RESPONSE OF THE HAND-ARM SYSTEM TO VIBRATION

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A complex of vascular, neurological and musculo-skeletal disturbances, often referred to as the hand-arm vibration syndrome, may occur among operators of hand-held power tools. The driving-point mechanical impedance of the hand-arm has been extensively investigated to enhance an understanding of its biodynamic response to vibration excitations, and to permit development of effective vibration isolators. Although, the impedance characteristics of the hand-arm have, invariably, been measured on human subjects under carefully controlled test conditions, considerable deviations exist among the impedance data reported by different investigators. These deviations may be attributed to the strong dependence of the biodynamic response of the hand-arm on: (*i*) grip and thrust forces; (*ii*) posture; (*iii*) anthropometric parameters of the hand-arm; (*iv*) amplitude and nature of vibration excitation; and (*v*) the nonlinear properties of the biological materials.

In this study, the test procedures and measured driving-point mechanical impedance data reported in published studies are analyzed to synthesize the envelopes of mean values of impedance magnitude and phase, as a function of the excitation frequency. The weighted mean values, derived for each of the three orthogonal directions of vibration specified by ISO 5349 [1], are considered to characterize the idealized driving-point impedance of the human hand-arm system. A lumped-parameter four-degrees-of-freedom (DOF) model of the hand-arm system is developed using the *idealized* impedance characteristics in conjunction with a nonlinear programming based optimization algorithm.

SYNTHESIS OF DRIVING-POINT IMPEDANCE DATA

Driving-point mechanical impedance, widely used to describe the dynamic properties of the hand-arm system, is defined as the ratio of the complex driving force to the complex velocity measured at the driving point. Mechanical compliance and accelerance have also been employed to describe the biodynamic response of the hand-arm system. The mechanical impedance, compliance or accelerance properties of the human hand-arm have been measured using different experimental methods, number of male subjects, amplitude and nature of vibration excitations, grip force, response variables, handle size and elbow angle. The range of test variables, employed in various studies, are summarized below:

Direction of Vibration:	X_h and / or Y_h and / or Z_h
Test Handle:	Circular (Diameter 19-45 mm) Elliptical (31x 42 mm)
Grip Force:	Constant magnitude (10-200 N)
Frequency Range:	From 8-200 Hz to 20-2000 Hz
Nature of Vibration:	Sine sweep, pseudo-random, random or impulse of varying magnitudes.
Response Variable:	Impedance, compliance, accelerance
Elbow Angle:	Ranging from 50-180 degrees
Number of Subjects:	Ranging from 1 to 75

In view of above variations and the expected discrepancies among the results, the driving-point impedance characteristics reported for similar test conditions were analyzed to derive the range of *idealized* values of impedance magnitude and phase. Based upon the most common range of variables used in different studies, 9 impedance data reported in the published studies [2-9], were selected for synthesis. The reported data were selected when: (*i*) both magnitude and phase were reported in the 20-500 Hz frequency range; (*ii*) data was reported for either one or more orthogonal axes conforming with ISO 5349; (*iii*) the grip force was in 25-50 N range; and (*iv*) elbow angle was close to 90°.

The driving-point impedance data, reported in selected studies, are compared for all three orthogonal axes. In order to compare the data, the reported compliance data was converted to the equivalent impedance. Figure 1 illustrates the differences and similarities among the magnitude and phase data reported for Z_h direction. The two data sets reported by Gurram [8], and Reynolds [6] were obtained using sine-sweep and random excitations, and different handle sizes, respectively. Although most data sets exhibit a impedance magnitude peak in the 20-50 Hz frequency band, the magnitude data reported in [2,4,9] differ considerably from the entire ensemble in the frequency range 20-50 Hz, and above 500 Hz. While the impedance phase data does not indicate a definite trend, the data reported in [4,7,8 (random excitation only)] evidently form the outliers.

Sources of Variability

Although all the studies included in this analysis employed similar range of vibration frequencies, closely controlled grip forces, elbow angles, direction of vibration, and four or more male subjects, the comparison of the reported data revealed large variations in the impedance magnitude and phase. While these variations are quite disturbing and lead to questions concerning the validity of measurement procedures, it is extremely difficult to identify the sources of variability. The variations in hand-arm impedance evidenced in one investigation due to changes in a single parameter are therefore examined to determine some of the sources of variability, summarized below:

- Impedance magnitude measured under random vibrations is similar to that measured under sinusoidal excitations, while the phase response measured under random excitations tends to be somewhat greater [8].
- The X_h component of impedance is relatively insensitive to magnitude of sinusoidal excitation at frequencies above 250 Hz, the impedance magnitude and phase at lower frequencies however vary with the level of excitation [2].
- The impedance magnitude measured in all directions using a large diameter handle tends to be larger than that measured using a smaller diameter handle. The influence of handle size on the phase response, however, is insignificant [6].

Most Probable Values of Human Hand-Arm Impedance

The differences in mean values of impedance, and the patterns of agreements or disagreements among various studies serve to justify the exclusion of data that form the outliers from the synthesis. The range of most probable values of impedance magnitude and phase of the human hand-arm are derived from the envelopes of the mean values reported in selected studies for all three axes in the 10-1000 Hz frequency range. The envelop curves, smoothened using segmental cubic spline functions, define the range of mean values of all the selected data sets and may be considered to characterize the range of *idealized* values of the human male hand-arm impedance in all three directions. Figure 2 illustrates the range of Z_h component of *idealized* or most probable impedance magnitude and phase values. The impedance data that fall within the range of *idealized* values may be considered acceptable representations of the human hand-arm impedance. The weighted mean values of data sets included in this analysis are computed and illustrated as the central dotted curve in Fig. 2.

