Vibration Injury Network

Research Network on Detection and Prevention of Injuries due to Occupational Vibration Exposures

Review of experimental studies of the biodynamic properties of the hand and arm

Appendix H3B to Final Report

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prepared by P. Lenzuni, PhD
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1 Introduction

This review focuses on three quantities which are most commonly used to quantify the biodynamic properties of the human hand and arm: absorbed power, impedance, and transmissibility.

Two different methods have been developed for calculating the amount of power absorbed during exposure to hand – transmitted vibration. The first method requires the measurement of force and acceleration (or velocity) and their relative phase. This is known as the “direct” method. The second makes use of a known value of impedance, along with measurements of velocity or acceleration. The results obtained using this latter method will not be discussed in the following. A review of experimental studies of absorbed power is presented in § 2.

The mechanical impedance is determined by measuring force and velocity. If, as is often the case, these quantities are measured at the same location, the resulting quantity is called “Driving point mechanical impedance”. A review of experimental studies of this quantity is presented in § 3.

Transmissibility is calculated as ratios of accelerations measured at specific points, to the acceleration measured at the hand-handle interface. A review of experimental studies of this quantity is presented in § 4.

2 Absorbed Power

Direct measurements of the power absorbed by the hand and arm have been performed during the last 15 years by the group working at the Swedish National Institute for Working Life ([1] to [12]). Older studies have been performed by Reynolds, Wasserman and collaborators [13] to [16].

Experiments have been devoted to the investigation of the multi-dimensional parameter space defined by the many variables which determine to a greater or lesser extent the power absorbed in the hand and arm. These variables can be classified as either extrinsic (physical) or intrinsic (individual).

Physical variables include

1) Direction of vibration
2) Frequency of vibration
3) Magnitude or level of vibration
4) Grip force exerted by the subject
5) Feed force exerted by the subject

Individual variables include

6) Posture (usually characterized by the flexion at the elbow and the shoulder abduction)
7) Anthropometry (usually the size or mass of different body parts)
8) Gender
9) Age

Variables 1-3 determine the mechanical properties of the tool vibration
Variables 4-5 determine the coupling
Variables 6-9 determine the quantity and the quality of tissue (i.e. absorbing material)
Attention has also been paid to the effects of temperature.

Even for constant experimental conditions, absorbed power may show some variability in time because of changes in quantities which have not been kept under control, or it may depend on the intermittency of the exposure, i.e. the inclusion of rest periods between actual exposure periods. Therefore another variable associated to the “Time History” has also been investigated.

2.1 Power and frequency

The behaviour of power as a function of frequency appears to be sensitive to the nature of signal. Experiments have been run using either sinusoidal (sine sweep) signals ([1], [2]) or random broad band signals ([5], [6], [7], [10], [12]). Results are discussed separately in the following two subsections.

2.1.1. Sinusoidal signals

The investigated range is 4 ÷ 1500 Hz. The essential features do not show substantial dependence on the vibration magnitude, the grip force, the feed force or the other parameters listed above.

X Axis: Absorbed power rises steeply up to 10 Hz [2], then the rise becomes more shallow, up to 100 Hz [1], [2]. Beyond this point the curve becomes roughly flat up to 500 Hz [1],[2]. There maybe local peaks in this range, but evidence is inconclusive. A final steep rise sets in around 500 Hz, continuing at least until 1500 Hz [1].

Y Axis: Absorbed power increases very quickly up to 20 Hz, even more than in the X axis. This stage is followed by a flat section which goes all the way to 1000 Hz [2].

Z Axis: Absorbed power shows a steep decline in the low frequency region up to 15 ÷ 20 [2], followed by a more gentle drop, or possibly a flat region, up to 100 Hz [1], [2]. Beyond this frequency power increases again, first slowly then quickly up to until 1500 Hz [1].

2.1.2. Random signals

The investigated range is 4 ÷ 5000 Hz. Because of handle resonances, results at the highest frequencies may be questionable.

X Axis: Absorbed power shows a possible early peak around 8 Hz [7], followed by a shallow drop from 10 to 80 Hz [6]. Absorption then increases to a peak around 125 Hz [6], which may extend to 200 Hz [7], then declines first slowly up to 300 – 400 Hz, then quickly [6].

Y Axis: An initial rise leads to a peak around 20 Hz [6]. A second, more pronounced peak shows up around 80 Hz. Absorption drops quickly at higher frequencies [6].

