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Journal of Sound and Vibration 317 (2008) 1051–1056
JOURNAL OF SOUND AND VIBRATION
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Discussion

Comments on "A discussion on comparing alternative measures with frequency-weighted accelerations defined in ISO Standards" [R.G. Dong, J.Z. Wu, D.E. Welcome, T.W. McDowell, *Journal of Sound and Vibration*]

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Received 18 February 2008; accepted 11 March 2008
Handling Editor: S. Bolton

1. Introduction

This commentary is a reply to Dong et al. [1] whom we thank for their interest in our paper [2]. First, we would like to recall the first equation used by Dong et al. in their discussion [1]. The relation between the driving-point mechanical impedance (DPMI) of the hand–arm system (Z), the absorbed power by the hand–arm system (P) and the rms value of the acceleration (A) as a function of frequency (f_i) is given by

$$P(f_i) = \mathrm{Re}\left[Z(f_i)\right]\left(\frac{A(f_i)}{2\pi f_i}\right)^2 \tag{1}$$

This equation assumes that the DPMI of the human hand–arm system is linear with respect to the acceleration. In the particular case where the power spectral density (PSD) of the acceleration is constant with frequency (as in Ref. [2]), the acceleration is equal to a constant

$$A(f_i) = A \tag{2}$$

Thus, in that case, it can be easily shown that the absorbed power is independent of the acceleration spectral distribution:

$$P(f_i) = A^2\frac{\mathrm{Re}[Z(f_i)]}{(2\pi f_i)^2} \tag{3}$$

Alternatively, one could define, as Mansfield and Griffin have done for the absorbed power by the whole-body [3], a normalized absorbed power (P_n) by dividing the absorbed power by the square

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DOI of original article: 10.1016/j.jsv.2008.03.028

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doi:10.1016/j.jsv.2008.03.027

of the acceleration:

$$P_n(f_i) = \frac{P(f_i)}{[A(f_i)]^2} = \frac{\mathrm{Re}[Z(f_i)]}{(2\pi f_i)^2} \tag{4}$$

We think that these equations are in contradiction with Dong et al. statement: "(I) the VPA spectrum measured with a specific excitation cannot usually be used to represent the VPA frequency dependency because the VPA spectrum is excitation spectrum specific." However, in our paper [2], we clearly stated: "measurements were undertaken under two different levels of broadband random vibration with constant acceleration PSD in the 8–1000 Hz frequency range." Then, the subsequent statement made by Dong et al.: "(II) consequently, the reported percentages of absorption in different frequency ranges cannot be generally applied" does not hold, as we used accelerations with constant PSD. Following, Dong et al. state in their discussion: "(III) it is invalid to directly compare the shape of this excitation-specific VPA spectrum with that represented by ISO frequency weighting. Therefore, the fundamental study approach is questionable." First, the absorbed power spectrum presented in our paper is not excitation specific, as we used a constant PSD acceleration. Second, the same approach has been used by Mansfield and Griffin [3], where the authors compared the trend of the absorbed power of the whole-body by seated subject with the ISO 2631 frequency weighting on the same graph (Fig. 6 in their paper). This approach is correct since it consists in representing the health risk associated to vibration, as a function of frequency. The risk can be estimated from weighted acceleration, or absorbed energy. Further in their discussion, Dong et al. suggest that: "(i) the alternative measure should be a linear function of acceleration and (ii) the specific spectrum of the alternative measure to be used for the comparison should be measured using an excitation with constant acceleration value at each one-third octave band […] an excitation with a constant acceleration PSD in the one-third octave bands does not have a constant acceleration at each frequency band." While we disagree on point (i) for the reasons we already stated above, point (ii) concerns something that we may have overlooked in our previous paper [2]. The next section will examine the consequences of having expressed in one-third octave bands a quantity (absorbed power) that was computed for a constant PSD acceleration.

