HAND-ARM VIBRATION: IMPLICATIONS DRAWN FROM LUMPED PARAMETER MODELS

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ABSTRACT

Models of the hand-arm complex are given; these are developed from mechanical impedance data, and describe the combination as a three-degree-of-freedom system, consisting of three masses, interconnected by springs and dampers. The mass actually vibrating decreases as frequency increases because of low transmissibility at higher frequencies. Absorbed power was found to increase both along an equal sensation line and along the ISO tentative exposure hand-arm standards.

INTRODUCTION

Although the correlation between exposure of the hand to vibration and Raynaud's phenomenon is well established, the mechanism of the damage is obscure. Histological and blood flow studies of the hand have contributed significantly to our understanding of the mechanism. However, good dynamic models are needed to determine vibration transmissibility to a given tissue, frequencies involved, spring rate (stiffness), damping, and power absorption.

The objective of this study was to measure mechanical impedance and develop dynamic models of the hand-arm system. Further objectives were to determine "absorbed power" for various input frequency spectra including equal sensation curves and ISO hand-arm tentative standards.

METHODS

Driving point mechanical impedance methods were used because they yield the dynamic response of the entire hand-arm system without requiring attachment of transducers to the body. Recently developed micro-accelerometers attached to the surface may now make it possible to measure the dynamic response of various small body components such as fingers.

The system providing the vibration (Figure 1) consisted of a sweep oscillator to scan across the frequency range of interest, an acceleration controller, and a power amplifier driving an electrodynamic shaker. An impedance head, which sensed force and acceleration, was used to physically connect the shaker output to the handle that the subject gripped. A round handle split longitudinally and fitted with strain gauges provided a measure of the subject's grip, which could be continuously monitored on a meter dial.

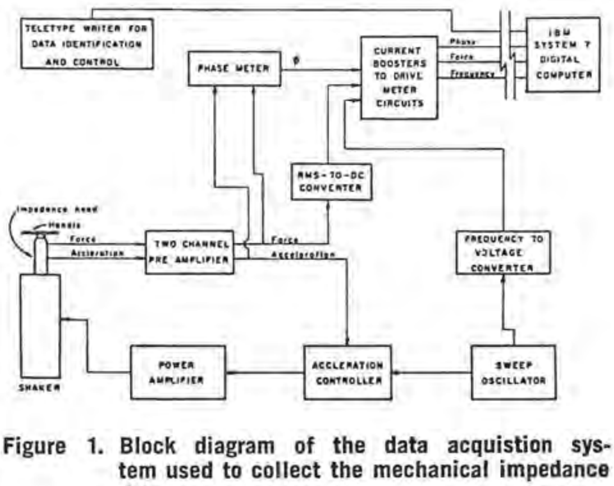


Figure 1. Block diagram of the data acquistion system used to collect the mechanical impedance data.

Output signals were amplified, and phase was determined. Inputs to a current booster, a force signal, and a signal proportional to frequency were obtained. Acceleration was held constant through each test so that it could be included in the calculation of the scale factor. These signals, along with appropriate calibration factors, were then transmitted on-line to a digital computer for storage, calculation of mechanical impedance, and calculations associated with modeling. A "T" shaped handle consisting of a tube welded to a piece of flat metal stock, the lower end of which was attached to the shaker, was used in the vertical and front to rear directions of excitations. An "I" shaped handle, the lower end of which was attached to the shaker, was used in the transverse excitations; see Wood and Suggs[1] for a diagram of the split handle. Dynamic responses of the two handles were determined so that impedance data could be corrected to reflect the characteristics of the subject's hand and arm.

RESULTS

Mechanical Impedance

The transverse (A_x) mechanical impedance response of subject JP, approximately characteristic of the group, shows a minimum at about 300 Hz preceded by a region of spring-like behavior and followed by a region of mass-like behavior (Figure 2).

