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Design and Fabrication of an Ergonomic Handlebar Structure of a Hand Tractor for Vibration Suppression

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The hand tractor is one of the major farm machineries used by Filipino farmers. It exposes farmers to excessive hand-arm vibration (21.09 m s^{-2} at 2400 rpm), which may lead to disabling diseases if not controlled or reduced. This study evaluated the effectiveness of changing the design of the handlebar structure of the locally made hand tractor to reduce vibration transmitted to operators during idling operation of the tractor. The actual vibration during idling operation of the hand tractor was measured based on the standards set by ISO 5349:2001. Using the results of the study by Bureerat and Kanyakam (2007) as basis for the improvement of the handlebar design, the principles set by the Philippine Agricultural Engineering Standards (PAES), and the engineering design process, an improved handlebar design was fabricated. The alterations made on the original handlebar design include: change in the material of the main frame from galvanized iron steel pipe to black iron steel pipe of greater diameter which significantly reduced the manufacturing cost and increased the strength of the structure through the principle of polar moment of inertia, addition of square steel bar stiffeners to the handlebar structure which increased the strength and rigidity of the structure, and inclusion of bending in the design which helped to dissipate the vibration. With the installation of the new design, the vibration transmitted to the operator was reduced by as much as 55.87% at 2400 rpm, 40.94% at 3000 rpm, and 19.87% at 3600 rpm. Moreover, the proposed design weighed less (by 25%) and was cheaper (by 5.11%, considering labor and production) than the original design.

Key Words: daily vibration exposure, hand-arm vibration syndrome, hand tractor, handlebar structure design, vibration exposure duration

Abbreviations: CALABARZON – Cavite, Laguna, Batangas, Rizal, and Quezon provinces, EAV – exposure action value, ELV – exposure limit value, FFT – Fast Fourier Transform, HAVS – hand-arm vibration syndrome, ISO – International Organization for Standardization, PAES – Philippine Agricultural Engineering Standards, RMS – root mean square, rpm – revolutions per minute, UPLB-AMD – University of the Philippines Los Baños-Agricultural Machineries Division

INTRODUCTION

Farming is a major source of livelihood in the Philippines where about 9.56 million ha (32%) of the total land area of 29.817 million ha is under cultivation, and 32% of the employment share is from agriculture (CountrySTAT Philippines 2012). The agricultural sector provides food for the Filipinos, provides raw materials for the manufacture of different products, contributes to the country's economic progress through export, provides employment to a large number of Filipinos, and if the agricultural sector progresses, it can support other sectors of the economy such as the manufacturing and service sectors (http://pulse101.hubpages.com/hub/The-Importance-of-Agriculture-to-the-Philippine-Economy).

Part of modernizing the agricultural sector is providing appropriate machineries for use in the cultivation of land to increase farm productivity. The hand tractor is one of the major farm machineries in the Philippines as of 2002. It is used for lowland farming and land preparation. Most of the tractors are two-wheel tractors since most farmers, especially those growing corn and rice, use them for land preparation (Amongo et al. 2011).

Like any other machine, the use of the hand tractor produces vibration. The vibration exposure in walking tractors causes hand-arm vibration syndrome (HAVS) which is a collection of symptoms caused by vibration transmitted to the arms and hands of operators. HAVS can be disabling if the vibration exposure is not reduced or eliminated. Vibration exposure from tools and equipment can be reduced in many ways, that is, by increasing the mass of the vibrating body, minimizing the tolerances of the systems, balancing the machines, and installing vibration isolators and dampeners. Another way is through engineering intervention, which is, designing tools and equipment to reduce the vibration they transmit. Modifications made in the design through engineering intervention is always the first consideration in reducing vibration exposure since the changes are made during the design and fabrication stage as opposed to modifications through retrofitting which can be very expensive and difficult (http://work.alberta.ca).

Studies have been conducted to further explore the attainment of passive vibration suppression. Xu et al. (2005) found that particle damping provides vibration suppression with granular particles embedded within their containing holes in a vibrating structure. The study focused on the form of damping due to shear friction induced by strain gradient along the length of the structure. After several experiments on different structures, it was found that particle damping can be applied on a broad range and that shear friction was the major contributing mechanism of damping, especially at a high volumetric packing ratio. Nair and Keane (2001) presented a different way of achieving passive vibration suppression, that is, through an experimental framework for the design of large flexible space structures with non-periodic geometries. Their results showed that the best way of achieving passive vibration suppression is through the use of a two-dimensional cantilevered space structure.

More methods of passive vibration suppression have been discovered with the advances in technology. For two decades, the use of smart materials and structures are now in place and are now being tested for both active and passive vibration suppression. One useful property of smart materials is that they have an energy dissipating effect during vibration suppression. Wang (2012) focused on advanced modelling of smart materials and structures and their potential applications on passive structural vibration suppression. Both numerical simulation and experimental results showed that use of advanced modelling methods can help reduce vibration and improve structural safety.

Locally made hand tractors transmit excessive daily vibration to operators by as much as 21.09 m s^{-2} (derived from the baseline experiment), emphasizing the need to improve the handlebar system of the tractor by using engineering modification, specifically, by alteration of the design of the hand tractor to reduce the vibration transmitted to the operator.

