Characteristics of the mechanical impedance of the hand-arm system

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CHARACTERISTICS OF THE MECHANICAL IMPEDANCE OF THE HAND-ARM SYSTEM

by

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A thesis submitted in partial fulfillment of the requirements for the

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Characteristics of the Mechanical Impedance of the Hand-Arm System

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

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Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

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ABSTRACT

Characteristics of The Mechanical Impedance of The Hand-Arm System

by

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Professor of Mechanical Engineering
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The mechanical impedance of the human hand-arm system was measured within the frequency range of 5-1000 Hz. A handle specially designed for such measurements, was used. The studies were carried out on ten healthy male subjects during different experimental conditions defined by, three different vibration amplitudes (0.01, 0.005, and 0.001 m/s) different combinations of push (0-75 N) and grip (25-50 N) forces, and two different methods of handle mass subtraction (mathematical and electronic). The effect of test subjects’ weight on the results was also studied. The outcome shows that the mechanical impedance of the hand-arm system depends on the frequency of the vibration stimuli. Impedance was found to increase rapidly with the increase of frequency starting from 80 Hz (for the 0.001 m/s vibration amplitude) and from 200Hz (for the 0.01 and 0.005 m/s amplitudes) to reach a maximum of about 950 Ns/m at 1000Hz. Generally speaking, it was found that impedance increases with the increase of push and grip forces especially at the mid range frequency (30-250 Hz). It was found also at this mid frequency, that impedance did not show consistence in decrease or increase in magnitude with the change of vibration amplitude while there was no significant effect for the
change of vibration amplitude at high and low frequencies. In addition, it was observed that the accuracy of the results decreased with the decrease of vibration amplitude. Moreover, test subject weight increase was observed to increase impedance at low frequencies (below 200 Hz for the 0.01 and 0.005 m/s amplitudes and below 15 Hz for the 0.001 m/s amplitude), while it did not cause significant change at high frequencies. The outcome of this study showed that the use of electronic mass subtraction caused major phase shifts and was not suitable for use with random vibration stimuli. Finally, a non-linear relationship between mechanical impedance and the studied experimental variables was found to exist. More studies are needed in order to be able to establish a better correlation between impedance and experimental variables that was not covered in this study.
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CHAPTER 1

INTRODUCTION

In this chapter, an overview of the problem understudy will be highlighted. That will be followed by specifying the objective of this thesis and finally an outline of the thesis will be presented.

Overview

Research has shown that prolonged exposure to hand arm vibration is related to the development of neurological, vascular and musculoskeletal disorders [1]. These disorders are known collectively by the name of vibration syndrome. It is estimated that two to four million workers in the United States are exposed to on the job vibration [2]. Some of the vibrating tools that are used by these workers in the industry are: pneumatic, electrical, hydraulic or engine-driven chain saws, pressure tools, and grinders. Table 1 gives the number of workers and the type of the tools used in the US based on a 1974 study of occupational exposures to vibration [3]. Depending on the type of the vibration source and the work condition, the vibration transmitted can be localized in the hand of the worker and also can be transmitted up to the shoulder [4]. This in turn determines the parts of the hand-arm system that is in danger of developing the previously mentioned disorders.
Table 1  Number of workers and the type of the tools used in the US

<table>
<thead>
<tr>
<th>No. of Workers Affected</th>
<th>Industry</th>
<th>Type of tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>500,000</td>
<td>Construction</td>
<td>Hand tools</td>
</tr>
<tr>
<td>200,000</td>
<td>Farming</td>
<td>Gasoline chain saws</td>
</tr>
<tr>
<td>14,000</td>
<td>Metal working</td>
<td>Hand tools</td>
</tr>
<tr>
<td>54,000</td>
<td>Steel</td>
<td>Powered hand tools</td>
</tr>
<tr>
<td>30,000</td>
<td>Lumber and wood</td>
<td>Gasoline chain saws</td>
</tr>
<tr>
<td>34,000</td>
<td>Furniture manufacturing</td>
<td>Hand tools</td>
</tr>
<tr>
<td>100,000</td>
<td>Mining</td>
<td>Pneumatic drills</td>
</tr>
<tr>
<td>250,000</td>
<td>Auto manufacturing</td>
<td>Hand tools</td>
</tr>
<tr>
<td>64,000</td>
<td>Foundries</td>
<td>Hand tools</td>
</tr>
</tbody>
</table>

The exact relationship between vibration syndrome and the physical properties of vibration is not well known [5]. Many studies have been conducted in an effort to understand the physical properties of the coupled hand-arm-tool system. These studies aim at getting a better understanding of the nature of the vibration interaction to the human hand-arm system. This is necessary in order to establish new concepts that will result in the reduction of the amount of vibration transmitted to the hand-arm system and, consequently, the reduction, or even better, the elimination of the disorders that are associated with vibration.

A better understanding of the human hand-arm system interaction with vibration can be obtained from conducting mechanical impedance measurements. Impedance

---

1 Based on a 1974 study
measurements can be considered as an excellent indication of the response of the hand-arm system to vibration. Impedance is defined as the dynamic force, applied to the hand-arm system, divided by the obtained velocity. Other studies or measurements could be conducted in order to get a better understanding of the hand-arm vibration interaction which is out of the scope of this thesis such as conducting transmissibility testing, calculating the amount of energy absorbed by the hand-arm system, and by doing hand-arm models that can be used to predict the biodynamic response of the hand-arm system to vibration. Mechanical impedance is the main data that are used to derive the previously mentioned quantities.

Human response to vibration depends on several physical factors such as frequency, direction, intensity of vibration, duration of vibration, push and grip force when tools are used as well as biological variations among individuals [6, 7, and 8]. The interaction of all of these factors together lead to the vast variations of results of impedance measurements conducted by investigators [8]. Generally speaking, more research is needed in order to correlate the variations in results to the previously mentioned factors and to the methods used in conducting the tests. In this thesis, the effect of some of these factors will be investigated in detail.

Objective

The main objective of this thesis is to investigate in more detail some of the physical and biological factors that are known to affect mechanical impedance results. Previously unstudied factors that may affect the values of impedance will be also investigated. Moreover, the results of this thesis along with the results of other studies will be used to
revise ISO 10068 standard [9]. This is needed because impedance data reported in different studies are not consistent. Some studies also did not report the exact testing conditions that were used, which makes these data of less reliability since different testing conditions are known to affect the testing results. Modern instrumentation will be used in this work in order to improve the accuracy of the results. The ISO 10068 standard has some limitations that need to be further investigated as will. These objectives will be accomplished through accumulating impedance data for different combinations of grip and push forces, different vibration amplitudes, different subject's weights categories, and different methods of subtracting handles mass. In the following sections, the exact testing conditions and procedures that will be used to accomplish these objectives will be outlined in detail.

Outline

In chapter two of this thesis, an overview of the different types of disorders associated to vibration, and methods of protecting workers from developing such disorders will be discussed. A historic overview of the problem will be also highlighted. This will be followed in chapter three by a literature review of the mechanical impedance measurements methods conducted in previous studies. In chapter four, definition of mechanical impedance, factors that affect the measurement of impedance, the scope of this thesis, and calculation method used will be discussed in detail. The instruments that were used in this study as well as detailed description of the methods of conducting measurements will be presented in chapter five. In chapter six, the results of this work
will be presented and discussed. Finally, this work will be concluded in chapter seven along with recommendations for future work.
CHAPTER 2

VIBRATION SYNDROME

In this chapter, an overview of the vibration syndrome disease will be presented. This will be followed by a discussion of the methods of protection of this disease. Finally a historic background will be outlined.

Vibration Syndrome

Hand-arm vibration syndrome (HAVS) is a disease that involves circulatory disturbances, sensory and motor disturbances and musculoskeletal disturbances [10]. The symptoms of HAVS are:

1) Blush discoloration of the skin of fingers and hands.
2) Whitening of fingertips after cold or damp exposure (known as Raynaud’s phenomenon).
3) Numbness, with or without tingling happens, before, during or after blanching.
4) Attacks, more common in winter, but eventually may occur year round.
5) Palms of the hands are rarely affected.
6) Sense of touch and pain perception reduces, sometimes forever.
7) Decreasing grip strength and ability to sustain muscle power.
Table 2 shows the Stockholm (Revised) hand-arm vibration syndrome classification system.