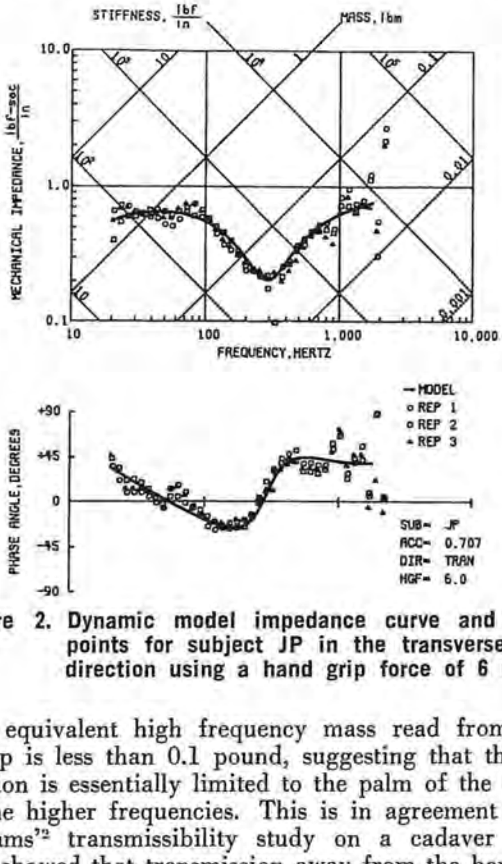


Figure 2. Dynamic model impedance curve and data points for subject JP in the transverse (A_x) direction using a hand grip force of 6 lb.

The equivalent high frequency mass read from the group is less than 0.1 pound, suggesting that the vibration is essentially limited to the palm of the hand at the higher frequencies. This is in agreement with Abrams'[12] transmissibility study on a cadaver arm that showed that transmission away from the hand at 250 Hz was approximately 5%.

Impedance in the vertical (A_y) direction (hand palm down) (Figure 3) with the force driving the hand by means of compression of the palm tissue is different from the transverse (A_x) result where the excitation force acts on the palm in shear. The curve shows a low frequency behavior dominated by a mass of about 1 pound up to 100 Hz followed by a damper response to about 500 Hz. The higher frequencies are again dominated by a mass, but the mass is about twice as large as the one in the transverse curve.

The impedance response to proximal-distal (A_z) vibration (along the direction of the lower arm) (Figure 4) is appreciably different from the other

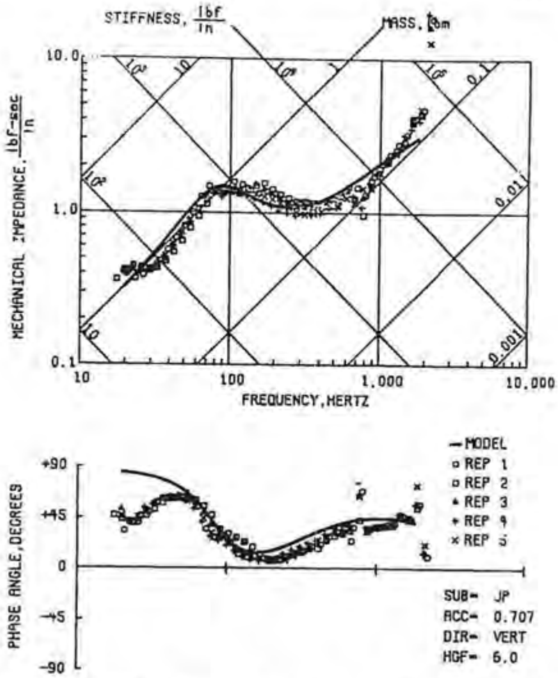
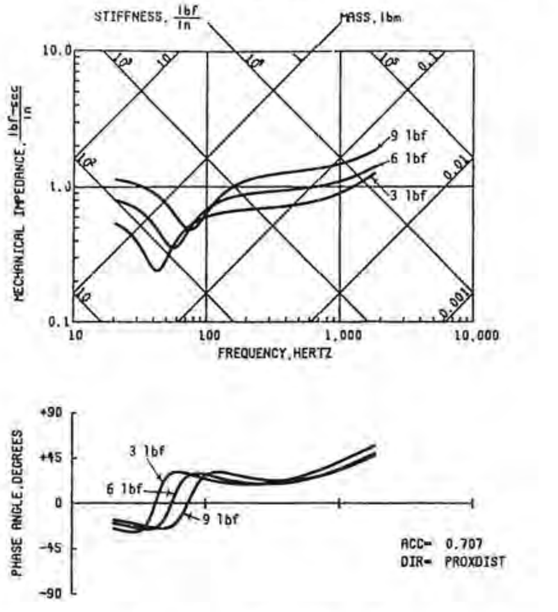


Figure 3. Dynamic model impedance curve and data points for subject JP in the vertical (approximately A_y) direction using a hand grip force of 6 lb. The model parameter values are M1 = 0.009; M2 = 0.15; M3 = 0.81; C1 = 4.70; C2 = 1.06; K1 = 69.2; K2 = 699.