Vibration of hand tractors causes hand-arm vibration syndrome that is "serious, disabling and costly but preventable" according to the Health and Safety Executive (2005). The exposure action value (EAV) is the amount of vibration exposure per 8-h working day above which actions must be taken to control exposure and is specified at 2.5 m s^{-2}; the exposure limit value (ELV) is the maximum amount of vibration an operator may be exposed to during a day and is specified at 5.0 m s^{-2} (http://www.ilo.org).

This study was conducted to design and fabricate a new handlebar structure for the walking type hand tractor to reduce hand-transmitted vibration to operators. The handlebar structure designs used in the study of Bureerat and Kanyakam (2007) were fabricated. In the current study, we measured and compared the daily vibration exposure transmitted to the hand tractor operator by the fabricated designs and the original handlebar structure of the hand tractor, designed and fabricated an improved handlebar design with better vibration suppression than that of the existing designs by Bureerat and Kanyakam (2007), and measured the daily vibration exposure transmitted to the hand tractor operator by the proposed handlebar structure.

MATERIALS AND METHODS

This study provided a design of a new handlebar structure for the walking type hand tractor in the Philippines to reduce hand-transmitted vibration to operators. Four handlebar designs were evaluated – the original handlebar design, the two designs based on the study by Bureerat and Kanyakam (2007), and a proposed design based on the latter study and the engineering design process. The daily vibration exposures transmitted to the operator by using the two studied designs (B-K Design 1 and B-K Design 2) were measured and compared with those of the original handlebar design. An improved handlebar design was then generated from the good characteristics of these two designs.

Limitations of the Study

The study was limited to analysis of the hand-arm vibration transmitted from the hand tractor known as the UPLB-AMD Ergonomically Designed Two-Wheel Tractor. It was designed based on the anthropometric characteristics of farmers in the provinces of Cavite, Laguna, Batangas, Rizal, and Quezon (CALABARZON), Philippines.

Another limitation of the study was the material used in fabricating the handlebar structure. The proponent used black iron steel because of its availability, affordability, and its compliance with the standards set by the Philippine Agricultural Engineering Standards (PAES) 109:2000. The engineering design of the handlebar is bound by basic engineering and ergonomic considerations.

Optimization of the proposed design was not done. Also, the method used for vibration measurement only followed the recommended standard of ISO 5349:2001 (Mechanical Vibration – Measurement and Evaluation of Human Exposure to Hand Transmitted Vibration). Measurement of the vibration of the hand tractor was done during static operations only to eliminate the variability caused by environmental factors during actual operation. It is expected to be higher than the vibration in actual operating conditions because of the dampening factor of the ground. However, it can be used as an estimate for comparing handlebar structure designs. This measurement is believed to be sufficient since the study is concerned with the vibration reduction that can be caused by modifying the design of the handlebar structure only.

Lastly, the evaluation of the effectiveness of handlebar structures only considered the daily vibration exposure to operators, structural mass, and vibration reduction.

Locale of the Study

The study was conducted from April 2014 to April 2015 at the University of the Philippines Los Baños (UPLB), College, Laguna, Philippines. Specifically, the data gathering and evaluation of vibration was conducted at the laboratory grounds of the Industrial Engineering Department, College of Engineering and Agro-Industrial Technology, UPLB.

Factors Considered in the Study

The factors considered in this study are the engine speed and the handlebar structure design of the UPLB-AMD ergonomically designed two-wheel tractor.

Engine speed. The engine speeds tested were 2400 rpm, 3000 rpm, and 3600 rpm. These speeds were used as they are the common speed settings used in experimentation.

Handlebar design. Four designs were considered and tested: the original handlebar design, B-K Design 1, B-K Design 2, and the proposed design. The original handlebar design is made of galvanized iron steel with a diameter of 2.5 cm and a thickness of 0.3 cm. B-K Designs 1 and 2 were selected from two sets of designs – one which minimizes natural frequency and weight, and the other which minimizes frequency response function and weight. These two designs were fabricated using the anthropometric data of CALABARZON farmers; also, the material used for the main frame of the design is black iron steel pipe as suggested by the standards of PAES while the material used for the stiffener is black iron square steel bar with a thickness of 0.9 cm. Finally, the proposed design was fabricated using the same materials. It was basically a combination of the good characteristics of B-K Design 1 and B-K Design 2. Figure 1 illustrates the four design structures.

Fig. 1. Handlebar designs used in the study: Original handlebar design (A), B-K Design 1 (B), B-K Design 2 (C), and the proposed design (D).

Subject under Study

One representative male operator was chosen for this study and it was ensured that the operator was within the range of the normal body mass index (BMI) acceptable to the scientific community. One operator was chosen since it is considered constant in the study and only the performance of the different handlebar designs was measured. The male operator does not need to be a hand tractor operator because the subject will just hold the handle of the hand tractor and no skill is needed for its operation. Furthermore, the subject was oriented about the experimental protocol and consent for full cooperation in the experiment was reached. Specifically, the subject for vibration measurement is the metacarpal of the male operator.

Equipment and Accessories Used

The main machinery used in the study was the UPLB-AMD ergonomically designed two-wheel tractor which was developed by the UPLB-AMD and has a 5.5 HP gasoline engine. This hand tractor is shown in Figure 2.