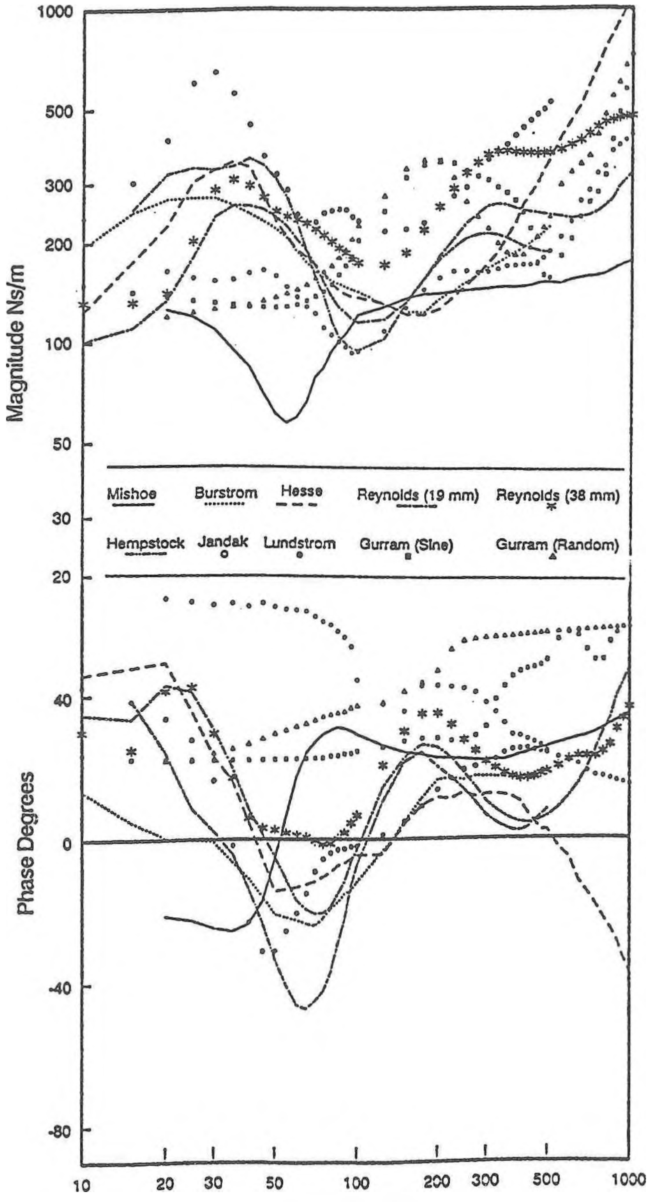

Fig. 1: Comparison of Z_h component of driving-point impedance.

Hand-Arm Impedance Model

A four-DOF lumped-parameter model of the hand-arm system is formulated for each orthogonal axis using the *idealized* impedance magnitude and phase values. A constrained optimization function, comprising the magnitude and phase erros between the *idealized* and model response, is formaulated for excitations in the 10-1000 Hz frequency range [8]. A sequential search algorithm is used to derive the hand-arm impedance model parameters for each orthogonal axis. A comparison of the model response (dashed curve) with the *idealized* values, shown in Fig. 2, reveals good agreement in both the impedance magnitude and phase response.

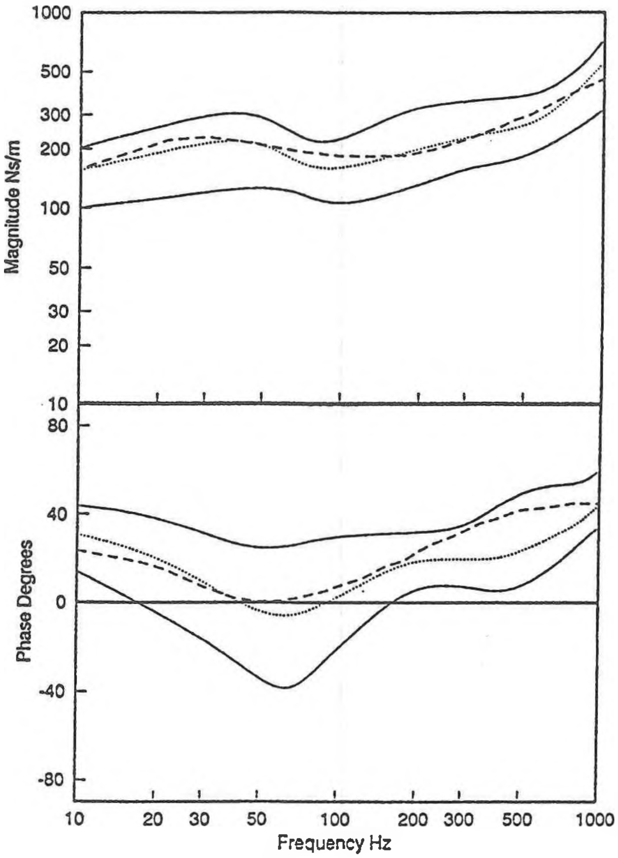

Fig. 2: Mean, range of *idealized* values, and the model response of impedance in the Z_h direction.

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