HAND-ARM VIBRATION: A REVIEW OF 3 YEARS' RESEARCH*

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ABSTRACT

A 3-year study investigating such parameters as the nature and influence of the transmission of vibratory energy from a hand tool to an operator's hand; the attendant vibratory acceleration levels and the transmissibility from hand tool to various locations on the operator's hand and arm; the factors influencing an individual's subjective response to hand-arm vibration; and the physiological mechanisms involved with regard to subjective response to vibration have revealed, in part, the following:

- *—The mechanical and subjective response characteristics of individuals to hand vibration were a function of the manner of clasping the vibratory tool handle and the orientation of the vibration relative to the hand.*
- *—The vibration response of the hand was indicative of only local response characteristics of the hand and fingers.*
- *—Attenuation of vibration as it proceeded up the arm occurred in the tissue adjacent to bone and not the bone itself; similarly, there was little attenuation across the joints.*
- *—The results of subjective response tests indicate that Ruffini endings, joint capsules, and Meissner's corpuscles were responsible for subjective response to low frequency (≤ 100 Hz) discrete-frequency hand-induced vibration, whereas Merkel's discs, Ruffini endings, and pacinian corpuscles were responsible for subjective responses above 100 Hz (discrete-frequency vibration). Broad band vibration was subjectively determined mainly from the response characteristics of tonic receptors.*

Salient findings indicate a questionable credibility with regard to using subjective response data for the purpose of establishing hazardous hand-vibration criteria. It can also be inferred from the results that high frequency vibration (above 100 Hz) is responsible, in part, for the destructive effects associated with vibration syndrome.

INTRODUCTION

In recent years, several investigators have revealed a relationship between various vascular-muscular disorders and vibration induced into the hand.[1-4] Although the most common of these disorders is Raynaud's phenomenon or vibration induced white finger (VWF), there is a recent trend to classify all of the disorders associated with hand-induced vibration as "the vibration syndrome."[2] Although there is increasingly more information available on this topic, little solid evidence is available establishing the exact nature of the relationship that exists between vibration directed into the hands and any of the disorders associated with the vibration syndrome.

Several researchers have investigated the subjective response of individuals to hand-induced vibration. The results of this research have been presented in the form of equal sensation contours similar to equal loudness contours for hearing, threshold and annoyance levels, and proposed hazardous-vibration exposure criteria for vibration directed into the hand.[5-18] Similarly, information that describes the mechanical response characteristics of the hand and arm to vibration directed into the hand has been presented in the form of the measured driving point mechanical impedance of the hand (i.e., measured vibration response of the hand due to a driving force applied to the hand). Initial analytical mechanical models of the hand and arm and the measured transmissibility (i.e., measured vibration response at specified locations on the hand and arm due to a vibration input to the hand) relative to different locations on the hand and arm have been developed.[18-25] The information from the above studies has been very valuable in gaining an understanding of the subjective and mechanical response characteristics of individuals to vibration directed into the hand. The usefulness of this

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information has been seriously limited, however, by the inability to correlate the results that have been presented by different researchers. Inconsistencies and differences in experimental techniques used by different investigators and the lack of accurate information with regard to human test populations used for the various studies have added to the inability to correlate the results of the different investigators.

In recent years there has been a strong effort by some organizations to formulate and enact hazardous-hand-vibration criteria with regard to allowable vibration levels and exposure times to these levels.[6,7,9,26] There has been little national and international acceptance of any of the proposed hand-vibration criteria. The reasons for this appear to be two-fold. First, more definitive information is needed that more accurately describes the mechanical interaction occurring between a tool operator's hand and the vibrating handle he clasps, the nature of the transfer of vibration energy between a vibrating tool handle and the operator's hand, and how this transfer of energy affects the operator's response to hand-induced vibration. Second, information is needed clearly indicating the vibration levels and the exposure times to these levels that are necessary to cause the onset of the different vascular-muscular disorders associated with the vibration syndrome.

As a result of the need for the above information before any meaningful hazardous-hand-vibration exposure criteria can be established, the National Institute for Occupational Safety and Health has sponsored an initial 3-year study aimed at obtaining some of the above information. The specific questions that this study has answered and that will be discussed are

1. What is the nature of the transmission of vibration energy from a vibrating tool handle to the operator's hand? What factors influence and to what extent do these factors affect this transfer of energy?
2. What vibration levels relative to the vibration levels incident upon the hand are transmitted to other specified locations on the hand and arm? What are the phase relations between the incident vibration and the vibration measured at other locations?
3. What factors influence an individual's subjective response to hand-induced vibration? What physiological mechanisms are involved with regard to an individual's subjective response to vibration directed into the hand?

This presentation summarizes and discusses the implications of the information that has been obtained concerning these questions. More detailed discussions about this information and the experimental procedures used to obtain it are presented in References 27 through 30.

TEST PARAMETERS

Work completed by Reynolds and Soedel, Reynolds and Jokel, and others during this study indicated that there are several variables that influence an individual's mechanical and subjective response to hand-induced vibration.[18,23-25,27-31] Griffin, who presented a list of these parameters, separated them into extrinsic (characteristic of the vibration input) and intrinsic (characteristic of the body) variables.[8] The extrinsic variables were frequency of vibration, amplitude of vibration, time history of vibration, direction of vibration, type of grip used to clasp a vibrating handle, tightness of grip, and the effects of clothing, etc. The intrinsic variables were body size, body posture, and muscle tension. Care was exercised during this study to monitor and determine the effects these variables had upon an individual's response characteristics to hand-induced vibration.

Brief discussions are presented relative to each of the above variables.

Extrinsic Variables

Frequency, Amplitude, and Time History of Vibration Signal

Most investigators who have conducted research in the area of hand-arm vibration have found that the response characteristics of the hand and arm to vibration directed into the hand was a function of both the frequency and amplitude of the vibration signal. Also evidence has been presented that indicates that in some cases the vibration response characteristics of the hand and arm differ, depending upon whether the signal is a discrete frequency signal or a signal consisting of several frequencies. Thus, tests were conducted using both discrete frequencies and ⅓-octave-band broad band frequencies. Relative to the time history of the vibration signals, all of the signals used were steady state discrete or ⅓-octave-band broad band signals. The frequency range used varied between 5 Hz and 1,000 Hz. These limits were used because they represented the limits of the instrumentation and test apparatus used for most of the tests.

Direction of Vibration

Three mutually perpendicular directions of vibration were investigated (Figure 1): the vertical direction in which the handle was vibrated up and down in a vertical plane parallel to the subject's torso, the horizontal direction in which the handle was vibrated in a horizontal plane perpendicular to and directed towards the torso, and the axial direction in which the handle was vibrated from right to left in a horizontal plane perpendicular to the torso. For the tests that were conducted, the relative spatial orientation of the handle with respect to the subject was kept as constant as possible for all three directions.

Grip Type and Grip Tightness

The grip type refers to the area of the hand in which the vibrating handle was clasped. Two grip types were used. One was the finger grip in which the handle was clasped, using only the fingers (Figure 2a). The other was the palm grip in which the handle was clasped with the fleshy part of the palm (Figure

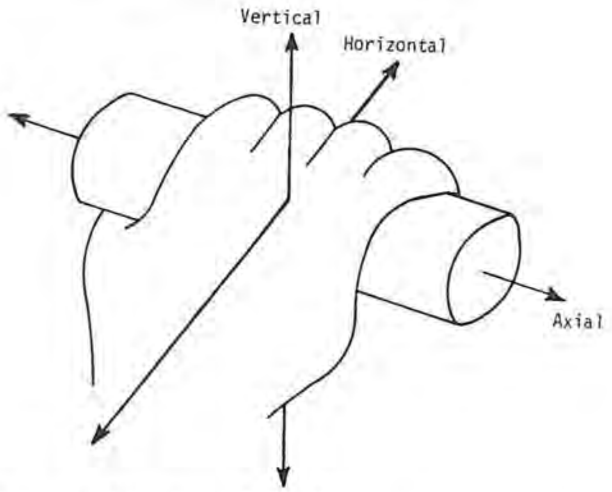

Figure 1. Directions of vibration.

2b). The grip tightness refers to the force with which the handle was squeezed. Two grip forces were used: 2 lb_f and 8 lb_f. The 2 lb_f grip was a loose grip and the 8 lb_f grip corresponded to holding the handle tightly. These forces were monitored by using a handle that had a horizontal slit and a calibrated strain gauge bridge as shown in Figure 3. The handle was always mounted such that the slits remained in the horizontal plane, regardless of the direction of vibration (Figure 4). For the tests that were conducted during this study, a grip configuration was specified by first stating the grip tightness and then the grip type. Four grip configurations were investigated: 2 lb_f finger grip, 8 lb_f finger grip, 2 lb_f palm grip, and 8 lb_f palm grip.

Effects of Clothing

Clothing can affect the response characteristics of the body by acting as vibration damping. To minimize any possible effects of clothing, all subjects were dressed in street clothes, without jackets, and were asked to remove any jewelry, such as rings and watches, before being tested.

Intrinsic Variables

The effects of the intrinsic variables upon the vibration response of individuals to hand-induced vibration have been shown by past investigators to be of minor importance.[18,23,24,31] The results of this and past studies have indicated that it has not been possible to identify any meaningful trends relative to the effects of body size, posture, and muscle tension (with the exception of muscle tension in the hand due to grip tightness) upon either an individual's subjective or mechanical response to hand-induced vibration. However, to minimize the possible effects of these variables upon the results discussed herein, the test subjects were always seated such that the forearm was horizontal relative to the vibrating handle. They were instructed to relax the muscles in their arm and to apply force to the handle by only squeezing it with the specified grip tightness.

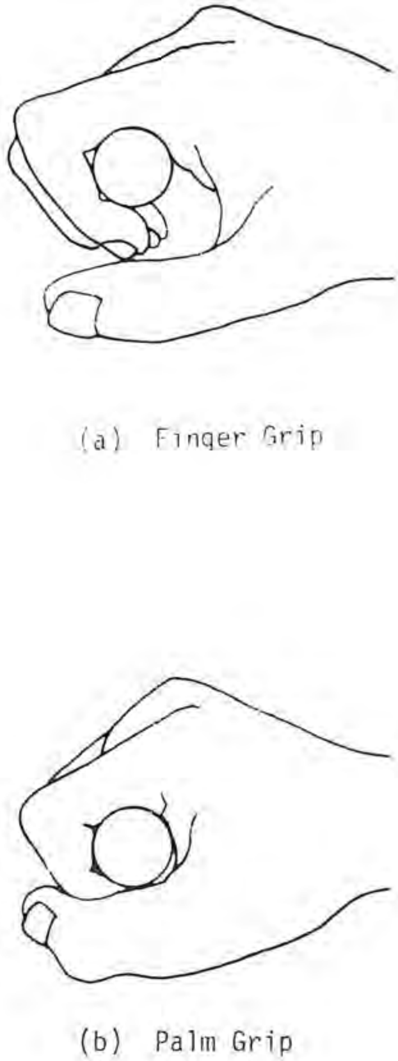

Figure 2. Types of grips.

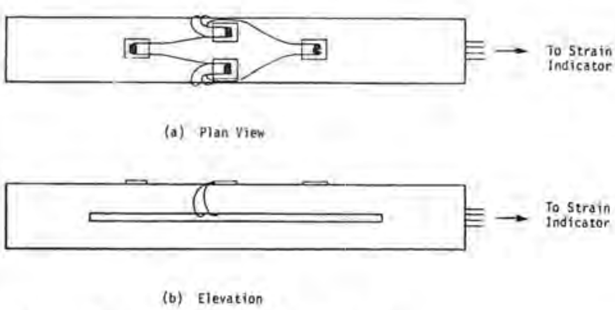

Figure 3. Strain gauge arrangement.

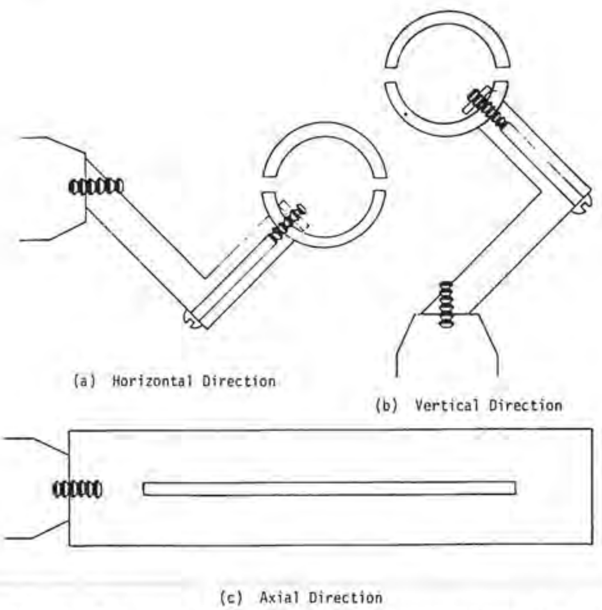

Figure 4. Cross section of handle connections for different directions of vibration.

TEST PROCEDURES

Four different series of tests were conducted during this investigation: (1) driving point mechanical impedance tests, (2) transmissibility tests, (3) threshold and annoyance tests, and (4) equal sensation tests. Data similar to that obtained from the above tests were available from previous investigators. However, because of differences in experimental procedures used by individual investigators to obtain these data, it was extremely difficult to correlate the available information in the above four areas. Therefore, it was decided to conduct tests in all of these areas using the same instrumentation, compatible test procedures, and as nearly as possible, the same test populations.

Work completed during this and past investigations has shown that the grip type and grip tightness a person uses to clasp a vibrating handle affects the individual's subjective and mechanical response characteristics to vibration. However, these parameters have been the least controlled parameters in past studies. This lack of control has made it extremely difficult to correlate test results from different investigators. Consequently, the grip type and tightness or the grip configuration were closely monitored and controlled during the four series of tests indicated above. The four grip configurations that were described in the previous section were used for each series of tests.

For all of the tests, vibration was directed into the hand by means of a "T bar" handle attached to an electromechanical shaker (Figure 4). A mechanical impedance transducer was placed between the shaker and the handle. With this transducer and other instrumentation, it was possible to measure the force directed into the hand and the acceleration at the point where the handle contacted the hand. Eight test subjects were used for all of the tests except the transmissibility tests. For this series of tests, only five test subjects were used.

A brief description of the test procedures used for each series of tests will be discussed individually. A more complete description of the test procedures and the instrumentation used for the tests discussed below can be found in References 27 through 30.

Driving Point Mechanical Impedance Tests

For the mechanical impedance tests, each test subject, using one of the specified grip configurations, was instructed to clasp the vibrating handle. The vibration signal that was directed into the hand was continuously varied from 5 Hz to 1,000 Hz. The acceleration and force signals from the impedance head were directed to a set of instruments manufactured by the Spectral Dynamics Corporation. The displacement mobility (displacement/force) and the phase between the displacement and force signals were directly obtained from these instruments and plotted on an X-YY′ recorder as a function of frequency. Figure 5 shows a plot of the individual test results from the test subjects used for one series of tests. Once a series of tests for a specified direction and grip configuration had been completed and the data plotted on a single graph, curves that were biased towards the heaviest concentration of data were drawn through

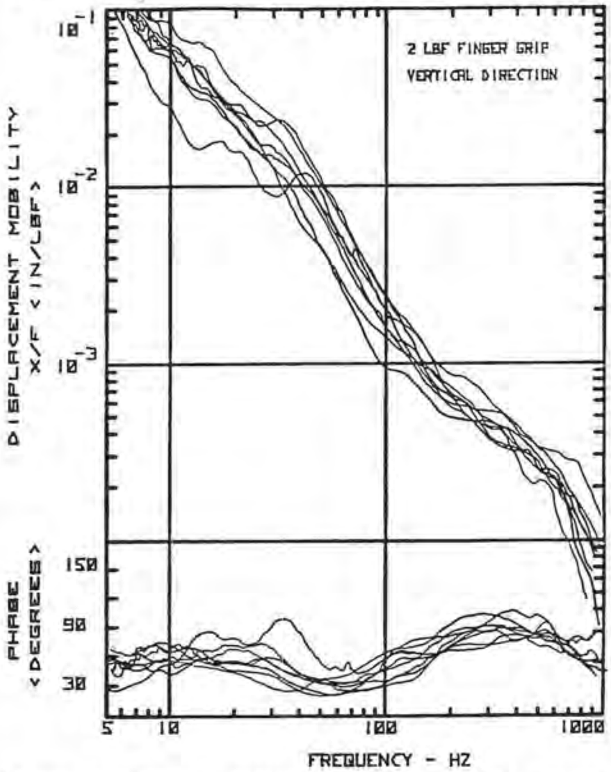

Figure 5. Typical displacement mobility data set for eight test subjects.

both the individual displacement mobility and phase curves (Figure 6). A series of tests was conducted for each of the three directions and the four grip configurations discussed in the section on parameters.

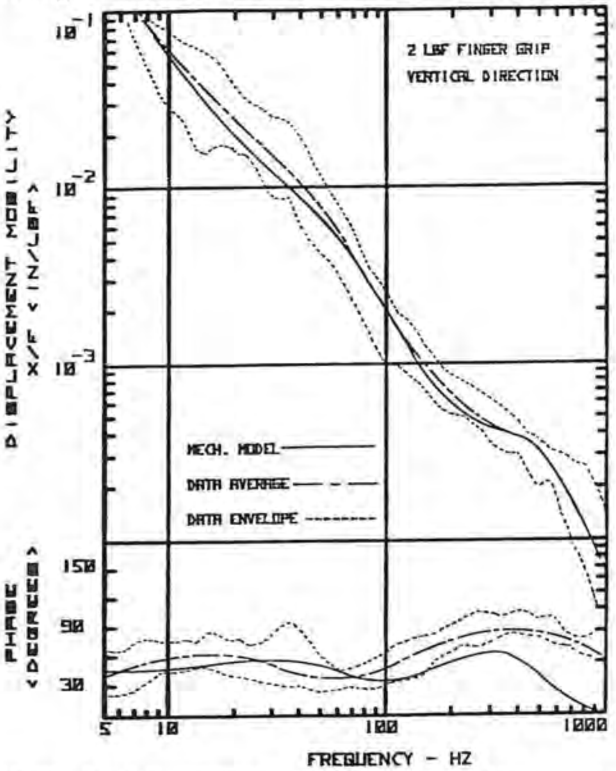

Figure 6. Data envelope, response of analytical model, and representative curve for data shown in Figure 5.

