Vibration-induced biodynamic response of a human hand arm model

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Abstract

Human vibration arises due to mechanical vibration effect on the human body. Mechanical vibration arises from a tool or powered process, entering the body through the palm and fingers which is known as the hand transmitted vibration. Long-term use of certain portable power tools can result in hand and finger symptoms. This study entails solid modelling of the human arm (up to the elbow) using SOLIDWORKS 2012 and mode shapes analysis ANSYS 14 software. Generating a 3-DOF mathematical model of the arm up to shoulder and calculating the transmissibility and power absorption of vibration from hand to wrist and hand to elbow using MATLAB Simulink software. An experiment is also done in-vehicle dynamic lab by taking six male subjects holding the impact drill in the right hand of 6.5 mm, 8 mm and 12.5 mm in diameter of drill size which was subjected to random vibration targeted on metal alloy, concrete block and wooden block in different postures. The transmissibility is verified in the vehicle dynamic lab using to NI data acquisition card (NI cDAQ-9232), and Lab VIEW 8.6.0. The result shows that transmissibility is higher in HTW than HTE and its increases as per the drill size increase. Also, transmissibility is higher in the head and horizontal direction than in the vertical direction, and transmissibility is higher in stiffer materials like metal and concrete blocks. Thus, transmissibility shows the linear relationship with drill size to be a drill.

Keywords: Hand-Arm Vibration (HAV), Hand Arm Vibration Syndrome (HAVS), MATLAB Simulink

1. Introduction

A body is said to vibrate if it has a to-and-fro motion. Usually, vibrations are due to elastic forces. Human exposure to vibration has been classified as (i) Whole-body vibration (ii) Motion sickness (iii) local segmental vibration (HTV). Whole-body vibration basically occurs when the greatest part of the body is in contact with the vibrating tool or the vibrating surfaces. Its comfort frequency range is found from 1 Hz to 20 Hz [1]. When a person is exposed to real or apparent low-frequency motion below 1 Hz, motion sickness can occur. (e.g. vibration produces when the finger taps on the table.). Human vibration arises due to mechanical vibration effect on the human body. Mechanical vibration arises from a tool or powered process, entering the body through the palm and fingers called hand transmitted vibration (local segmental vibration). Mechanical vibration or shock is applied or communicated directly to the hand-arm system (often through the hand or fingers), such as from power tool handles or workpieces rattled by vibrating or hitting instruments. Hand transmitted vibration can cause many syndromes which are called as Hand-arm vibration syndromes (HAVS).

Factors that affect the hand-arm due to vibration: -

Physical factors-

- Vibration acceleration.
- Vibration frequency.
- Each workday's exposure time.
- Years of experience working in a vibration-prone environment.
- The state of tool upkeep.
- Personal protective equipment and practices, including as gloves and boots, as well as work-rest hours.

Biodynamic factors-

- Grip forces - the worker's grip on the vibrating equipment.
- The surface area, position, and mass of the areas of the hand that come into touch with the vibration source.
- The hardness of the substance that the hand-held instruments come into contact with, such as metal in grinding and chipping.
- Hand and arm position in relation to the body.
- Handle texture: soft and supple vs. stiff substance
- A medical history of finger and hand injuries, particularly frostbite.

Vibration or we can say human vibration and hand-arm vibration can occur in many directions.

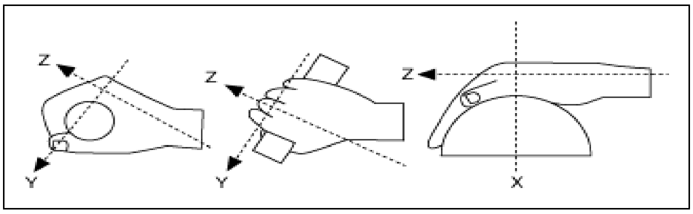


Figure1- vibration axis (Source ISO 5349 1986) [2]

The x-axis runs across the palm, the y-axis runs across the palm towards the thumb, and the z-axis runs parallel to the back of the hand, extending towards the fingers. The coordinate system is defined at the third metacarpal, ensuring that there is no confusion about axes for palm or power grips or any other hand orientation.