Hand Grip	M1	C1	K1	M2	C2	K2	M3	C3	K3
3	0.036	0.67	7.85	0.051	0.58	646	1.1	0.37	227
6	0.037	0.91	8.67	0.051	0.58	642	1.08	0.58	398
9	0.046	1.24	8.86	0.05	0.50	640	0.97	0.79	649

Figure 4. Dynamic model impedance curve for proximal-distal (approximately A_z) excitation.

two directions in that there is a minimum below 100 Hz. Also, the low frequency response is spring-like instead of mass-like. We would expect a different response because the exciter, acting along the line of the forearm, is more directly coupled with the torso.

Models

A lumped parameter mass-excited model consisting of three masses connected by springs and dampers in parallel (Figure 5) was capable of representing the response to vertical and transverse acceleration. For proximal-distal excitation, it was necessary to add a spring and parallel damper to connect the mass most remote from the input to ground (Figure 6). The spring-damper attachment to ground appears to be associated with the better coupling between the hand and upper torso when the excitation is along the forearm.

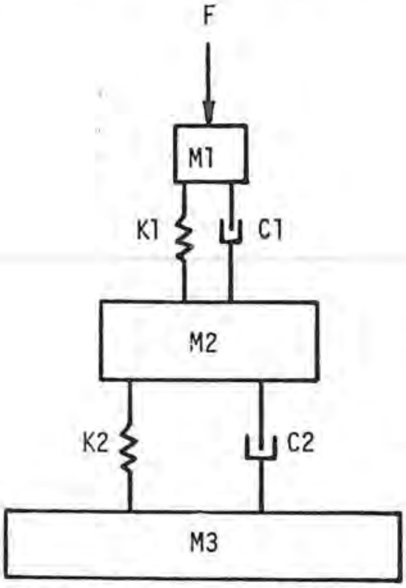


Figure 5. Dynamic hand-arm model for transverse (A_x) and vertical (A_y) excitation. See Figures 3, 4, 7, and 8 for typical model values.

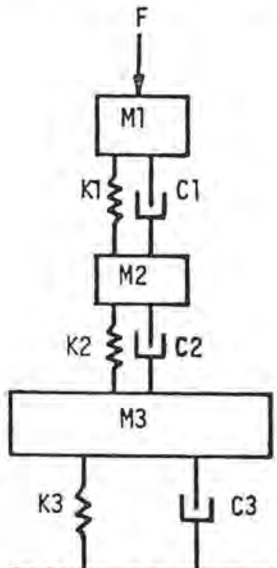
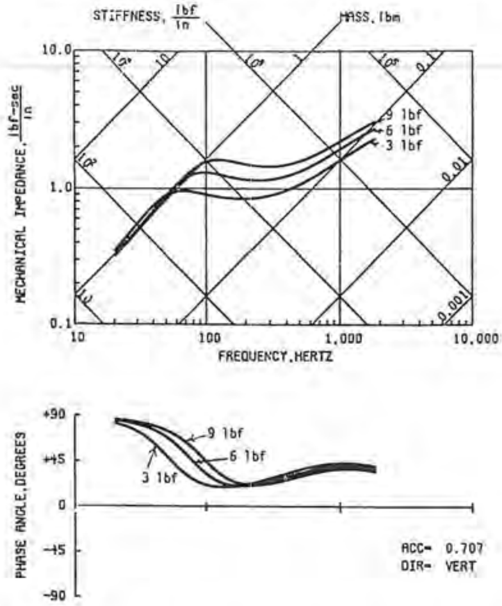


Figure 6. Hand-arm model for proximal-distal (A_z) excitation. See Figure 9 for typical model values.