Transmissibility Tests

For the transmissibility tests, subminiature accelerometers were attached to the locations indicated in Figure 7. The accelerometers were attached to the skin with stiff, double-faced carpet tape placed between the accelerometer and the skin at locations where little skin exists over the bone, such as at joints. The accelerometers were then securely pressed against the skin by means of surgeon's tape placed over the accelerometer with a piece of soft foam between the tape and the accelerometer. Tests were conducted in which the acceleration signals from an individual accelerometer at one of the indicated locations on Figure 7 and from the impedance head located between the "T bar" handle and the electromechanical shaker were directed into the Spectral Dynamics instruments. The amplitudes of the acceleration levels at the specified location on the hand or arm divided by the corresponding acceleration levels of the impedance head were plotted as a function of frequency on an X-YY′ recorder. For some tests the phase angles between the two measured acceleration signals were also plotted on an X-YY′ recorder. As was the case with the driving point mechanical impedance test, the vibration signal directed into the hand was continuously varied from 5 Hz to 1,000 Hz. After a series of tests was completed, all of the individual transmissibility curves from each test subject were plotted on a single graph and a line representing the average transmissibility as a function of frequency was drawn through the plotted data in the same manner as was used for the impedance data. All four grip configurations were investigated in each of the three directions of vibration. For the vertical direction, subminiature piezoresistive accelerometers were located at positions 1, 3, 4, 5, 6, 7, and 8. For the horizontal direction they were located at positions 2, 5, 7, and 8. For the axial direction they were located at positions 2, 4, 5, 7, and 8. The accelerometers were always oriented such that the axis of sensitivity of the accelerometers corresponded to the direction of vibration.

Threshold and Annoyance Tests

For the threshold and annoyance tests, the test subject's hand was excited by either a single discrete frequency or a single ⅓-octave-band broad band vibration signal. The subject was instructed to clasp the handle with one of the four specified grip con-

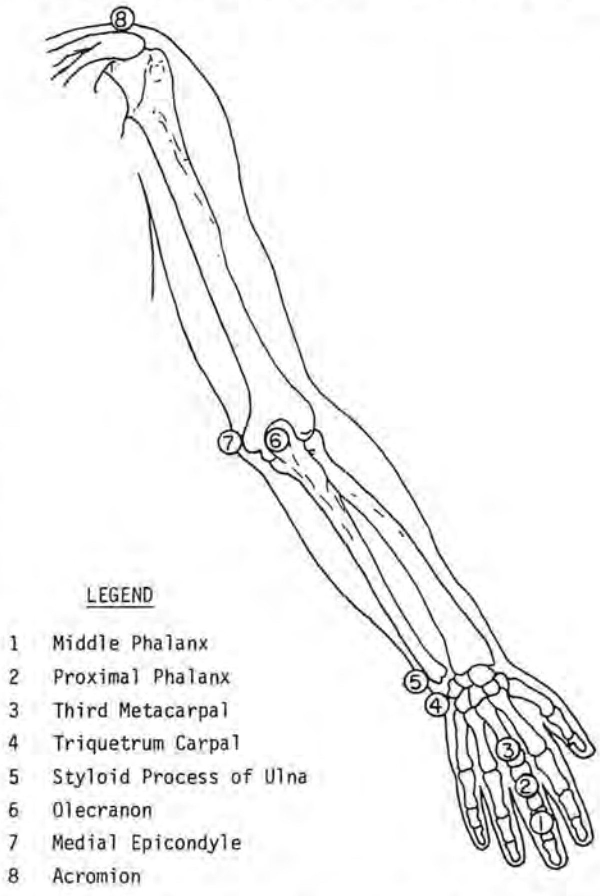

Figure 7. Location of accelerometers for transmissibility tests.

figurations. For the threshold tests, he was asked to adjust the amplitude of the vibration signal until he determined that the sensation produced by the vibration was just barely perceptible. For the annoyance tests, he was instructed to adjust the amplitude of the vibration signal until he determined that the sensation due to the vibration was such that he would not want to clasp the handle for an extended period of time. For the discrete frequency tests, the vibration frequencies were the ⅓-octave-band center frequencies between 25 Hz and 1,000 Hz. The ⅓-octave-band signals were obtained by passing white noise through ⅓-octave-band filters whose center frequencies ranged from 25 Hz to 630 Hz. The test subjects were asked to specify the threshold and annoyance levels for each individual discrete or ⅓-octave-band signal. Once all the subjects had been tested for one test condition, the resulting data for the threshold and annoyance tests were plotted on a single graph and the threshold and annoyance curves, which represented the average values of the data, were drawn through the plotted data (Figure 8). All four grip configurations were investigated in each of the three directions. Both threshold and annoyance curves were obtained for the discrete frequency tests. Only the threshold curves were obtained for the ⅓-octave-band broad band tests. It was not possible to deliver enough power to the electromechanical shaker to produce annoyance for the ⅓-octave-band broad band tests.

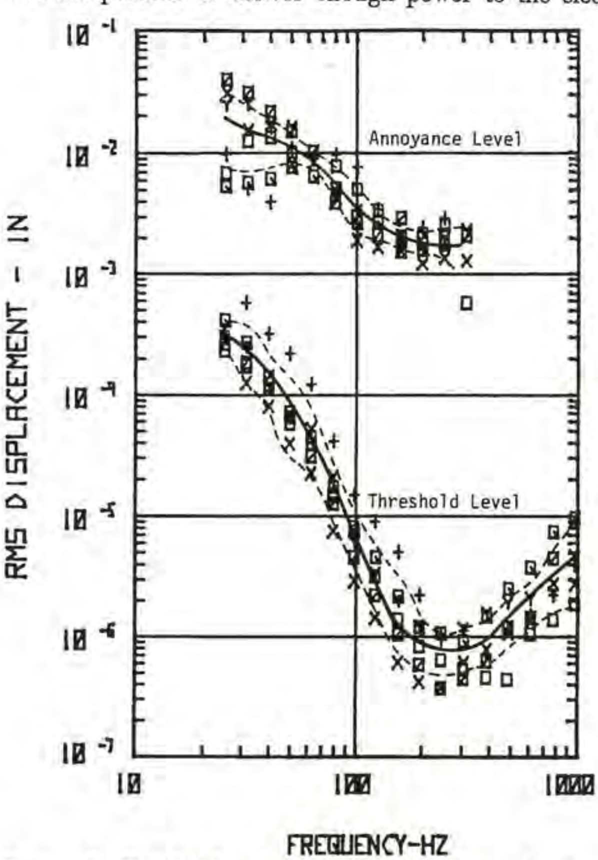

Figure 8. Threshold and annoyance level data of various subjects for discrete frequency vibration in the vertical direction; 8 lb., finger grip.

Equal Sensation Tests

The equal sensation tests were conducted to determine an individual's perception of vibration at specified frequencies relative to a reference vibration signal. For this series of tests, 100 Hz was determined to be an optimum reference frequency.[28] The reference vibration levels that were used were 0.1 g, 0.5 g, 1 g, and 5 g's. For a given series of tests, a grip configuration and a reference vibration level at the reference frequency were specified. The test subject was instructed to clasp the handle with the selected grip configuration. His hand was then vibrated at the reference frequency and vibration level. When he indicated, his hand was then excited by a test frequency signal. For the discrete frequency tests, the test frequency signals consisted of the ⅓-octave-band center frequencies between 16 Hz and 1,000 Hz. The test frequency signals used for the ⅓-octave-band broad band tests consisted of ⅓-octave bands, obtained by filtering random white noise between 25 Hz and 1,000 Hz. The test subject adjusted the test vibration signal until it produced the same perceived sensation as was produced by the reference vibration signal. Often it was necessary to switch from the reference frequency signal to the test frequency signal several times before the proper adjustments had been made. This procedure was repeated for all of the test frequencies and for all of the reference vibration levels. Once all of the tests subjects had been tested for a given set of tests conditions, the resulting data were plotted on a single graph and a curve that represented the average values of the data was drawn through the plotted data (Figure 8). All four grip configurations were investigated in each of the three directions.

MATHEMATICAL MODEL OF THE VIBRATION RESPONSE OF THE HAND AND ARM

Work completed by Abrams, Reynolds, Soedel, Jokel, and Suggs has demonstrated that the hand and arm can be modeled as a lumped parameter mass-excited vibration system.[20,23-25,27,31] Such a system is composed of a finite number of mass (m), stiffness (k), and damping (c) elements. The results of the impedance tests conducted during this investigation indicated that between the frequencies of 5 Hz and 1,000 Hz the hand could be modeled as a three-degree-of-freedom, mass-spring-damper system for vibration in each of the three directions (Figure 9). The force exciting the system in Figure 9 is directed into mass m_3. The functions $x_1(t)$, $x_2(t)$ and $x_3(t)$ represent the motions of masses m_1, m_2 and m_3, respectively.

Summing the forces acting on the three masses yields three coupled, second-order ordinary differential equations.

$$m_3 \ddot{x}_3(t) + c_3 \dot{x}(t) + k_3 x_3(t) - c_3 \dot{x}_2(t) - k_3 x_2(t) = f(t) \tag{1}$$

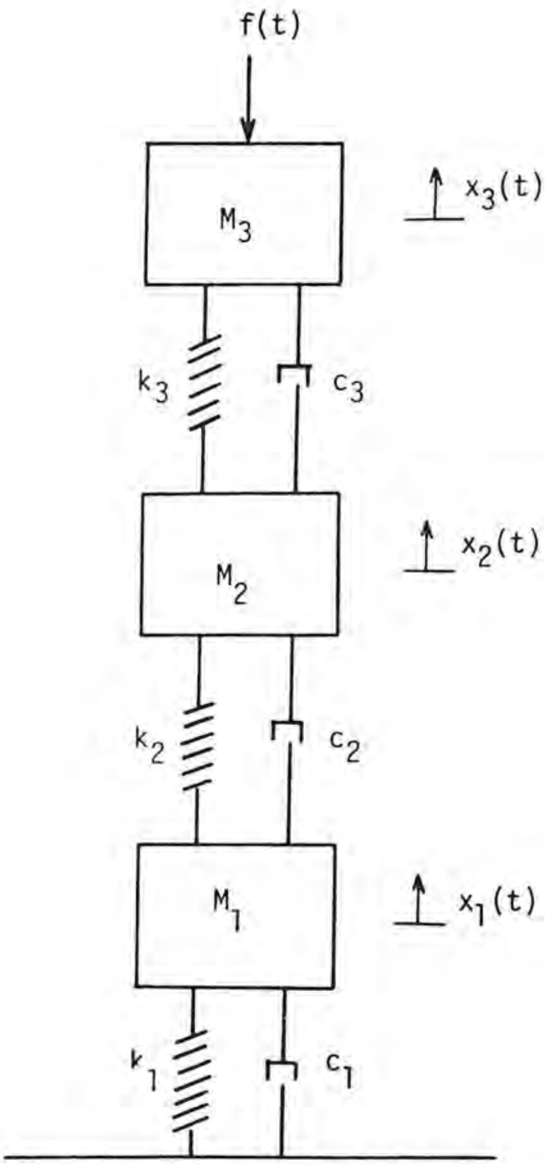

Figure 9. Conceptual schematic of three degree-of-freedom mass spring damper system.

$$m_2 \ddot{x}_2(t) + (c_2 + c_3)\dot{x}_2(t) + (k_2 + k_3)x_2(t) - c_2\dot{x}_1(t) - c_3\dot{x}_3(t) - k_2 x_1(t) - k_3 x_3(t) = 0 \quad (2)$$

$$m_1 \ddot{x}_1(t) + c_1\dot{x}_1(t) + k_1 x_1(t) - c_2\dot{x}_2(t) - k_2 x_2(t) = 0. \quad (3)$$

If $f(t)$ is assumed to be a complex exponential of the form

$$f(t) = F e^{j\omega t} \quad (4)$$

then $x_1(t)$, $x_2(t)$ and $x_3(t)$ can be written

$$x_1(t) = \bar{x}_1 e^{j\omega t} \qquad x_2(t) = \bar{x}_2 e^{j\omega t} \qquad x_3(t) = \bar{x}_3 e^{j\omega t}. \quad (5)$$

$\bar{x}_1$, $\bar{x}_2$ and $\bar{x}_3$ are complex amplitudes. Substituting equations (4) and (5) into equations (1) through (3) yields

$$-(k_3 + j\omega c_3)\bar{x}_2 + (k_3 - \omega^2 m_3 + j\omega c_3)\bar{x}_3 = F \quad (6)$$

$$-(k_2 + j\omega c_2)\bar{x}_1 + (k_2 + k_3 + j\omega(c_2 + c_3) - \omega^2 m_2)\bar{x}_2 - (k_3 + j\omega c_3)\bar{x}_3 = 0 \quad (7)$$

$$(k_1 + k_2 + j\omega(c_1 + c_2) - \omega^2 m_1)\bar{x}_1 - (k_2 + j\omega c_2)\bar{x}_2 = 0. \quad (8)$$

Equations (6) through (8) are linear simultaneous algebraic equations. Thus, Crammer's rule can be used to determine the expression for $\bar{x}_3$ or

$$\bar{x}_3 = \frac{\det A}{\det B} \quad (9)$$

where the det A is given by

$$\begin{vmatrix} (k_1 + k_2 + j\omega(c_1 + c_2) - \omega^2 m_1) & -(k_2 + j\omega c_2) & 0 \\ -(k_2 + j\omega c_2) & (k_2 + k_3 + j\omega(c_2 + c_3) - \omega^2 m_2) & 0 \\ 0 & -(k_3 + j\omega c_2) & F \end{vmatrix} \quad (10)$$

and where the det B is given by

$$\begin{vmatrix} (k_1 + k_2 + j\omega(c_1 + c_2) - \omega^2 m_1) & -(k_2 + j\omega c_2) & 0 \\ -(k_2 + j\omega c_2) & (k_2 + k_3 + j\omega(c_2 + c_3) - \omega^2 m_2) & -(k_3 + j\omega c_3) \\ 0 & -(k_3 + j\omega c_3) & (k_3 + j\omega c_3 - \omega^2 m_3) \end{vmatrix} \quad (11)$$

Expanding the determinates yields

$$\det A = (k_1 + k_2 - \omega^2 m_1 + j\omega(c_1 + c_2))(k_2 + k_3 - \omega^2 m_2 + j\omega(c_2 + c_3))F - F(k_2 + j\omega c_2)^2 \quad (12)$$

$$\det A = -(k_3 + j\omega c_3)^2(k_1 + k_2 - \omega^2 m_1 + j\omega(c_1 + c_2)) + (k_1 + k_2 - \omega^2 m_1 + j\omega(c_1 + c_2))(k_2 + k_3 - \omega^2 m_2 + j\omega(c_2 + c_3))(k_3 - \omega^2 m_3 + j\omega c_3) - (k_2 + j\omega c_2)^2(k_3 - \omega^2 m_3 + j\omega c_3). \quad (13)$$

To simplify the analysis of equation (9), the following substitutions were made

$$\frac{m_3}{m_2} = r_1 \qquad \frac{m_3}{m_1} = r_2 \quad (14)$$

$$\frac{k_1}{m_1} = \beta_1^2 \qquad \frac{k_2}{m_2} = \beta_2^2 \qquad \frac{k_3}{m_3} = \beta_3^2 \quad (15)$$

$$\frac{c_1}{2\sqrt{k_1 m_1}} = \zeta_1 \qquad \frac{c_2}{2\sqrt{k_2 m_2}} = \zeta_2 \qquad \frac{c_3}{2\sqrt{k_3 m_3}} = \zeta_3 \quad (16)$$

$$\frac{c_1}{m_1} = 2\zeta_1\beta_1 \qquad \frac{c_2}{m_2} = 2\zeta_2\beta_2 \qquad \frac{c_3}{m_3} = 2\zeta_3\beta_3 \quad (17)$$

The displacement mobility $\bar{x}_3/F$ for the three-degree-of-freedom system shown in Figure 9 was obtained by performing the operations indicated in equation (9) and then dividing the results by the force amplitude F. Thus, the displacement mobility was written

$$\frac{\tilde{x}_3}{F} = \frac{C}{D} \tag{18}$$

where

$$\begin{aligned} C = {} & (1/m_3)\ [\ \omega^4 - \omega^2\ [\ \beta_1^2 + (1+r_1/r_2)\ \beta_2^2 + \beta_3^2\ /\ r_1 \\ & + 4\ \beta_1\ \beta_3\ \zeta_1\ \zeta_3\ /\ r_1 + 4\ \beta_1\ \beta_2\ \zeta_1\ \zeta_2 + 4\ \beta_2\ \beta_3\ \zeta_2\ \zeta_3\ /\ r_2\ ] \\ & - j\ \omega\ [\ 2\ \beta_2\ \zeta_2\ \beta_1^2 + 2\ \beta_3\ \zeta_3\ \beta_1^2\ /\ r_1 + 2\ \beta_3\ \zeta_3\ \beta_2^2\ /\ r_2 \\ & + 2\ \beta_1\ \zeta_1\ \beta_2^2 + 2\ \beta_1\ \zeta_1\ \beta_3^2\ /\ r_1 + 2\ \beta_2\ \zeta_2\ \beta_3^2\ /\ r_2\ ] \\ & - j\ \omega^3\ [\ 2\ \beta_1\ \zeta_1 + (1+r_1/r_2)\ 2\ \beta_2\ \zeta_2 + 2\ \beta_3\ \zeta_3\ /\ r_1] \\ & + \beta_2^2\ \beta_1^2 + \beta_1^2\ \beta_3^2\ /\ r_1 + \beta_2^2\ \beta_3^2\ /\ r_2\ ] \end{aligned} \tag{19}$$

$$\begin{aligned} D = {} & -\ \omega^6 + j\ \omega^5\ [\ 2\ \zeta_1\ \beta_1 + 2\ \zeta_2\ \beta_2\ (1+r_1/r_2) \\ & + 2\ \zeta_3\ \beta_3\ /\ r_1\ ] + \omega^4\ [\ \beta_1^2 + \beta_2^2\ (1+r_1/r_2) \\ & + \beta_3^2\ /\ r_1 + 4\ \zeta_2\ \beta_2\ \zeta_1\ \beta_1 + 4\ \zeta_3\ \beta_3\ \zeta_1\ \beta_1\ /\ r_1 \\ & + 4\ \zeta_2\ \beta_2\ \zeta_3\ \beta_3\ /\ r_2 + 4\ \beta_3\ \zeta_3\ \zeta_1\ \beta_1 + \beta_3^2 \\ & + 4\ \zeta_2\ \beta_2\ \zeta_3\ \beta_3\ (1+r_1/r_2)\ ] - j\ \omega^3\ [\ 2\ \zeta_1\ \beta_1\ \beta_3^2 \\ & + 2\ \zeta_2\ \beta_2\ (\ \beta_1^2 + \beta_3^2\ /\ r_2) + 2\ \zeta_3\ \beta_3\ (\ \beta_1^2\ /\ r_1 + \beta_2^2\ /\ r_2\ ) \\ & + 2\ \zeta_1\ \beta_1\ (\ \beta_2^2 + \beta_3^2\ /\ r_1) + 2\ \beta_3\ \zeta_3\ \beta_1^2 \\ & + 2\ \beta_3\ \zeta_3\ \beta_2^2\ (1+r_1/r_2) + 8\ \zeta_3\ \beta_3\ \zeta_2\ \beta_2\ \zeta_1\ \beta_1 \\ & + 2\ \zeta_2\ \beta_2\ \beta_3^2\ (1+r_1/r_2)\ ] - \omega^2\ [\ \beta_1^2\ \beta_2^2 + \beta_3^2\ \beta_1^2\ /\ r_1 \\ & + \beta_3^2\ \beta_2^2\ /\ r_2 + \beta_3^2\ \beta_1^2 + 4\ \zeta_2\ \beta_2\ \zeta_3\ \beta_3^2\ /\ r_2 \\ & + 4\ \zeta_1\ \beta_1\ \beta_3\ \zeta_3\ \beta_2^2 + \beta_2^2\ \beta_3^2\ (1+r_1/r_2) + 4\ \zeta_2\ \beta_2\ \zeta_1\ \beta_1\ \beta_3^2\ ] \\ & + j\ \omega\ [\ 2\ \beta_3\ \zeta_3\ \beta_1^2\ \beta_2^2 + 2\ \zeta_2\ \beta_2\ \beta_3^2\ \beta_1^2 + 2\ \zeta_1\ \beta_1\ \beta_3^2\ \beta_2^2\ ] \\ & + \beta_1^2\ \beta_2^2\ \beta_3^2 \end{aligned} \tag{20}$$