Table 2  Stockholm (Revised) hand-arm vibration syndrome classification system

<table>
<thead>
<tr>
<th>Stage</th>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Vascular Component</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Mild</td>
<td>Occasional blanching attacks affecting tips of one or more fingers</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>Occasional attacks distal and mild phalanges of one or more fingers</td>
</tr>
<tr>
<td>3</td>
<td>Severe</td>
<td>Frequent attacks affecting all phalanges of most fingers</td>
</tr>
<tr>
<td>4</td>
<td>Very Severe</td>
<td>As in 3 with trophic skin changes (tips)</td>
</tr>
<tr>
<td>B) Sensorineural component</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0SN</td>
<td></td>
<td>Vibration exposed – no symptoms</td>
</tr>
<tr>
<td>ISN</td>
<td></td>
<td>Intermittent or persistent numbness with or without tingling</td>
</tr>
<tr>
<td>2SN</td>
<td></td>
<td>As in 1SN with reduced sensory perception</td>
</tr>
<tr>
<td>3SN</td>
<td></td>
<td>As in 2SN with reduced tactile discrimination and manipulative dexterity</td>
</tr>
</tbody>
</table>

Studies show that, depending on the conditions of exposure, 6 to 100% of workers can suffer HVAS after using vibrating power tools [10]. On average, about 46% get HVAS symptoms. Raynaud’s phenomenon can occur from 0 to 14% with a mean of 5.4%, in workers who are not exposed to hand-arm vibration because it may be caused by other diseases, e.g. constitutional white finger (Raynaud’s disease) or scleroderma. The
high incidence of HVAS in the hand-arm vibration exposed group clearly confirms an association between HVAS and exposure to hand-arm vibration from hand-held power tools or objects.

HVAS is a chronic and progressive disorder and the time from first exposure to vibration and the blanching of fingertips in the cold (latent interval) can vary from a few months to several years [10]. At the beginning stages, blanching and tingling may occur only occasionally and be ignored. Often, it is only diagnosed at later stages when it can interfere with activities, including work. This makes prevention the key to managing vibrating tool exposures and health effects. Just as important is how long it takes acute symptoms to disappear. There appears to be a threshold in middle age. Symptoms that appear at about this time take longer to resolve or may not resolve at all. The circulation and neurological components of HVAS may develop independently. If exposure to vibration is discontinued, the vascular (circulatory) effects of HVAS can often be reversed but full recovery from neuropathy (disease of the nerves) is less likely to happen.

Methods of protection

Reducing the incidence of HVAS requires numerous actions. Table 3 shows some of the action that may be appropriate [10].
<table>
<thead>
<tr>
<th>Group</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Health &amp; Safety Committee</td>
<td>1) Ask management to provide safe hand tools, and regular maintenance of tools.</td>
</tr>
<tr>
<td></td>
<td>2) Measure vibration exposure</td>
</tr>
<tr>
<td></td>
<td>3) Get technical advice</td>
</tr>
<tr>
<td></td>
<td>4) Get medical advice</td>
</tr>
<tr>
<td></td>
<td>5) Warm the hands of exposed workers</td>
</tr>
<tr>
<td></td>
<td>6) Provide full training to exposed workers</td>
</tr>
<tr>
<td></td>
<td>7) Review exposure times and provide adequate rest breaks away from vibrating tools (e.g. Reduce exposure hours, decrease the number of days exposed to vibrating tool by job rotation)</td>
</tr>
<tr>
<td></td>
<td>8) Have a policy on removal/reduction of vibration from workplace</td>
</tr>
<tr>
<td>Tool Manufacturers</td>
<td>1) Measure tool vibration</td>
</tr>
<tr>
<td></td>
<td>2) Design tools to minimize vibration</td>
</tr>
<tr>
<td></td>
<td>3) Use ergonomic design to reduce grip force, awkward hand posture, etc.</td>
</tr>
<tr>
<td></td>
<td>4) Design tools to keep hands warm (e.g. heated handles, relocate air vents)</td>
</tr>
<tr>
<td></td>
<td>5) Provide guidance on tool maintenance</td>
</tr>
<tr>
<td></td>
<td>6) Provide warning of dangerous vibration levels</td>
</tr>
<tr>
<td>Physicians</td>
<td>1) Perform routine medical checks of those at risk</td>
</tr>
<tr>
<td></td>
<td>2) Record all signs and reported symptoms of HAVS</td>
</tr>
<tr>
<td></td>
<td>3) Warn workers of health risks</td>
</tr>
</tbody>
</table>

History

The association between the development of Raynaud’s phenomenon and the use of vibrating hand tools was first noted among Italian miners in 1911, and the first
investigation in the United States was conducted by the Department of Labor in 1918 under the direction of Dr. Alice Hamilton [11]. There are now more than 500 articles in the world literature on vibration syndrome. In the 1918 American study, a systematic evaluation was made of vibration syndrome among limestone cutters in Bedford, Ind., granite cutters in Vermont and Massachusetts, and marble workers in Vermont, Long Island city, and Baltimore. All of these workers used pneumatic impact hammers to cut and dress stone. It was found that 90% of the limestone workers, 86% of the granite workers, and 56% of the marble workers examined experienced Raynaud's phenomenon [11].

There were a few reports concerning this condition in the European scientific literature during the 1930s and several in the late 1940s in Europe and United States describing vibration syndrome among World War II workers who used pneumatic hammers and other vibrating tools. In 1970, anti-vibration chain saws, which produced only one tenth as much vibration as unmodified saws, were developed. Recent reports suggest that the use of anti-vibration saws has prolonged the number of years that loggers can use chain saws before they develop HAVS and thus has decreased the incidence of new cases among lumberjacks using anti-vibration chain saws. In 1960, Pecora et al, investigators with the Public Health Service, conducted a survey of occupational physicians and industry managers regarding the prevalence of vibration syndrome among Americans exposed to hand arm vibration [11]. They have concluded that vibration syndrome may have become an uncommon occupational disease approaching extinction in this country. In a 1962 and 1964 study, investigators demonstrated that extensive pathological damage to the arteries of the fingers could result from prolonged exposure to
vibration transmitted to the hands of tool users. In 1974, it was found that workers did not report symptoms of vibration syndrome because of fear of not being able to get employed. In response, the National Institute for Occupational Safety and Health (NIOSH) sponsored an international conference on occupational hand-arm vibration on October 1775, to discuss the epidemiologic, medical, physiological, and engineering aspects of vibration syndrome and vibration measurements [11]. During the 80's and 90's, there have been nine international conferences about hand arm vibration conducted in different locations in the world. Extensive research about all different aspects of the relation between vibration and the humans hand arm system were investigated. However, many inconsistencies between different studies are present especially in impedance data. The 10"Th international conference on hand arm vibration was held in the United States of America in 2004. In this conference, a revision of ISO standard 10068 that standardize the mechanical impedance data based on data from previous studies was considered for revision due to inaccuracies and limitations of this standard.
CHAPTER 3

LITARATURE REVIEW

In the literature there are many studies that aim at conducting measurements of the impedance of the hand-arm system. Some other studies aim at developing models that represent the biodynamic response characteristics of the hand-arm system. Other studies aim at studying the absorption of mechanical energy by the hand-arm system due to exposure to vibration. A short overview of the studies involving models and energy absorption will be presented in the following paragraphs, which will be followed by a more detailed overview of studies involving measurements of the mechanical impedance, which is the subject of interest of this work.

Generally speaking, it is found that the vast majority of hand-arm models cannot be applied for the development of a mechanical hand-arm simulator or the assessment of dynamic behavior of the coupled hand-tool system [12]. This is due to the fact that these models failed with a varying extent to describe the biodynamic response of the hand and arm under vibration. Actual natural frequencies and damping ratios of the hand arm system also did not agree well with the natural frequencies and damping ratios predicted from the models. The higher order models, with three and four degrees of freedom, in general, yield impedance characteristics within the range of idealized values, but exhibit excessive static deflections. Moreover, these models involve very light masses, and exhibit either one or two vibration modes at frequencies below 10 Hz. The majority of the
lower order models yield reasonable magnitudes of static deflection but relatively poor agreement with idealized values of driving point mechanical impedance.

Lage Burstrom conducted a study in which the energy absorption by the hand arm system was measured [13]. The outcome showed that the vibration exposure levels made a significant contribution to the vibration absorption as well as to the strength of the grip and feed forces. Moreover, it was found that the hand forces decrease while the absorption of energy increases. Furthermore, the influence of shock-type exposure gave a significantly higher hand forces and absorption of energy compared with the non-impulsive exposure.

Ronnie Lundstrom and Lage Burstrom conducted measurements of the mechanical impedance of the human hand-arm system in the frequency range of 20-1500 Hz [7]. The study was carried on 8 subjects during different experimental conditions. The experimental conditions adopted in this study included measuring impedance in the X, Y, and Z directions. Grip forces of 25, 50, 75 N were used. Vibration amplitudes of 27, 38, 53 mm/s were used as well as different vibration stimuli direction. The outcome of this study showed that the mechanical impedance of the hand-arm system depends on the frequency of the vibration stimuli. Above 200 Hz, the impedance increased quite rapidly, from about 150 Ns/m up to about 500 Ns/m at 1500 Hz, with the frequency. The study showed that at lower frequencies, various shapes of impedance curves were found which were most pronounced between different hand-arm postures. The study showed that for the transverse direction, the impedance increased from about 50 Ns/m at 20 Hz to maximum about 150 Ns/m at 20 Hz to minimize at about 100 Hz. The study showed that impedance increased with increase of vibration amplitude as will as with the increase of
grip force at frequencies above 100 Hz. The opposite was observed for lower frequencies. The study showed that a nonlinear relationship between mechanical impedance and the studied experimental variables. Fig 1 shows the average impedance magnitude and phase in the Z-direction for the average of all 8 subjects for the three different vibration amplitudes used in the study conducted by the researcher. Fig 2 shows comparison of the hand-arm impedance curves obtained by the researcher in the Z-direction to the results of earlier investigations.