Grip Force

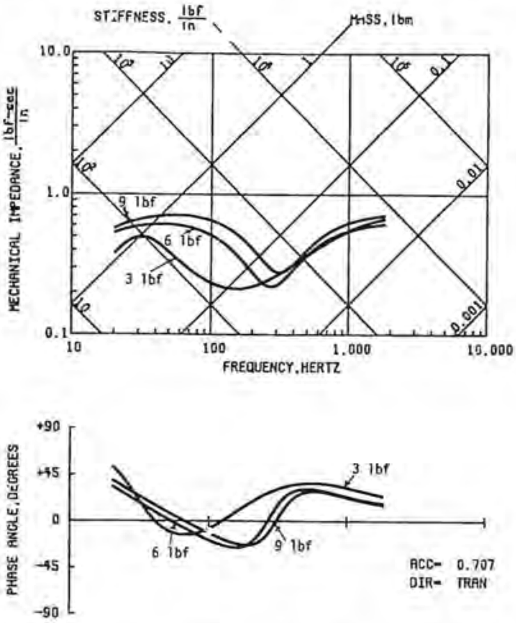
The use of a split handle instrumented with strain gauges made it possible to control hand grip at the desired levels of 3, 6, and 9 pounds of force, which covers the range normally used with hand tools. Increasing grip force caused an increase in the mechanical impedance values. For all directions of excitation (Figures 4, 7, 8), the coupling between the handle and hand is improved as grip force is increased; this results in higher mechanical impedance and, unless there is a concurrent shift of the phase angle further away from zero, an increase in absorbed power.



Hand Grip	M1	C1	K1	M2	C2	K2	M3
3	0.0098	3.05	68.5	0.12	0.92	307	0.84
6	0.009	3.67	69.1	0.14	1.24	639	0.78
9	0.008	4.19	69.4	0.17	1.58	1032	0.77

Figure 7. Effect of hand grip on mechanical impedance, vertical (A_y) excitation.

Increases in grip force resulted in appreciable increases in the M2, C2, and K2 parameters for both the vertical and transverse directions of excitation (Table 1). For the proximal-distal direction, the changes are concentrated in C3 and K3, the parameters not present in the other two directions.



Hand Grip	M1	C1	K1	M2	C2	K2	M3
3	0.002	0.73	9.9	0.06	0.26	125	0.93
6	0.0018	0.63	10.3	0.09	0.31	682	2.08
9	0.0017	0.73	10.5	0.1	0.40	1047	2.13

Figure 8. Effect of hand grip on mechanical impedance, transverse (A_x) excitation.

Table 1. Percent increase in parameter values as grip force increased from 3 to 9 pounds, 0.707 g (rms) excitation

Excitation direction	M1*	C1†	K1‡	M2	C2	K2	M3	C3	K3
Vertical A_y	−18	37	1	42	72	236	−8	–	–
Transverse A_x	−15	0	−6	67	53	738	129	–	–
Proximal-distal A_z	28	85	13	−2	−16	−16	−1	114	186

* Pounds mass.
† lb f-sec/in.
‡ lb f/in.

Acceleration Level

A system that can be exactly represented by masses, linear springs, and viscous dampers would be *linear;* that is, its mechanical impedance would not change with excitation intensity (acceleration). The human hand-arm system is not linear (Figure 9), but in the vertical direction, the deviations are not large in the excitation range between 0.707g and 3.50g (rms).

Absorbed Power

Power can be calculated by multiplying mechanical impedance by the square of the velocity. Absorbed or dissipated power is the real part of the total power and can be calculated by multiplying by the cosine of the phase angle. In the model, it represents the rate

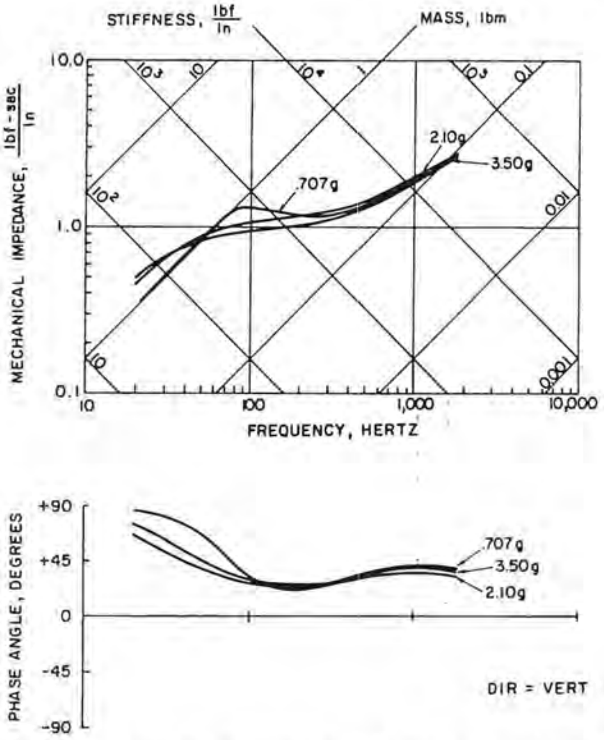


Figure 9. Effect of acceleration level on mechanical impedance.

at which energy is degraded into heat by the dampers. In the real system, it represents the rate at which work is being done on the hand-arm, most being degraded into heat but possibly some being used to modify or break down structure. Hence, there is some thought that constant levels of absorbed power should represent equal comfort levels or perhaps equal damage risks.