Both C and D are complex quantities. Therefore, they were written

$$C = g + j\,h \tag{21}$$

$$D = q + j\,s \tag{22}$$

where

$$\begin{aligned} q = {} & -\ \omega^6 + \omega^4\ [\ \beta_1^2 + \beta_2^2\ (1+r_1/r_2) + \beta_3^2\ /\ r_1 \\ & + 4\ \zeta_2\ \beta_2\ \zeta_1\ \beta_1 + 4\ \zeta_3\ \beta_3\ \zeta_1\ \beta_1\ /\ r_1 + 4\ \zeta_2\ \beta_2\ \zeta_3\ \beta_3\ /\ r_2 \\ & + 4\ \beta_3\ \zeta_3\ \zeta_1\ \beta_1 + \beta_3^2 + 4\ \zeta_2\ \beta_2\ \zeta_3\ \beta_3\ (1+r_1/r_2)\ ] \\ & - \omega^2\ [\ \beta_1^2\ \beta_2^2 + \beta_3^2\ \beta_1^2\ /\ r_1 + \beta_3^2\ \beta_2^2\ /\ r_2 + \beta_3\ \beta_1^2 \\ & + 4\ \zeta_2\ \beta_2\ \zeta_3\ \beta_3^2\ /\ r_2 + 4\ \zeta_1\ \beta_1\ \beta_3\ \zeta_3\ \beta_2^2 + \beta_2^2\ \beta_3^2 \\ & (1+r_1/r_2) + 4\ \zeta_2\ \beta_2\ \zeta_1\ \beta_1\ \beta_3^2\ ] + \beta_1^2\ \beta_2^2\ \beta_3^2. \end{aligned} \tag{23}$$

$$\begin{aligned} s = {} & \omega^5\ [\ 2\ \zeta_1\ \beta_1 + 2\ \zeta_2\ \beta_2\ (1+r_1/r_2) \\ & + 2\ \zeta_3\ \beta_3\ /\ r_1\ ] - \omega^3\ [\ 2\ \zeta_1\ \beta_1\ \beta_3^2 \\ & + 2\ \zeta_2\ \beta_2\ (\ \beta_1^2 + \beta_3^2\ /\ r_2\ ) + 2\ \zeta_3\ \beta_3\ (\ \beta_1^2\ /\ r_1 \\ & + \beta_2^2\ /\ r_2\ ) + 2\ \zeta_1\ \beta_1\ (\ \beta_2^2 + \beta_3^2\ /\ r_1\ ) \\ & + 2\ \beta_3\ \zeta_3\ \beta_1^2 + 8\ \zeta_3\ \beta_3\ \zeta_2\ \beta_2\ \zeta_1\ \beta_1 \\ & + 2\ \beta_3\ \zeta_3\ \beta_2^2\ (1+r_1/r_2) + 2\ \zeta_2\ \beta_2\ \beta_3^2\ (1+r_1/r_2)] \\ & + \omega\ [\ 2\ \beta_3\ \zeta_3\ \beta_1^2\ \beta_2^2 + 2\ \zeta_2\ \beta_2\ \beta_3^2\ \beta_1^2 \\ & + 2\ \zeta_1\ \beta_1\ \beta_3^2\ \beta_2^2\ ] \end{aligned} \tag{24}$$

$$\begin{aligned} g = {} & \frac{1}{m_3}\ [\ \omega^4 - \omega^2\ [\ \beta_1^2 + (1+r_1/r_2)\ \beta_2^2 \\ & + \beta_3^2\ /\ r_1 + 4\ \beta_1\ \beta_3\ \zeta_1\ \zeta_3\ /\ r_1 + 4\ \beta_1\ \beta_2\ \zeta_2\ \zeta_1 \\ & + 4\ \beta_2\ \beta_3\ \zeta_2\ \zeta_3\ /\ r_2\ ] + \beta_2^2\ \beta_1^2 + \beta_1^2\ \beta_3^2\ /\ r_1 \\ & + \beta_2^2\ \beta_3^2\ /\ r_2\ ] \end{aligned} \tag{25}$$

$$\begin{aligned} h = {} & -1/m_3\ [\ \omega^3\ [\ 2\ \beta_1\ \zeta_1 + (1+r_1/r_2)\ 2\ \beta_2\ \zeta_2 \\ & + 2\ \beta_3\ \zeta_3\ /\ r_1\ ] + \omega\ [\ 2\ \beta_2\ \zeta_2\ \beta_1^2 + 2\ \beta_3\ \zeta_3\ \beta_1^2\ /\ r_1 \\ & + 2\ \beta_3\ \zeta_3\ \beta_2^2\ /\ r_1 + 2\ \beta_1\ \zeta_1\ \beta_2^2 + 2\ \beta_1\ \zeta_1\ \beta_3^2\ /\ r_1 \\ & + 2\ \beta_2\ \zeta_2\ \beta_3^2\ /\ r_2\ ] \end{aligned} \tag{26}$$

The displacement mobility can be expressed

$$\frac{\tilde{x}_3}{F} = \left|\frac{\tilde{x}_3}{F}\right| e^{j\theta} \tag{27}$$

where

$$\left|\frac{\tilde{x}_3}{F}\right| = \sqrt{\frac{g^2 + h^2}{q^2 + s^2}} \qquad \theta = \tan^{-1}\left(\frac{h\,q + g\,s}{g\,q + h\,s}\right) \tag{28}$$

Equation (27) is the complex driving point displacement mobility of the three-degree-of-freedom system shown in Figure 9.

Since the measured displacement mobility curves of the hand-arm system for vibration in each of the three orthogonal directions exhibited the general characteristics of a three-degree-of-freedom system, equation (27) was used to model the response of the hand-arm system. The analytical displacement mobility curves for the different grip configurations that were investigated were plotted with the use of a programmable calculator and a digital plotter. For each plot, nine model parameters had to be specified. They were $\beta_1, \beta_2, \beta_3, \zeta_1, \zeta_2, \zeta_3, r_1, r_2$ and m_3. Because of the complexity of the three-degree-of-freedom model, it was not possible to choose the various model parameters directly from the data. However, at frequencies much greater than the third natural frequency predicted by equation (27), the amplitude of the displacement mobility reduces to

$$\left|\frac{\tilde{x}_3}{F}\right| = \frac{1}{m_3\,\omega^2} \tag{29}$$

Therefore, it was possible to make a rough estimate of m_3 from the data at frequencies around 1,000 Hz. The other model parameters were selected on the basis of trial and error until the displacement mobility predicted by the analytical model corresponded as closely as possible to measured displacement mobility for the condition being analyzed. This process often involved some minor adjustments of the initial estimates of m_3. After a satisfactory fit of the data had been obtained, the model parameters were converted into the corresponding mass, spring, and damping coefficients of the model by the use of equations (14) through (17).

DISCUSSION OF RESULTS

Mechanical Impedance Tests and Model

Before discussing the specific results obtained from the driving point mechanical impedance tests, it is desirable to review the energy state that can exist in the hand and arm due to hand-induced vibration. The hand is a complex continuous elastic system. The elasticity and the mass of the hand are capable of storing potential and kinetic energy, respectively. Potential energy is stored as a result of the relative compression or expansion of adjacent tissue. Kinetic energy results from the motion of the tissues in the hand. These two elements are necessary to support vibratory motion. The capability of the hand to support this type of motion has been clearly proven.[11-25,27-30] In an ideal system with no damping, steady oscillatory motion results in the transfer of energy between the system being excited (the hand) and the exciting mechanism (the tool handle). Over part of a cycle of oscillation, energy imparted to the hand by the handle is stored in the form of potential and kinetic energy in the hand. Over the rest of the cycle, the energy stored in the hand is transmitted back to the handle. Thus, the net or time averaged transfer of energy between the hand and handle is zero. In physical-mechanical systems that are highly elastic, this type of energy transfer may not be destructive. The systems can undergo very large numbers of oscillations without failing or fatiguing. Because of the highly elastic nature of the different types of tissues in the hand, one would expect this to be true for vibration excitation of the hand. However, there has been no evidence presented that either proves or disproves this fact.

One of the unifying factors that ties together the results of the different mechanical impedance investigations of the hand is the fact that the hand has been found to be highly damped. Damping, when it is present, has the effect of dissipating energy that is transferred to a system. With regard to hand vibration, this implies that all of the energy, which is initially transferred to the hand by a vibrating handle, is not stored in the form of potential and kinetic energy and then transferred back to the handle. A portion of the energy that is initially incident upon the hand is absorbed or dissipated in the tissue of the hand. The higher the damping, the greater the amount of energy dissipated.

The amplitude of the instantaneous kinetic plus potential energy $|E_s|$ stored in the hand can be expressed in terms of the displacement mobility $|\tilde{x}_3/F|$, the amplitude of vibration $|\tilde{x}_3|$, and the phase angle θ between the force and displacement signal, or

$$|E_s| = |\tilde{x}_3|^2 \, \mathrm{Re}(\frac{F}{\tilde{x}_3}) \quad \text{or} \quad |E_s| = |\tilde{x}_3|^2 \left|\frac{F}{\tilde{x}_3}\right| \cos\theta. \tag{30}$$

Similarly, the amplitude of the instantaneous energy dissipated $|E_d|$ can be expressed

$$|E_d| = |\tilde{x}_3|^2 \, \mathrm{Im}(\frac{F}{\tilde{x}_3}) \quad \text{or} \quad |E_d| = |\tilde{x}_3|^2 \left|\frac{F}{\tilde{x}_3}\right| \sin\theta. \tag{31}$$

The amplitude of the total instantaneous energy $|E|$ transferred to the hand is given by

$$|E| = (|E_s|^2 + |E_d|^2)^{1/2} \quad \text{or} \quad |E| = |\tilde{x}_3|^2 \left|\frac{F}{\tilde{x}_3}\right| \tag{32}$$

Equations (30) and (31) indicate that if the phase angle θ between the force and displacement signals is close to zero, most of the energy that is initially transferred to the hand is stored in the form of kinetic and potential energy. On the other hand, if it is close to 90°, most of the energy that is initially transferred to the hand is dissipated in the hand. The above equations also indicate that the instantaneous energy values are a function of the inverse of the displacement mobility. Therefore, if the amplitude of vibration directed into the hand $|\tilde{x}_3|$ is held constant and the displacement mobility amplitude decreases, the amplitude of the corresponding instantaneous energies will increase.

The instantaneous time rate of change of energy or the instantaneous power supplied to the hand is often of interest. In terms of equations (30) through (32), the amplitudes of the instantaneous power stored $|P_s|$, the instantaneous power dissipated $|P_d|$, and total instantaneous power supplied to the hand $|P|$ can be written

$$|P_s| = |E_s|\omega \qquad |P_d| = |E_d|\omega \qquad |P| = |E|\omega \tag{33}$$

where ω is the angular frequency in radians/second. The above equations indicate that if the amplitude of energy is held constant, the amplitude of the instantaneous power supplied to the hand increases with increasing frequency.

Figures 10 through 15 show the average displacement mobility levels and the average phase angles between the force and displacement signals as a function of frequency that were measured for all of the investigated conditions. Tables 1 through 3 show the values of the identified mass, stiffness, and damping coefficients specified by equation (28) that were obtained for the different test conditions. The agreement between the experimentally measured mobility and phase curves and the corresponding curves predicted by equation (28) is shown in Figures 10 through 15.

Figures 10 through 15 indicate that the mechanical response characteristics of the hand were a function of frequency. Assuming constant displacement amplitudes and noting that the instantaneous energy that was directed into the hand was inversely proportional to the displacement mobility, the figures indicate that for all of the conditions that were analyzed the instantaneous energy into the hand increased as a function of frequency. Noting that the instantaneous power supplied to the hand was directly proportional to both energy and frequency, the amplitudes of the instantaneous power supplied to the hand increased at an even faster rate than did energy as frequency was increased.

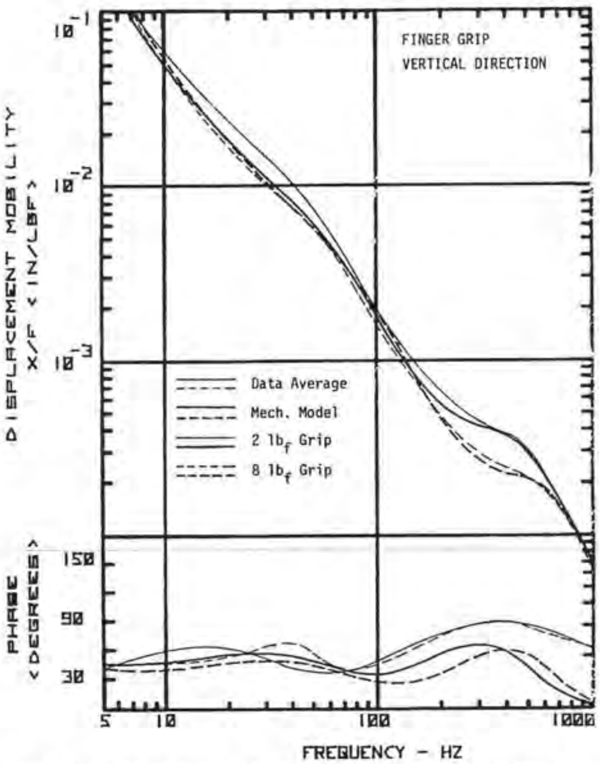

Figure 10. Comparison of the displacement mobility response of the hand and the response predicted by the mechanical model for the 2 lb_f and 8 lb_f finger grip (vertical direction).

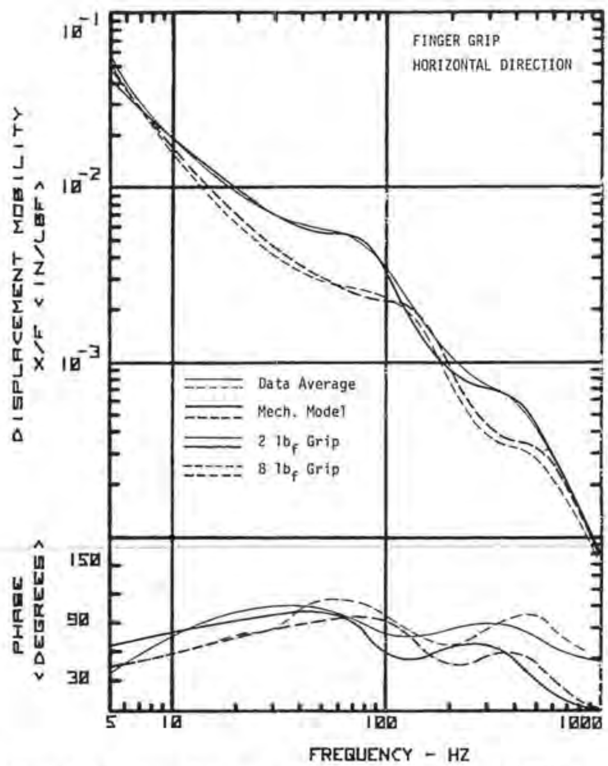

Figure 11. Comparison of the displacement mobility response of the hand and the response predicted by the mechanical model for the 2 lb_f and 8 lb_f finger grip (horizontal direction).

Table 1. Model coefficients for grip types in the vertical direction

Elements	2 lb_f-Finger	8 lb_f-Finger	2 lb_f-Palm	8 lb_f-Palm
*Mass**				
m_1	0.00081	0.00090	0.00103	0.00114
m_2	0.000203	0.000275	0.000171	0.000171
m_3	0.00045	0.00050	0.00057	0.00057
Stiffness†				
k_1	89.82	127.9	146.0	162.0
k_2	0.20	0.271	0.167	0.169
k_3	860.0	2021.0	441.0	900.0
Damping‡				
c_1	0.971	1.22	1.39	1.55
c_2	0.019	0.0259	0.0161	0.0161
c_3	1.49	2.01	1.30	1.862

* lb_f-sec^2/in.
† lb_f/in.
‡ lb_f-sec/in.

Table 2. Model coefficients for grip types in the horizontal direction

Elements	2 lb_f-Finger	8 lb_f-Finger	2 lb_f-Palm	8 lb_f-Palm
*Mass**				
m_1	0.000648	0.000858	0.00114	0.00114
m_2	0.000144	0.000279	0.000285	0.000342
m_3	0.00036	0.000429	0.00057	0.00057
Stiffness†				
k_1	5.76	22.9	11.5	30.4
k_2	0.0696	0.705	0.72	0.864
k_3	888.0	2075.0	1406.0	2757.0
Damping‡				
c_1	0.183	0.056	0.149	0.149
c_2	0.0127	0.0673	0.0244	0.0481
c_3	1.47	1.32	1.70	2.0

* lb_f-sec^2/in.
† lb_f/in.
‡ lb_f-sec/in.

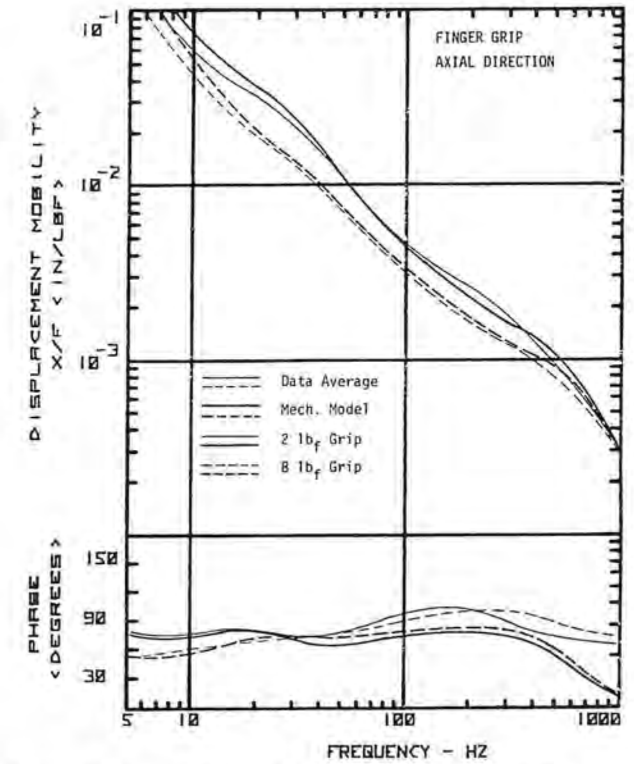

Figure 12. Comparison of the displacement mobility response of the hand and the response predicted by the mechanical model for the 2 lb$_f$ and 8 lb$_f$ finger grip (axial direction).