Three equipment and accessories were used in the experiment during data collection – a tachometer, a tri-axial accelerometer, and a LabQuest2 data logger. The tachometer was used to measure the engine's speed while the tri-axial accelerometer and the LabQuest2 data logger were used to record and store the vibration transmitted from the hand tractor to the operator. The accelerometers are tri-axial accelerometers which measure the vibration at the x-, y-, and z-axis of the operator's hand as specified by ISO 5349:2001. Each accelerometer measured vibration at the three axes, corresponding to three channels of the LabQuest2. The specifications of the tri-axial accelerometer are shown in Table 1. This device read the actual vibrations measured by the accelerometers and these data were automatically viewed in a laptop computer. The LabQuest2 device is able to directly measure the vibration acceleration (i.e., the unit of measurement or vibration is acceleration in m s^{-2}) unlike obsolete data loggers that measure vibration in voltage. A laptop computer was used to store, view, and analyze the data gathered from the vibration measurement using the accelerometers connected to the

Fig. 2. The UPLB-AMD ergonomically designed two-wheel tractor.

Table 1. Tri-axial accelerometer specifications.

Parameter	Specifications
Model	Vernier
Power	30 mA @ 5V DC
Range (per axis)	± 49 m s^{-2} (± 5 g)
Accuracy (per axis)	± 0.5 m s^{-2} (± 0.0 5 g)
Frequency response (per axis)	0–100 Hz
Resolution:	
13-bit	0.018 m s^{-2}
12-bit	0.037 m s^{-2}
10-bit	0.15 m s^{-2}

Source: Vernier Software & Technology 2014

LabQuest2 devices. The specifications of LabQuest2 are presented in Table 2.

Table 2. Technical specifications of LabQuest® 2.

Category	Specifications
Model	Vernier LabQuest® 2
Data Acquisition	12-bit resolution Built-in GPS, 3-axis accelerometer (± 2 g), ambient temperature sensor, light sensor (uncalibrated intensity), and microphone Maximum Sampling Rate • 1 sensor - 100,000 samples/s (0.02 seconds max) • 2 or more sensors - 10,000 samples/s (0.21 seconds max) Minimum Sampling Rate • 0.00125 samples/s (800 s/sample) Maximum Samples (standalone) • 1 sensor - 2000 samples 20K - 100K samples/s • 1 sensor - 14,000 - 21,000 samples <= 10K samples/s • 2 or more sensors - 12,000 - 14,000 samples @ ≤ 10K samples/s

Source: Vernier Software & Technology 2014

Specific Methodology Used in the Study

A. Set-up Evaluation of the Original Design and the Three Designs

Set-up 1: Evaluation of the original handlebar design. The experiment was performed during static operation of the tractor using the original handlebar design of the tractor at the laboratory grounds of the Industrial Engineering Department, UPLB. The subject for testing was the hand of the operator, the handlebar-tractor connection, and the base of the engine. The testing was performed at three engine speeds (2400 rpm, 3000 rpm, and 3600 rpm) with four replications for each speed. Each replication was due for 1 min where 60,000 data points were gathered and analyzed. The measurements were later compared with those generated using B-K Design 1, B-K Design 2, and that of the proposed design.

Set-up 2: Evaluation of B-K Design 1. The same laboratory conditions were used for set-up 2; the only variable change was the handlebar design installed in the hand tractor. The first handlebar design by Bureerat and Kanyakam (2007) was used. The design changes made in the original handlebar structure include: (1) change of the main frame material from galvanized iron steel pipe to black iron steel pipe, (2) change of the diameter of the main frame from 2.5 cm to 3.4 cm to increase the polar moment of inertia and reduce the vibration, and (3) installation of stiffeners using 0.9 cm black iron square steel bar in the main frame to reduce the vibration transmitted to the operator. The design impact of these changes include lighter handlebar structure weight (from 9.60 to 8.20 kg), higher manufacturing cost (from PhP 825.00 to PhP 889.50), and increased manufacturing processes.

Set-up 3: Evaluation of B-K Design 2. The same laboratory conditions were used for set-up 1 and 2; the only variable change was the handlebar design installed in the hand tractor. The second handlebar design by Bureerat and Kanyakam (2007) was used. The design changes made from the original handlebar structure include: (1) change of the main frame material from galvanized iron steel pipe to black iron steel pipe, (2) change of the diameter of the main frame from 2.5 to 3.4 cm to increase the polar moment of inertia and reduce the vibration, and (3) installation of stiffeners using 0.9 cm black iron square steel bar in the main frame to reduce the vibration transmitted to the operator. The design impact of these changes include lighter handlebar structure weight (from 9.60 to 6.60 kg), reduced manufacturing cost (from PhP 825.00 to PhP 763.75), and increased manufacturing processes.

Set-up 4: Evaluation of the proposed handlebar design. The same laboratory conditions were used for set-up 3; the only variable change was the handlebar design installed in the hand tractor. The proposed handlebar design generated using the good characteristics of B-K Designs 1 and 2 was used. The design changes made from the original handlebar structure include: (1) change of the main frame material from galvanized iron steel pipe to black iron steel pipe, (2) change of the diameter of the main frame from 2.5 to 3.4 cm to increase the polar moment of inertia and reduce the vibration, and (3) installation of stiffeners using 0.9 cm black iron square steel bar in the main frame to reduce the vibration transmitted to the operator. The design impact of these changes include lighter handlebar structure weight (from 9.60 to 7.20 kg), lower manufacturing cost (from PhP 825.00 to PhP 782.875), and increased manufacturing processes.