The effect of vibration is larger whenever the input direction is toward the body or can say through the arm. At 20 Hz hand-arm acted as a whole body at low-frequency vibration. Frequency about 1000 Hz a small and sensitive body part like tissue being excited, thus the absorbed power not much decreases as the energy dissipated a minimal (lower) tissue volume [3]. As the forces like grip force and push force increase the magnitude of transmission vibration also increases. Aatola basically works on the vibration transmission magnitude to the wrist of the hand-arm. The complex parameter of hand-arm and wrist are not possible to measure individually but found that the transmissibility depends upon the forces and it increases as well as all the forces increase [4].Steve Kihlberg [5] studied on the impact hammer and grinder, which described the movable behaviour of the human hand-arm system under vibration which shows the different biodynamic responses value of the human hand-arm like transfer function and driving point mechanical impedance etc. and shows that when the same grip force and push force applied on both the impact of the case hammer and grinder, not much changes occur in the biodynamic values of driving point mechanical impedance and transfer function. But as their forces of them increase or decrease frequent changes occur in the transfer function as well as driving point mechanical impedance which indicates that the biodynamic responses are directly dependent on the forces (grip or push) and frequency contents. R. Gurram et al [6] studied and test the biodynamic behaviour of different subjects of hand-arm using the driving point mechanical impedance which shows the nonlinear characteristic of the human hand-arm at the limited frequency range. M.J.Griffin et al [7] studied the hand-arm syndrome and diseases which affect the hand-arm under vibration and also discussed how to improve or overcome such types of diseases. R.G. Dong et al [8] studied the theoretical foundations for future measurement and evaluation of HTV. ++The anti-vibration gloves are not much effective in the much higher frequency range and using high power vibrating tool but in some cases where the frequency range is lower and the apparent mass range in favour it works and reduces the human hand-arm vibration and reduces the diseases. Y.Aldien et al [9] described the human hand-arm vibration in terms of driving point. Antonio Jose Besa et al [10] worked on the effect of absorption of energy per unit time and the transmission magnitude, and observed resonating frequency magnitude increases when exerted pushing force which caused by muscular force. K.N. Dewangan & V.K.Tewari [11] described the vibration energy absorption (VAE) per unit time of tarmacadam road, rota-tilling in dryland (soil) and rota-pulling in wetland condition during the transportation using the hand tractor in field level. S.A.Adewasi & S.rakheja [12] calculated the vibration transmission magnitude from handle to fingers, wrist, elbow and shoulder and observed that the biodynamic response transmissibility magnitude was lesser in the extended arm posture as compared to the bent arm posture.G. Moschioni et al [13] predicted the anonymous uncertainty in the measurement of the vibration magnitude in the hand-arm system.S. Xu Xueyan et al [14] shows that the values of biodynamic responses like transmissibility and driving point response change as per the different point of each finger.R .G. Dong et al [15] investigate 3-orthogonal axis mechanical impedance under the vibration exposure at fingers and palm and observed that the mechanical impedance is not similar at each location of the fingers and palm. S.K.Chand found that transmissibility from handle to wrist is higher than the transmissibility from handle to elbow on both materials and both postures. C.A.Subhas found that transmissibility from handle to wrist is higher than the transmissibility from handle to elbow for both postures. G.B. Kamlakar et al found that anti-vibration isolators had significantly better damping characteristics and reduced the vibration transmission effect.

2. Methodology

2.1. Modal analysis of hand-arm using ANSYS 14.0

Solid modelling of hand-arm using Solid works

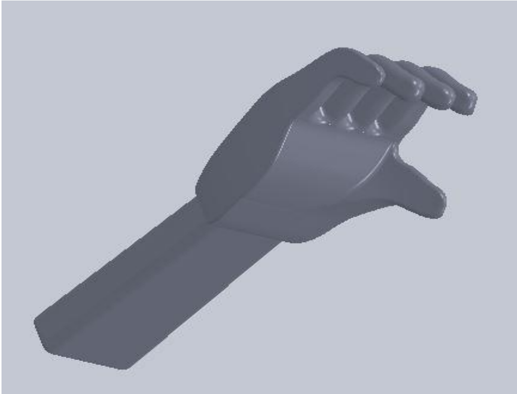


Figure2-hand-armm solid model [12]

The solid model is first convert in IGES model then imported into the ANSYS. Modal analysis of solid hand-arm model analyzed in ANSYS 14. Material properties are taken in Table1.