Z Axis: Absorbed power declines at a very regular rate from 10 to 200 Hz, then the drops gets much steeper up to at least 1250 Hz [6].

2.2 Power and vibration magnitude

The investigated range is 8 ÷ 53 mm/s for sinusoidal vibration ([1], [2]), 1 to 12 ms^{-2} ISO - weighted acceleration (hereafter a_w) for random vibration ([5], [7], [10]). Generally speaking, higher vibration magnitudes always result in larger values of the absorbed power. A power law

$$W(f) = p(f) \times v^{g} \quad (1)$$

can be assumed to provide a reasonable functional form. In equation (1) p(f) is a power spectrum for an unspecified reference velocity level.

X Axis: Experiments based on sinusoidal signals provide good evidence [2] supporting a quadratic relationship (γ = 2) between absorbed power and velocity. Data span a considerable range of magnitudes (8 to 45 mm/s). A quadratic relation appears to apply equally well to all frequencies of interest for this type of studies, i.e. the absorbed power spectra at different levels are to a large extent (though not exactly) parallel to one another [2].

Experiments performed using random vibration point to a more complex behaviour. In this case γ is close to 2 for low magnitudes (a_w between 1 and 3 ms^{-2}) [10], but appears to decrease to values of order 1.8 for a_w between 3 and 6 ms^{-2} [7], dropping to 1.65 for a_w between 6 and 12 ms^{-2} [5].

Y Axis: There are no available data for sinusoidal vibration. Data for random vibration follow a similar trend to the one seen for the X axis, with even lower values of γ, ranging from 1.6 for a_w between 3 and 6 ms^{-2} to 1.4 for a_w between 6 and 12 ms^{-2} [5].

Z Axis: Experiments performed using sinusoidal signals support small values of γ, around 1.4 between 27 and 53 mm/s [1]. Data for random vibration point to slightly higher values of γ, replicating the declining trend with the vibration magnitude already seen for the X and Y axes. Specifically, one finds γ = 1.9 for a_w = 3 to 6 ms^{-2}, and γ = 1.5 for a_w = 6 to 12 ms^{-2} [5]. Given that magnitudes used in sinusoidal vibration experiments are usually, for any given frequency, somewhat larger than those used in random vibration experiments (e.g. velocities in [5] are 6.5 to 26 mm/s while extend to 53 mm/s in [1]), the results from the two datasets look consistent with each other.

2.3 Power and grip force

The range investigated is 25 - 75 N. Generally speaking, there is a tendency for higher grip forces to result in larger values of the absorbed power. There is no consensus on the magnitude of this effect.

X Axis: A twofold increase in the grip force from 25 to 50 N has been associated to an increase in absorbed power ranging from very small (8 % [1]) to substantial (30 % [2]). The effect appears to be larger in the low frequency range (below 20 Hz [2], [6]) and in the 100 – 400 Hz range [2], [6]. There are indications of saturation for higher grip forces (50 to 75 N [2]) but other studies [5] do not support this result. Given that each of the quoted studies consists of just three values (25, 50, 75 N), all this is rather speculative. It is interesting to note that a recent study [11] has found an increase in time of absorbed power associated to declining grip (and feed) forces.

Y Axis: A twofold increase in the grip force from 25 to 50 N results in power increasing by about 20 % [5]. A further increase to 75 N gives a mere 7 % increase, so the trend is definitely non linear.

Z Axis: A twofold increase in the grip force from 25 to 50 N results in power increasing by about 12 % [5]. A threefold increase to 75 N gives a 16 % increase, so the trend is again non linear.

2.4 Power and feed force

X Axis: Higher values of the absorbed power have been reported [6] for higher feed forces, particularly in the low frequency range. There are indications of an inverse relation at mid frequencies (100 – 150 Hz).

Y Axis: Higher feed forces result in higher absorption at frequencies below 100 Hz [6].

Z Axis: Higher feed forces result in higher absorption at frequencies below 100 Hz [6].

2.5 Power and posture

The only quantity related to posture that appears to have an impact on absorbed power is the flexion at the elbow. Power appears to increase to increase by about 4% for each 30° reduction of the flexion angle. The effect is largest below 50 Hz, where absorption is low, so the overall impact on frequency – integrated values is small.