B. Manufacturing Details of B-K Design 1, B-K Design 2, and the Proposed Design

Manufacturing processes involved. The only manufacturing processes involved in the production of the handlebar structure were continuous welding, bending, and cutting. Continuous welding should be used over spot welding to provide a more rigid connection between the elements to be welded. Table 3 compares the manufacturing processes of the three designs evaluated based on the number of component parts or joints and the corresponding processes associated with each.

Table 3. Manufacturing processes of handlebar designs.

Design Considered	No. of Component Parts per Process			
	Welding		Cutting	Bending
	Main Frame	Stiffener		
Original design	2	0	3	2
Proposed design	8	4	19	2

Weight of the structure. The limit for the weight of the tractor is 103 kg; the weight of the tractor body without the handlebar is 85 kg. Thus, the limit for the weight of the handlebar design is 18 kg.

Materials and manufacturing costs. The costs were considered in the manufacture of the handlebar structure were labor and materials.

C. Data Analysis

The standards set by ISO 5349:2001 (Mechanical Vibration – Measurement and Evaluation of Human Exposure to Hand Transmitted Vibration) were used to measure the vibration transmitted by the hand tractor to the operator. Tri-axial accelerometers were attached to the hand of the operator and these accelerometers were connected to the LabQuest2 which, in turn, was connected to a laptop computer. With the use of the LabQuest2 data logger, the time-based vibrations (in m s^{-2}) received by the operator were measured and stored. These time-based vibrations were converted to frequency-based vibrations using the Fast-Fourier Transform function of the data logger. The frequency-based vibrations were then analyzed in the one-third octave band using frequency-weighting (shown in Eq. 1).

$$a_{hw} = \sqrt{\sum_i (W_i a_{hi})^2} \quad (1)$$

where a_{hw} is the frequency-weighted acceleration (m s^{-2}), W_i is the weighting factor for the i^{th} one-third-octave band, and a_{hi} is the RMS acceleration measured in the i^{th} one-third-octave band (m s^{-2}).

From the single-axis frequency-based vibration in the one-third octave band generated, the total vibration acceleration was computed (using Eq. 2) and then converted to its corresponding daily exposure vibration (using Eq. 3) which was the basis for the vibration exposure evaluation.

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \quad (2)$$

where a_{hv} is the total vibration (m s^{-2}), and a_{hwi} is the RMS single-axis acceleration of the frequency-weighted hand-transmitted vibration for the axes denoted by x, y, and z, respectively (m s^{-2}).

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \quad (3)$$

where *A (8)* is the daily vibration exposure (m s^{-2}), T is the total daily duration of exposure to the vibration a_{hv} (h), and T_0 is the reference duration of 8 h (28 800 s).

Statistical Analysis

The statistical method used for the study was ANOVA: two-factor with replication and Tukey's method of multiple comparisons. ANOVA was performed to determine if there is a significant difference between the vibration acceleration at different speeds of the four designs evaluated and Tukey's Method was used to perform pair-wise comparison (between designs) between the vibration accelerations measured at different speeds. ANOVA was performed using Microsoft Excel 2013 and Tukey's Method was performed by comparing the pair-wise differences in the means of the vibration acceleration of the designs with Tukey's value (T) which was computed using the formula (Montgomery 2001):

$$T = q_{a(a,f)}\sqrt{\frac{\text{MSE}}{R}} \quad (4)$$

where T is the Tukey's value; $q_{a(a,f)}$ is the percent point of the total studentized range statistic for a specific number of replications (a), degrees of freedom of the errors (f), and confidence interval (1-a); MSE is the mean square error within the replications; and R is the number of replications.

RESULTS AND DISCUSSION

The daily vibration exposure measure was used to analyze the vibration transmitted to the operator. Also, the frequency considered was from 6.3 to 500 Hz. The measurement using three engine speeds was considered to see if there was a significant impact on the results with varying engine speeds.

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Vibration Acceleration of the Four Designs

A. Original Handlebar Design (Baseline Measurement)

The total vibration accelerations measured were high as a result of using the original handlebar design. The highest vibration was measured at 2400 rpm with a value of 21.78 m s^{-2}. The total vibration accelerations are shown in Table 4. The measured values show that the operators are exposed to very high vibration during operation. After converting the total vibration accelerations to daily vibration exposures, the vibrational impact of the hand tractor to the operator was found to be 21.09 m s^{-2} at 2400 rpm. This value is almost four times higher than the exposure limit value of 5 m s^{-2} and is very dangerous if the machine is operated even for an hour. The computed daily vibration exposures are shown in Table 5.

B. Evaluation of B-K Design 1

Change in the design of the original handlebar structure of the hand tractor resulted in reduced vibrational impact

Table 4. Total vibration acceleration at various locations of the accelerometer using the original handlebar structure of the duplicated UPLB-AMD ergonomically designed two-wheel tractor.

Engine Speed (rpm)	Vibration at the Locations of Accelerometer ($m\ s^{-2}$)		
	Metacarpal	Handlebar-tractor Connection	Engine Base
2400	21.78	13.72	3.33
3000	10.95	2.67	3.22
3600	3.22	1.90	3.03

Table 5. Daily vibration exposure at various locations of the accelerometer using the original handlebar structure of the duplicated UPLB-AMD ergonomically designed two-wheel tractor.