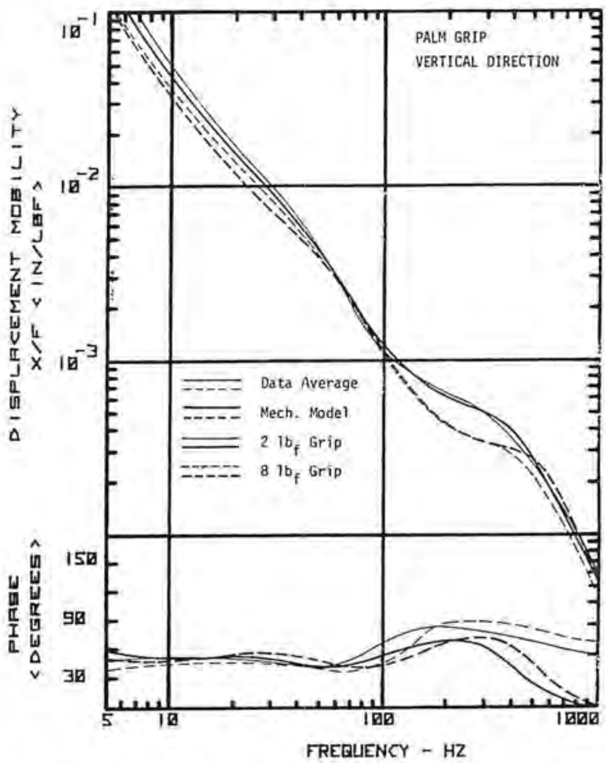

Figure 13. Comparison of the displacement mobility response of the hand and the response predicted by the mechanical model for the 2 lb$_f$ and 8 lb$_f$ palm grip (vertcal direction).

Table 3. Model coefficients for grip types in the axial direction

Elements	2 lb$_f$-Finger	8 lb$_f$-Finger	2 lb$_f$-Palm	8 lb$_f$-Palm
*Mass**				
m_1	0.00024	0.00028	0.00012	0.00028
m_2	0.0000108	0.0000098	0.0000048	0.0000098
m_3	0.00012	0.00014	0.000080	0.00014
Stiffness†				
k_1	23.7	17.7	0.474	4.42
k_2	0.0426	0.0557	0.0189	0.0387
k_3	47.4	79.6	102.0	141.0
Damping‡				
c_1	0.226	0.1688	0.0226	0.106
c_2	0.00136	0.00103	0.00181	0.00148
c_3	0.377	0.507	0.29	0.422

* lb$_f$-sec^2/in.
† lb$_f$/in.
‡ lb$_f$-sec/in.

The figures indicate that the nature of the energy directed into the hand was a function of the direction of vibration. Again, assuming constant displacement amplitudes, the instantaneous energy supplied to the hand in the axial direction was less than the corresponding energy directed into the hand for the vertical and horizontal directions. The energy supplied to the hand in the horizontal direction at frequencies below 40 Hz was greater than the corresponding energy supplied to the hand in the vertical direction. At frequencies above 40 Hz, the opposite was true.

By observing the phase relations between the force and displacement signals, some statements can be made with regard to the types of energy that were directed into the hand for vibration in each of the three orthogonal directions. Since the phase between the force and displacement signals below 100 Hz was much less than 90° for vibration in the vertical direction, the energy supplied to the hand in this direction was fairly evenly distributed between stored kinetic and potential energy and dissipated energy. However, at frequencies above 100 Hz, the fact that the phase between force and displacement approached and stayed around 90° indicates that almost all of the energy that was directed into the hand at those frequencies for vibration in the vertical direction was dissipated. For vibration in both the axial and horizontal directions, the phase between the force and dis-

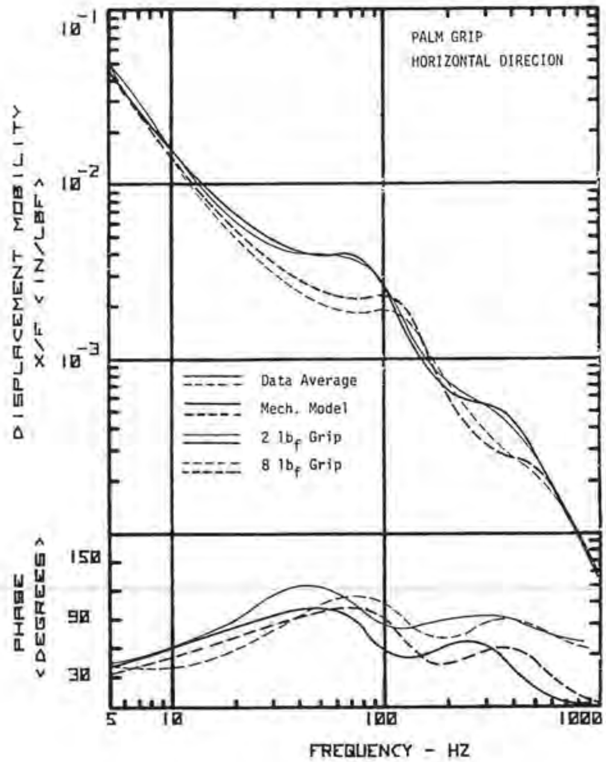

Figure 14. Comparison of the displacement mobility response of the hand and the response predicted by the mechanical model for the 2 lb_f palm grip (horizontal direction).

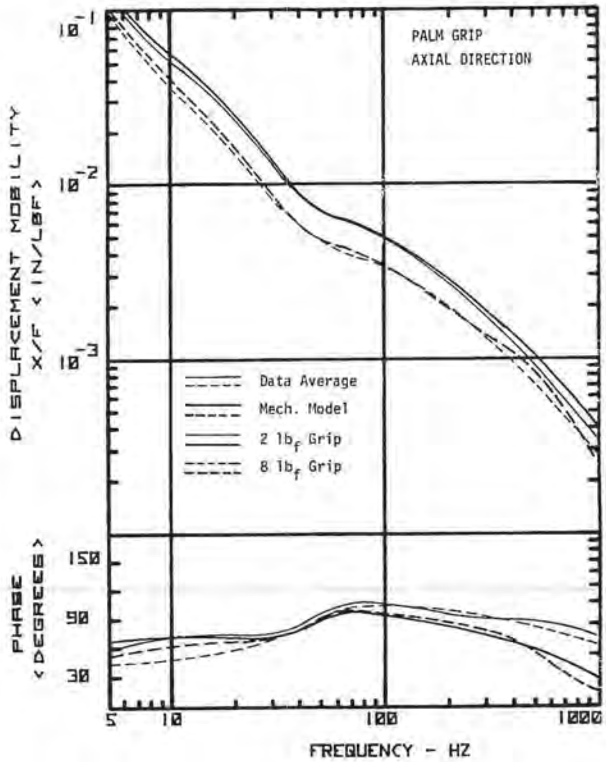

Figure 15. Comparison of the displacement mobility response of the hand and the response predicted by the mechanical model for the 2 lb_f and 8 lb_f palm grip (axial direction).

placement varied between around 60° and 120°. This indicates that for nearly all frequencies in these two directions almost all of the energy that was directed into the hand was dissipated or absorbed by the hand.

Figures 10 through 15 indicate that the instantaneous values of energy supplied to the hand were a function of grip configuration. In general, the energy directed into the hand (assuming constant displacement amplitudes) was slightly higher for the palm grips than for the finger grips. Also, more energy was supplied to the hand for the 8 lb_f grip than was for the 2 lb_f grip. These statements were true for all three directions of vibration.

Figures 10 through 15 show that the displacement mobility amplitudes that were predicted by the analytical model correlated very well with the measured mobility amplitudes for all of the test conditions that were investigated. The phase relation between the displacement and force predicted by the model correlated fairly well with the measured phase at frequencies below 100 Hz. At frequencies above 100 Hz, the predicted phase was always less than the measured phase. This discrepancy was probably because the hand was modeled as a three-degree-of-freedom system for vibration in each of the three orthogonal directions when, in reality, it had more than three degrees of freedom.

One of the most common perceptions related to hand vibration is the fact that vibration directed into the hand at very low frequencies can be felt all the way up to the shoulder; the vibration becomes progressively more localized to the hand and then the fingers as frequency is increased. This phenomenon has lead researchers to postulate that the masses indicated in Figure 9 have represented different parts of the hand and arm. However, the maximum value of total mass associated with the mechanical model of the hand developed by Reynolds and Soedel was around 0.68 lb_m.[23,31] Similarly, for the mechanical model of the hand developed by Abrams, the maximum value of mass was found to be around 0.1 lb_m.[20] The maximum value of total mass obtained from this study was around 0.79 lb_m. One would intuitively anticipate that if the mechanical model predicted the vibration response of both the hand and arm, the above values of total mass would have been larger. The fact that they were fairly small tends to imply that the mechanical model represented only the localized effects in the hand due to hand-induced vibration.

It is possible to make some statements with regard to the values of the mass, stiffness, and damping coefficients associated with the mechanical model of the hand. Mass m_2 was from 0.07 (axial direction) to 0.6 (horizontal direction) times the value of mass

m_3. Mass m_1 was generally around twice the value of m_3 for most of the conditions that were investigated. The coupling indicated by the large values of k_3 and c_3 between masses m_2 and m_3 was very strong whereas the coupling implied by the very small values of k_2 and c_2 between masses m_1 and m_2 was very weak. The coupling indicated by the intermediate values of k_1 and c_1 between mass m_1 and "ground" was much stronger than the coupling between masses m_1 and m_2 but somewhat less than the coupling between masses m_2 and m_3. Figure 16 shows a conceptual representation of the mechanical model of the hand with regard to the above statements.

A discussion of the locations and coupling that exist between the different tissues in the finger and hand reveals some striking similarities with the above statements on the mechanical model of the hand. The outer tissue of the finger and hand are composed of the dermis and epidermis. These tissues are very dense and are composed of very closely packed cells. Some nerve endings extend up into the epidermis. Below the dermis is the subcutaneous tissue. This tissue, in contrast to the dermis and epidermis, is not very dense. Most of the veins, arteries, and arterioles carrying blood and fluids to and from the hand and fingers and the nerve endings located in the hand and fingers are located in the subcutaneous tissue. The cells making up the subcutaneous tissue are very loosely packed and the tissue is highly mobile. The elastic bond between the subcutaneous tissue and the dermis is fairly strong. The muscle tissue is located below the subcutaneous tissue. The attachment between the subcutaneous and muscle tissues is very weak. When these statements are compared with the statements made about the mechanical model, mass m_1 corresponds to the dermis and epidermis; m_2 corresponds to the subcutaneous tissue; and m_3 corresponds to the muscle tissue. "Ground" corresponds to the skeletal system; k_3 and c_3 represent the strong coupling that exists between the dermis and subcutaneous tissue; k_2 and c_2 represent the weak coupling that exists between the subcutaneous and muscle tissues; and k_1 and c_1 represent the coupling between the muscle tissue and the skeletal system.

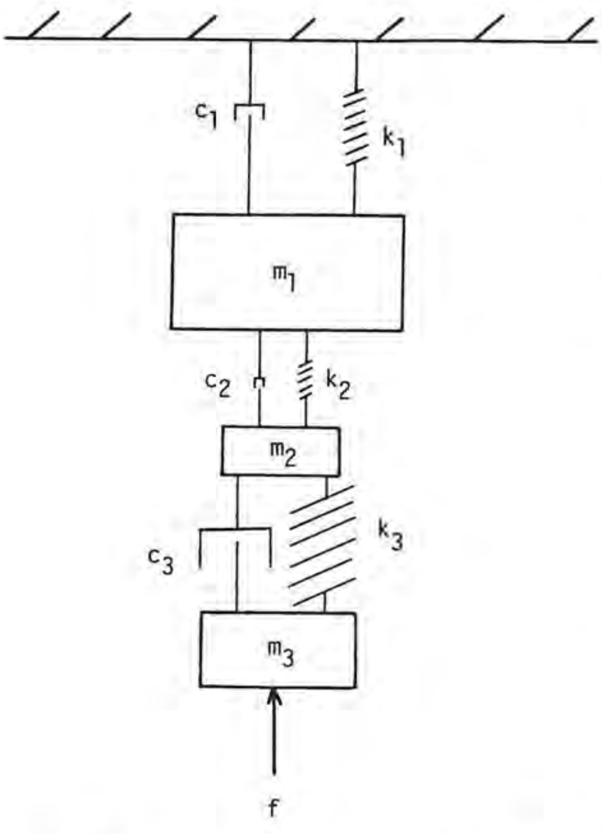

Figure 16. Conceptual representation of a three degree-of-freedom model showing the relative size of the various parameters as found by impedance modeling of the H-A-S.

If the above correlation between the mechanical model and the hand and fingers exists, some very significant statements can be made about energy states that can exist in the hand and fingers. At low frequencies, the vibration that is directed into the hand and fingers is directed through the epidermis, dermis, and subcutaneous tissue to the muscle tissue and then to the skeletal system. The vibration is then transmitted to other parts of the hand and arm through the skeletal system. However, because of the very weak coupling that exists between the subcutaneous and muscle tissues, there will be a frequency (as the frequency is increased) above which the subcutaneous tissue will effectively be dynamically decoupled from the muscle tissue. The subjective response test conducted by Reynolds and Jokel and the transmissibility tests conducted during this investigation imply that this decoupling occurs between the frequencies of 100 Hz and 200 Hz.[27]

The impedance tests indicated that energy was dissipated in the fingers and hand at frequencies below 100 Hz. Even though some of this energy was probably dissipated in the subcutaneous tissue, most of it was probably dissipated because of the relative motion between the subcutaneous and muscle tissues and between the muscle tissue and the skeletal system.

At frequencies above 100 Hz to 200 Hz, the subcutaneous and muscle tissues are probably decoupled. This implies that nearly all of the vibration energy above these frequencies directed into the hand is stored and dissipated in the epidermis, dermis, and subcutaneous tissue. Because of the strong coupling between the dermis and subcutaneous tissue and the fact that the mass of the dermis and epidermis is much larger than the corresponding mass of the subcutaneous tissue, energy directed into the hand that causes a relatively small displacement of the dermis and epidermis can result in a relatively large displacement of the subcutaneous tissue. If the motions of the dermis and the subcutaneous tissue are out of phase, the relative motion between the two tissues can be even larger than the individual motions of each tissue. The results of the transmissibility tests indicate that the above may be true.

From the results of the mechanical impedance tests, it can be inferred that when vibration was directed into the hand in each of the three orthogonal directions, almost all of the energy induced into the hand and fingers at frequencies above 100 Hz was dissipated. The discussion in the above paragraph indicates that this energy was dissipated because of the motion of the subcutaneous tissue and because of the relative motion between the subcutaneous tissue and the dermis. Energy was probably also dissipated because of the relative motions between the vessels and other tissues comprising the subcutaneous tissue. The energy was most likely dissipated in the form of heat caused by the relative motions between the different tissues. If an object is continually rubbed over the surface of the skin, the skin becomes warm, and if the rubbing persists, the skin may become irritated and blister. This usually results in reddening of the skin, a flow of blood and other fluids into the area of the irritation, and a tingling and burning sensation. It is reasonable to assume this same thing happens as a result of the relative motions that occur in the subcutaneous tissue and between the subcutaneous tissue and the dermis. As indicated above, this can result in irritation and consequently, a flow of blood and other fluids into the area of irritation. The noted results of this are a burning sensation and a swelling of the fingers or hand. These results have been observed in the hands and fingers of individuals who have been exposed to hand-induced vibration. If the above irritation persists over a very long period of time, it could possibly result in cell destruction in the subcutaneous tissue. Many researchers who have investigated the pathological effects of the vibration syndrome have reported definite cell destruction in the small vessels and destruction of other tissues contained in the subcutaneous tissue

From this discussion it can be very strongly inferred that the vibration energy above 100 Hz to 200 Hz that has been directed into the hand and dissipated in the subcutaneous tissue may have been primarily responsible for the cell and tissue destruction associated with the vibration syndrome.

Transmissibility Tests

Figures 17 through 19 show the average value curves for the transmissibility tests that were conducted at the indicated locations in the vertical, horizontal, and axial directions for the 2 lb_f finger grip. The results that were obtained for the other three grip configurations were very similar to those obtained for the 2 lb_f finger grip. Subminiature piezoresistive accelerometers attached to the skin surface directly over the bone at the indicated joints were used to obtain these results. Therefore, these results cannot be used to specify the absolute energy state at the indicated locations, but they can be used to comment on the relative vibration levels, referenced to the vibration levels directed into the hand and fingers, at the specified locations.

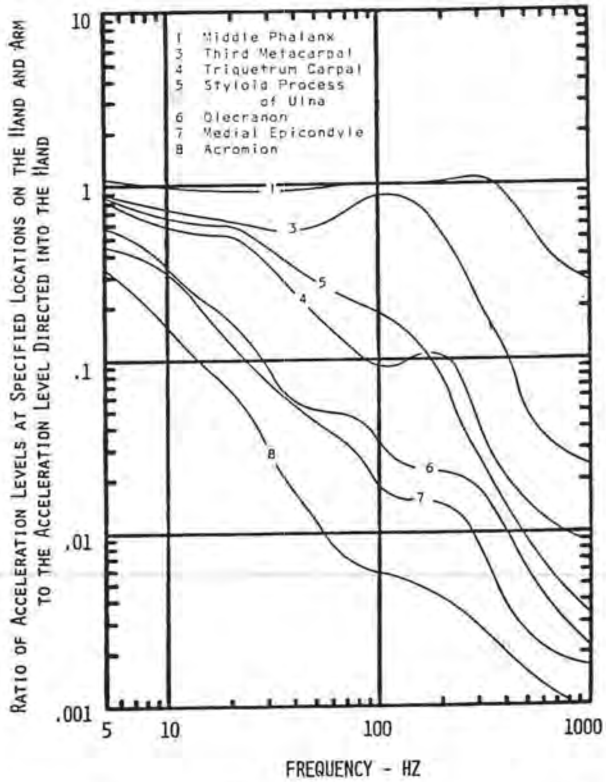

Figure 17. Average value transmissibility curves for vibration in the vertical direction for the 2 lb_f finger grip.