2.6 Power and anthropometry

The correlation between power absorption and several anthropometric parameters has been investigated for sinusoidal vibration [2]. Not surprisingly the largest correlation coefficients were found with sizes/masses of smaller and smaller structures for higher and higher frequencies. More in detail, the largest correlation coefficients have been found with the arm volume at 5 Hz, with the forearm volume at 10 and 20 Hz, with the hand volume or thickness at 50 and 100 Hz. Correlation coefficients are usually large, except in the very low frequency range (below 10 Hz). No structures smaller than the full hand have been considered.

2.7 Power and gender

Power absorption was found to be 40% larger in males than in females using sinusoidal vibration [2]. Similar values (25 to 40 %) were found using random vibration [5]. Other studies [10] find substantially lower differences (10 to 20 %). These figures may not be inconsistent as the last ones are relative to lower vibration magnitudes and values appear to increase with increasing vibration magnitudes. Given that absorption is strongly correlated with sizes / volumes of anthropometric structures, differences between males and females may reflect different body size, more than biological tissue differences for the same size.

2.8 Power and age

Power absorption has been reported to increases by an average of about 1 % per year of age [5].

2.9 Power and temperature

Air temperature has been found to have some effect on power absorption, particularly at the frequencies between 100 and 500 Hz. Absorption increases by 15 to 20 % when temperature increases from 6 °C to 26 °C [7].

2.10 Power and time history

A recent study [12] has shown that when exposure is split in two or more periods, the average absorbed power decreases by about 10 – 15 % compared to a situation of continuous exposure.

2.11 References on absorbed power

1. Burström L., Lundström R., (1988), Mechanical energy absorption in human hand-arm exposed to sinusoidal vibration, Int. Arch. Occup. Environ. Health 61, 213 - 216
2. Lundström R. Burström L., (1994), Absorption of vibration energy in the human hand and arm, Ergonomics 37, 879 - 890
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10. Sorensson A., Burström L., (1996), Energy absorption in the hand for higher frequencies, J. Low Freq. Noise Vib. 15, 71 - 79
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12. Burström L., Bylund S. H., (1999), The relationship between vibration dosage and the absorption of mechanical power in the hand

13. Reynolds D. D., Wasserman D. E., Basel R., Taylor W., (1982), Energy entering the hands of operators of pneumatic tools used in chipping and grinding operations, Vibration effects on the hand and arm in industry, Brammer A. J., Taylor W. (eds), pag 133 – 146
14. Wasserman D. E., Reynolds D. D., Behrens V., Samueloff S., Basel R., (1982), Vibration white finger disease in U. S. workers using pneumatic chipping and grinding tools. II Engineering testing, NIOSH Publ. 82-101
15. Reynolds D. D., Basel R., Wasserman D. E., Taylor W., (1984), A study of hand vibration on chipping and grinding operators. Part III power levels into the hands of operators of pneumatic tools used in chipping and grinding operations. J. Sound Vib. 95, 515 – 524

3 Mechanical Impedance

We discuss mechanical impedance taking the recent ISO standard 10068 [1] as a reference frame. This document is based on a large collection of literature and can be deemed updated to 1993. It includes tables and figures illustrating the driving point mechanical impedance of the hand and arm in numerical and graphical form respectively. Separate tables and figures are provided for the three orthogonal X, Y and Z axes as defined in ISO 5349. Data presented are appropriate for moderate to intermediate grip forces (25 to 50 N), and feed forces (less than 50 N).

Similarly to what has been done for absorbed power, recent experiments have been devoted to the investigation of the multi-dimensional parameter space defined by the many variables which determine to a greater or lesser extent the quantity under investigation. The investigated variables are Direction, Frequency, Vibration magnitude or level, Grip force, Feed force, Posture (usually characterized by the flexion at the elbow and the shoulder abduction), Gender, and Age.

3.1 Impedance and frequency

ISO 10068 [1]. The investigated range is 10 – 500 Hz. The essential features are:

X Axis: Impedance increases from about 40 Ns/m at 10 Hz to about 200 Ns/m at 100 Hz, then it remains constant until 350 Hz, and finally rises again, approaching 300 Ns/m at 500 Hz.

Y Axis: Impedance increases from 55 Ns/m at 10 Hz to 100 Ns/m at 30Hz, then it moves very slowly down to 65 Ns/m at 300 Hz, and finally slowly up again. Given the associated uncertainties, a constant value around 80 Ns/m would be consistent with data at all frequencies.