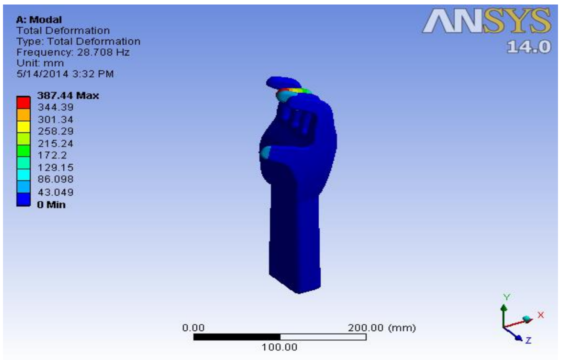


Figure3- first mode shape

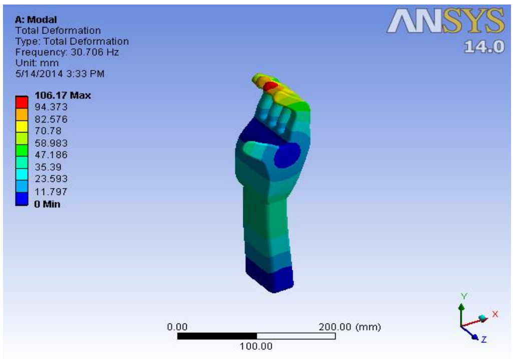


Figure4-second mode shape

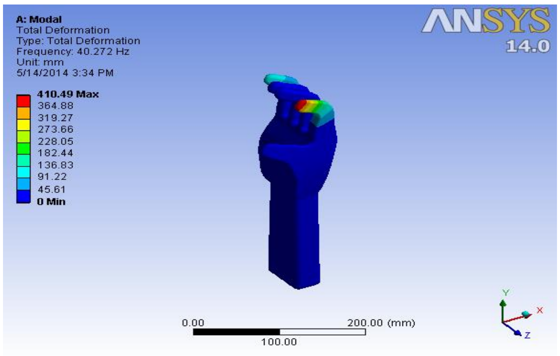


Figure5-third mode shape

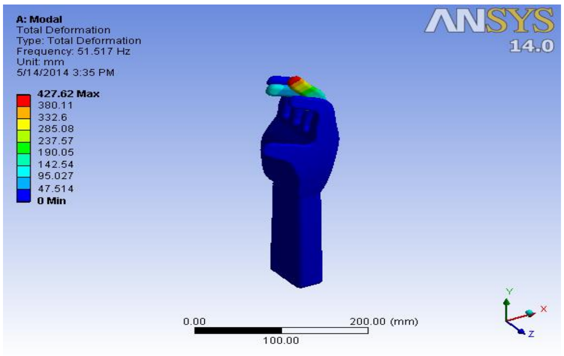


Figure6-fourth mode shape

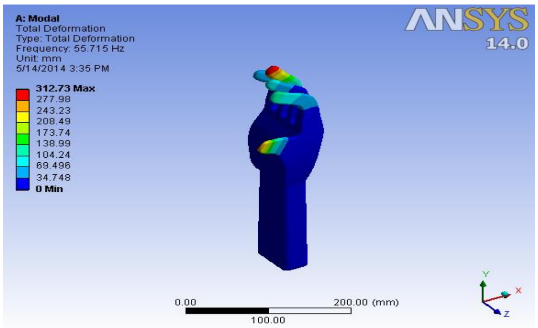


Figure7-fifth mode shape

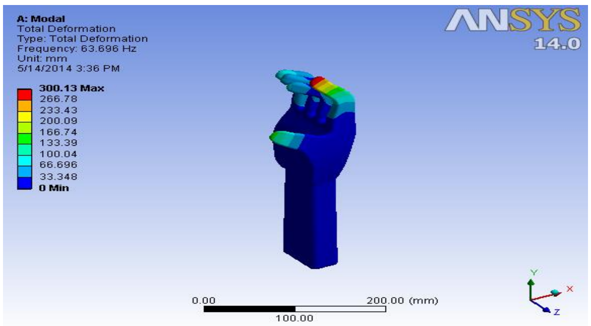


Figure8-sixth mode shape

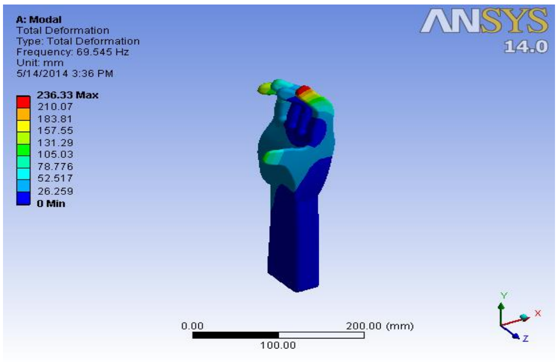


Figure9-seventh mode shape

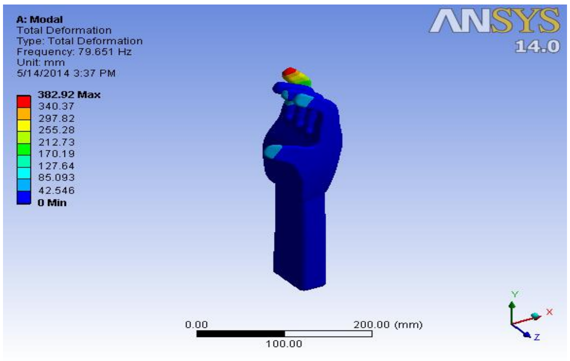


Figure10-eighth mode shape

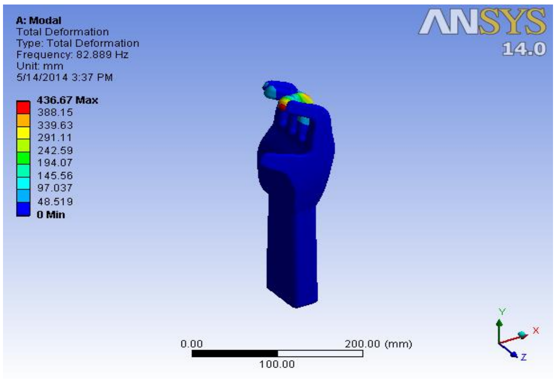


Figure11-ninth mode shape

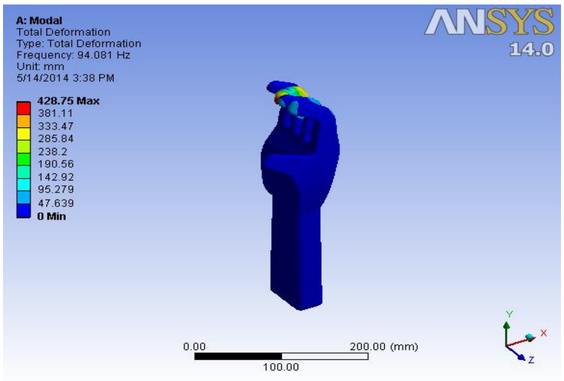


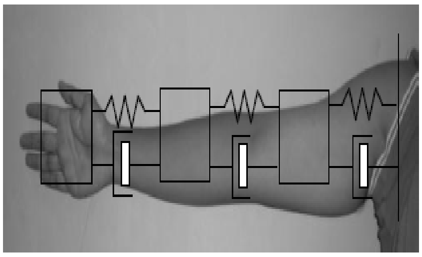
Figure12-tenth mode shape

Model number	Frequency (Hz)
1	28.70
2	30.71
3	40.17
4	51.52
5	55.72
6	63.69
7	69.54
8	79.65
9	82.8
10	94.08

Table1: Natural frequencies for the solid model.

2.2 Mathematical modelling of 3 DOF hand arm

In this model, we consider the whole arm up to the shoulder and jointly consider as the spring and damper system and the palm, lower arm and upper arm as fixed mass. These values are listed below in table 2.



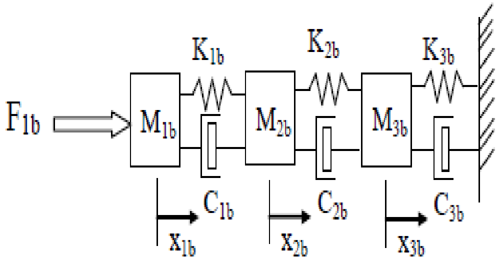


Figure13- 3 DOF hand-arm system