Figure 1. Average impedance curves for all subjects for three different stimulus amplitudes in the Z-direction

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Figure 2  Comparison of the hand-arm impedance curves obtained by the researcher in the Z-direction

Steve Kihlberg conducted a study on the biodynamic response of the hand arm system to two types of vibration sources [14]. The two vibration types used were from impact hammer and a grinder. Three biodynamic quantities were studied in this investigation. These were: the transfer function to finger, wrist, and elbow; driving point impedance and its changes with grip and push forces; and dissipated power. The study found that the type of vibration, whether impact or harmonic, did not have an impact on impedance or transfer function when push and grip forces were kept constant. The study found that impedance magnitude as well as resonant frequency increased with the increase of grip and push forces. That means that the dissipated power depends on both frequency content and grip and push forces. The study found also that exposure to vibration at lower frequencies caused a greater load on the elbow and shoulder joints than
exposures with higher frequencies. In addition, the study found that up to about 250 Hz, the finger acts like a rigid body and that the hand-arm system has nonlinear characteristics.

R. Gurram conducted a study in which the driving point impedance of the human hand-arm system was investigated using sinusoidal and stochastic excitations using an identical apparatus to study the influence of various physical and biodynamic factors on the response of hand-arm system [15]. The measured data were further utilized to propose a method of developing grip force dependent hand-arm vibration models. The study revealed that the measured impedance data exhibit a high degree of inter-subject variations that may be attributed to the differences in weights and sizes of hands of the subjects. The peak inter-subject variations reported is 20-40%, while the peak intra-subject variations were reported to be in the range of 3-5%. The study revealed that impedance increases with increase of frequency and grip force. The study found also that the impedance characteristics measured under sinusoidal and stochastic excitations differed. Finally, a methodology to derive grip force dependent hand arm vibration models was proposed to characterize the dependence of impedance on the grip force. The three degree of freedom model developed correlated well in meeting the overall pattern of the measured data at different grip forces.

R. Gurram conducted another study in which the test procedures and experimental data reported in published studies on the driving point mechanical impedance of the human male hand-arm system were examined in the light of known sources of variability [8]. The data that were found suitable were used to synthesize envelopes of mean values of impedance magnitude and phase, as a function of frequency for all three directions of
vibration X, Y, and Z directions. A four degree of freedom lumped parameter model was then derived for each direction of vibration using a non-linear programming based optimization algorithm. It was found in this study that there is a small dependence of the X component of impedance magnitude on the hand grip forces. It was found also that the dependence of the phase of the corresponding impedance component on the hand grip force is insignificant. It is noted in this study that large variations exist among the mean values of both impedance magnitude and phase reported by different investigators. It is noted also that the error in impedance magnitude tends to increase with frequency which approaches 30-37% at 1000 Hz. The phase error was reported also to increase with frequency in the X and Y components while in the Z direction the error peaked at around 70 Hz. The model derived in this study revealed almost identical masses of the hand-arm system in all three orthogonal axes of vibration. And the impedance of the model correlated well with the mean impedance. The masses calculated for the model were observed to be concentrated near the fixed base of the system, close to the torso. The dynamic mass of the hand-arm system in contact with the handle was found to be extremely small in all three directions. Figures 3 and 4 show a comparison conducted by the researcher of the magnitudes and phases of the driving point impedance measured in the Z-direction for different investigators.

\[^2\] For more details about the exact conditions that were adopted during the testing phase for the development of each curve and the name of the researcher who developed the curve, please refer to reference number 8.
Figure 3. A comparison of the magnitude of impedance in the Z-direction for different investigators

Figure 4. A comparison of impedance phase angle measured in the Z-direction for different investigators
It is clear from this survey that the mechanical impedance data reported by different investigators do not show consistency. This inconsistency is due to the fact that impedance values are affected by different test setups used by each investigator such as the method used for subtracting the vibration excitation system handle’s mass, system calibration, and types of instrumentation used. The inconsistency is related also to the use of different testing conditions such as grip and push forces, vibration amplitudes, and biological characteristics of test subjects used. Impedance data are the main quantity used by most investigators to derive other quantities that may help in understanding the response of the hand-arm system to vibration, such as, the amount of energy absorbed by the hand-arm system and for developing hand arm models. Thus, it’s of great importance to investigate the factors that affect the impedance data in an attempt to reach a testing methodology that could be used by all investigators in order to eliminate the inconsistency of the results. This is needed in order to be able to get a unified impedance data that is recognized internationally, which will be of more reliability than the existing data. In this work, a step for achieving this objective will be attempted by clearly identifying test conditions and factors that have been poorly or never investigated in previous studies along with the use of modern instrumentation in order to accumulate new impedance data with more clearly defined relations to testing conditions and factors. The testing conditions and factors used in this study will be outlined in detail in the following sections.
CHAPTER 4

MECHANICAL IMPEDANCE MEASUREMENT

In this chapter, the definition of mechanical impedance will be presented along with the factors that may affect the mechanical impedance measurements. This will be followed by a presentation of the scope of this thesis. Next, the theory of conducting calculations, including mass cancellation, and the quantities used for quantifying the biodynamic response of the hand arm system will be presented.

Definition of Impedance

One of the methods that can be used to understand humans hand-arm system response to vibration, is the mechanical impedance, MI. Free impedance is defined as the complex ratio of the applied periodic excitation force at frequency $f$, $F(f)$, divided by the resulting vibration velocity at the same frequency, $v(f)$, with all other connection points to the system free. That is, they have zero externally applied force. Accordingly, the mechanical impedance as a function of frequency can be written as:

$$MI(f) = \frac{F(f)}{v(f)}$$

Driving point free mechanical impedance is defined similar to the free impedance, with the condition of measuring both force and velocity at the same point, which is the point of introduction of vibration to the hand-arm system [9]. The mechanical impedance,
MI, can be described as a mechanical structure’s resistance to vibrate according to an applied vibration. It describes the resistance and absorbing properties of the structure. The amplitudes of Force, Velocity, and their reciprocal phase relation determine the absolute value of the mechanical impedance. The impedance reaches its maximum value when \( F \) and \( v \) are in phase with each other. The impedance can be expressed in terms of two components, real component \((MI_r)\) and imaginary component \((MI_i)\). The exact value of each component can be determined if the phase relationships are known [7].

The human hand-arm system can be interpreted as a complex mass-spring-damping system. The phase angle of the measured impedance can be used to interpret which one of these three factors plays the dominant role for the dynamic behavior for a given vibration frequency range. Theoretically speaking, the mechanical impedance phase angle is \( 90^\circ \) for a pure mass, \( 0^\circ \) for a pure damping, and \( -90^\circ \) for a pure spring [16].

The mechanical impedance of the hand arm system is required for:

1) Design and development of vibration reducing and protective devices [16].
2) Design and development of test rigs with which to measure the handle vibration of power tools [16].
3) Estimation of the mechanical power transmitted to the hands [15, 13, and 17].
4) Description of the biodynamic properties of the hand-arm system [22, 23, 17, 14].
5) Development of hand-arm models [18, 19, 20, 21].

ISO standard 10068 used some of the wide range of impedance data available in the literature that it found suitable in order to standardize the free mechanical impedance at the driving point for all three orthogonal translatory directions of excitation, \( x_h, y_h, \) and
$z_h$ defined in ISO 5349 and ISO 8727. The values of impedance have been derived from the results of impedance measurements performed on groups of live, male subjects. Insufficient data are available from independent sources to specify hand-arm impedance for females. In this standard (ISO 10068), the most probable values of impedance modules and phase are defined, as a function of frequency, by upper and lower envelopes, which encompass the mean values of all accepted data sets at each frequency. The envelopes have been constructed from segmental cubic spline functions, and define at each frequency for the range of accepted values of the male hand-arm impedance. Impedance for all three directions are defined as a function of frequency from 10 Hz to 500 Hz for specific arm positions, grip and feed forces, handle diameters, and intensities of excitation. Some of the limits of applicability of this standard include:

a) The hand grasps a handle which is between 19 mm and 45 mm in diameter.

b) The hand grip force is between 25 N and 50 N. The feed force applied by the hand is not greater than 50 N.

c) The magnitude of acceleration of the handle applicable is believed to be up to 50 m/s$^2$.

Table 4 shows the values of the free, mechanical impedance of the hand-arm system at the driving point in the $z_h$ direction, at one-third-octave band center frequencies adopted in this standard (ISO 10068).
Factors that affect the measured impedance

The hand-arm system response to vibration depends on several factors. In order to obtain reliable and accurate test results of impedance, it is necessary to control these factors and report the conditions that were set during testing. These factors can be classified into two major groups; natural factors and instrumentation factors [16].