Z Axis: Impedance increases slowly from 150 Ns/m at 10 Hz to 220 Ns/m at 40 Hz, then it moves down to a minimum of 160 Ns/m at 100 Hz then up again reaching 265 Ns/m at 500 Hz.

Other studies. The range investigated is 4 to 2000 Hz

X Axis: Recent studies confirm that impedance does increase, slowly, from the lowest sampled frequencies (4 Hz) up to a broad peak in the 150 – 250 Hz region where values of order 200 Ns/m are found [2], [3]. A first shallow maximum is possibly located around 40 Hz [2],[4]. Impedance then drops again to values around 100 Ns/m [3],[4] before rising steeply above 600 Hz, approaching 1000 Ns/m at 1000 Hz [2].

Results shown in [3] appear to be consistent with ISO 10068 in the low and medium frequency range, but drop somewhat below the lower ISO curve in the 300 – 500 Hz frequency range. Results shown in [4] appear to be consistent with ISO 10068 between 150 and 400 Hz, but lie well below ISO at both lower and higher frequencies.

Y Axis: Recent studies often disagree with each other as well as with ISO 10068. Results presented in [3] show a large peak in the 80 Hz region (around 250 Ns/m), while a peak of similar magnitude is shifted in [4] to the 30 – 40 Hz region. A steep drop is shown in [3], leading to values of impedance below 50 Ns/m around 150 Hz, while a more shallow decrease is shown in [4]. A final increase in shown in [3] to proceed from 200 Hz all the way to 1000 Hz, while the declining trend continues to at least 350 Hz in [4], possibly flattening at the highest frequencies.

All in all, recent studies predict a more wavy behaviour of impedance, with higher maxima and lower minima, compared to ISO 10068, which is almost flat.

Z Axis: Recent studies appear to confirm the general features of ISO 10068. Impedance displays a shallow rising section up to a first peak in the 30 – 40 Hz area [2], [3], [4]. Impedance then stays flat [3] or possibly rises slowly [2], [4] from 80 to 500 Hz. A final steep section above 500 Hz [3] is absent in [4].

Results presented in [3] are largely consistent with ISO 10068 except in the high frequency range, above 500 Hz. Results shown in [4] tend to be always on the low side of ISO 10068.

3.2 Impedance and vibration level

The range investigated is 3 to 12 ms^{-2} ISO - weighted acceleration for random vibration over the 4 – 2000 Hz frequency range.

In principle impedance should be independent of vibration magnitude, if the body displays a linear response to vibration. Any variation of impedance reflects therefore a non – linear behaviour of the human hand and arm.

X Axis: No clear effect is visible.

Y Axis: Impedance does seem to decrease when vibration magnitude increases. The effect is more clearly visible in the low and mid frequency range (below 100 Hz), whereas the picture is more blurred at high frequencies [3].

Z Axis: Some effect can be seen at low frequencies, below 50 Hz, and it becomes very large below 6 Hz [3].

3.3 Impedance and grip force

The range investigated is 25 to 100 N. Generally speaking, there is a tendency for higher grip forces to result in larger values of impedance. An increase in grip force has been quoted in ISO 10068 as resulting in larger values of impedance, especially at frequencies above 50 Hz. No uniform picture emerges in more recent studies, neither concerning the absolute value of the effect, nor concerning the frequency ranges where the effect is largest. No estimates of frequency – integrated changes in impedance due to different grip forces are provided.

X Axis: Impedance increases appreciably when firmer handgrips are used. Significant increases are shown in [3] mostly around 10 – 20 Hz and in the region of the largest peak, around 150 Hz. A more widespread increase has been found in [4], which extends to the entire frequency range investigated.

Y Axis: A general increase of impedance is found, except possibly in the low frequency region below 25 Hz. Larger effects are reported in [4] than in [3].

Z Axis: A general increase of impedance is again found, the effect being largest in the peak region, that is around 30 – 50 Hz and smallest (or absent) below 25 Hz.

3.4 Impedance and feed force

The range investigated has been 20 to 100 N. Generally speaking, there is a tendency for higher feed forces to result in larger values of impedance. A minor increase in impedance has been quoted in ISO 10068 to occur at low frequencies (below 100 Hz), the effect being no larger than 10%.

X Axis: Very little difference is seen between 20 and 60 N, except in the 10 – 20 Hz region [3].