As Figure13 shows that the hand-arm arm system is a mass-spring system where each constraint has its specific value and push and force value taken in between (20-35 N). And all other parameters taken are listed in table 2 and this equation of motion is listed below these equations are solved by using MATLAB Simulink method which gives a result in the domain so this result converts into the frequency domain by using FFT.

Equations of motion are-

$M_{1b}\ddot{X}_{1b} + K_{1b}(X_{1b} - X_{2b}) + C_{1b}(\dot{X}_{1b} - \dot{X}_{2b}) = F_{1b}$ (1)

$M_{2b}\ddot{X}_{2b} = K_{1b}(X_{1b} - X_{2b}) + C_{1b}(\dot{X}_{1b} - \dot{X}_{2b}) - K_{2b}(x_{2a} - x_{3b}) - C_{2b}(\dot{X}_{2b} - \dot{X}_{3b})$ (2)

$M_{3b}\ddot{X}_{3b} = K_{2b}(X_{2b} - X_{3b}) + C_{2b}(\dot{X}_{2b} - \dot{X}_{3b}) - K_{3b}(X_{3b}) - C_{3b}(\dot{X}_{3b})$ (3)

Where,

M_{1b}, M_{2b}, M_{3b} = Fixed masses of palm, lower arm and upper arm respectively

K_{1b}, K_{2b}, K_{3b} = Spring stiffness coefficients of joints and shoulders as shown in Figure13

C_{1b}, C_{2b}, C_{3b} = Damping coefficients of joints and shoulders as shown in Figure 13

Material Properties: -

Sr. No.	**Property**	**Value**
1	M_{1b}	0.55E-02 kg
2	K_{1b}	7.20E+03 N/m
3	C_{1b}	7.06E+01
4	M_{2b}	2.14E-02 kg
5	K_{2b}	0.90E+02 N/m
6	C_{2b}	2.10E+01
7	M_{3b}	3.82E-00 kg
8	K_{3b}	5.56E+05 N/m
9	C_{3b}	6.02E+01

Table2- Properties of the human hand [12]