1) Natural factors

Natural factors include the following:

a) Vibration magnitude

b) Vibration frequency

---

Table 4  Values of the free, mechanical impedance of the hand-arm system at the driving point in the $z_h$ direction, at one-third-octave band center frequencies.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Modulus (N.s/m)</th>
<th>Phase (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Limit</td>
<td>Mean</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>153</td>
</tr>
<tr>
<td>12.5</td>
<td>104</td>
<td>165</td>
</tr>
<tr>
<td>16</td>
<td>108</td>
<td>180</td>
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<tr>
<td>20</td>
<td>112</td>
<td>190</td>
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<tr>
<td>25</td>
<td>116</td>
<td>200</td>
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<tr>
<td>31.5</td>
<td>121</td>
<td>215</td>
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<tr>
<td>40</td>
<td>125</td>
<td>220</td>
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<td>50</td>
<td>126</td>
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<td>63</td>
<td>122</td>
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<td>200</td>
<td>130</td>
<td>200</td>
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<tr>
<td>250</td>
<td>146</td>
<td>216</td>
</tr>
<tr>
<td>315</td>
<td>160</td>
<td>231</td>
</tr>
<tr>
<td>400</td>
<td>169</td>
<td>246</td>
</tr>
<tr>
<td>500</td>
<td>183</td>
<td>265</td>
</tr>
</tbody>
</table>
c) Direction of vibration exposure

d) Vibration type (sinusoidal, random, pseudo-random, and impulsive)

e) Individuals anthropometry and tissue properties

f) Hand and arm postures

g) Vibration exposure direction

h) Vibration duration

i) Push and grip forces

j) Environmental conditions (temperature and moisture)

2) Instrumentation factors

Instrumentation factors include the following:

a) Cancellation of the handle’s mass

b) Phase shift of acceleration and force signals measured

c) Algorithm or software used for calculations or data processing

d) Force and acceleration transducers calibration

e) Nonlinearity of force and acceleration transducers that may exist

f) Calibration and display of grip and push forces

The natural factors can be either controlled during the experiment or considered as fixed or random variables in the study design. The impedance values may be expressed as a function of these natural factors if a study is appropriately designed, sound experimental procedures are used, and the data are statistically analyzed using a suitable method. The instrumentation factors should not be treated as random variables by the experimental design or statistical analysis. Instrumentation problems could lead to misleading and inaccurate experimental results. However, the results could be accepted if
it is within an acceptable error range. Most of the instrumentation factors could be eliminated by proper calibration and evaluation methods.

Scope

Many studies have been published that involve impedance measurements. Most of these studies show inconsistency with regard to their results. This may be due to the use of different grip or push forces, hand-arm postures, experimental techniques, or any of the natural or instrumentation factors that were previously discussed. Thus, the main aim of this thesis is to verify the effect of some of these factors on the impedance results. The factors that will be verified are:

1) The effect of using different combinations of grip and push forces. The values of push forces that were examined are: 0, 25, 50, and 75 N. The values of the grip forces that were examined are: 25, 50 N. The ISO 10068 indicates that an increase in grip force results in an increase in impedance modules; especially at frequencies in excess of about 50 Hz. ISO 10068 also indicates that the impedance modules and phase do not appear to be substantially influenced by feed or push force at frequencies above 100 Hz. The values may be expected to change by less than 10% for feed forces up to 150 N. These reports will be verified in this thesis.

2) The effect of using different vibration amplitudes. Three velocity amplitudes will be examined: 0.01, 0.005, and 0.001 \( \frac{m}{s} \).

3) The effect of electronically subtracting the handle mass using a subtraction electronic circuit and digitally using post data processing software was
investigated. The use of the subtraction circuit is believed to introduce an additional phase shift and potential circuit error into the measurement system. In addition, the effective handle mass may vary with frequency. Such a variation makes the use of the circuit with a random source of vibration questionable. However, many investigators have used this method in their impedance testing methodology [16]. On the other hand, the subtraction of the handle mass using a post processing software may not be very reliable at high frequencies due to the fact that the handle mass at such frequencies will dominate the effective mass of the hand. In this thesis the results from both methods will be compared in an effort to determine the best method to be used for impedance measurements.

4) The effect of the weight of test subjects. The impedance results will be compared for two subject weight categories. The first will be of weight range of 135-166 lb; the second will be of weight range of 174-230 lb.

ISO 10068, provides established standardized values for human hand-arm impedance. This standardized establishment is required in order to foster the development of effective vibration reducing and protective devices and meaningful test procedures [9]. The International Organization for Standardization (ISO) has set forth this standard based on some of the wide range of human hand impedance values available in the literature that it finds acceptable. This standard, however, has several deficiencies and limitations. Some of these limitations are:

1) The recommended values only go up to 500 Hz, which is not consistent with the assessment requirements of the ISO 53418

2) The recommended values are only for male subjects
3) The range of push force range adopted is between 25-50 N only.

4) No push force range was set due to insufficient test data that apply push force as a test factor.

Some of these factors will be investigated in more detail in order to provide more data sets that can be used along with other studies to revise ISO 10068. The additional factors and ranges that will be studied in this thesis that are not covered in the standard are:

1) Vibration frequencies range of 5-1000 Hz.

2) Wider range of push force as was mentioned above.

Although there are a large number of studies that have reported hand-arm impedance data, many of the results of these studies may not be reliable enough and may not be acceptable due to the lack of the reporting of testing conditions that was used in these studies. These include instrumentation characteristics, systematic measurement, system evaluations, and dynamic calibrations; and due to the use of inappropriate measurement or analysis methodology [12, 16]. It is necessary to conduct more impedance measurements that take these factors into account, which will be done in this thesis.

**Theory**

**Biodynamic response**

It is often desired to measure and analyze the detailed mechanical response of the complex hand arm system, such as the dynamic stress, strain, and energy dissipation. Such measurements are often very difficult to be conducted. As an alternative, the biodynamic response of the hand-arm system, such as apparent mass, mechanical impedance, and apparent stiffness, can be easily measured at the hand driving point.
These biodynamic responses provide a practical and effective measure to describe the mechanical responses of the hand-arm system to a vibration excitation and are widely used in investigations of engineering structure dynamics.

According to the ISO standard 7626/1, Vibration and Shock-Experimental Determination of Mechanical Mobility-Part 1, there are six related frequency response functions that can be used to describe the response of a vibration system. They are:

1) Dynamic compliance \((\frac{D}{F}, m/N)\) (1)

2) Mobility \((\frac{V}{F}, m/N - s)\) (2)

3) Accelerance \((\frac{A}{F}, m/N - s^2 \text{ or } Kg^{-1})\) (3)

4) Dynamic stiffness, DS \((\frac{F}{D}, N/m)\) (4)

5) Mechanical impedance, MI \((\frac{F}{V}, N - s/m)\) (5)

6) Effective mass, EM \((\frac{F}{A}, N - s^2 / m \text{ or } Kg)\) (6)

Where:

\(F\) : Dynamic force
\(A\) : Acceleration
\(V\) : Velocity
\(D\) : Displacement

As can be seen, the dynamic stiffness, impedance, and effective mass are the reciprocals of the dynamic compliance, mobility, and accelerance, respectively. It is not necessary to measure all of these quantities at the same time since anyone of them can be
easily derived from the others. For example, if the impedance is directly measured, effective mass (EM) and dynamic stiffness (DS) can be calculated from the following formulas:

\[ EM(\omega) = \frac{MI(\omega)}{j\omega} \]  \\
\[ DS(\omega) = MI(\omega) \cdot j\omega \]

Where:

\[ \omega \] : Frequency in radians/s

Another important biodynamic response that has been frequently used in the study of hand transmitted vibration is the vibration energy/power transmission (VPT) from a tool handle to a hand. It is defined as:

\[ VPT = F \cdot V \]

VPT can be derived from MI using the following formula:

\[ VPT(\omega) = MI(\omega) \cdot |V(\omega)|^2 \]

All of these biodynamic responses are complex quantities in the frequency domain. That is, they are composed of real and imaginary parts. The real part of the VPT represents the vibration energy/power absorption, which may be associated with the etiology of vibration-induced disorders [16].

As mentioned above, any of these biodynamic responses can be derived from each other. Thus only one of these quantities needs to be measured. The most widely used biodynamic response in the literature is the mechanical impedance. This is also the reason that ISO 10068 standard uses only mechanical impedance values in its data.

In this thesis, the effective mass will be measured, and the required mechanical impedance will be calculated using equation (7).
In the frequency domain, the effective mss can be obtained by performing a transfer function calculation using the following equation:

\[ EM = \frac{G_{fn}(\omega)}{G_{nn}(\omega)} \]  

(11)

Where:

\[ G_{fn} \]: The cross spectrum of force and acceleration

\[ G_{nn} \]: The auto spectrum of the motion

The calculations involved in equation (11) can be conducted using any of the data acquisition software’s available in the market.

Mass cancellation

Fig 5 shows the free body diagram of the handle under vibration while it is griped by a test subject hand.