2. Frequency-dependent power absorption by the human hand–arm

In Aldien et al. [2], the authors have expressed in one-third octave bands a quantity that should have been expressed in a constant bandwidth, giving that their acceleration had a constant PSD. Thus, we reanalyzed our data measured on seven subjects, for the 40 mm cylindrical handle, with the 30 N grip and 50 N push forces, for the high excitation spectra ($a_{hw} = 5.0\,\mathrm{m/s^2}$) [2], using this time a constant bandwidth fast Fourier transform (FFT) approach (at the time of the experiments, the acquisitions have been done both in FFT and one-third octave bands). The results, averaged on the seven subjects, are presented in Fig. 1, along with the corrected version of the one-third octave bands approach. The corrected one-third octave band absorbed power response has been computed by dividing each one-third octave band by their respective bandwidths, while the FFT absorbed power response has been normalized by dividing it by the squared value of the acceleration (see Eq. (4)). Then, the normalized absorbed power responses, presented as a risk factor that is a function of frequency, have been scaled to provide a quick comparison. By comparing the corrected one-third octave spectra (corrected for the different bandwidths but not normalized with respect to the acceleration spectra) with the normalized absorbed power (with respect to the acceleration spectra), it is possible to verify if both approaches (corrected one-third octave bands and FFT) lead to comparable results, and also to verify if not normalizing the absorbed power by the excitation spectra leads to important discrepancies. Fig. 1 shows that both approaches diverge below 20 Hz and around 40 Hz. This is due to the fact that the PSD of the excitation acceleration is not completely flat, as shown in Fig. 2, presenting the PSD acceleration applied for all seven subjects. However, these divergences are rather small when compared with the slope of the risk factor, decreasing at the rate of about 20 dB/decade above 30 Hz. Thus, when correcting for the one-third octave bandwidths, the decrease of the risk, based on absorbed energy, is larger than the decrease reported in our previous paper [2]. However, this corrected response is very different from the response obtained by Dong et al. [4], reporting an energy-based risk factor decreasing at the same rate as the ISO 5349-1 frequency

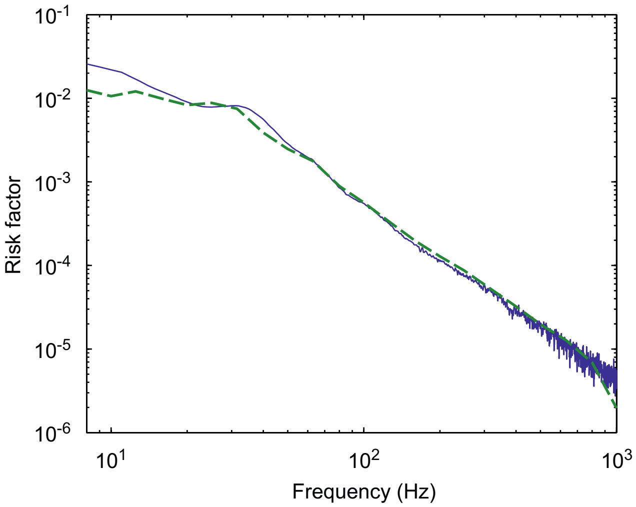

Fig. 1. Risk factor as a function of frequency (40 mm handle, 30 N grip and 50 N push forces, $a_{hw} = 5.0\,\mathrm{m/s^2}$). Computed from the FFT response: —; computed from the corrected one-third octave response: – – –.

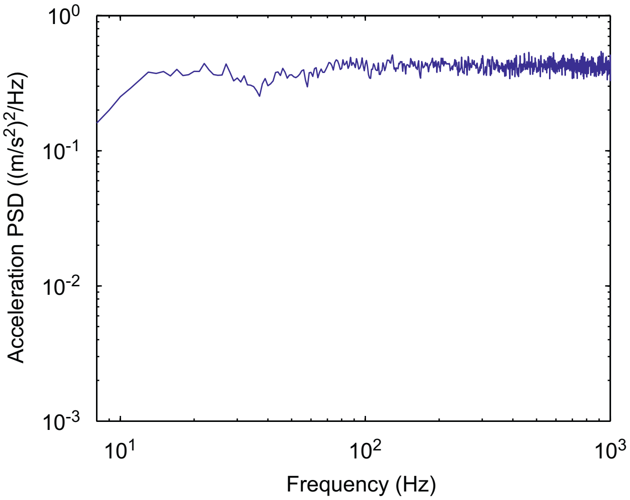

Fig. 2. Power spectral density (PSD) of the acceleration used for the absorbed power experiment (40 mm handle, 30 N grip and 50 N push forces, $a_{hw} = 5.0\,\mathrm{m/s^2}$).

