix}$$

$$[C]=\begin{bmatrix} 205.20 & -112.10 & 0.0000 & 0.00000 \\ -112.1 & 235.700 & -39.70 & -83.90 \\ 0.0000 & -39.700 & 123.600 & -83.90 \\ 0.0000 & -83.900 & -116.70 & 200.600 \end{bmatrix}$$

Mass and stiffness matrices for the five DOF modified model were

$$[C]=\begin{bmatrix} 503.00 & -103.00 & 0.0000 & 0.00000 \\ -103.0 & 528.000 & -40.00 & -385.0 \\ 0.0000 & -40.000 & 425.000 & -385.0 \\ 0.0000 & -385.90 & -39.000 & 424.000 \end{bmatrix} \quad [M]=\begin{bmatrix} 7.5000 & 0.00000 & 0.0000 & 0.0000 \\ 0.0000 & 1.02600 & 0.0000 & 0.0000 \\ 0.0000 & 0.00000 & 0.0670 & 0.0000 \\ 0.0000 & 0.00000 & 0.0000 & 5.0800 \end{bmatrix}$$

$$[K]=\begin{bmatrix} 16229.00 & -8170.00 & 0.00000000 & 0.00000000 \\ -8170.0 & 91765.000 & -39667.00 & -44220.00 \\ 0.000000 & -39667.0 & 83595.000 & -44220.00 \\ 0.000000 & -43928.0 & -95711.00 & 139639.00 \end{bmatrix}$$

Appendix 4.6: vibration transmitted to hand with second and third gear operations

Descriptive statistics	***RMS vibration magnitude [m/s^2]***					
	Second			**Third**		
Descriptive statistics	Vertical	Forward	Lateral	Vertical	Forward	Lateral
Mean	10.2553	6.5130	9.2355	11.948	6.851	10.508
Standard Error	0.1214	0.0546	0.1923	0.211	0.059	0.104
Median	10.2095	6.4050	8.7100	11.420	6.745	10.932
Standard Deviation	2.2721	1.0216	3.5982	3.949	1.100	1.936
Sample Variance	5.1624	1.0437	12.9472	15.597	1.210	3.749
Range	12.6378	10.8800	15.1300	15.760	11.360	9.046
Minimum	6.6344	4.0800	3.8800	4.130	4.430	6.126
Maximum	19.2721	14.9600	19.0100	19.890	15.790	15.173

Appendix 4.7: vibration transmissibility with second and third gear operations

Descriptive statistics	***Vibration transmissibility***					
	Second			**Third**		
	Vertical	**Forward**	**Lateral**	**Vertical**	**Forward**	**Lateral**
Mean	0.67	0.69	0.64	0.54	0.62	0.51
Standard Error	0.02	0.01	0.02	0.01	0.01	0.01
Median	0.59	0.66	0.53	0.5	0.6	0.52
Standard Deviation	0.33	0.26	0.38	0.19	0.14	0.12
Sample Variance	0.11	0.07	0.15	0.04	0.02	0.01
Range	1.51	2.03	2.91	0.87	1.3	1.09
Minimum	0.21	0.11	0.07	0.18	0.31	0.23
Maximum	1.72	2.14	2.98	1.05	1.61	1.33

Appendix 4.8: Vibration magnitude of the three models Simulink output

Descriptive Statistic	Hand transmitted vibration magnitude, [m/s2]								
	2 DOF model			*3 DOF model*			*4 DOF model*		
	Vertical	Forward	Lateral	Vertical	Forward	Lateral	Vertical	Forward	Lateral
Frequency, [Hz]	2	2	25	8	6.3	8	25	25	6.3
Mean	10.51	5.86	8.77	18.62	4.04	5.24	12.19	4.45	12.67
Standard Error	0.14	0.12	0.09	0.13	0.05	0.03	0.03	0.02	0.03
Median	11.52	6.54	9.86	20.54	4.48	5.81	13.50	4.93	13.80
Standard Deviation	5.20	2.85	3.88	9.13	1.93	2.54	5.93	2.15	6.31
Sample Variance	27.03	8.13	15.07	83.30	3.72	6.47	35.15	4.64	39.87
Range	18.74	9.99	10.70	29.70	6.87	8.85	19.55	7.08	33.85
Minimum	0.02	0.08	3.12	0.01	0.01	0.00	0.00	0.00	0.00
Maximum	18.75	10.07	13.81	29.70	6.88	8.85	19.55	7.08	33.85

Appendix 4.9: Vibration transmissibility by Simulink of the three models

Descriptive Statistic	Hand transmitted vibration transmissibility								
	2 DOF model			*3 DOF model*			*4 DOF model*		
	Vertical	Forward	Lateral	Vertical	Forward	Lateral	Vertical	Forward	Lateral
Frequency, [Hz]	2	2	25	8	6.3	8	25	25	6.3
Mean	0.51	0.53	0.39	0.83	0.36	0.25	0.55	0.40	0.61
Standard Error	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Median	0.55	0.56	0.36	0.90	0.39	0.28	0.59	0.42	0.66
Standard Deviation	0.26	0.27	0.18	0.42	0.18	0.13	0.27	0.21	0.31
Sample Variance	0.07	0.07	0.03	0.18	0.03	0.02	0.08	0.04	0.10
Range	1.05	1.11	0.69	1.77	0.78	0.52	1.16	0.86	1.82
Minimum	0.00	0.01	0.10	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	1.05	1.12	0.80	1.77	0.78	0.52	1.16	0.86	1.82