The vibration transmissibility through the finger at the middle phalanx (1, see curves on figures) for vibration in the vertical direction and at the proximal phalanx (2) for vibration in the horizontal and axial directions indicates that vibration up to approximately 100 Hz was directed, nearly unattenuated, from the point of contact between the finger and the vibrating handle through the finger to the back surface of the finger. At frequencies above 100 Hz for vibration in the horizontal and axial directions and above 400 Hz for vibration in the vertical direction, the vibration amplitudes of the backs of the fingers decreased as the vibration frequency increased. The vibration levels at the third metacarpal (3) for vibration in the vertical direction decreased at an even faster rate, compared with the middle phalanx, as the vibration frequency was increased (Figure 17). These factors tend to indicate that at frequencies below 100 Hz most of the vibration that was directed into the fingers was transmitted to the hand. However, as the vibration frequency was progressively increased above 100 Hz, the vibration tended to become more and more localized at the fingers. For vibration in horizontal and axial directions, the vibration tended to become more localized to the area of the fingers directly in contact with the vibrating handle. This happened for vibration in the

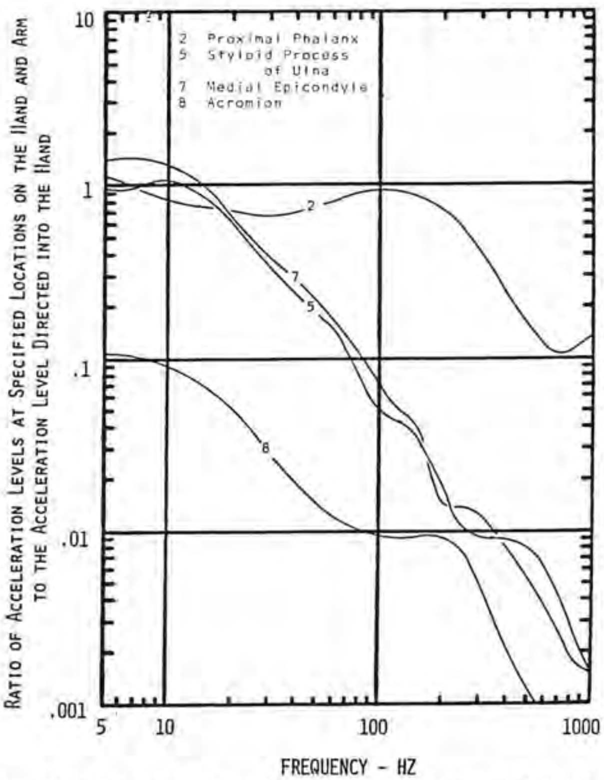

Figure 18. Average value transmissibility curves for vibration in the horizontal direction for the 2 lb_f finger grip.

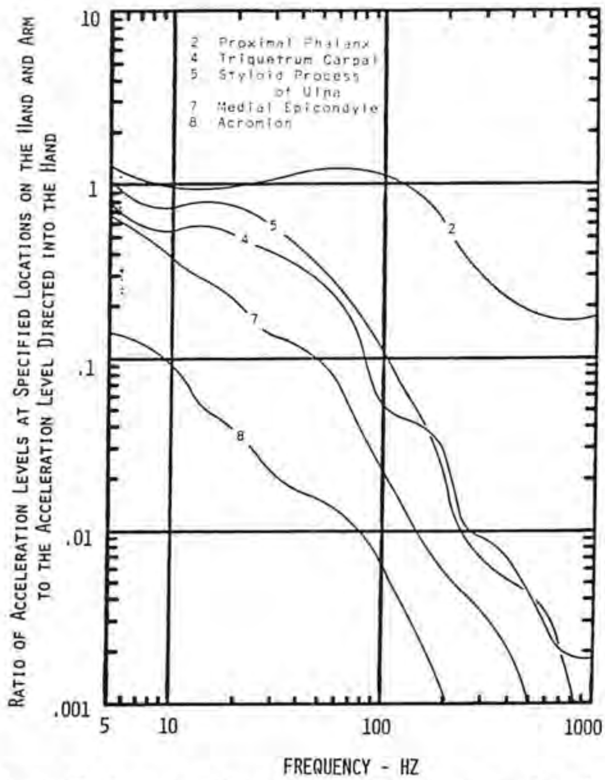

Figure 19. Average value transmissibility curves for vibration in the axial direction.

vertical direction for frequencies above 400 Hz. These observed trends support the discussions in the mechanical impedance section that concerned the vibration response of the epidermis, dermis, and subcutaneous tissue at frequencies above 100 Hz to 200 Hz.

Location 4, the triquetrum carpal, and location 5, the styloid process of ulna, represent a part of the wrist joint. The results, indicated in Figures 17 through 19, can be used to show that for vibration in all three directions the vibration amplitudes at the wrist progressively decreased as frequency increased throughout the entire test frequency range. The vibration transmissibility amplitude at the wrist had decreased to around 0.1 for a vibration amplitude incident upon the fingers at 100 Hz; and at a frequency of 1,000 Hz, to 0.01 for vibration in the vertical direction and to 0.001 for vibration in the horizontal and axial directions. These results indicate almost all of the vibration directed into the fingers at frequencies above 100 Hz was confined to the hand and fingers. This further supports the statements that were made in the mechanical impedance section concerning the fact that almost all of the energy directed into the hand and fingers at frequencies above 100 Hz was dissipated in the hand and fingers.

Attention should be focused on the transmissibility levels for locations 4 and 5, the wrist joint, in Figures 17 through 19 and for locations 6 and 7, the elbow joint, in Figure 17. These results indicate that, in general, very little vibration attenuation occurred across a joint. In some cases at certain frequencies, a slight vibration amplification occurred across a joint.

The vibration levels transmitted to most locations on the hand and arm were approximately the same, regardless of the direction of vibration. However, one notable exception was considered worthy of further analysis. For vibration in both the vertical and axial directions, a noticeable reduction in the vibration levels between the wrist and elbow (locations 5 and 7) was evident at all frequencies (Figures 17 and 19). For vibration in the horizontal direction, this vibration reduction was not present (Figure 18). It is important to recall that because of the orientation of the forearm to the vibrating handle, vertical and axial vibration was perpendicular to the forearm whereas horizontal vibration was normal to the forearm. To analyze this phenomenon more closely, the average value transmissibility curve for these two locations were isolated and superimposed for vibration in the vertical and horizontal directions. Figure 20 shows this comparison for the 2 lb_f finger grip. The transmission levels indicated by this plot were used to calculate the ratio of the vibration level of the elbow divided by the vibration level of the wrist. These results for the vertical and horizontal directions

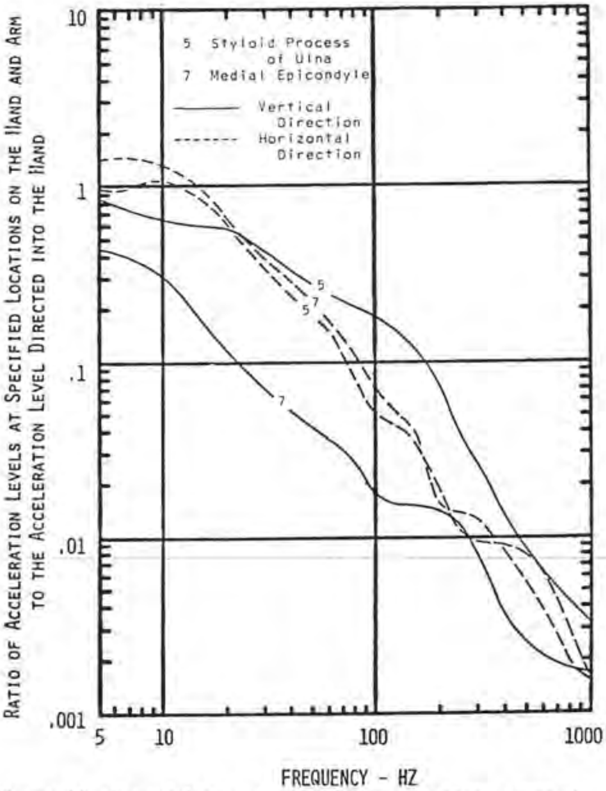

Figure 20. Comparison of the average value transmissibility curves for the elbow and wrist joints for vibration in the horizontal and vertical directions for the 2 lb, finger grip.

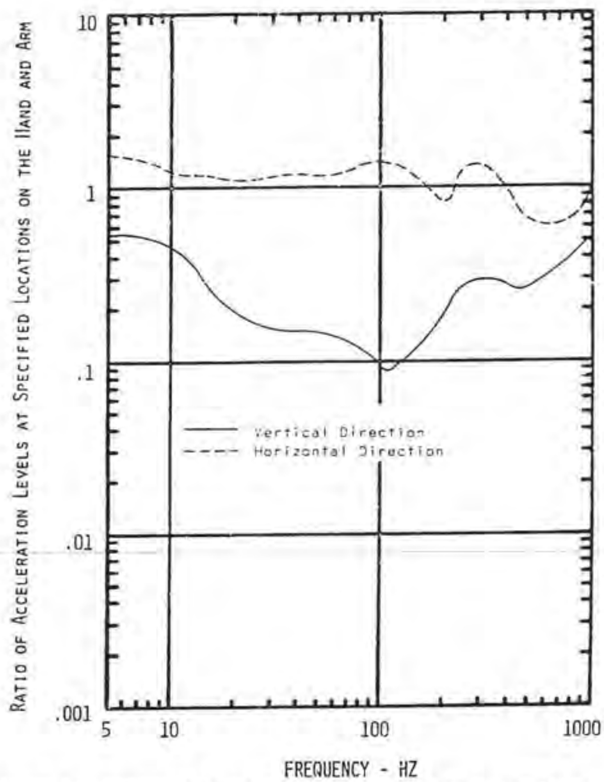

Figure 21. Calculated ratios of the vibration levels at the elbow divided by the vibration levels at the wrist for vibration in the horizontal and vertical directions for the 2 lb, finger grip.

are plotted in Figure 21. From information in Figure 21, it can be inferred that longitudinal vibration (vibration amplitudes normal to propagation of vibration) is transmitted along a bone nearly unattenuated whereas transverse vibration (vibration amplitudes perpendicular to propagation of vibration) is substantially attenuated as it travels along a bone. The degree of attenuation is probably a function of frequency.

Figures 22 through 26 indicate both the transmissibility levels and the phase relations between corresponding vibration signals at the indicated locations on the finger and hand. The discussions about the vibration levels transmitted to the specified locations on the finger and hand and across the indicated joints are the same as before. However, it is interesting to note the phase relations between the corresponding signals. Even though the vibration levels on the back of the finger at the middle phalanx and the proximal phalanx were nearly the same as the vibration levels directed into the finger up to around 300 Hz to 400 Hz (at which they began to decrease), the phase between the corresponding signals began to increase from zero degrees at a frequency around 100 Hz. At frequencies below 100 Hz, all the corresponding signals were in phase. The fact that the vibration signals at the back of the finger were out of phase with the vibration signal induced into the finger at frequencies above 100 Hz is significant; it indicates that because of the phase difference between the corresponding signals, even though the transmissibilities at the back of the finger were unity up to 300 Hz to 400 Hz, the relative motion between the inside and the back of the finger was up to twice that indicated by the individual vibration levels or the transmissibilities alone. The same statements also apply to the third metacarpal (Figure 24). This information supports the discussions in the mechanical impedance section with regard to the relative motion between the muscle tissue, subcutaneous tissue, dermis, and epidermis.

Figures 25 and 26 indicate, as before, that there was very little vibration reduction across the joint between the third metacarpal and the proximal phalanx and across the joint between the styloid process of the ulna and the triquetrum carpal. The attenuation for individual test subjects may have been substantial, but the overall average of all test subjects was near unity. As before, the phase relations between the corresponding signals became quite significant. Thus, even though the attenuation across a joint may have been small, the relative motion across the joint, indicated by the phase difference, was significant.

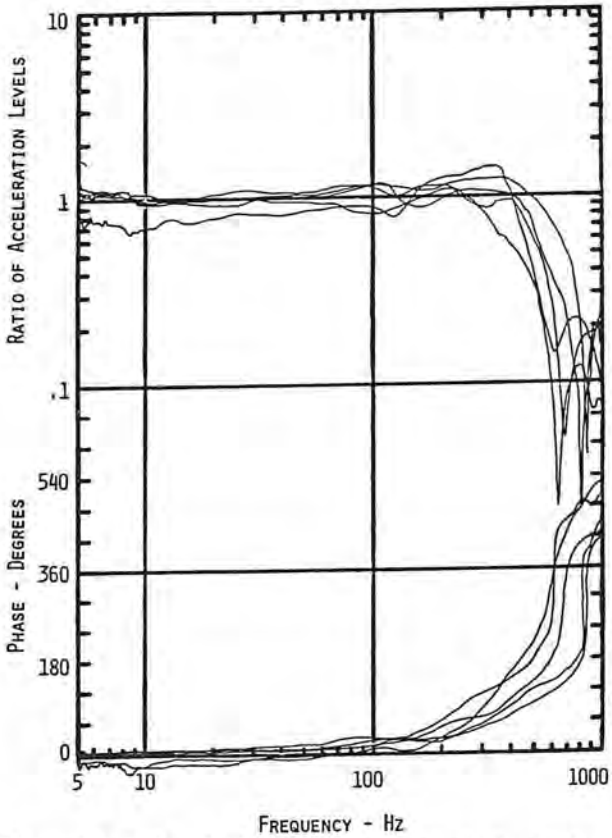

Figure 22. Ratio of vibration levels at middle phalanx (location 1) divided by vibration levels induced into the hand with phase difference between corresponding signals for individual test subjects for the 2 lb, finger grip (vertical direction).

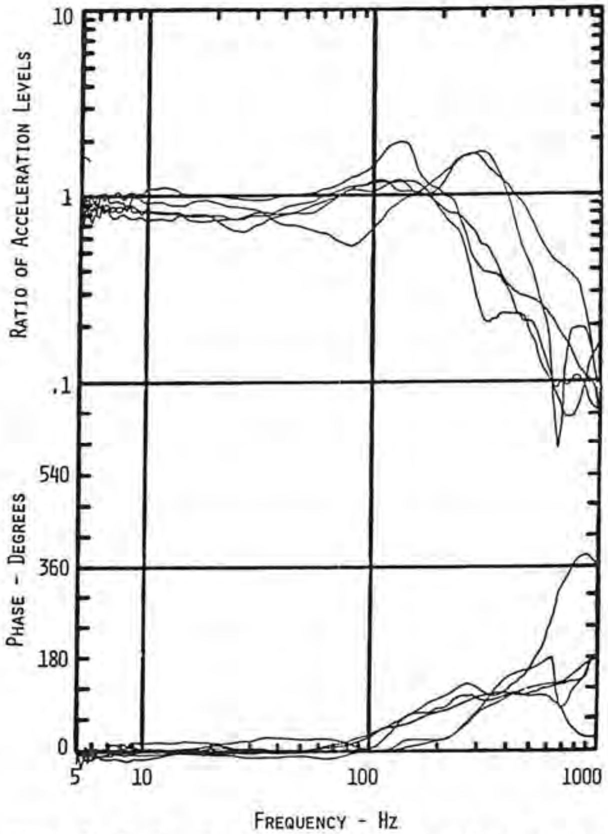

Figure 23. Ratio of vibration levels at proximal phalanx (location 2) divided by vibration levels induced into the hand with phase difference between corresponding signals for individual test subjects for the 2 lb, finger grip (vertical direction).

Subjective Response to Vibration

Before discussing the results of the equal sensation, threshold, and annoyance tests, it is desirable to describe the physiological mechanisms involved in the perception of vibration. The perception of a sensation is composed of four parameters: quality, intensity, locus, and affect.[32] Quality is the subjective difference that enables a subject to name sensations: hot and cold, taste, smell, etc. Intensity is the strength or amplitude of the stimulus. Locus indicates the location from which the sensation appears to come. Affect is that aspect of the sensation that enables the subject to classify it as pleasant or unpleasant. This emotional response can at times become so intense that it may have the effect of diminishing the quality and intensity of the sensation, thus altering the subjective response to the stimulus.

Mechanoreceptors that respond to mechanical deformation of the tissue are used by individuals to detect the presence of vibration. Figure 27 shows a cross section of glabrous skin with most of the mechanoreceptors indicated. When the tissue is deformed, the mechanoreceptors produce a generator potential by a process known as depolarization.[32,33] The generator potential is a stationary potential that is proportional to the magnitude of the stimulus applied to the tissue. If the amplitude of the generator potential exceeds a certain value, called the threshold of the nerve fiber being stimulated, an action potential of the nerve fiber will be produced. The action potential is an "all-or-nothing" firing action, the amplitude being constant for a given receptor or nerve fiber.[33] This action potential is then transmitted along the nerve pathways to the central nervous system where it is encoded in such a manner as to make it possible for the individual to determine the nature of the stimulus. The magnitude of the stimulus is encoded in the number of action potentials per unit time. Once the threshold has been exceeded, the number of action potentials per unit time is a function of the amplitude of the generator potential (Figure 28). If a stimulus is of such an intensity as to saturate one nerve fiber, this greater intensity can be encoded by several nerve fibers relaying action potentials from a group of mechanoreceptors to the central nervous system.

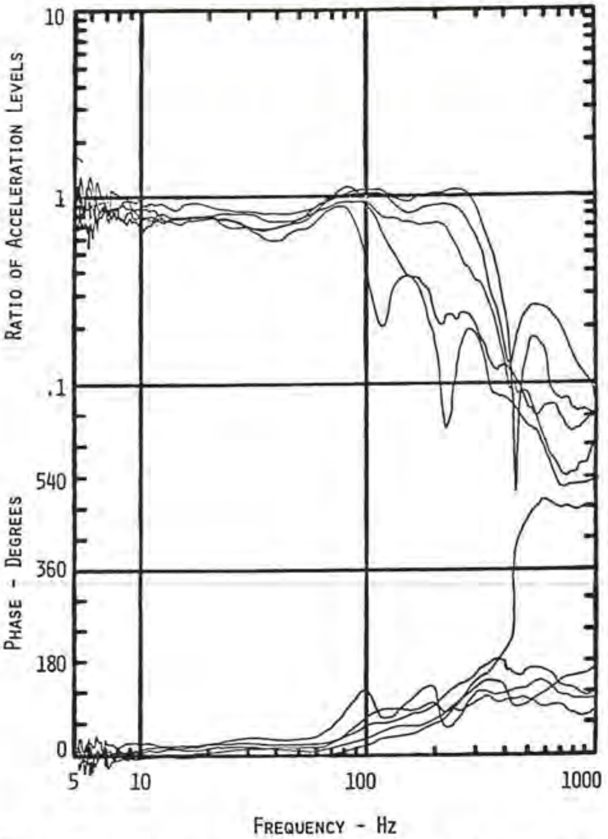

Figure 24. Ratio of vibration levels at third metacarpal (location 3) divided by vibration levels induced into the hand with phase difference between corresponding signals for individual test subjects for the 2 lb_f finger grip (vertical direction).