![Free body diagram of mass of handle.](image)

Figure 5. Free body diagram of mass of handle.
From Newton's law the following relation can be derived.

\[ F = F_i + ma \]  \hspace{1cm} (12)

Where:

- \( F \): The force measured by the impedance transducer
- \( F_i \): The reaction force of the hand
- \( m \): The mass of the handle
- \( a \): The acceleration measured by the impedance transducer

In impedance measurements, it is required to measure the reaction force of the hand only. So it is necessary to subtract the inertia force of the shakers handle. The inertia force of the handle can be subtracted using one of two methods. The first is by using a software package such as Microsoft Excel to do the required mass cancellation mathematically. This type of cancellation will be conducted in the frequency domain. The problem with this method is that the inertia force of the handle is believed to dominate the reaction force of the hand especially at high frequencies above 500 Hz. The following equation can be used for the mass cancellation in the frequency domain:

\[ EM_{hand}(\omega) = H_{pp}(\omega)[EM_{total}(\omega) - EM_{handle}(\omega)] \]  \hspace{1cm} (13)

Where:

- \( EM_{hand} \): The pure effective mass of the hand arm system
- \( EM_{total} \): The total mass response measured in a subject test
- \( EM_{handle} \): The handle effective or apparent mass
- \( H_{pp} \): The measurement systems FRF

The measurement system FRF can be calculated from the following equation:
\[ HI_{pp}(\omega) = \frac{m_1}{EM_{handle}(\omega)} \approx \frac{\text{Re}(EM_{handle}(\omega))}{EM_{handle}(\omega)} \] (14)

Where:

- \( m_1 \): The effective mass on the sensor-sensing end

The measurement system FRF is used in equation (14) in order to eliminate the phase shift error that may occur between the force signal and the acceleration signal. However, if the characteristics of the force and motion sensors, the signal conditioners, and the filters are good matches, the system phase shift may be ignored. In such a situation, the instrument system FRF becomes unity. Then, the mass cancellation can be directly computed from the following equation:

\[ EM_{hand}(\omega) = [EM_{total}(\omega) - EM_{handle}(\omega)] \] (15)

The second method used to subtract the mass of the handle can be conducted in the time domain. This cancellation can be achieved electronically using an electronic subtraction circuit. The design of the circuit and the theory that it uses in doing the cancellation will be discussed in the following sections in detail.

The test setup for conducting impedance testing using the electronic mass-cancel is shown in Fig 6.
Figure 6. Test setup for conducting impedance testing (Mass cancelled in the time domain)

The test setup for the second method, in which the handles mass will be subtracted mathematically after signal processing, is shown in Fig 7.

Figure 7. Test setup for impedance measurements (Mass cancelled in the frequency domain)
The circuit is composed of two stages. Each stage uses an operational amplifier, LM741. The first stage, which consists of one resistor, one potentiometer, and one op-amp, solves for the following equation.

\[ V_2 = -V_1 \times \frac{R_2}{R_1} \quad (16) \]

This circuit inverts the input voltage and amplifies it by a value equal to the ratio of the two resistors \( R_2/R_1 \), which is called the closed loop gain. The second stage, which is composed of three resistors and one op-amp, is designed to solve for the following equation.

\[ V_4 = -V_2 \times \frac{R_3}{R_4} - V_3 \times \frac{R_3}{R_3} \quad (17) \]

Thus the output of this stage will be the summation of both of the input signals \( V_2 \) and \( V_3 \) after inverting each of them and multiplying each by its closed loop gain. Using equations (16) and (17), one can write:

\[ V_4 = V_1 \frac{R_2}{R_4} \frac{R_3}{R_4} - V_3 \frac{R_3}{R_3} \quad (18) \]

Equation (5) shows that the desired circuit actually subtracts \( V_3 \) from \( V_1 \) after multiplying each by a certain gain.

Force transducer:
A piezoelectric force transducer was used to measure the dynamic force at the handle. The transducer has a sensitivity of 11241mV/kN. The transducer used is manufactured by PCB PIEZOTRONICS INCORPORATION, and the model number of the transducer used is 208C02.
Charge amplifiers:

Bruel & kjaer manufactured the charge amplifier under use, and its model number is 2647-B. There are two main functions of this charge amplifier. The first function is to transform the charge signal of the charge accelerometer into a voltage signal. The second function is to amplify this signal. The gain of the model used was selected to be 0.1, which means that the acceleration signal was scaled down by 10 times.

Power amplifier:

A power amplifier is used to supply the power needed to operate the force and accelerometer transducers as well as scaling them up or down as required by adjusting the gain of each of the channels of the power amplifier. The power amplifier used was manufactured by Svantek Corporation, and the model number used is SV08A.

Push-grip force calibrator:

A calibrator was used to calibrate the push or grip force in use. The calibrator is used to exert a known amount of push or grip force. The corresponding reading of these forces
on the strain gage indicator boxes is recorded. The calibrator used is manufactured by Chatillon Corporation and the serial number of the model being used is 707036.

Voltmeter:

A voltmeter was used in order to measure the force or acceleration voltage signals coming out from the force or accelerometers used. The voltmeter used is manufactured by Radio Shack and its model number is 22-805.

Function generator:

A function generator was used to excite the shaker. The function generator was used to generate a sinusoidal signal in which its amplitude and frequency can be controlled as desired. The function generator used was manufactured by BK Precision Company and its model is 3010.

Digital-analog signal Amplifier:

An amplifier was used to amplify the signal of the function generator or vibration view. The amplifier also was used for transforming the signal from digital to analog formats and vice versa as needed. The serial number of the model used is N35852842 and it was manufactured by Vibration Research Corporation.

Vibration View:

Vibration view is a software used to control the vibration of the handle of the shaker. It can be adjusted to generate the required amplitude signal over the desired frequency range. A feedback of the acceleration of the shakers handle was used to maintain the vibration profile as required. Fig 10 shows the main display screen of Vibration View software.
Amplifier:

A power amplifier was used to amplify the signal of the vibration view in order to be strong enough to drive the shaker as required. The amplifier used was supplied with the shaker in use and it was manufactured by TIRA Maschinenbau Corporation. The model number used is TIRA vib A51312.

Shaker:

An electromechanical shaker was used to vibrate the handle. The model number used is TIRA vib 5500LS, and it is manufactured by TIRA Maschinenbau Corporation.

SignalCalc:

SignalCalc was the software used to acquire the force and acceleration signals and analyze them. The FFT analyzer of the software was used. The software was adjusted to record the impedance magnitude and phase for a range of frequency of 5-1000Hz. Fig 11 shows the main display screen of SignalCalc software.
Method

In this section, the calibration method used for calibrating the force and accelerometer transducers will be discussed. This will be followed by a discussion of the test setup for conducting the impedance measurements. Subjects' position, hand arm posture, grip and push forces display, and a description of the coordinate system used will be also discussed.

Calibration of accelerometer

The first step in the process of calibrating the accelerometer is to check the accuracy of the calibration provided with the specification sheet of the accelerometer. Fig 12 shows a schematic drawing of the test setup used for checking the calibration provided with the specification sheet of the accelerometer.
A 1 g calibrator was used to check the calibration of the accelerometer. The calibrator generates an acceleration of 9.81 m/s\(^2\). After fixing the transducer on top of the calibrator, the signal was carried to the charge amplifier and from there it will be input into a power amplifier. The charge amplifier multiplies the signal by 10, while the power amplifier is adjusted to divide the signal by 10. The final signal will be measured using a voltmeter. The expected reading of the voltmeter was 9.92 mV. If the reading of the voltmeter was as expected, the sensitivity provided with the accelerometer was used as it is to define the sensitivity of the accelerometer into SignalCalc software. If the reading of the voltmeter was not as expected, a correction factor was calculated according to the following equation:

\[
f_c = \frac{s_1}{s_2}
\]

Where:

- \(f_c\) : Correction factor
- \(s_1\) : Actual sensitivity

Figure 12. Test setup for calibrating accelerometer.
$s_2$: Provided sensitivity

Calibration of force

Fig 13 shows the test setup that was used for calibrating the force transducer. A known mass was fixed on top of the force transducer. The accelerometer and the force transducers were fixed on the shaker. The function generator was adjusted to produce an acceleration of 1g. This can be done by measuring a signal of 9.92 mV from the accelerometer. As the mass on top of the transducer was known as well as the acceleration, the force was calculated using the following equation.

\[ F = m \times a \]  

(20)

Where:

- $F$: The calculated force
- $m$: The known mass fixed on the force transducer
- $a$: The acceleration measured from the accelerometer

The attached masses that were used are:

- $m_1 = 217.56$ g
- $m_2 = 409.5$ g
- $m_3 = 1088$ g

The reason of using more than one mass in the calibration was to check if the force transducer had any nonlinear characteristics.
Figure 13. Test setup for calibrating force transducer.

The force signal was first input into the power amplifier and then into the voltmeter. The power amplifier was adjusted to divide the signal by 10. The reading of the voltmeter was computed with the sensitivity of the force transducer provided with the specification sheet. The reading of the voltmeter was used in the following equation in order to obtain the measured sensitivity.

\[ s_2 = \frac{V_o}{m \times a} \]  

(21)

Where:

- \( s_2 \): Measured sensitivity
- \( V_o \): Voltage reading of the voltmeter

If the measured sensitivity equaled the provided sensitivity, the provided sensitivity can be used as it is to define in the SignalCalc software. If they are different a correction factor can be calculated using equation (17) and the actual sensitivity will be used to
define the force sensitivity in SignalCalc software. After using the first mass, \( m_1 \), for the calibration, the same procedure was repeated for each of the remaining masses.