Engine Speed (rpm)	Vibration at the Locations of Accelerometer ($m\ s^{-2}$)		
	Metacarpal	Handlebar-tractor Connection	Engine Base
2400	21.09	13.29	3.23
3000	10.60	2.59	3.12
3600	3.12	1.84	2.94

of the hand tractor to the operator. From 21.09 $m\ s^{-2}$ at 2400 rpm, 10.60 $m\ s^{-2}$ at 3000 rpm, and 3.12 $m\ s^{-2}$ at 3600 rpm using the original design, the daily vibration exposures were reduced to 12.10 $m\ s^{-2}$ at 2400 rpm, 5.34 $m\ s^{-2}$ at 3000 rpm, and 3.02 $m\ s^{-2}$ at 3600 rpm. These values correspond to 42.63% vibration reduction at 2400 rpm, 49.62% at 3000 rpm, and 3.21% at 3600 rpm.

C. Evaluation of B-K Design 2

Use of B-K design 2 showed consistent reduction in the vibrational impact of the hand tractor to the operator. From 21.09 $m\ s^{-2}$ at 2400 rpm, 10.60 $m\ s^{-2}$ at 3000 rpm, and 3.12 $m\ s^{-2}$ at 3600 rpm using the original design, the daily vibration exposures were reduced to 14.07 $m\ s^{-2}$, 6.10 $m\ s^{-2}$, and 7.40 $m\ s^{-2}$, respectively. These values correspond to 33.29% vibration reduction at 2400 rpm and 42.45% at 3000 rpm.

D. The Proposed Design

To further reduce the vibration reduction with the variation of the handlebar structure design, some good characteristics of the designs by Bureerat and Kanyakam were combined to propose a better handlebar design. The changes made from the original design to the proposed design are discussed in Table 6. The vibrational impact of this design seemed consistent with the premise that combining the good characteristic of the individual designs by Bureerat and Kanyakam will yield better vibration reduction. From 21.09 $m\ s^{-2}$ at 2400 rpm, 10.60 $m\ s^{-2}$ at 3000 rpm, and 3.12 $m\ s^{-2}$ at 3600 rpm using the original design, the daily vibration exposures were reduced to 9.31 $m\ s^{-2}$, 6.26 $m\ s^{-2}$, and 2.50 $m\ s^{-2}$, respectively. These correspond to 55.86% vibration reduction at 2400 rpm, 40.94% at 3000 rpm, and 19.87% at 3600 rpm.

Table 6. Functional requirements of the handlebar design and corresponding design alterations from the original design to the proposed design.

Functional Requirement	Changes in the Design	Justification
Reduction of vibration	I. Changing the diameter of the main frame from 2.5 cm to 3.4 cm II. Addition of stiffeners III. Use of square steel rod stiffeners IV. Employment of bending in the main axis V. Use of steel pipe as main connection between handles	I. To increase the polar moment of inertia thus increasing the structure's strength II. As inferred from the characteristics of Bureerat and Kanyakam's simulation and from Saint Venant's Principle III. To increase the polar moment of inertia and to increase resistance from shear stress IV. As inferred from the second design of Bureerat and Kanyakam which aims to dissipate the vibration V. To increase rigidity of the structure as inferred from the first design by Bureerat and Kanyakam
Reduction of manufacturing cost	Changing the main frame from galvanized iron steel pipe to black iron steel pipe	As recommended by PAES 109:2000
Reduction of weight	Changing the main frame from galvanized iron steel pipe to black iron steel pipe	As recommended by PAES 109:2000

PAES – Philippine Agricultural Engineering Standards

Comparison of B-K Design 1, B-K Design 2, and the Proposed Design

Generally, the original design exhibited the highest daily vibration exposure regardless of the engine speed used. It was observed that at engine speeds of 2400 rpm and 3600 rpm, the proposed design provided the greatest vibration reduction of 55.87% and 19.87%, respectively. On the other hand, at 3000 rpm, B-K Design 1 delivered the highest vibration reduction amounting to 49.62%.

To further determine the differences of the designs, statistical analysis (ANOVA and Tukey's Method) was done. The means considered in the analysis are the means of the replications of the vibration accelerations measured at the hand of the operator. From the summary of ANOVA shown in Table 7, there is a significant difference at 95% confidence interval in the means of the four designs considered (p-value of design variation is 1.38^{-16} which is lower than 0.05).

To specify which design structure significantly differs from the others, Tukey's method of multiple

Table 7. Results of the ANOVA done using Microsoft Excel 2013.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	P-Value	F Critical
Sample	904.8638	2	452.4319	461.026	2.23E-26	3.2594
Designs	256.9989	3	85.6663	87.2935	1.39E-16	2.8663
Interaction	215.8094	6	35.9682	36.6515	6.64E-14	2.3638
Within	35.3289	36	0.9814			
Total	1413.001	47				

comparison was done. The $q_{a(a,f)}$ specified in the analysis is 3.82 while the computed Tukey's value is 1.8921. This value is then compared with the pair-wise differences in the means of the vibration accelerations for each speed considered. If this value is less than the computed difference in means, there is a significant difference between the two means compared. The summary of the comparisons and the conclusions of the statistical analysis are presented in Table 8 where at 2400 rpm and 3000 rpm, the vibration acceleration of the proposed design significantly differed from that of the original design value.