Y Axis: Results [3] confirm that most changes are limited to frequencies below 100 Hz, but the effect looks much bigger than the 10 % quoted in ISO 10068, and it gets bigger as frequency decreases.

Z Axis: Results [3] point to an appreciable increase at frequencies below 150 Hz, which is largest in the 30 Hz region, where it substantially enhances the peak. Much smaller effects are shown in [4].

3.5 Impedance and posture

The only parameter that seems to affect impedance is the flexion at the elbow. Impedance increases as the flexion angle increases. The effect is limited in absolute terms, but is clearly visible at low frequencies, in all three axes, and particularly in the Z axis below 30 Hz and in the X axis below 10 Hz.

3.6 Impedance and gender

Impedance is quoted by ISO 10068 to be 20% lower in females than in males [1].

3.7 References on mechanical impedance

1. International Standard ISO 10068 (1998) Mechanical vibration and shock – free, mechanical impedance of the human hand-arm system at the driving point
2. Hewitt S. M., (1994), Measurement of vibration energy absorption by the hand arm system, Proceedings of the 29th UK informal group meeting on human response to vibration, Institute of Naval Medicine, Alverstoke, United Kingdom
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4 Transmissibility

Values of transmissibility have been usually calculated using are random vibration spectra, rarely with sinusoidal signals. Many different positions on the hand as well as at the elbow have been selected to locate accelerometers or any other appliances used to measure acceleration (e.g. reflective tape to be used for Laser - Doppler accelerometers, [5], [6]). The numbering scheme of measurement points illustrated in [5] has been adopted in this document.

4.1 Transmissibility, position and frequency

a) Middle finger tip (#1). Transmission is unity at all frequencies up to about 800 Hz [5]. Frequencies above 800 Hz show signs of moderate attenuation through the finger layer, though the drop with frequency is not huge (about 6 dB between 630 and 1000 Hz). The drop occurs earlier (around 500 Hz) and is steeper in [2].

b) Middle finger (#2, 5) and knuckle (# 6). There are indications of resonant behaviour, with a proper frequency around 80 Hz for all three points [5], [6]. This has been attributed to surface waves travelling on the skin. Transmission drops below unity around 160 - 200 Hz [3], [5], [6], which is also the case at point #9, lying beyond the knuckle, on the hand's back along the same bony structure [5]. There are signs that transmissibility as a function of frequency may saturate at a level between – 20 and –25 dB [3], [5], [6].

c) Small finger (#3). Full transmission takes place only up to 250 Hz, where attenuation sets in.

d) Thumb (#4). Transmission shows a behaviour similar to the one seen at point #1, except that it drops at a slightly lower frequency (around 600 Hz) and the drop itself is much steeper, more than 20 dB between 500 and 1000 Hz.

e) Knuckles (#7, 8). Transmission at the other knuckles behaves much in the same way as at point #6.

f) Wrist (#10, 11, 12). There are no indications of resonances. Transmission is unity until about 40 – 50 Hz [4], [5], [6]. Beyond this point transmissibility has been reported to drop at a rate ranging from a moderate 7 – 8 dB per octave [5] to a hefty 11 – 12 dB per octave [1], [4].

g) Elbow. Transmissibility is quite low already around 20 Hz (about – 10 dB, [1], [6]). The rate of decline with increasing frequency is again controversial, ranging from moderate [6] to high [4].

4.2 Transmissibility and vibration level

Velocities associated to random vibration are usually low (6 – 10 mm/s, [5], [6]). Much higher values have been used with sinusoidal vibration (30 mm/s, [6]) but the combined effects of magnitude and nature of stimulus are hard to disentangle. Reasonable agreement exists between the values found at the wrist at 60 Hz with a very large magnitude of about 50 mm/s [4], and with 10 mm/s [5]. This may be interpreted as an indication of insensitivity of transmissibility to vibration magnitude.

4.3 Transmissibility and grip force

A study based on just 1 subject may indicate that transmissibility remains more flat (lower absorption) at high frequency when firmer grips are used (the investigated range is 10 – 40 N) [5].

4.4 Transmissibility and gender

No clear differences have been found [5].

4.5 References on transmissibility

1. Reynolds D. D., Angevine E. N., (1977), Hand-arm vibration. Part II : Vibration transmission characteristics of the hand and arm, J. Sound Vib. 51, 255 - 265
2. Griffin, MacFarlane & Norman (1982) Vibration effects on the Hand and Arm in industry
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