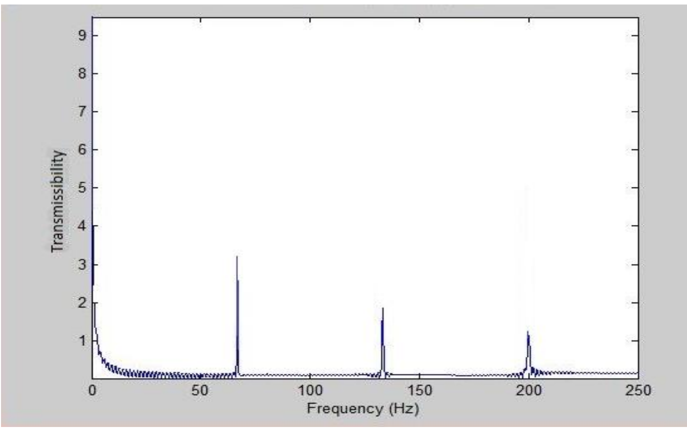


Figure14- transmissibility vs. Frequency (FFT)

As the graph shows that the frequencies peak is found in the range of 50 Hz to 200 Hz and the maximum peak is found near about 50 Hz which is approx. 3.5. thus, it shows that the maximum variation occurs in the hand transmitted vibration in between the 50Hz to 200Hz and also decreases as the frequency increases which also shows that transmissibility affects low as per the longer distance.

As per the power absorption of hand-arm system (P) calculated as-

P(t)= F(t)*V(t) (4)

Where F(t) is the driving force and V(t) is the velocity at the driving point.

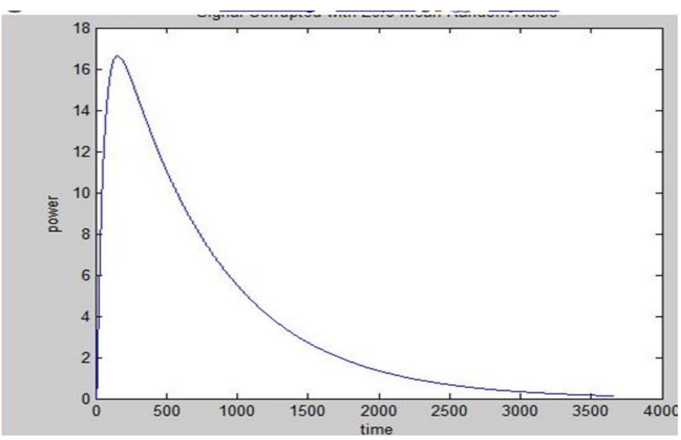


Figure15- power absorbed vs. Time

3. Experimental Study

In this experimental study, six male subjects were exposed to random hand vibration during the drilling operation. whose anthropometric data are given in the below table 3

Subject	Age (years)	Weight (kg)	Height (mm)	Hand length (L) (mm)
Sub1	23	72	1700	465
Sub2	24	55	1625	445
Sub3	24	75	1725	460
Sub 4	24	68	1775	450
Sub 5	25	78	1675	455
Sub 6	23	74	1750	460
Mean	28.3	70.3	1708.3	455.8
L – length of fore arm from elbow to tip of the middle finger				

Table 3. Anthropometric data of test subjects

4. Result and Discussion: -

Transmissibility function on wrist is expressed as:

$T1(f) = a_{wrist}(f)/a_{handle}(f)$ (5)

Where,

T1(f)-Handle to wrist transmissibility,

$a_{wrist}(f)$ -wrist acceleration,

$a_{handle}(f)$ – handle acceleration respectively.

Similarly, Transmissibility function on elbow is expressed as:

$T2(f) = a_{elbow}(f)/a_{handle}(f)$ (6)

Where,

T2(f)-handle to elbow transmissibility,

$a_{elbow}(f)$ -elbow acceleration,

$a_{handle}(f)$—handle acceleration respectively.

The graph (Figureure14) shows that the transmissibility magnitude of the 3 DOF mathematical model is given in between the frequency range of 50Hz to 200Hz and the maximum peak found at 3.6 at 60Hz. As well as the frequency increases transmissibility magnitude decreases as shown in the graph (Figureure14), the second and the third peak found near about the 140Hz and 200Hz respectively. Transmissibility is much affected by the grip force and driving (push) force which is taken as 20N-50N.

So result shows that as the frequency range increases the transmissibility magnitude decreases towards the minimum value, thus at the much higher value of the frequency range it affect the human body lesser than in the lower frequency range. And also the working hour and power consumption makes a big role in the HAVS. As the graph (Figureure.15) shows that the maximum power absorption is about 16.7mw. So the 3DOF model system max power as per grip force and push force value 20N-50N found that 16.67mw. absorbed power as much higher can cause many HAVS like a White finger (WTF), muscular disease, bone-joint problem etc.