Frequency-based and Time-based Data Analysis

A comparison of the three designs with the original design showed that the vibration acceleration of the proposed was significantly different from that of the original design at 2400 rpm and 3000 rpm. Moreover, on the average, the vibration reduction from the proposed design is higher (at 2400 rpm and 3600 rpm) compared with that of B-K Design 1 and B-K Design 2. Thus, a frequency-based and time-based data analysis between the original design and the proposed design was done to further support the gathered result.

A. Frequency-based Analysis

Figure 3 illustrates the vibration accelerations (at 2400 rpm) at the x, y, and z-axis (m s^{-2}) of the metacarpal at the frequency range of 6.3 to 500 Hz using the original and proposed handlebar structure. The blue line represents the x-axis, the red line represents the y-axis, and green line represents the z-axis. Figure 4 illustrates the result at 3000 rpm, while Figure 5 is the result at 3600 rpm. These figures show that vibration is at its peak within the range 31.5 to 125 Hz and that the vibration acceleration using the proposed handlebar structure is evidently lower than that of the original handlebar.

B. Time-based Analysis

For the time-based acceleration, there is no evident difference in the vibration acceleration during the 1-min test experiment since the vibration experienced is at high frequency. The time-based data (Fig. 6) for the original handlebar design just showed the maximum and the minimum amplitude of the vibration during the actual experiment. The same analysis was obtained for the time-based data for the proposed design (Fig. 7). These figures further show that changing from the original handlebar structure to the proposed handlebar structure results in lower amplitude (from as much as 50 m s^{-2} to as low as 20.50 m s^{-2}).

It should be noted that the changes in the color of the graphs are just inaccuracies, green means that the collected data are more accurate while other colors indicate less accurate data gathered.

Manufacturing Cost

Tables 9 and 10 show the bill of materials used in the design of the original design and the proposed design amounting to a total of PhP 825 and PhP 782.875, respectively. The proposed design is cheaper (5.11% cost reduction) compared with the original design. Moreover, the proposed design weighs 25% lighter than the original design.

CONCLUSION

Through the baseline experiment, it was proven that the handlebar structure amplifies the vibration transmitted from the handlebar-tractor connection to the hand of the operator by 58.71%. This amplification may be due to the flaccid design of the original handlebar structure or the natural mechanism of vibration to dissipate energy to the least rigid parts of the structure. Different handlebar structure designs were therefore evaluated to determine possible vibration reduction using the results of the study by Bureerat and Kanyakam (2007).

The daily vibration exposures on the hand of the operator using the original design and the designs of Bureerat and Kanyakam (B-K Designs 1 and 2) were compared and it was confirmed that the design of the handlebar structure can significantly reduce the vibration transmitted to the operator, especially during low-speed operation (i.e., at a speed of 2400 rpm). After comparing B-K Designs 1 and 2 with the original design, inferences were made to develop an improved handlebar structure in terms of vibration reduction to the operator; this procedure made use of the engineering design process. The product of the engineering design process was then fabricated and its total vibration acceleration was measured and converted to the daily vibration exposure to compare with those of the three previous designs. The results showed a significant reduction in the daily vibration exposure using the proposed design, given that the operation of the hand tractor is static.

The percentage reduction in the daily vibration exposure at the hand of the operator at speeds of 2400 and 3600 rpm from the original design to the proposed design generated the greatest improvement amounting to 55.87% and 19.87%, respectively. On the other hand, reduction in the daily vibration exposure from the original design to B-K Design 1 at a speed of 3000 rpm resulted in the best value of 49.62%. Moreover, it is safe

Table 8. Tukey's multiple comparison of the differences in the means of vibration acceleration of the four handle bar designs at different engine speeds.

Engine Speed (rpm)	Tukey's Value	Difference in Means (Conclusion)		
		Original vs. B-K Design 1	Original vs. B-K Design 2	Original vs. Proposed
2400	1.8921	9.6890 (significantly different)	7.2451 (significantly different)	12.1748 (significantly different)
3000	1.8921	5.6471 (significantly different)	4.3578 (significantly different)	4.5231 (significantly different)
3600	1.8921	0.2132 (not significantly different)	4.4233 (significantly different)	0.6506 (not significantly different)