It is required now to check the calibration of both the accelerometer and the force transducer when they are in use together. Fig 14 shows the test setup for checking the calibration of both transducers at the same time.

![Diagram of test setup](image)

Figure 14. Test setup for checking the calibration of both transducers at the same time

Vibration View software was used to generate a constant velocity input over a frequency range of 5-1000 Hz to drive the shaker. The acceleration signal was carried to the charge amplifier and from there to the power amplifier, and finally to SignalCalc software. The force signal was carried to the power amplifier and from there to SignalCalc software. The actual sensitivities of both the accelerometer and the force transducer calculated previously were used to define sensitivities in SignalCalc software.
The shaker handle, with mass \( m = 1.088 \text{ Kg} \), was attached to the force transducer.

SignalCalc software was adjusted to display the effective mass, \( \frac{F}{a} \), and the phase angle. It was expected that the effective mass would be a constant line over the whole frequency range. The constant line should be at a value that equals the mass of the shaker handle. When that was obtained, the calibration of both the accelerometer and force transducer was acceptable. If not, then the calibration of one or both of the transducers should be redone. The phase angle was also a straight line over the whole range of frequency at -90 degrees. This was expected because theoretically the phase angle of a pure mass should be -90 degrees.

Test setup

The force and accelerometer transducers as well as the feedback accelerometer were fixed on the shaker handle as shown in Fig 15. The force transducer was installed as close to the hand-handle interface to reduce possible errors in the mass cancellation. The instrumented handle was then installed on the shaker; the handle was attached to the shaker through the force transducer.
Test subjects were instructed to stand on top of the force plate upright facing the shaker handle. They were then instructed to grip the handle from the middle using their right hand according to Fig 16. It was recommended that the test subject position his hand at the middle of the handle to eliminate any off-center loading that may generate unwanted non-axial vibration and change the vibration distribution on the handle [16].
That configuration used allowed the measurement of the impedance in the Z direction, which is the direction of interest in this thesis. Three directions of measurements were defined in ISO 5349. These are the $X_h$, $Y_h$ and $Z_h$ directions shown in Fig 17.

![Figure 17. Coordinate system according to ISO 5349 standard.](image)

Test subjects were instructed to watch the reading of the two strain gages used for displaying the values of the grip and push forces and maintain the reading at a constant value according to the desired grip and push force under investigation. The strain gage box readings were obtained by using the push-grip force calibrator to apply the desired grip and push force and record the corresponding values on the strain gage boxes. Practically speaking, it is impossible for the test subjects to maintain the reading at a constant value. Actually, the reading will fluctuate about ±15% around the target value. The effect of these variations can be evaluated using the coefficient of standard deviation. Table 5 lists the anthropometric data of the 10 test subjects that were used.
Table 5  Anthropometric data of the 10 test subjects used

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Height (ft in)</th>
<th>Weight (lb)</th>
<th>Hand dimensions (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Length</td>
</tr>
<tr>
<td>1</td>
<td>KA</td>
<td>5 7.5</td>
<td>160</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>AH</td>
<td>5 11</td>
<td>163</td>
<td>7.5</td>
</tr>
<tr>
<td>3</td>
<td>NA</td>
<td>5 11</td>
<td>166</td>
<td>7.5</td>
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<td>MO</td>
<td>5 11</td>
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<td>8.25</td>
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<tr>
<td>5</td>
<td>CH</td>
<td>5 10</td>
<td>135</td>
<td>7.5</td>
</tr>
<tr>
<td>6</td>
<td>CS</td>
<td>5 6</td>
<td>155</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>KU</td>
<td>5 10</td>
<td>180</td>
<td>7.5</td>
</tr>
<tr>
<td>8</td>
<td>KB</td>
<td>5 10</td>
<td>174</td>
<td>7.5</td>
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<tr>
<td>9</td>
<td>RE</td>
<td>5 6</td>
<td>200</td>
<td>7.25</td>
</tr>
<tr>
<td>10</td>
<td>ER</td>
<td>6 3</td>
<td>230</td>
<td>8.25</td>
</tr>
</tbody>
</table>

Impedance measurement

Two methods were used to measure the mechanical impedance of the hand-arm system. The difference between the two methods that were used was in the way the shaker handle mass was cancelled. In the first method, the handles mass was electronically cancelled using the subtraction circuit. In the second method, the handles mass was cancelled mathematically using a Microsoft Excel macro. A total of 10 test subjects were used for both methods. Each test subject was instructed to position himself and adjust his arm posture as was described previously. For each of the two testing methods, a total of 24 test conditions were set to be conducted by each test subject. Each of these tests was repeated twice. The total number of tests conducted by each subject for each test method was 48 tests. For each test condition, 20 test runs were made, which were then averaged. Different combinations of push forces, grip forces, and vibration amplitudes were used. Table 6 shows the design conditions that were used for each test.

For all of these tests, only one handle was used, as described previously. Vibration View software was used to vibrate the shakers handle with the required vibration...
amplitude over range of frequency of 5-1000 Hz. Three vibration amplitudes signals of constant velocity over the whole range of frequency were set to be produced by Vibration View software and used when needed.

Table 6 The conditions that were design for each test

<table>
<thead>
<tr>
<th>Push force (N)</th>
<th>Vibration amplitude (m/s)</th>
<th>0.01</th>
<th>0.001</th>
<th>0.005</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grip force (N)</td>
<td>25</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>0</td>
<td>test 1</td>
<td>test 2</td>
<td>test 3</td>
<td>test 4</td>
</tr>
<tr>
<td>25</td>
<td>test 7</td>
<td>test 8</td>
<td>test 9</td>
<td>test 10</td>
</tr>
<tr>
<td>50</td>
<td>test 13</td>
<td>test 14</td>
<td>test 15</td>
<td>test 16</td>
</tr>
<tr>
<td>75</td>
<td>test 19</td>
<td>test 20</td>
<td>test 21</td>
<td>test 22</td>
</tr>
</tbody>
</table>

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CHAPTER 6

RESULTS AND DISCUSSION

The results from various variable combinations were composed in order to determine how the mechanical impedance for the hand-arm system is influenced by different experimental conditions in the Z direction of random vibration excitation over a range of frequency that extends from 5 to 1000 Hz. In all the figures to come, the letter $G$ will be used to refer to grip force and the letter $P$ to refer to the push force.

Experimental discussion

Figure 18, 19 and 20 show the coherence function curves that were recorded during the testing phase. Coherence function is a measure of the correlation between the force signal and its response, which is the acceleration signal. In other words, coherence function gives an indication if the two signals are related to each other or not. The desired coherence, for the test to be sound and be accepted, is to be not less than 0.9.
Figure 18 Coherence function for: 0.01 m/s

Figure 19 Coherence function for: 0.005 m/s

Figure 20 Coherence function for: 0.001 m/s
As can be seen from Figure 18, 19 and 20, there are some coherence disturbances at the low frequency ranges. The disturbance at this frequency range increases with the decrease of the excitation amplitude. At these frequencies, in which coherence magnitude is less than 0.9, impedance results may be questionable. Impedance results at frequencies below 15 Hz for the vibration amplitude of 0.001 and below 10 Hz for the vibration amplitude of 0.005 should not be accepted, while the whole range of frequency for the vibration amplitude of 0.01 should be accepted. The reason for bad coherence at these frequencies may be due to noise signals interfering with impedance signals. It may be also due to the looseness of the attachment of the handle to the impedance transducer and to the shaker in use. This looseness could be causing some undesired non-axial vibration. In an effort to reduce the effect of this looseness, two bolts where added as a guide for the handle to slide on freely. These bolts did not really improve impedance results at the affected ranges of frequencies and it did ad small damping effect to the system, which resulted in de-scaling impedance curves by about 1%. The bolts, however, helped in preventing the handle rotation around its axis while it was held by a test subject.

It should be noted that during the early phases of testing, it was noticed that the natural frequency of the handle was at around 800 Hz, which falls in the frequency range under study in this work. This of course resulted in the presence of a spike, due to resonance, at this frequency in all of the impedance results. Thus it was necessary to shift the natural frequency of the handle to a frequency higher than the upper limit used which is 1000 Hs. Thus the handle was remanufactured using aluminum while taking into consideration increasing the stiffness of the handle. This resulted in shifting the natural frequency of the handle up to around 2500 Hz.
Generally speaking, the push and grip forces reported in this study fluctuated about ±15% around the target value. This is mainly due to the difficulty that test subjects found in maintaining the strain indicator boxes at a fixed reading. Another reason was that the sensitivity of the strain gages in use changed slightly during testing, which may be due to residual stresses in the strain gages or may be due to some inaccuracies in the strain indicator boxes used.