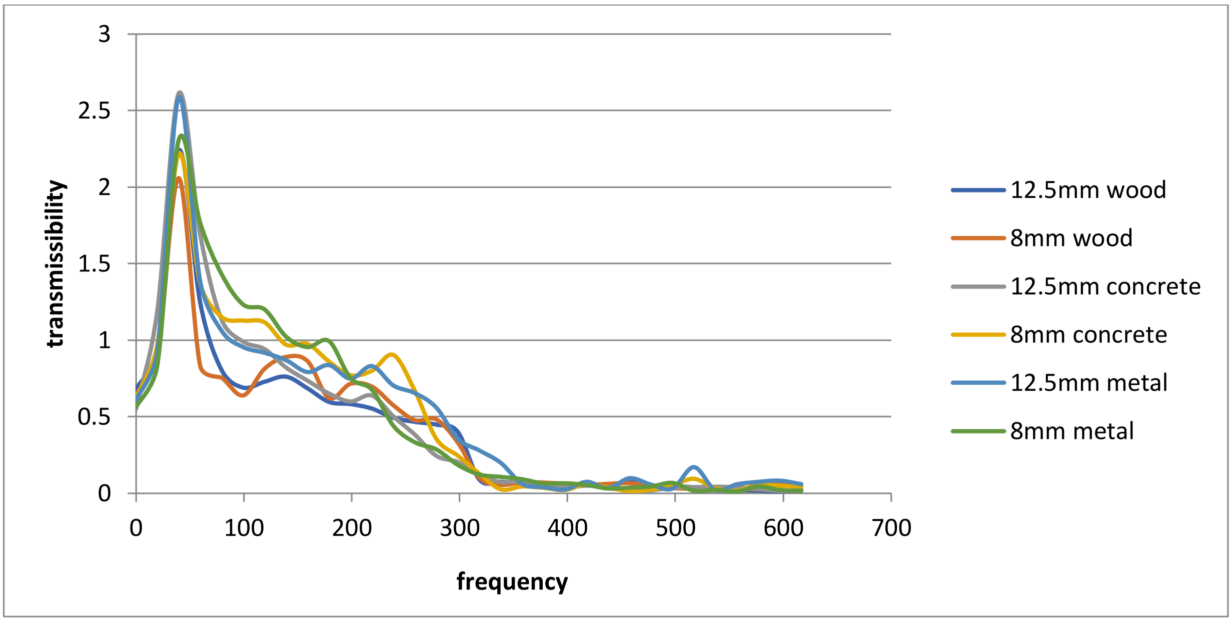
(Experimental Result)

Experiments were conducted in the 'Vehicle Dynamic Lab' to calculate the transmissibility from Hand to wrist (HTW) and Hand to elbow (HTE), using six male subjects in a standing manner, grasping the drilling machine in the right hand with different drill size 6.5mm, 8mm and 12.5mm respectively. Experiments were done in different postures (P1) horizontal direction (P2) vertical direction (P3) over the head and in different material (i) metal (aluminium alloy) (ii) concrete (iii) wood.

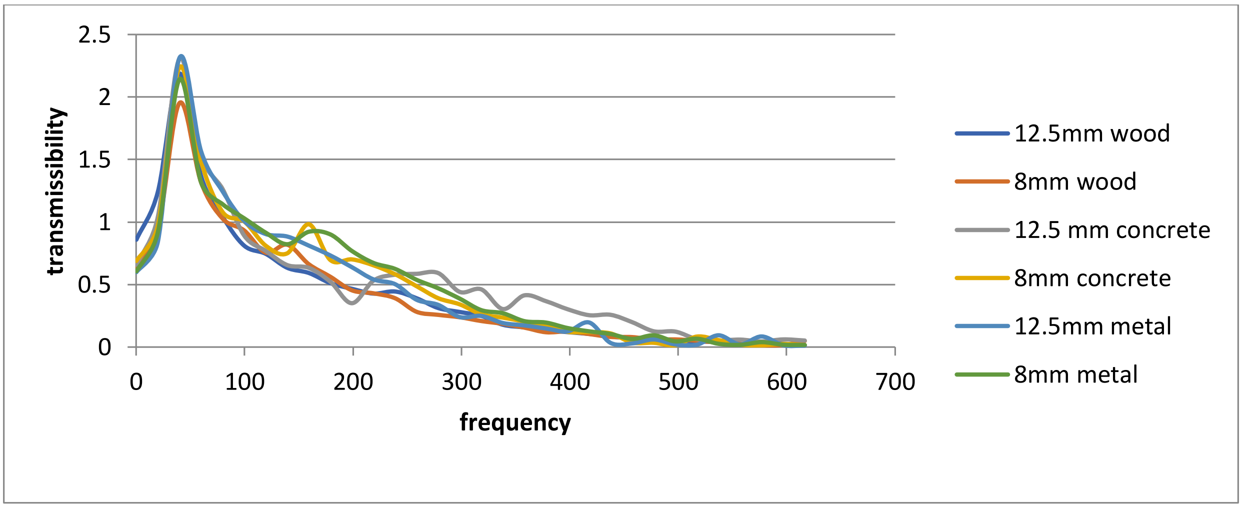
Posture	**Drill size(mm)**	**Materials**
Vertical	6.5	wood
Horizontal	8.0	aluminum
Over the head	12.5	concrete

Table 4. Experimental Criteria Matrix

The vibration signals from the accelerometers will be passed to NI data acquisition card (NI cDAQ-9232), and then it will be attached to the Lab VIEW 8.6.0., for the transmissibility responses.