weighting (10 dB/decade). We will investigate the reason for this obvious contradiction between our results [2] and Dong et al. results [4] in the next section.

3. Frequency-dependent square root of absorbed power by the human hand–arm

In their paper [4], Dong et al. use the square root of absorbed power rather than the absorbed power for their frequency weighting. Thus, in the abstract of their paper, the statement: "this study predicted that the total power absorption of the entire hand–arm system is likely to be correlated with psychophysical response or subjective sensation" is not true, since the correlation they obtained is with the square root of the absorbed power, not with the absorbed power. This is evident when we look at Eq. (8) in their paper [4] (same as Eq. (4) in their discussion [1]), showing that their frequency weighting is proportional to the square root of the real part of the DPMI, while Eq. (1) shows that the absorbed power is proportional to the real part of the DPMI.

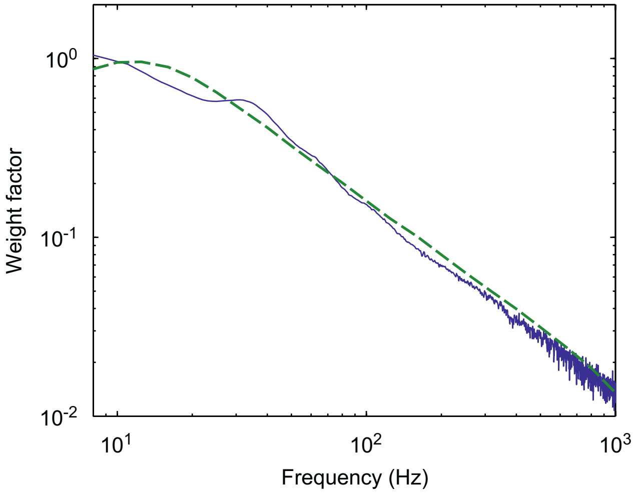

Fig. 3. Risk factor as a function of frequency. Square root of absorbed energy (40 mm handle, 30 N grip and 50 N push forces, $a_{hw} = 5.0\,\mathrm{m/s^2}$): —; ISO 5349-1 frequency weighting:– – –.

The same criticism applies to the statement made in their discussion [1]: "This similarity also suggests that the VPA of the hand–arm system could be associated with the overall subjective sensation of the hand–arm system because the ISO weighting was based on sensation data." Again, the authors refer to the absorbed power, while they should refer to its square root.

To further illustrate our point, we chose to plot the square root of the normalized absorbed power obtained from our own experimental data (seven subjects, 40 mm handle, 30 N grip and 50 N push forces), along with the ISO 5349-1 frequency weighting. The response has been scaled for comparison purpose and is presented in Fig. 3, as a risk factor that is a function of frequency. We note that we obtain about the same agreement between the square root of the normalized absorbed power and the ISO 5349-1 frequency weighting, confirming that Dong et al. have used the square root of the absorbed power and not the absorbed power as they stated in their papers [1,4].