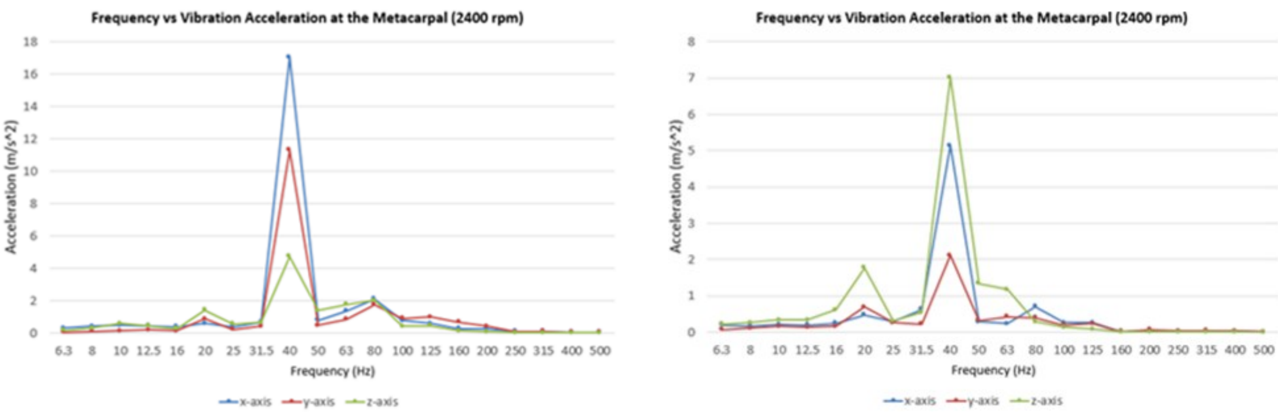

Fig. 3. Frequency versus vibration acceleration at the metacarpal (2400 rpm) for the original design (left) and the proposed design (right).

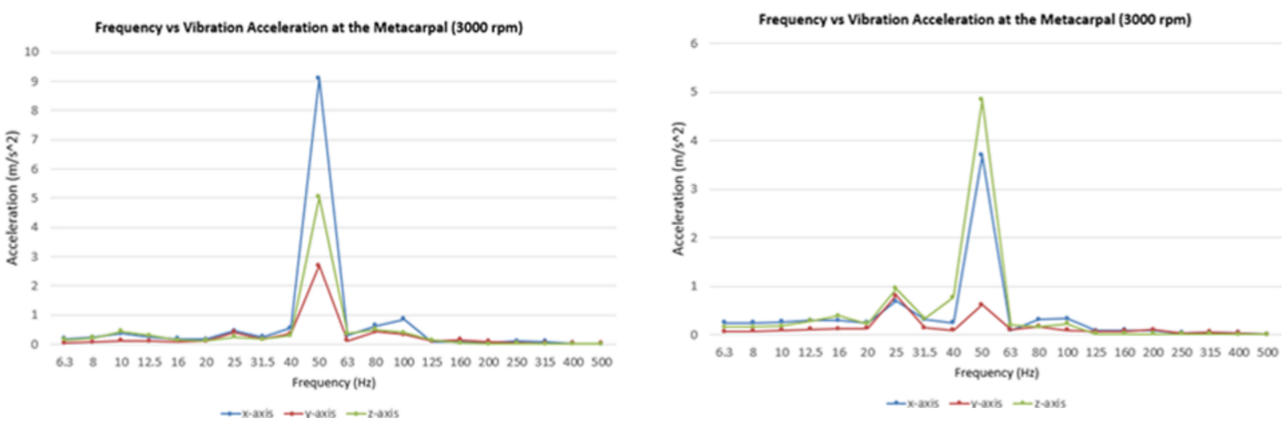

Fig. 4. Frequency versus vibration acceleration at the metacarpal (3000 rpm) for the original design (left) and the proposed design (right).

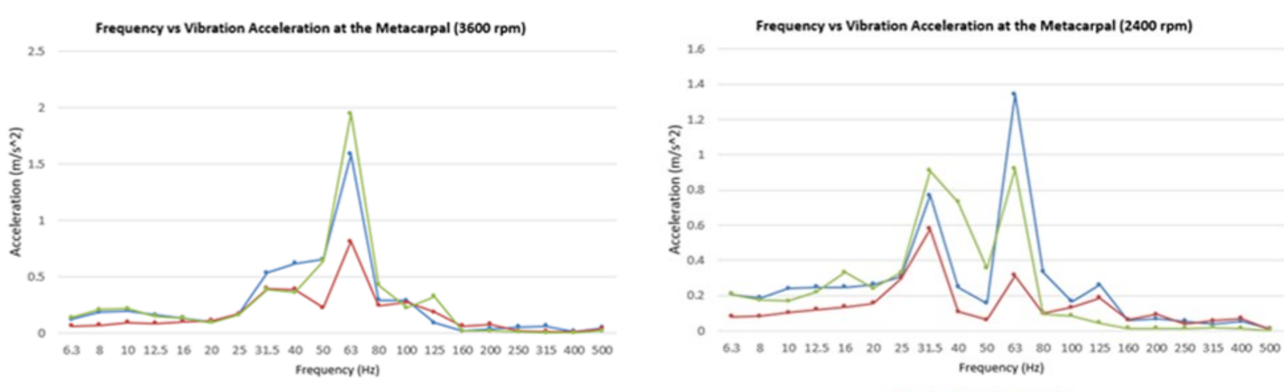

Fig. 5. Frequency versus vibration acceleration at the metacarpal (3600 rpm) for the original design (left) and the proposed design (right).