Figureure16 Comparison of mean HTW transmissibility for metal plate, concrete block and wooden block in P1 posture



Figureure 17 Comparison of mean HTE transmissibility for metal plate, concrete block and wooden block in P1 posture

Peak magnitudes of HTW transmissibility have been observed to be 2.58 and 2.30 during the drilling operation on a metal plate (Al alloy) in posture P1 for 12.5 mm and 8 mm drill sizes respectively. Peak magnitudes of HTW transmissibility have been observed to be 2.2 and 2.0 during the drilling operation on a wooden block in P1 for 12.5 mm and 8 mm drill sizes respectively as shown in Figure 6.25. And Peak magnitudes of HTW transmissibility have been observed to be 2.6 and 2.2 during the drilling operation on concrete in P1 for 12.5 mm and 8 mm drill sizes respectively as shown in Figure 16. And it shows the variation of mean HTW transmissibility in posture P1 for metal plates, concrete blocks and wooden blocks. The peak magnitude of HTE transmissibility has been observed to be 2.3 and 2.1 during the drilling operation on a metal plate in the P1 posture for 12.5 and 8 mm drill sizes respectively. Same as magnitudes 2.30 and 2.2 were observed in a concrete block during drilling in P1 posture for 12.5 and 8 mm respectively. And the peak transmissibility magnitude observed in the wooden block during drilling in P1 posture for 12.5 mm and 8 mm drill sizes is 2.18 and 1.94 respectively as shown in Figure 6.