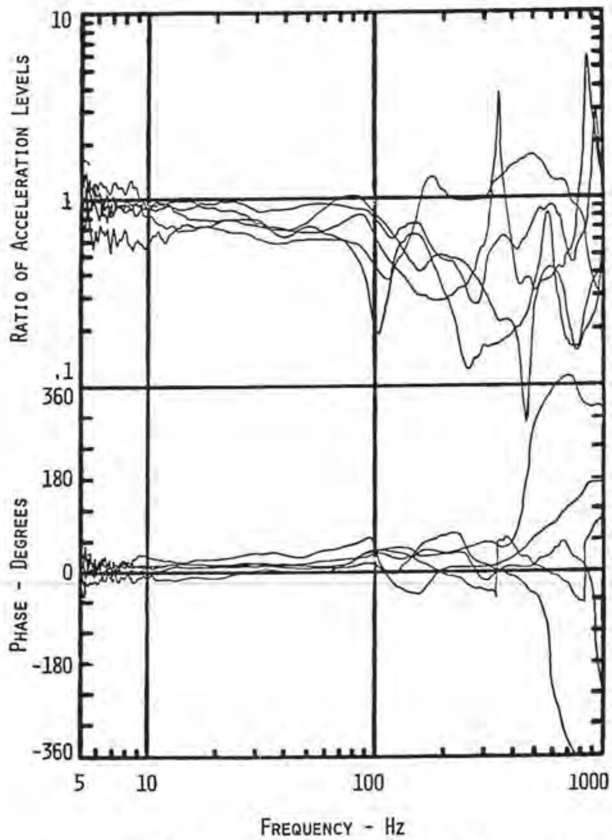

Figure 25. Ratio of vibration levels at third metacarpal (location 3) divided by vibration levels at proximal phalanx (location 2) with phase difference between corresponding signals for individual test subjects for the 2 lb_f finger grip (vertical direction).

Mechanoreceptors have the ability to adapt either partially or completely to a stimulus after a period of time. That is, when a static signal is applied, the receptor responds with a high generator potential that decreases with time. Adaptation occurs at different rates for different receptors (Figure 29). The mechanoreceptors associated with the sensation of touch and vibration are classified according to their rates of adaptation. Tonic receptors are slow-adapting nerve afferents. They include Merkel's disc, Ruffini's endings, muscle spindles, Golgi tendon-organs, and free nerve endings. Phasic receptors are fast-adapting nerve afferents. They include pacinian corpuscles, Meissner's corpuscles, hair end organs, and free nerve endings.

Tonic receptors produce a generator potential because of both static and dynamic components of a stimulus (Figure 30). The static component is determined by the amplitude of the deformation of the tissue. The dynamic component is determined by the time rate of change of the deformation. If the stimulus is changing with respect to time, the generator potential is primarily determined by the dynamic component. If the intensity of the stimulus is very high, both the dynamic and static components may be involved in determining the amplitude of the generator potential. If the stimulus does not change with time, the generator potential decreases with time to the amplitude determined by the static component alone.

Figure 31 indicates the relationship between a displacement stimulus, the generator potential produced by the stimulus, and the action potentials excited by the generator potential. The static and dynamic components of the stimulus determine the initial amplitude of the generator potential, which then decreases to a level determined by the static component alone. Thus, the number of action potential spikes are initially determined by the onset of the displacement and are proportional to the time rate of change of the stimulus. After the static displacement has been applied and is continuously applied without changing, the number of action potential spikes is proportional to the static deflection experienced by the skin.

After an action potential spike has excited a nerve fiber, the threshold to a second stimulus is increased. For a very short time (the absolute refractory period), the resulting threshold is infinite and the nerve

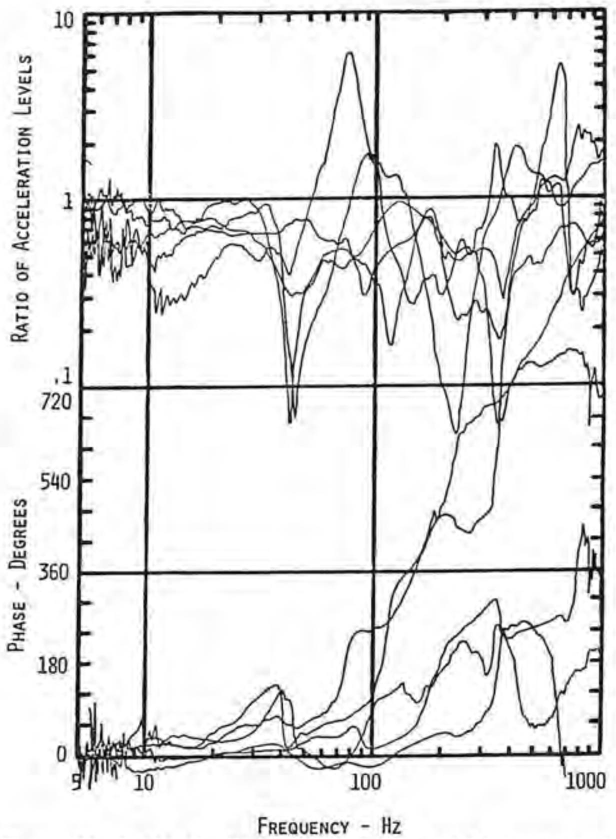

Figure 26. Ratio of vibration levels at styloid process of ulna (location 5) divided by vibration levels at triquetrum carpal (location 4) with phase difference between corresponding signals for individual test subjects for the 2 lb, finger grip (vertical direction).

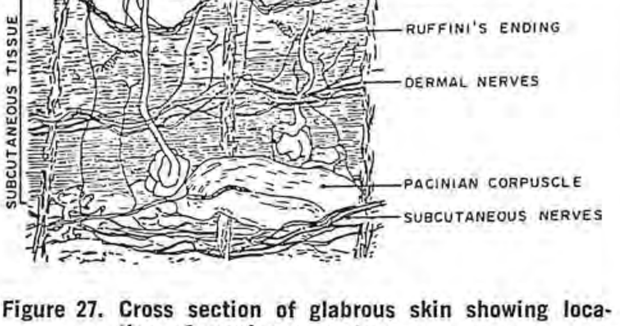

Figure 27. Cross section of glabrous skin showing location of mechanoreceptors.

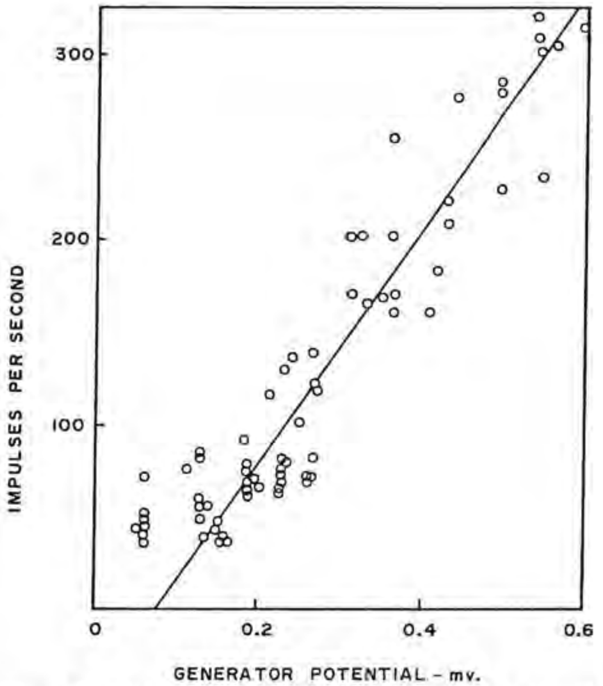

Figure 28. Relationship between the generator potential of a muscle spindle and the frequency of the sensory impulses transmitted.

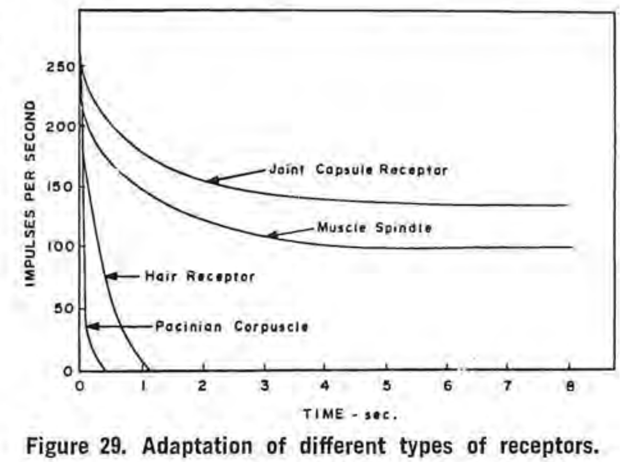

Figure 29. Adaptation of different types of receptors.

fiber cannot be excited by a second stimulus. Thereafter, for an additional time (the relative refractory period), a second stimulus can excite the nerve fiber only if it is greater than the normal threshold level (Figure 32). Measured refractory periods indicate that the upper limit of most tonic receptors is from 100 to 200 pulse per second. At frequencies greater than 200 Hz, tonic receptors will generally not respond to a vibrating signal unless the amplitude is so great that it produces a perceived static displacement.[32]

The fast-adapting phasic receptors respond only to stimuli that are continuously changing. If subjected to a static signal, they respond with only one action potential spike, indicating the onset of the stimulus. Thereafter, the generator potential goes to zero very rapidly. The number of action potential spikes excited by the phasic receptors in response to a vibrating signal is proportional to the frequency of the stimulus.[32] It is believed that the amplitude of a vibration stimulus may be encoded in the number of phasic receptors that are excited by the stimulus.

For a given frequency, the minimum amplitude at which a phasic receptor responds with one action potential spike per cycle is known as a "tuning point." When tuning points are established for selected frequencies, it is possible to determine the frequency range at which a phasic receptor will respond. Mountcastle indicated that vibration is detected by two different types of phasic receptors, one tuned to low frequency vibrations and one tuned to high frequency vibrations.[33] He indicated that Meissner's corpuscles appeared to be tuned to frequencies below 200 Hz whereas pacinian corpuscles were tuned to frequencies between 70 Hz and 400 Hz (Figure 33). Mountcastle also found that the high frequency detectors were more sensitive than the low frequency detectors. This corresponds to indications by others that the phasic receptors are most sensitive at frequencies around 200 Hz.[32]

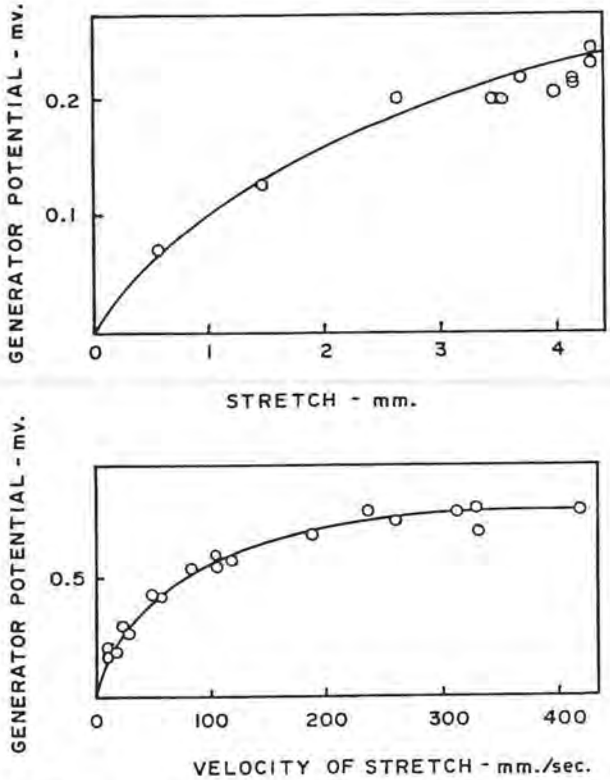

Figure 30. Effect of static and dynamic components of generator potential produced in frog muscle spindle. Relationship between static component (ordinate) and magnitude of stretch (abscissa), (top). Relationship between dynamic component and velocity of stretch (bottom).

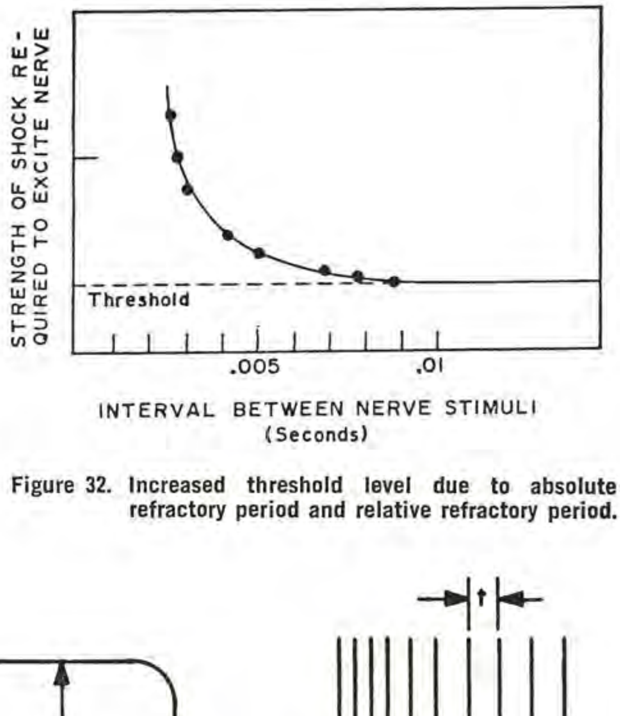

Figure 32. Increased threshold level due to absolute refractory period and relative refractory period.

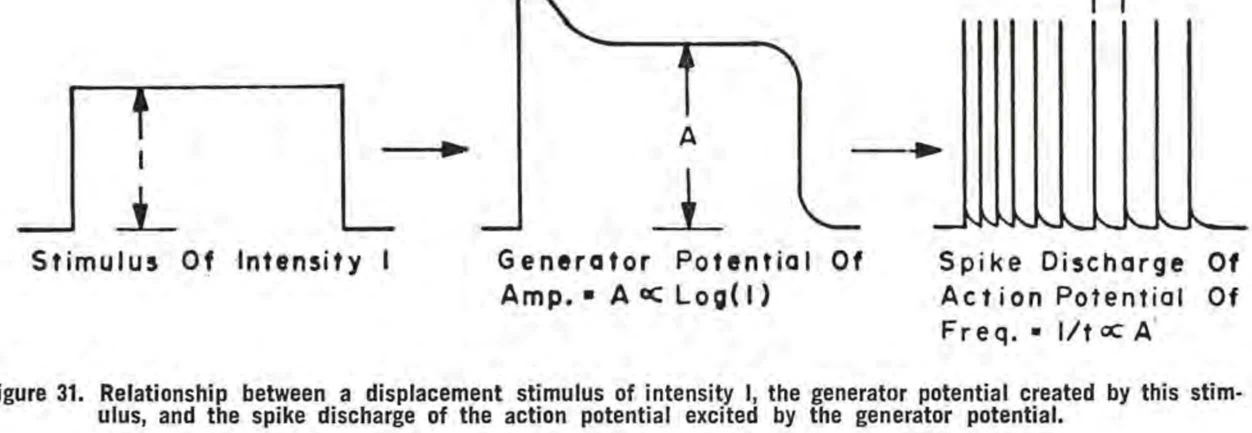

Figure 31. Relationship between a displacement stimulus of intensity I, the generator potential created by this stimulus, and the spike discharge of the action potential excited by the generator potential.

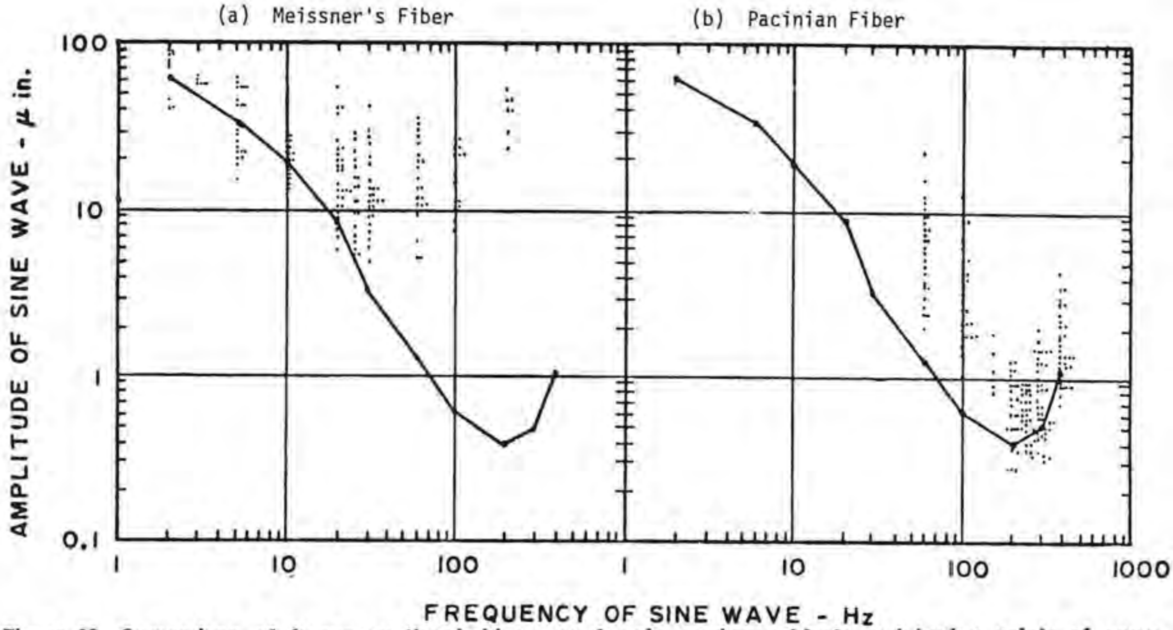

Figure 33. Comparison of frequency threshold curves for six monkey subjects and tuning points of nerve fiber of monkey hands. Each dot indicated a tuning point for a phasic receptor fiber; (a) Meissner's fiber; (b) Pacinian fiber.

Figure 34 shows the equal sensation curves for discrete frequency vibration for the 2 lb_f finger grip, and Figure 35 shows the equal sensation curves for the ⅓-octave-band broad band frequency vibration for the 2 lb_f finger grip. These curves indicate an individual's perception of vibration relative to a reference signal at 100 Hz. That is, the indicated vibration levels at frequencies other than 100 Hz produced the same perceived sensation as was felt at 100 Hz. The results of the equal sensation tests for all four grip configurations in each of the three directions indicated that an individual's relative perception of vibration was a function of the direction of vibration, the grip configuration, the amplitude of the reference signal, and the frequency content of the signal.

At present there is no adequate theory to explain the differences in an individual's perception due to the above-mentioned parameters. It is possible, however, to explain an individual's overall perception of vibration. The results of the discrete frequency equal sensation tests indicated that, physiologically, there were both low and high frequency receptors used for perceiving vibration (Figure 34). The shape of the equal sensation curves were very similar to the curves presented by Mountcastle (Figure 33). This correlation implies that phasic receptors were primarily responsible for an individual's perceived sensation due to discrete frequency vibration. Meissner's corpuscles tuned to low frequencies and pacinian corpuscles tuned to high frequencies were possibly the phasic receptors involved in determining the sensation felt.