Using the impedance response of a typical subject in the vertical direction in conjunction with the equal sensation curve of Mishoe and Suggs,[3] it is possible to construct an absorbed power curve (Figure 10). Clearly, the absorbed power of the equal sensation curve is not constant over frequency. In fact, the absorbed power increases rapidly with frequency; this suggests that at higher frequencies the vibration is progressively better isolated from the mechanisms that sense comfort.

Absorbed power along the ISO[4] tentative hand-arm exposure curve (Figure 11) is not constant over frequency but increases with frequency as it did for the equal sensation curve. Thus, our work fails to support the concept that equal absorbed power represents equal comfort.

Transmissibility

The hand and arm form a good isolation system so that at higher frequencies relatively little vibration is transmitted to the arm. In fact, it appears from the

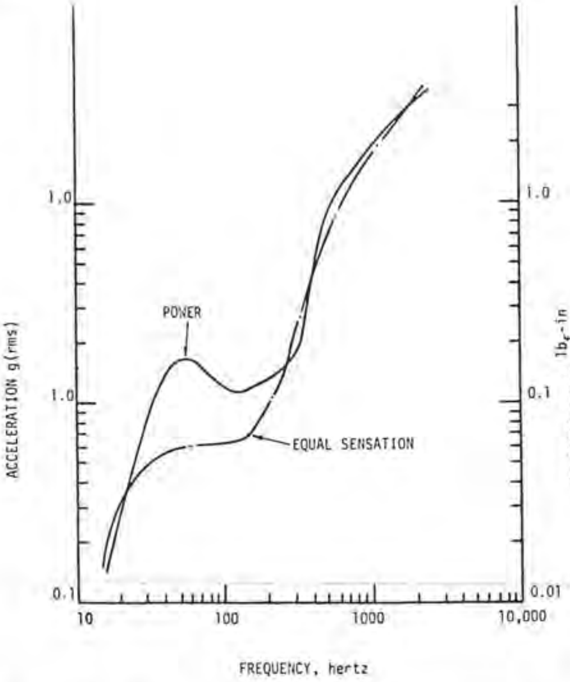


Figure 10. Absorbed power versus frequency for the equal sensation line shown.

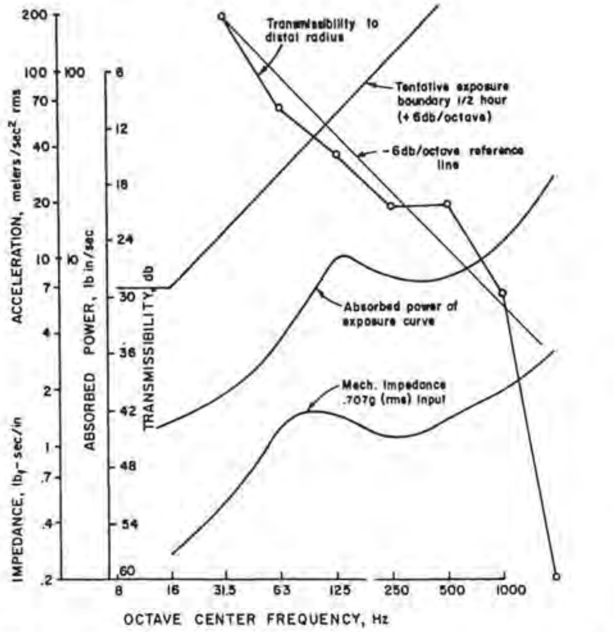


Figure 11. Comparison of absorbed power, transmissibility, mechanical impedance, and the ISO tentative exposure boundary.

impedance curves shown that most of the higher frequencies are isolated in the palm. A curve of transmissibility[5] shows a frequency attenuation of approximately 6 db per octave. Simultaneous consideration of this curve with either of the absorbed power curves suggests that as frequency increases, increasingly more power is being absorbed in increasingly less tissue. The mode of absorption cannot be determined from the model of the measurements. Thus, the relationship between frequency and the proportion of the absorbed energy involved in modifying hand structure, as opposed to being degraded directly into heat, is not known.