Impedance magnitude and phase description

It is desired to examine the variation of the individual test subject impedance result to the average of all ten subjects. Figures 21, 22, and 23 show the average of all ten subjects used in this study along with the result of each subject individually for a grip force and push force of 25 N and 50 N respectively for all three excitation amplitudes used in the study. The curves show also the standard deviation. As can be seen from these curves, the overall deviation of the results of individual subjects from the average is within the acceptable range.
Figure 22. Impedance magnitude and phase for: 0.005 m/s: G 25, P 50: Individual subjects

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Figure 23. Impedance magnitude and phase for: 0.001 m/s: G 25, P 50: Individual subjects
Figures 24, 25, and 26 show the magnitude and phase of the impedance results for vibration amplitudes of 0.01, 0.005, 0.001 m/s, respectively, for different combinations of push and grip forces. As can be seen, a total spread in impedance magnitude of about 60-1000 Ns/m was found. Generally speaking, for all of the three vibration amplitudes used, it was found that impedance magnitude increased with the increase of frequency. However, at the mid range frequency, a decrease in impedance magnitude was observed that was followed by increase in magnitude again at high frequency range.
Figure 24. Impedance magnitude and phase for: 0.01 m/s, all G, all P
Figure 25. Impedance magnitude and phase for: 0.005 m/s, all G, all P
Figure 26. Impedance magnitude and phase for: 0.001 m/s, all G, all P
It is noted that impedance has a maxima and a minima, which is due to the presence of resonant frequency areas for the hand-arm system at around 50 and 80 Hz. It can be seen from the curves that the peaking trend of impedance sharpens with the decrease of vibration amplitude. As the natural frequency of the handle is designed to be beyond the upper limit of the range of frequency of interest in this study, i.e. 1000 Hz, it can be concluded that the impedance of the hand-arm system is exhibiting a nonlinear behavior, as noted by the presence of the maxima and minima which can be interpreted as one of the sub resonant frequencies usually associated with a nonlinear system.

The phase curves shown in Figures 24, 25, and 26 shows that the hand-arm system has high damping characteristics especially at the mid (between 40-150 Hz) and high (above 150 Hz) frequency ranges. This is concluded from the phase angle of the impedance of the hand-arm system which fluctuates between around -15 and 45 degree and it is known theoretically that the MI phase angle is 0 for pure damping. From this observation, it can be concluded that vibration is transmitted to the arm and up to the shoulder of a test subject at low frequencies, while it will be localized at the hand tissues at high frequencies, which means that the influence of mass elements which are most distant from the vibration source decreases due to energy absorption in associated parts of the hand-arm system. Thus, at the high frequency region, large amounts of energy are dissipated in small volumes of tissues, which may be responsible for the cell and tissues destruction associated with vibration syndrome.
Effect of push and grip forces

From Figures 24, 25, and 26, it is clear that the grip and push force have significant effect on the magnitude of impedance, while the general trend is not affected. Generally speaking, there was no significant effect of either the grip or push force on impedance at low frequencies. For the middle range frequencies, the effect of push and grip forces was the most pronounced, in which impedance increased with the increase of both push and grip forces. In this region, there exist the resonant frequencies of impedance of the hand arm system. The largest difference in impedance magnitude (for the whole range of excitation frequency) was found to be 245, 400, and 350 Ns/m for vibration excitations of 0.01, 0.005, 0.001 m/s respectively. It is worth noting that for the 0.001 m/s excitation amplitude, the maxima magnitude of impedance at the middle range frequency was, however, almost as high as the impedance magnitude at 1000 Hz which is the frequency in which impedance reaches its highest value relative to all other frequencies while this is not true for the excitations amplitudes of 0.01 and 0.005 m/s i.e. the maxima at the middle range frequency is much lower than the heights magnitude at 1000 Hz. At high frequencies, there was slight increase in impedance with the increase of push and grip forces and the amount of increase were found to be more significant for lower vibration amplitudes.

Figures 27, 28, and 29 show impedance curves in which the sum of the grip and push forces were kept equal to a constant number such as 75 N or 50 N, e.g. push=25 N and grip=50 N and vice versa. Comparing these curves revealed that the increase of grip force has more influence on increasing impedance than the increase of push force. Therefore it
can be concluded that the effect of the grip force on impedance dominates the effect of the push force.

Figure 27. Impedance magnitude and phase for: 0.01 m/s, P+G=75

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Figure 28. Impedance magnitude and phase for: 0.005 m/s, P+G=75
Figure 29. Impedance magnitude and phase for: 0.001 m/s, P+G=75
Effect of vibration amplitude

Comparing Figures 24, 25, and 26 revealed that impedance is not affected significantly by the change of excitation amplitude at low and high frequencies. However, there was a significant effect of the excitation amplitude on impedance at the mid range of frequency in which it was found that impedance increases with the decrease of excitation amplitude from around 30 to 70 Hz; and visa versa from about 70 to 200 Hz. For example, figure 30 shows a comparison of the impedance magnitude and phase for the three different excitation amplitudes used in this study for a grip force of 25 N and push force of 50 N.
Figure 30  Impedance magnitude and phase for: P50, G25: 0.01, 0.005, 0.001 m/s
Further more, it can be stated that the impedance of the hand-arm system is non-linear, since an increase of the stimulus amplitude should lead to a corresponding increase in the force component provided that the mechanical properties of the mechanical system are linear within the amplitude range in question, which is not the case as discussed earlier. For more detailed curves of the previously discussed factors, the reader is advised to refer to appendix A.

Effect of test subjects weight

Test subjects were divided into two different groups, each consisting of five subjects, according to weight. The average weight of the first group was equal to 156 lb, and the average weight of the second group was equal to 195 lb. Figures 31, 32, and 33 show the impedance magnitude and phase for a push force of 50 N and a grip force of 25 N for all three excitation amplitudes for the two test subjects’ groups. The curves show that impedance increases with the increase of test subject’s weight at the low and mid frequency ranges (up to 200 Hz), and is almost the same at frequencies above around 200 Hz.

The increase of impedance with the increase of test subjects weights at low and mid frequencies while not being significantly affected at high frequencies can be explained from the fact that, at low frequencies, vibration is transmitted up to the shoulder of the test subject, while at high frequencies vibration is localized at the tissues of the hand of the test subject. Thus, at low frequencies, the total mass responding to vibration increases leading to the increase of impedance as can be shown from Newton’s law and the
definition of impedance. For all other combinations of push and grip forces, almost the same trend was observed.

Figure 31 Impedance magnitude and phase for: 0.01 m/s, P50, G25: 156 and 195 lb groups

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Figure 32. Impedance magnitude and phase for: 0.005 m/s, P50, G25: 156 and 195 lb groups
Figure 33. Impedance magnitude and phase for: 0.001 m/s, P50, G25: 156 and 195 lb groups

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The curves showing the comparison of the effect of test subject weight on impedance for all other combinations of push and grip forces are shown in appendix A.

Effect of mass cancellation

Figure 34, shows impedance when the handle mass is not subtracted at all and when the handle mass is subtracted using two different methods; electronically and mathematically using equation number 15 presented earlier in the theory section:

\[ EM_{\text{hand}}(\omega) = [EM_{\text{total}}(\omega) - EM_{\text{handle}}(\omega)] \]

The curve shows the importance of subtracting the handle mass, since impedance results without the mass subtraction is out of the expected impedance results. This is, of course, is due to the influence of the handle’s impedance which was discussed in equation form in the theory. As shown in the figure, impedance difference between the curves of impedance when the handle mass is subtracted and when it is not subtracted is insignificant at low frequencies (below 70 Hz), while the difference is much more larger at high frequencies (above 70 Hz), which means that the handle mass effect is more dominant at the high frequency range, and thus more care should be taken in the accuracy of subtracting the handle mass at such high frequencies.

It should be noted that the electronic subtraction circuit that was used in this study can be used to subtract the handle mass at only a single frequency and not at the whole range of frequency in use. The impedance curve shown in Figure 34 for the electronic mass subtraction method was produced as the circuit was adjusted to cancel the mass at a frequency equal to 1000 Hz. As can be seen from the figure, the two impedance curves
for which the mass was cancelled electronically and mathematically coincide at this
frequency, 1000 Hz.

Figure 34 Impedance magnitude and phase for: Different methods of mass cancellation
This means that using the electronic mass subtraction method is accurate only at the frequency chosen for the mass cancellation to be done at, while at all other frequencies, it is clear that the electronic method is not reliable. Thus, it can be said that the use of the electronic method of mass subtraction is not recommended for use if a random source of vibration is used.

Figure 34 shows also that the subtraction circuit is causing some phase problems (at frequencies above 40 Hz) which makes its use not recommended. The cause of this phase shift or error may be due impedance mismatching between the circuit and the reminder of the system. If the electronic method of mass subtraction is wished to be used, a more advanced circuit design may be needed and care should be taken in making sure that the circuit and the system is in good mach.
CHAPTER 7

CONCLUSION AND RECOMMENDATION

The outcome of this investigation clearly shows that the mechanical impedance of the human hand-arm system is not only dependent on the frequency but also on the conditions of the vibration exposure, at least with respect to push and grip forces, vibration amplitude, test subjects weights, and method of mass cancellation. The following points summarize the outcomes of this study.

1) Impedance of the hand arm system behaves in a non-linear way. This is due to the presence of sub-resonant frequencies and due to the interchangeable decrease or increase of impedance with the decrease of vibration amplitude.

2) The hand-arm system shows high damping characteristics especially at the mid and high frequency ranges (above 40 Hz).

3) Vibration tends to get more and more localized near the hand with the increase of frequency.