The equal sensation curves also give some indication that tonic receptors were also used to determine

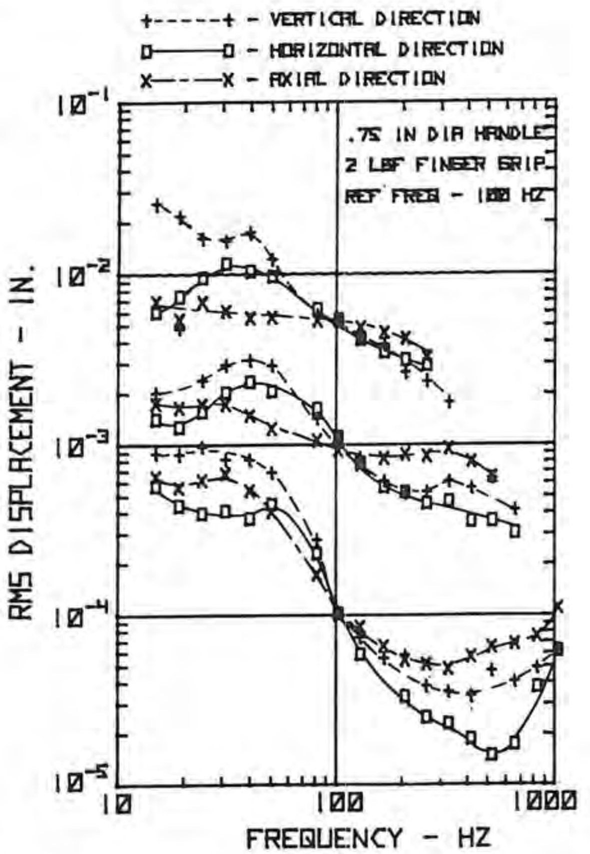

Figure 34. Discrete frequency equal sensation curves for vibration in the vertical, horizontal, and axial directions for 2 lb_f finger grip.

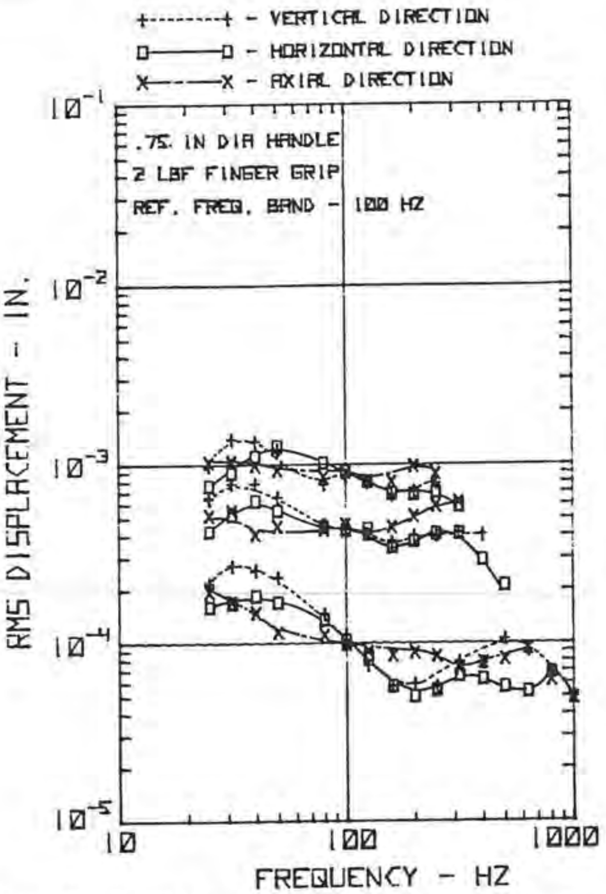

Figure 35. One-third octave broad band equal sensation curves for vibration in the vertical, horizontal, and axial directions for the 2 lb_f finger grip.

perceived sensation. Tonic receptors, as stated earlier, are more sensitive to static displacement than are phasic receptors. The number of action spikes fired or released in the connecting nerve fibers of a tonic receptor is directly related to the displacement amplitude of the stimulus. Thus, equal sensation associated with tonic receptors would be caused by equal displacements. The flattening of the equal sensation curves (meaning constant displacement for equal sensation) in the low and high frequency ranges as the vibration intensity was increased indicated that tonic receptors were possibly being used to determine the perceived sensation. As the intensity levels of the vibration increased, the contrast in the displacements necessary for equal sensation for low and high frequency vibration decreased.

Test subjects stated that low frequency vibration induced into the hand (20 Hz to 80 Hz) was felt in a region between the shoulder and wrist. The elbow and wrist are joints containing large numbers of tonic receptors such as Ruffini's endings and joint capsules and a small number of pacinian corpuscles (phasic receptor). Low frequency vibration induced into the hand caused movements or rotations of both the elbow and wrist. The movement of these joints would have been detected by the tonic receptors mentioned above. Thus, the use of Ruffini's endings and joint capsules (tonic receptors) and Meissner's corpuscles (phasic receptor tuned to low frequencies) could have possibly been responsible for an individual's perception of low frequency vibration.

Test subjects indicated that high frequency vibration (125 Hz to 1,000 Hz) was primarily localized to the hand and fingers. This region of the body contains Merkel's discs and Ruffini's endings (tonic receptors) embedded in the glabrous skin of the hand and pacinian corpuscles (phasic receptor) in the subcutaneous tissue of the hand. The cumulative detection of vibration by these receptors could possibly have resulted in the shapes of the equal sensation curves for high frequency vibration.

From the flattening of the equal sensation curves for ⅓-octave-band broad band vibration indicated by Figure 35, perhaps more tonic receptors than phasic receptors could be responsible for the perceived sensation due to broad band vibration. The role of the phasic receptors in the perception of broad band vibration may have been hampered by the random vibration within the frequency band. The unsteady, inconsistent pattern of vibration in the band may have caused subjects to rely heavily upon the steady output associated with the tonic receptors.

In Figures 36 through 39 are the results of the threshold and annoyance tests for discrete frequency vibration. As was the case with the equal sensation tests, the results indicated by these curves were a function of the direction of vibration and of the grip configuration used for the individual tests. Some interesting observations can be made with regard to the different vibration levels associated with the three directions of vibration that were required to produce annoyance. In general, the vibration levels required to produce annoyance were greatest in the axial direction and least in the vertical direction, although at lower frequencies, vibration in the vertical direction tended to be less annoying than the same vibration applied in the horizontal direction.

In Figures 40 through 42 are plotted the amplitudes of the instantaneous stored potential and kinetic energies, the dissipated energy, and the total energy directed into the hand for the 2 lb_f finger grip. These curves were obtained by substituting the appropriate measure data into equations (30) through (32). They indicate that, for vibration in the vertical direction above 100 Hz and in the horizontal and axial directions at all measured frequencies, almost all of the energy directed into the hand for the corresponding annoyance levels was dissipated. This fact supports the corresponding statements that were made in the mechanical impedance section. The curves also indicate that the energy required to produce annoyance decreased as frequency increased.

The curves representing the stored potential and kinetic energies for vibration in each of the three directions were plotted in Figure 43. These curves in-

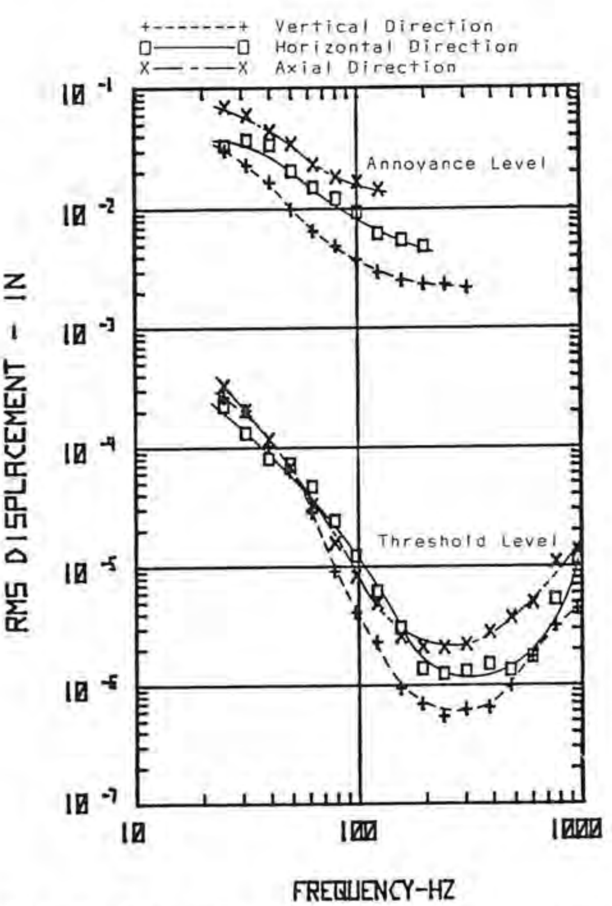

Figure 36. Discrete frequency threshold and annoyance level curves for vibration in the vertical, horizontal, and axial directions for the 2 lb, finger grip.

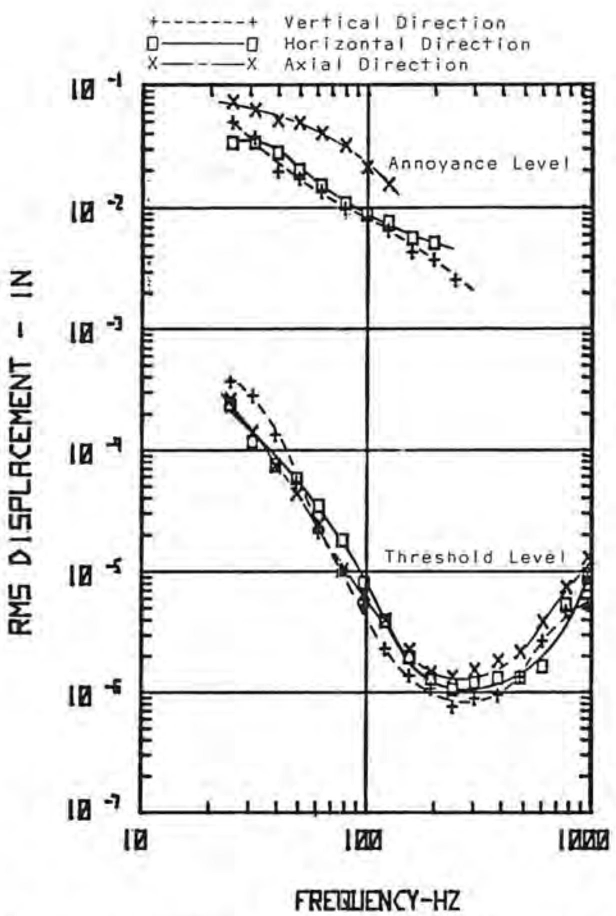

Figure 37. Discrete frequency threshold and annoyance level curves for vibration in the vertical, horizontal, and axial directions for the 8 lb, finger grip.

dicate that an individual's perception of annoyance is due primarily to the levels of energy that are necessary to cause the tissues to deform, or move, or both. Essentially, the test subjects did not perceive the energy that was dissipated in their hands while vibration was being directed into the hands. After the vibration was stopped, they sensed the results of this dissipated energy in the form of burning sensations and slight swellings of the hands and fingers. These results seem to be consistent with previous discussions on both the mechanical and subjective response characteristics of the hand and fingers.

Comparison of Results with Results Obtained by Other Investigators

As was mentioned in the Introduction, one of the problems associated with establishing a relationship between vibration exposure and the vibration syndrome is the lack of correlation between the results that have been obtained by different investigators. Thus, it is desirable to compare the results of this study with the results obtained by other investigators.

One of the investigations undertaken by Miwa was to establish threshold, unpleasant, and tolerance limit levels for hand-induced vibration.[13,16] Although Miwa used a plane vibration table against which his test subjects pressed the flat portion of the palm and fingers of their hand, rather than a vibrating handle, it is worthwhile to review his data. Miwa's data were presented in terms of acceleration, but it is possible to manipulate it and present it in terms of displacement. Miwa's tolerance, unpleasant, and threshold levels in terms of displacement as a function of frequency are presented in Figure 44. The threshold and annoyance curves for the 2 lb_f palm grip (vertical direction) are shown for comparison. The most important observation is that the threshold and tolerance limit curves obtained by Miwa approximate the threshold and annoyance level curves obtained during this study. Although the unpleasant level curve is formed of intermediate vibration levels, it does ex-

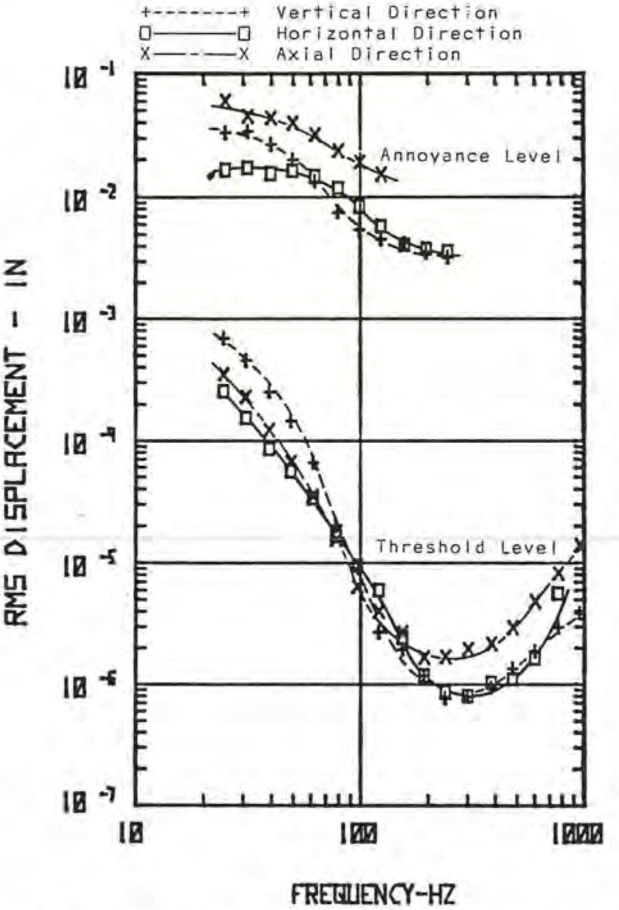

Figure 38. Discrete frequency threshold and annoyance level curves for vibration in the vertical, horizontal, and axial directions for the 2 lb_f palm grip.

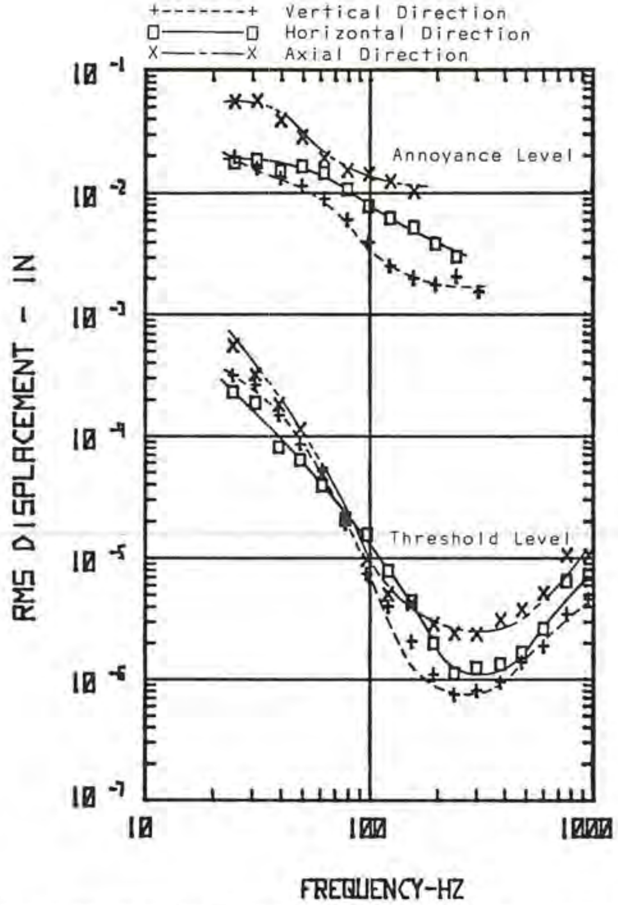

Figure 39. Discrete frequency threshold and annoyance level curves for vibration in the vertical, horizontal, and axial directions for the 8 lb_f palm grip.

hibit the same general shape as the annoyance level curves.

It is worthwhile to examine the criteria used to determine tolerance and unpleasant levels in Miwa's study. Each subject pressed his hand against the flat vibration table with a specified static force. The vibration level was increased by the test monitor, remaining constant at each level for 3 minutes. The subject was asked at each step whether the vibration was unpleasant or intolerable. If the subject found one level to be tolerable physically but stated that it was subjectively unbearable, the next increment was selected as the tolerance limit. Interestingly, even though the method used by Miwa to determine the tolerance levels was substantially different than that used for this study, the tolerance levels obtained by Miwa correlated very well with the annoyance levels determined by this study.

Mountcastle[33] investigated the threshold levels for both human and monkey subjects; the threshold level curves produced from his investigation are presented in Figure 45. The 2 lb_f palm grip (vertical direction) threshold level curve is superimposed on Mountcastle's curves for comparison. Although it was not the intent of this paper to analyze the data presented on monkey subjects, it should be noted that these curves have the same general shape as those presented for human subjects.

The most important observation that can be made with regard to Mountcastle's curves is that they exhibit the same general shape as those produced during this study. In both cases, the lowest threshold level occurred around 200 Hz. The threshold levels obtained by Mountcastle were appreciably lower at all frequencies than those developed during this investigation, probably because of differences in experimental technique. From the available literature, it was not possible to determine the equipment and experimental technique used by Mountcastle to obtain his data.

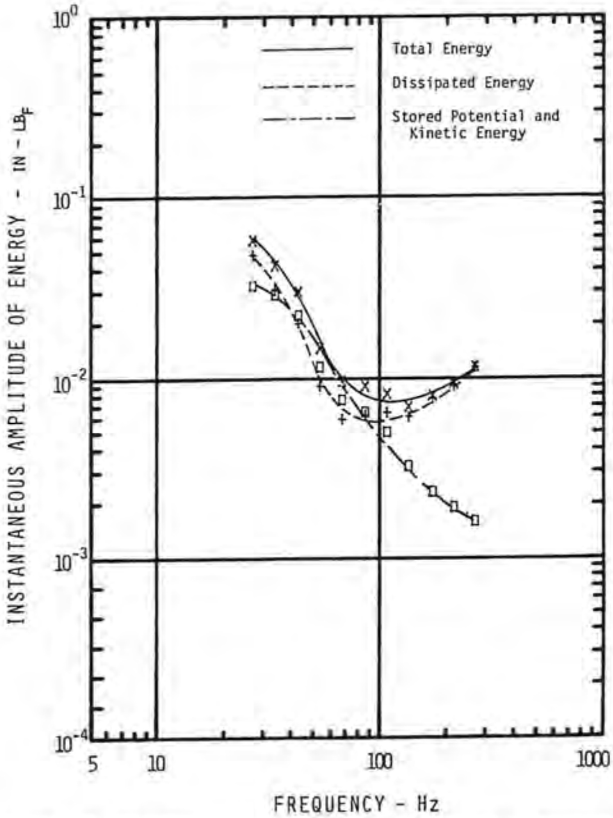

Figure 40. Spectrum of instantaneous energy directed into the hand for vibration in the vertical direction for the 2 lb, finger grip.