4. Some additional precisions

We would like to clarify some additional issues that were raised in Dong et al. discussion [1]. It is stated: "Whereas the aforementioned conclusions from Ref. [2] suggest that the highest VPA emphasizes the effect of vibration frequencies below 50 Hz, this study [5] suggested that the highest VPA values are produced by vibration excitation with frequencies from 50 to 200 Hz. These two studies are obviously contradictory." However, we see no contradiction between the two studies, as in Ref. [2], the authors used a constant acceleration PSD, while in Ref. [5], the authors used two tool acceleration spectra that increase with frequency (as shown from the unweighted NIOSH acceleration in Fig. 2 from Ref. [5]). Thus, it is perfectly normal that in Ref. [5], the frequency range of maximum absorbed energy is shifted to higher frequencies as their tool acceleration spectra are increasing with frequency. It is also possible that the frequency range of maximum absorbed energy shifts to well below 50 Hz, if the tool acceleration spectra is decreasing with frequency, as shown in Dong et al. [1] in Fig. 3b, for the petrol wacker. The conclusions in Ref. [2] are for a constant PSD acceleration, and are not related to a particular tool.

In referring to a paper from Burström and Lundström [6], Dong et al. state in their discussion: "Estimated using these impedance data and their corresponding frequencies in the range 5–1000 Hz, the imaginary part of the apparent mass ranges from 0.06 to 84 kg. Therefore, the maximum value of the imaginary apparent mass is greater than the average mass (64 kg) of the subjects who participated in the VPA measurement using a single hand [6]. This is obviously unrealistic, and it suggests that the reported VPA data and/or velocity value could contain serious errors; the VPA-based weighting derived from these data could be unreliable." However, there is a flaw in that statement, since the imaginary part of the apparent mass does not depend upon the mass of the

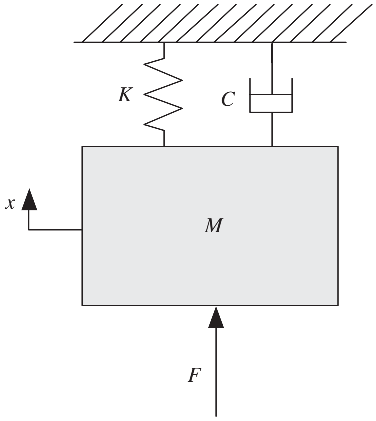

Fig. 4. Single-degree of freedom (sdof) mass–spring–damper system.

hand–arm structure. To illustrate this point, let us take a look at a simple single-degree-of-freedom (sdof) mass–spring–damper system, shown in Fig. 4. For such a system, it can be shown that the driving-point apparent mass is giving by

$$\frac{F}{a}=\frac{F}{-\omega^2 x}=\left(M-\frac{K}{\omega^2}\right)-\mathrm{j}\left(\frac{C}{\omega}\right) \tag{5}$$

where ω is the circular frequency, M the mass, K the spring constant, C the viscous damping coefficient and $\mathrm{j}=\sqrt{-1}$. This simple example clearly shows that the imaginary part of the apparent mass does not depend upon the mass element, but rather on the viscous damping coefficient that is related to the energy dissipated in the system. This is in contradiction with Dong et al. in their discussion [1].

5. Conclusion

Dong et al. [1,4] have used the square root of absorbed power instead of the absorbed power to derive their frequency weighting. Thus, it is normal that they are in contradiction with several other studies where the absorbed power has been used instead. Note that we do not state that the absorbed power measure should replace the current ISO 5349-1 frequency weighting for the health risks associated with the vascular and neurological components of hand–arm vibration syndrome. For these components of the disease, where a small amount of tissues are involved (the tissues directly in contact with the vibrating tool), other factors not necessarily related to the absorbed energy by the hand–arm system, such as the vasoconstriction of the finger blood vessels activated by the sympathetic component of the central nervous system [7], may play a more important role in the development of the disease. However, it is possible that the musculoskeletal disorders associated with exposure to hand–arm vibration, where large amount of tissues of the hand–arm structure are involved, are more closely related to the absorbed energy by the human hand–arm system than the current ISO 5349-1 frequency weighting. In addition, it should be noted that the squared value of the weighted acceleration (ISO 5349-1) is proportional to the absorbed energy by the hand–arm system (since the square root of Eq. (4) has the same trend as the ISO 5349-1 weighting, as shown in Fig. 3). Clearly, more research is needed to clarify the link between hand–arm vibrations and the different manifestations (vascular, neurological and musculoskeletal) of hand–arm vibration syndrome.

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