4) High frequency vibration could be the main reason for the tissues and cells destruction due to the associated high-energy absorption at these frequencies.

5) The increase of push and grip forces results in a significant increase of impedance at the mid range frequency (30-250 Hz). At high frequency range (above 250) there exist a slight increase of impedance with the increase of either push or grip force. At the low frequency range (below 30 Hz) the effect of grip and push forces...
are insignificant. It was found that the effect of grip force dominates the effect of push force.

6) Impedance increases with the decrease of vibration amplitude between around 30-70 Hz and visa versa between around 70-200 Hz. At low and high frequencies (below 30 Hz and above 200 Hz) the effect of vibration amplitude is almost insignificant.

7) Impedance was found to increase with the increase of test subjects weights up to a frequency of 200 Hz (for the 0.01 and 0.005 m/s amplitudes) and up to only 15 Hz (for the 0.001 m/s amplitude). At higher frequencies, the effect of test subject’s weight was found to be insignificant.

8) The accuracy of the results was noticed to decrease with the decrease of vibration amplitude.

9) Electronic mass subtraction method used in this study was found to cause significant phase shift at frequencies above 40 Hz. It was found also that this method is not suitable for use with a random source of vibration.

Comparison of results obtained in this investigation with studies carried out by other researchers is difficult if not impossible. This is due to the fact that investigators in general have used either different measuring techniques or other experimental conditions such as vibration amplitudes, hand-arm postures, and grip and push forces.

Some of the recommendations based on the outcome of this investigation include the following:

1) It is recommending changing the way the handle was used to be attached to the force transducer and to the shaker. This is needed because it was found that the
use of only one bolt for this attachment is not enough and may cause some undesired non-axial vibration. As a suggestion, two force transducers may be used in which the average signal of them could be measured. This configuration will allow the use of two bolts for the attachment which will result in the reduction of the looseness effects.

2) If the electronic method of mass subtraction is wished to be used with a random source of vibration, it is recommended that a new circuit design be implemented that has the capability of subtracting the handle mass over the whole range of frequency understudy, if possible. Impedance matching as well as other electronic considerations should be checked also in order to eliminate the phase shift produced by the circuit.

3) The strain indicator boxes used in this study for the grip and push forces display was not 100% accurate, although they were still accurate enough. However, if more accurate display of the push and grip forces, a computerized display system of these forces should be used. The use of static force transducers may also be more suitable than the use of strain gages.
REFERENCES


point" ISO 10068, International Organization for Standardization, Geneva, Switzerland.


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APPENDIX A

Magnitude and phase of mechanical impedance test results

Hints:

P: Stands for push force in Newton (N)

G: Stands for grip force in Newton (N)
Part 1

Comparison of impedance magnitude and phase for different combinations of grip and push forces for vibration amplitude of 0.01 m/s.
Figure 35  Impedance magnitude and phase for: 0.01 m/s, all P, G25
Figure 36  Impedance magnitude and phase for: 0.01 m/s, all P, G50
Figure 37. Impedance magnitude and phase for: 0.01 m/s, all G, P0
Figure 38 Impedance magnitude and phase for: 0.01 m/s, all G, P25
Figure 39. Impedance magnitude and phase for: 0.01 m/s, all G, P50
Figure 40. Impedance magnitude and phase for: 0.01 m/s, all G, P75
Figure 41 Impedance magnitude and phase for: 0.01 m/s, P+G=75
Part 2

Comparison of impedance magnitude and phase for different combinations of grip and push forces for vibration amplitude of 0.005 m/s.
Figure 42. Impedance magnitude and phase for: 0.005 m/s, all P, G25
Figure 43. Impedance magnitude and phase for: 0.005 m/s, all P, G50
Figure 44. Impedance magnitude and phase for: 0.005 m/s, all G, P0
Figure 45. Impedance magnitude and phase for: 0.005 m/s, all G, P25
Figure 46. Impedance magnitude and phase for: 0.005 m/s, all G, P50
Figure 47. Impedance magnitude and phase for: 0.005 m/s, all G, P75
Figure 48. Impedance magnitude and phase for: 0.005 m/s, P+G=75

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Part 3

Comparison of impedance magnitude and phase for different combinations of grip and push forces for vibration amplitude of 0.001 m/s.
Figure 49. Impedance magnitude and phase for: 0.001 m/s, all P, G25
Figure 50. Impedance magnitude and phase for: 0.001 m/s, all P, G50
Figure 51. Impedance magnitude and phase for: 0.001 m/s, all G, P0
Figure 52. Impedance magnitude and phase for: 0.001 m/s, all G, P25
Figure 53. Impedance magnitude and phase for: 0.001 m/s, all G, P50
Figure 54. Impedance magnitude and phase for: 0.001 m/s, all G, P75
Figure 55. Impedance magnitude and phase for: 0.001 m/s, P+G=75
Part 4

Comparison of impedance magnitude and phase results for the three vibration amplitudes used. Comparisons are shown for all different combinations of push and grip forces.
Figure 56. Impedance magnitude and phase for: P0, G25: 0.01, 0.005, 0.001 m/s
Figure 57. Impedance magnitude and phase for: P0, G50: 0.01, 0.005, 0.001 m/s
Figure 58. Impedance magnitude and phase for: P25, G25: 0.01, 0.005, 0.001 m/s
Figure 59. Impedance magnitude and phase for: P25, G50: 0.01, 0.005, 0.001 m/s
Figure 60. Impedance magnitude and phase for: P50, G25: 0.01, 0.005, 0.001 m/s
Figure 61. Impedance magnitude and phase for: P50, G50: 0.01, 0.005, 0.001 m/s

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Figure 62. Impedance magnitude and phase for: P75, G25: 0.01, 0.005, 0.001 m/s
Figure 63. Impedance magnitude and phase for: P75, G50: 0.01, 0.005, 0.001 m/s
Part 5

Comparison of impedance magnitude and phase for the 156 lb and 195 lb average weight test subjects groups. Comparisons are shown for all different combinations of push and grip forces when vibration amplitude of 0.01 m/s was used.
Figure 64. Impedance magnitude and phase for: P0, G25: 156 and 195 lb groups: 0.01 m/s
Figure 65. Impedance magnitude and phase for: P0, G50: 156 and 195 lb groups: 0.01 m/s
Figure 66. Impedance magnitude and phase for: P25, G25: 156 and 195 lb groups: 0.01 m/s
Figure 67. Impedance magnitude and phase for: P25, G50: 156 and 195 lb groups: 0.01 m/s
Figure 68. Impedance magnitude and phase for: P50, G25: 156 and 195 lb groups: 0.01 m/s
Figure 69. Impedance magnitude and phase for: P50, G50: 156 and 195 lb groups: 0.01 m/s

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Figure 70. Impedance magnitude and phase for: P75, G25: 156 and 195 lb groups: 0.01 m/s
Figure 71. Impedance magnitude and phase for: P75, G50: 156 and 195 lb groups: 0.01 m/s
Part 6

Comparison of impedance magnitude and phase for the 156 lb and 195 lb average weight test subjects groups. Comparisons are shown for all different combinations of push and grip forces when vibration amplitude of 0.005 m/s was used.
Figure 72. Impedance magnitude and phase for: P0, G25: 156 and 195 lb groups: 0.005 m/s
Figure 73. Impedance magnitude and phase for: P0, G50: 156 and 195 lb groups: 0.005 m/s
Figure 74. Impedance magnitude and phase for: P25, G25: 156 and 195 lb groups: 0.005 m/s
Figure 75. Impedance magnitude and phase for: P25, G50: 156 and 195 lb groups: 0.005 m/s
Figure 76. Impedance magnitude and phase for: P50, G25: 156 and 195 lb groups: 0.005 m/s
Figure 77. Impedance magnitude and phase for: P50, G50: 156 and 195 lb groups: 0.005 m/s
Figure 78. Impedance magnitude and phase for: P75, G25: 156 and 195 lb groups: 0.005 m/s

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Figure 79. Impedance magnitude and phase for: P75, G50: 156 and 195 lb groups: 0.005 m/s
Comparison of impedance magnitude and phase for the 156 lb and 195 lb average weight test subjects groups. Comparisons are shown for all different combinations of push and grip forces when vibration amplitude of 0.001 m/s was used.
Figure 80. Impedance magnitude and phase for: P0, G25: 156 and 195 lb groups: 0.001 m/s
Figure 81. Impedance magnitude and phase for: P0, G50: 156 and 195 lb groups: 0.001 m/s

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Figure 82. Impedance magnitude and phase for: P25, G25: 156 and 195 lb groups: 0.001 m/s
Figure 83. Impedance magnitude and phase for: P25, G50: 156 and 195 lb groups: 0.001 m/s
Figure 84. Impedance magnitude and phase for: P50, G25: 156 and 195 lb groups: 0.001 m/s
Figure 85. Impedance magnitude and phase for: P50, G50: 156 and 195 lb groups: 0.001 m/s
Figure 86. Impedance magnitude and phase for: P75, G25: 156 and 195 lb groups: 0.001 m/s
Figure 87. Impedance magnitude and phase for: P75, G50: 156 and 195 lb groups: 0.001 m/s

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