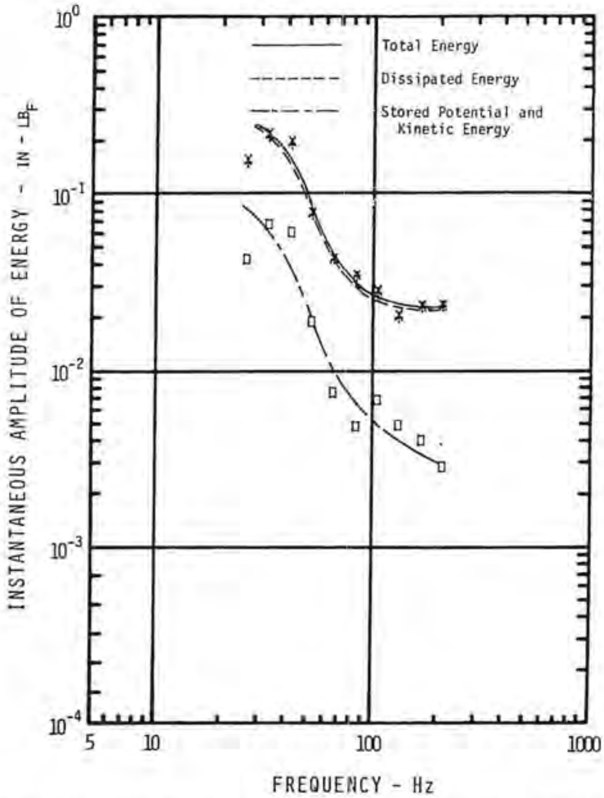

Figure 41. Spectrum of instantaneous energy directed into the hand for vibration in the horizontal direction for the 2 lb, finger grip.

CONCLUSIONS

The following statements can be made with regard to the results of this investigation.

1. The mechanical and subjective response characteristics of individuals to hand-induced vibration was a function of the manner in which a vibrating handle was clasped and the orientation of the vibration relative to the hand.
2. The mechanical model of the hand that was developed during this study was descriptive of the physical orientation and coupling that exist between the epidermis, dermis, subcutaneous, and muscle tissues and the skeletal system in the fingers and hand.
3. The results of the mechanical impedance tests and the curve fitting associated with the mechanical model tended to indicate that the vibration response of the hand (determined by measuring the vibration response of the hand, using a vibration input to the hand) was primarily indicative of only the local response characteristics of the hand and fingers.
4. The results of the mechanical impedance tests indicated that almost all of the energy directed into the hand and fingers at frequencies above 100 Hz for vibration in the vertical direction and at all frequencies for vibration in the horizontal and axial directions was either absorbed or dissipated in the hand and arm.
5. The results of the curve fitting associated with the mechanical model of the hand and the transmissibility tests indicated that vibration at frequencies above 100 Hz directed into the hand, or fingers, or both was isolated at the hand and fingers.
6. From the above results, it can also be inferred that vibration at frequencies above 150 Hz to 200 Hz tended to be isolated at the areas of the hand and fingers directly in contact with the vibrating handle. The mechanical model implied that this vibration was isolated to the epidermis, dermis, and subcutaneous tissues adjacent to the vibrating handle.
7. The results of the transmissibility tests indicated that the attenuation of vibration up the arm occurred in the tissue adjacent to the bone and not in the bone.
8. From the results of the transmissibility tests, it can be inferred that there was little attenuation of vibration across joints but that large relative motions across joints could exist.

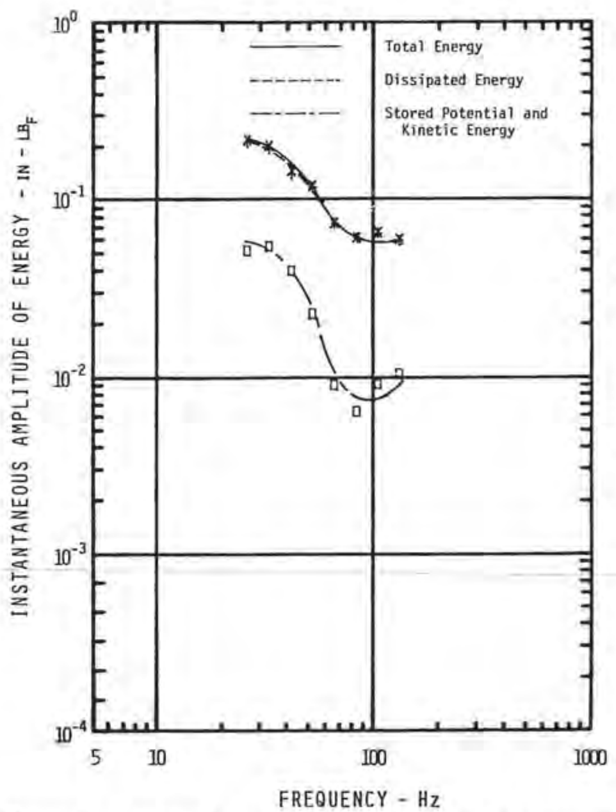

Figure 42. Spectrum of instantaneous energy directed into the hand for vibration in the axial direction for the 2 lb$_f$ finger grip.

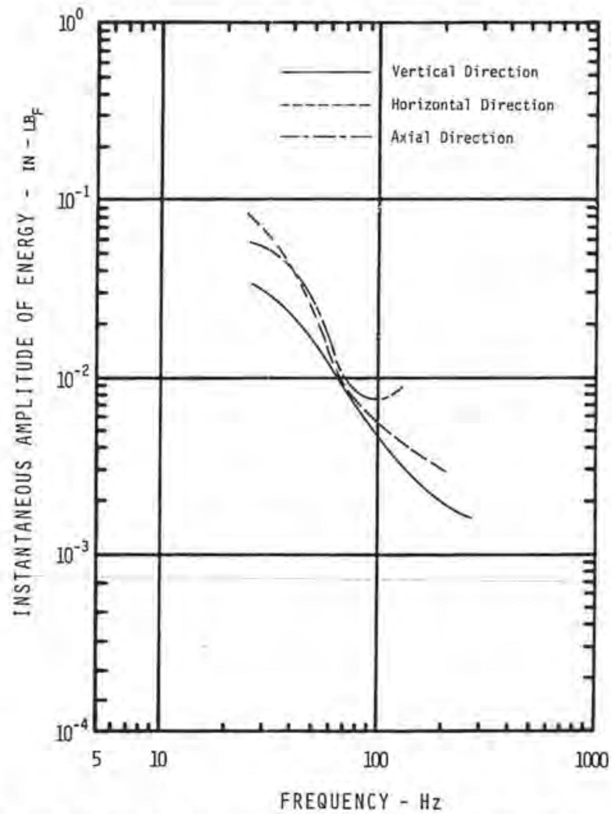

Figure 43. Amplitudes of the instantaneous stored potential and kinetic energies for vibration in the vertical, horizontal, and axial directions for the 2 lb$_f$ finger grip.

9. The results of the subjective response tests indicated that Ruffini's endings and joint capsules (tonic receptors) and Meissner's corpuscles (phasic receptors) were responsible for an individual's subjective response to low-frequency, discrete-frequency, hand-induced vibration. These results indicated that Merkel's discs and Ruffini's endings (tonic receptors) and pacinian corpuscles (phasic receptors) were responsible for an individual's subjective response to high-frequency discrete-frequency vibration.
10. The results of the subjective response tests indicated that an individual's response to broad-band hand-induced vibration was determined by the response characteristics of tonic receptors.
11. The results of the mechanical impedance and annoyance tests indicated that an individual's perception of annoyance caused by hand-induced vibration was based primarily on the stored potential and kinetic energies induced into the hand by a vibrating source. In most cases, this comprised a very small portion of the total energy directed into the hand.
12. The results of the mechanical impedance and annoyance tests implied that an individual did not perceive the energy directed into his hand that was absorbed or dissipated by the hand. This absorbed or dissipated energy generally comprised almost all of the energy directed into the hand by a vibrating source.
13. Subjective response data used to establish hazardous-hand-vibration criteria is of questionable value, based on the results above (paragraphs 1 through 12).
14. From the facts that high frequency vibration (above 100 Hz to 200 Hz) is isolated to the fingers (and possibly to the epidermis, dermis, and subcutaneous tissues) and that almost all of the energy associated with this high frequency vibration is dissipated, it can be inferred that high frequency vibration is in part responsible for the destructive effects associated with the vibration syndrome.

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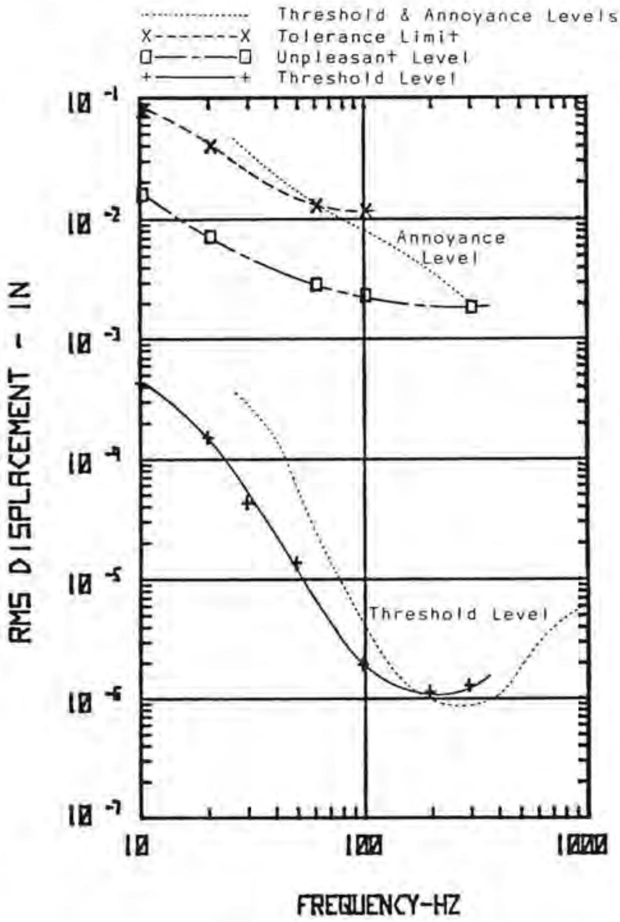

Figure 44. Comparison of 2 lb, palm grip threshold and annoyance level curves with the threshold, unpleasant, and tolerance limit curves obtained from the data of Miwa.

Safety and Health for sponsoring this 3-year research project; D. E. Wasserman and H. H. Cohen were the NIOSH co-technical advisors to this study. Finally, much gratitude is expressed for all of the students who volunteered their time as test subjects for this project.

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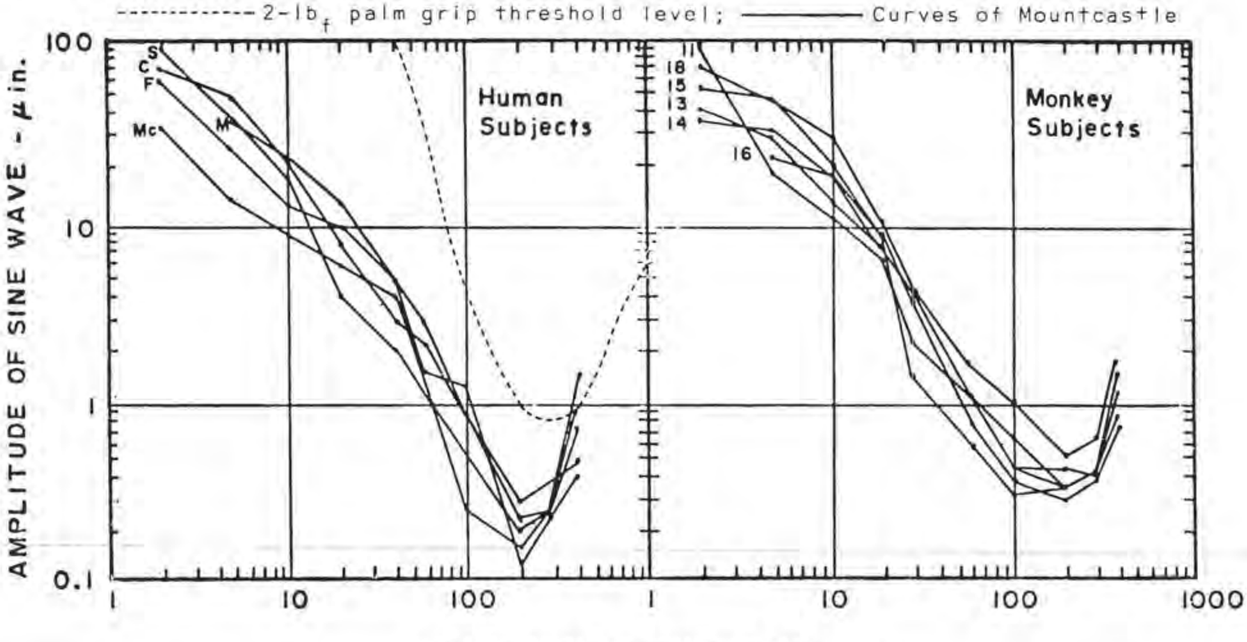

Figure 45. Comparison of 2 lb, palm grip threshold curve with the frequency threshold functions for five human subjects and six monkey subjects obtained by Mountcastle.

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QUESTIONS, ANSWERS, AND COMMENTARY

Question (G. C. Agarwal, University of Illinois): I have a couple of questions. One is, I didn't see any numerical values for m, c, and k. How sensitive are these numbers when you get nine parameters that you are fitting by some kind of curve fitting technique? You are going to have a lot of sensitivity problems?

Answer: What we did was devise a system of damping coefficients, resonant frequencies, and ratios of masses that all resulted from the overall development of the model. Then we worked with these parameters. We used a brute force, trial and error, parametric fit technique to identify the parameters. I feel confident that the curve fit we achieved was about the best we could do. When the values of these parameters were from the optimum values, substantial variation from the measured impedance curves occurred. The model was very sensitive to the values associated with k_3 and c_3 because they are very large. It was not very sensitive to k_2 and c_2 because these values were relatively small. So there were some of the parameters that the model was very sensitive to and there were other parameters in which there was quite a bit of latitude as to how they could be varied. I don't say that these are the absolute values of the corresponding parameters. The values of the parameters that were presented, however, yielded a good fit with regard to the measured data. I think the important thing is not the actual values of the parameters but rather the overall implication of the model itself and the fact that we observed and were able to obtain the same trends with regard to relative values between all the parameters throughout all the tests that we ran.

Question (G. Agarwal): In this case, were the c's and k's dependent on the grip force and frequency input?

Answer: They're independent of frequency.

Question (G. Agarwal): How can that be true because you were just fitting the total curve. Did you try to fit sections of the curve? Are c and k dependent on that?

Answer: No, because you have a three-degree-of-freedom system, you have to treat your system in its entirety. In other words, the model was a three-degree-of-freedom system model. Now the value of these parameters was a function of grip force, grip type, and direction of vibration. The corresponding values of these parameters were inserted into the mobility equation, which was a function of frequency, and then we obtained the final results.

Question (G. Agarwal): Well, the way you are doing it, yes; there would be an independence of frequency because you are assuming a linear system. But my feeling is this is not entirely a linear system. My last question concerns the phase shift you've shown. Does it depend on, for example, the transmission delay of the vibration? Because you have taken a lumped system rather than a distributed system. Is it a distributed system with corresponding phase shift? How much of this can you account for simply by the time delay?

Answer: We ran calibration curves for our phase information. Therefore, I believe the phase information that we measured was, in fact, the phase between the force and the displacement signals.

Question (H. Rafalski, IMS Medical Academy): Can you take your data of transmission vibration into other areas of the hand and arm and correlate it to my data according to response of blood vessels, muscular change, and bone changes? We find in the fingers, wrist, forearm, and elbow there was less influence of vibration than on the shoulder. Can you comment on transmission of vibration in these terms?

Answer: Well, I would say that high levels of low frequency vibration transmitted to the arm could partly be responsible for bone deformation damage in the arm. Looking to transmissibility, I would say that as frequency increases, the corresponding bone damage would travel down the arm. Now one thing our data did indicate was that on the average, there was very little vibration attenuation across the joints. It did indicate, however, there was substantial relative motion within the joint. Thus, if resonances are present in the joint, it is possible for the joint to experience twice or even more motion than is actually implied by the initial signals directed into the hand. I would say then this could result over a long period of time in bone damage at the joint.

Question (D. Koradecka, Central Institute for Labour Protection): The parameters of resonance include elastic components that tend to change according to muscular movements, and they change as a result of various disorders. For example, in muscles of the legs, you have resonances of about 8 to 11 Hz. During stress, you have resonances of about 30 to 40 Hz. So if you look at the phenomenon of resonance exchanges, don't you have different coefficients, depending mostly on dynamic and not static parameters?

Answer: I think one of the biggest problems in making any type of dynamic measurements is interpreting the results. Actually making the measurements is about 10% of the problem. Interpreting them and knowing what you have after you make the measurements are about 90% of the problem. As we vibrate the hand with low frequency vibration, we feel it up in the shoulder area, and as frequency is increased, the sensation of vibration creeps down the hand. It has long been thought that any mechanical model that we have of the hand ought to include the masses that correspond to mass of the hand, mass of the forearm, upper arm, etc. The identifying values of the masses that we measured did not indicate this was true. If we look at the very strong correlation to the actual physical situation that exists in the skin itself, between the finger and the bone, the strong implication (and I'm not going to say that this is the absolute implication) is that the measured driving point mechanical impedance of the hand gives only the mechanical response characteristics of that area of the hand directly in contact with the vibrating handle. I realize that's a very strong statement to make, but this is what our data indicate.

Comment and questions (H. Von Gierke, Aerospace Medical Research Laboratory): Many models are made to evaluate the vibration in connection with the tool, and certainly if you have tools of different weights, you need the whole mass as well as the mass of the arm and of the shoulder, and that of the man. So you still need the whole system to describe the effects of vibration.

I have two questions. When you based your model on these three degrees of freedom, which you indicated, did you have any measurements on the linearity of the whole system? Because you usually observe damage in tissue in the range where it becomes nonlinear and in the linear range we hardly observe damage, which of these three degrees first becomes nonlinear?

Answer: These are hard questions to answer, and it takes a lot of measurements to determine it. In the measurements that were made in earlier studies, we excited the hand with different levels of forces, measured the response, and then looked at the relation that existed between the data from the different tests. We used very strong levels of excitation and very weak levels of excitation, and in most cases, the average of these curves pretty much overlapped. I believe that there will probably be extremely high amplitudes where you will force the system into a nonlinear region. For modeling purposes that gets to be a very difficult problem, and so we've just limited our analysis to a linear system approach.

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