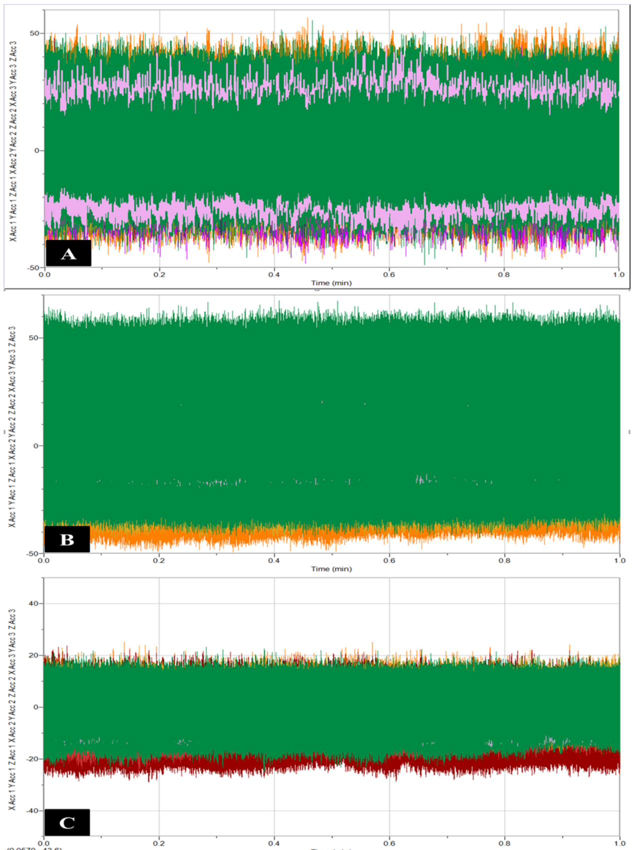

Fig. 6. Time-based acceleration for the original design at 2400 rpm (A), 3000 rpm (B), and at 3600 rpm (C).

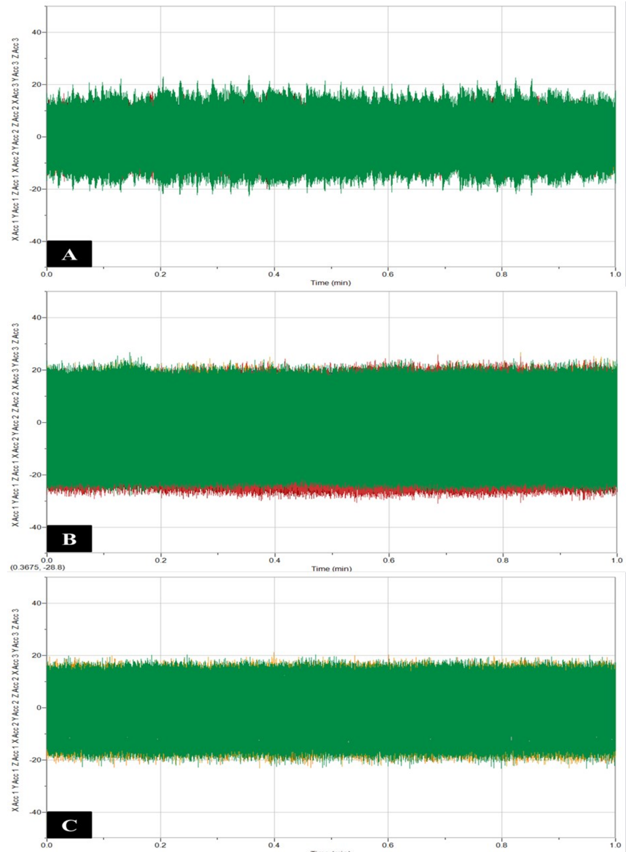

Fig. 7. Time-based acceleration for the proposed design at 2400 rpm (A), 3000 rpm (B), and at 3600 rpm (C).

Table 9. Bill of materials of the original handlebar design.

Item No.	Description of Work	Unit	Quantity	Materials	
				Per Unit (PhP)	Total (PhP)
1	GI steel pipe (OD = 2.5 cm, THK = 0.3 cm), schedule 40, for structure main frame	Feet	11	37.5	412.5
2	Flat bar, schedule 40 (THK = 0.3 cm)	Feet	2	15	30
3	Welding rod E6013	Kilo	0.25	90	22.5
4	Labor and overhead: welding, cutting, bend-ing	Day	0.5	500.00*	250
5	Grinding stone	Pc	0.25	120	30
6	Paint	Liters	1	80	80
TOTAL					825.00

*Rate a skilled worker (able to perform welding, cutting, bending, and others) per day.

Table 10. Bill of materials of the proposed handlebar design.

Item No.	Description of Work	Unit	Quantity	Materials	
				Per Unit (PhP)	Total (PhP)
1	BI steel pipe (OD = 3.4 cm, THK = 0.3 cm), schedule 40, for structure main frame	Feet	10	21.5	215
2	BI square steel rod (THK = 0.9 cm)	Feet	6.5	6.75	43.875
3	Flat bar, schedule 40 (THK = 0.3 cm)	Feet	0.6	15	9
4	Welding rod E6013	Kilo	0.33	90	30
5	Labor: welding, cutting, bending	Day	0.75	500.00*	375
6	Grinding stone	Pc	0.25	120	30
7	Paint	Liters	1	80	80
Total					782.875

*Rate a skilled worker (able to perform welding, cutting, bending, and others) per day.

to say that there is a significant reduction in the vibration accelerations produced by the original handlebar design and the proposed design at 2400 rpm and 3000 rpm but there is no significant difference at 3600 rpm.

It was also observed that manufacture of the proposed design would be cheaper in terms of labor and material costs compared with the original design. A savings of PhP 42.13 per unit can be obtained through production of the proposed design rather than the original. Moreover, the weight of the proposed design is 2.4 kg lighter than that of the original design (a 25% reduction in weight), making it easier to handle.

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