Equal Sensation

Comparison of the ISO[4] tentative exposure boundary with equal sensation results (Figure 12) shows

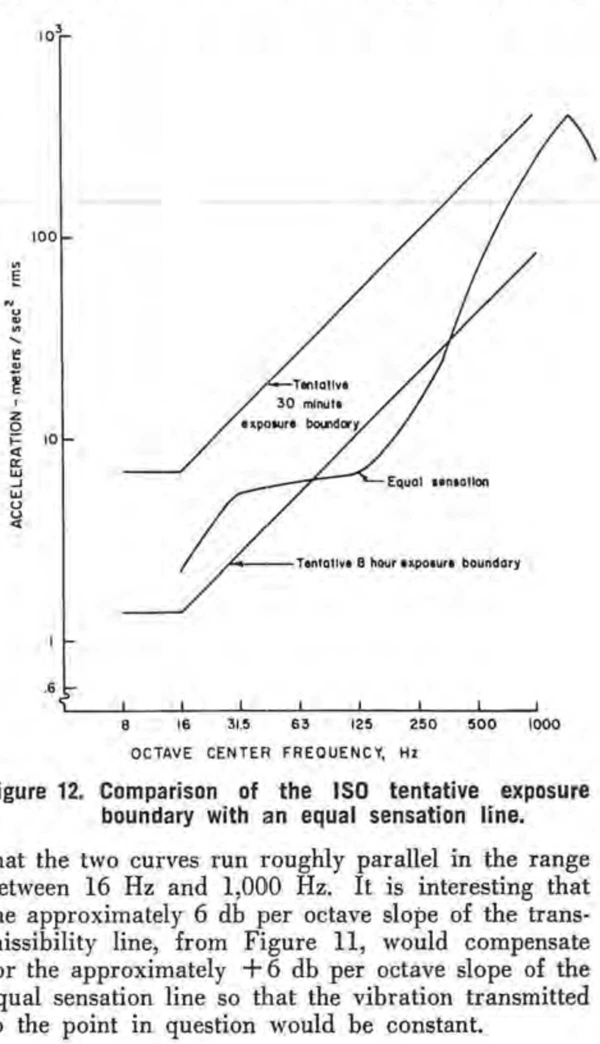


Figure 12. Comparison of the ISO tentative exposure boundary with an equal sensation line.

that the two curves run roughly parallel in the range between 16 Hz and 1,000 Hz. It is interesting that the approximately 6 db per octave slope of the transmissibility line, from Figure 11, would compensate for the approximately +6 db per octave slope of the equal sensation line so that the vibration transmitted to the point in question would be constant.

SUMMARY AND CONCLUSIONS

Lumped parameter approximations of the distributed parameter configuration of the hand-arm system have yielded solutions and models that have been useful in understanding and explaining observed responses. Mechanical impedance models show the frequency response from which vibration transmissibility can be inferred. Absorbed power is also available from mechanical impedance. These results show that power absorption increases with frequency both along an equal sensation curve and along the ISO tentative exposure boundary. Reduced transmissibility at high frequencies leads to the conclusion that power absorption at higher frequencies is primarily localized near the area of input.

REFERENCES

1. Wood, L. A., and Suggs, C. W.: A distributed parameter dynamic model of the human forearm. Proceedings, International Occupational Hand-Arm Vibration Conference. Cincinnati, Ohio. October 28-31, 1975.
2. Abrams, C. F.: A study of the transmission of high frequency vibration in the human arm. M.S. Thesis. North Carolina State University, Raleigh, N.C., 1969.
3. Mishoe, J. W., and Suggs, C. W.: Hand-arm vibration Part 1. Subjective response to single and multi-direction sinusoidal and non-sinusoidal excitation. J. Sound Vib. 35(4):479-488, 1974.
4. International Standards Organization: Draft proposal for guide for the measurement and the evaluation of human exposure to vibration transmitted to the hand. ISO/TC108/SC4, Sept. 1975.
5. Suggs, C. W.: Vibration of machine handles and controls and propagation through the hands and arms. 4th International Ergonomics Congress 6-10 July, Strassbourg, France, 1970.

QUESTIONS, ANSWERS, AND COMMENTARY

Professor Suggs' presentation was sequentially combined with that of L. A. Wood; Professor Suggs' answers to questions directed to both papers follow the next paper.

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