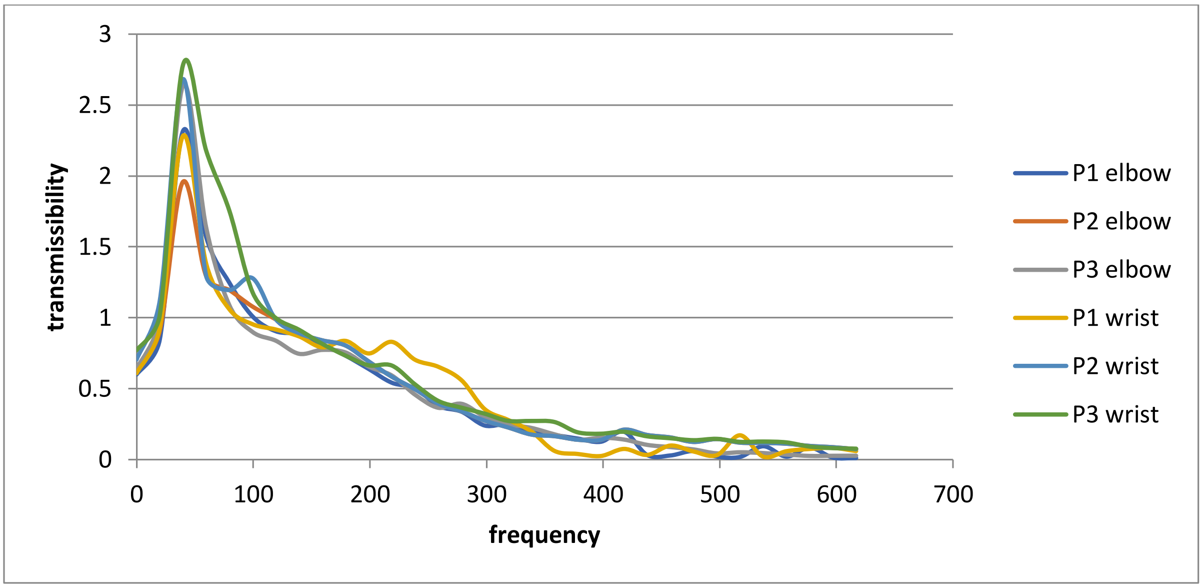


Figure 18 Comparison of mean transmissibility for drilling on metal plate

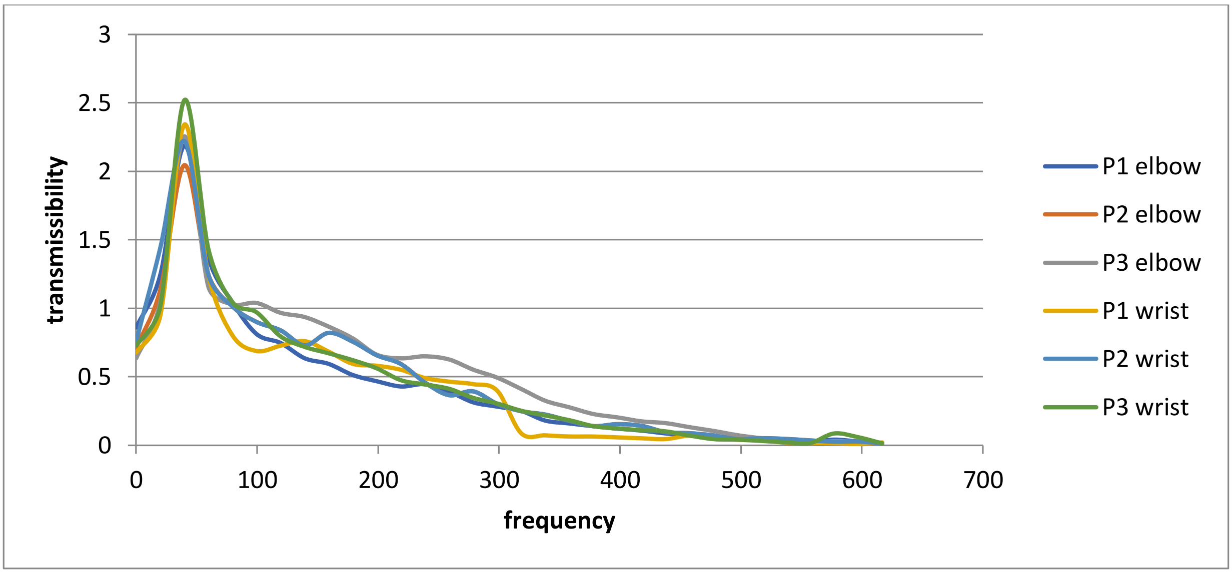


Figure 19 Comparison of mean transmissibility for drilling on a wooden block

As per the vibration magnitude transmissibility observation for metal plate (Al alloy) and wooden block in both the cases HTE and HTW, it was found that HTW transmissibility is greater than the HTE transmissibility in all the three posture P1 (horizontal), P2 (vertical) and P3 (over the head). It also found that as the drill size increases the magnitude of transmissibility increases, thus the transmissibility of the 12.5 mm drill size is maximum than other drill size of 8 mm and 6.5 mm drill size. Also, the peak magnitude of vibration transmissibility has been found to be more in the metal plate as compared to the wooden block. This difference may be occurring due to more force applied to the metal plate as compared to the wooden block and the hand-arm system becoming more rigid compared to when less force is applied by the subjects.

The mean transmissibility is higher in posture P3 (over the head) after that P1 (horizontal) as compared to posture P2 (vertical). This is irrespective of transmissibility measurement location (HTE or HTW) and material or drills size. This is due to work against the gravitation in posture P3 (over the head) which required more feed force to drill the object which cause more effort to drill any object, thus the hand-arm system becomes more rigid as compared to other posture. This may be attributed to the ease of gripping the drill machine and greater force application by the subjects in posture P1 which made the hand-arm system more rigid and compact. In the P1 posture, support from the body is available to reinforce the hand-arm system.

Moreover, the mean transmissibility is higher for HTW (hand-to-wrist) as compared to THE (hand-to-elbow) measurement in all three postures. This can be explained since vibrations damp out as they pass through the forearm from the wrist to the elbow due to the stiffness and damping properties of muscle tissues of the hand-arm system. And also, as we all know that as the distance increases from the source vibrations damped out or we can say magnitude decreases as time increases.

5. Conclusion

The laboratory experimental study which was conducted to measure the magnitude of vibration transmission from handle to wrist (HTW) and handle to elbow (HTE) of the dominant right hand-arm of six adult male subjects, while grasping an impact drilling machine with 12.5 mm, 8 mm and 6.5 mm drill diameters subject to z-axis vibration in different materials. This experiment was conducted in three different postures (i) P1 (horizontal) direction, (ii) P2 (vertical) direction and (iii) P3 (over the head).

- The transmissibility is higher with horizontal position and over the head position in harder material and larger size drills. The resonance peak occurs at 39 Hz to 40 Hz in both the direction horizontal and vertical positions and sometimes in the third direction over the head peak occur at 29 Hz. It might be caused by the sub height and weight because the over the head portion of drilling is fixed, thus peak varies due to the height of the subject and the feeding force to drill.
- It is observed that the transmissibility from HTW is higher than the transmissibility from HTE for all the postures and with all three drill sizes. It shows that when the human hand-arm system is exposed to vibration, transmissibility decreases as the distance from the vibration source increases along the hand-arm, and the risk of hand-arm vibration syndrome is higher at the fingertips, palm, and wrist than at other parts of the hand-arm system.
- The transmissibility is more during drilling on harder materials like concrete blocks and metal plates as it is a hard material to drill and the transmissibility is not much affected by the different dimensions of the human hand-arm of various subjects, it depends upon the grip force, push force and feed force.

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