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Estimation of tool-specific isolation performance of antivibration gloves

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Abstract

A methodology to estimate vibration isolation effectiveness of antivibration gloves as a function of handle vibration of specific tools is proposed on the basis of frequency response characteristics of the gloves. The handle vibration spectra of six different tools are synthesized in the laboratory and attenuation performances of two different gloves are characterized under tools vibration, and M- and H-spectra defined in ISO-10819 (1996). The vibration characteristics of gloves are measured using three male subjects in the laboratory under different excitation spectra. The results suggest that tool-specific vibration isolation performance of a glove cannot be derived from the standardized M- and H-spectra. Frequency responses of the gloves are thus characterized under broad-band vibration excitations of two different magnitudes, and grip and feed forces recommended in ISO-10819. The results suggest that frequency response characteristics of gloves are relatively insensitive to magnitude of vibration but strongly dependent upon visco-elastic properties of the glove materials. The mean measured frequency response characteristics are then applied to derive an estimate of tool-specific isolation effectiveness of the gloves. The estimated acceleration transmissibility characteristics of gloves are compared with the mean measured responses to demonstrate validity of the proposed methodology. From comparisons, it is concluded that the isolation effectiveness of gloves for selected tools can be effectively predicted using the proposed methodology. The deviations between the predicted and measured transmissibility values are within 8% for majority of the glove–spectra combinations, well within the intra- and inter-subject variabilities reported in different studies.

Relevance to industry

The methodology proposed in this study and the results can be applied to effectively assess the antivibration performance of the gloves for specific tools, and thereby select near optimal gloves to reduce the health hazards posed by the hand-transmitted vibration. © 2002 Published by Elsevier Science B.V.

Keywords: Hand-tools vibration; Antivibration gloves; Vibration attenuation; Hand-transmitted vibration; Assessment method; Selection of gloves

1. Introduction

Antivibration gloves, made of resilient materials or air bladder, are widely used to attenuate the vibration transmitted to the hands while operating hand-held power tools. The vibration isolation

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characteristics of such gloves are invariably evaluated through laboratory measurements conducted under idealized vibration excitations. The laboratory assessment methods essentially involve measurement of source vibration at the interface of the glove and a simulated handle, and the vibration transmitted at the glove–hand interface under controlled postures. Owing to the dependency of the transmitted vibration on the hand-grip and feed forces, a majority of the studies are conducted under controlled levels of either grip, or both grip and feed forces. The earlier studies have used considerably different vibration excitations, such as swept sine and white-noise random, and measurement locations, such as the palm, back of the palm, fingers, carpal bone and wrist (Goel and Rim, 1987; Rens et al., 1987; Christ, 1982; Griffin et al., 1982; Gurram et al., 1994; Starck et al., 1990; Paddan and Griffin, 1997). Although the differences in measurement locations and methods do not allow for a quantitative comparison of the reported results, the studies have invariably concluded that the majority of the gloves attenuate vibration at frequencies above 100 Hz and amplify vibration at lower frequencies.

Upon recognizing the lack of uniformity in the measurement and assessment methods, the International Standard Organization (ISO) has established a laboratory test method to assess the antivibration performance of gloves (ISO-10819, 1996). The standardized method includes the designs of an instrumented palm adapter to measure the vibration transmitted at the hand–glove interface and a handle that is capable of measuring grip force and acceleration due to handle vibration along the axial direction. The standard requires the assessment of gloves in terms of their overall mean frequency-weighted acceleration transmissibility under two excitation spectra: (i) medium frequency (M) spectrum in the 16–400 Hz range; and (ii) high-frequency (H) spectrum vibration in the 100–1600 Hz range. A glove is considered an ‘antivibration glove’, when its mean transmissibility values under M- (TR_M) and H- (TR_H) spectra are below 1.0 and 0.6, respectively. The standardized test method has been widely used to evaluate relative performance characteristics of antivibration gloves (Voss,

1996; Koton et al., 1996; Griffin, 1998; Hewitt, 1997, 1998; Reynolds and Jetzeer, 1998).

The vibration isolation performance of a glove may depend upon the nature of tool vibration (magnitude and frequency range), visco-elastic properties of the glove material, arm posture, and magnitudes of hand-grip and feed forces. The standardized test method requires the measurements under specific posture (forearm horizontal and parallel with the direction of vibration, and wrist angle between 0° and 40°), and constant static grip (30 ± 5 N) and feed (50 ± 8 N) forces. It has been reported that variations in the arm posture and the grip force affect the glove transmissibility only marginally (Paddan, 1996), while the effects of feed force variations have not been reported. The recommended test method, however, cannot predict the vibration isolation performance of antivibration gloves when used with a specific tool, since the vibration spectra of various hand-held power tools differ considerably from those of the idealized M- and H-spectra (Griffin, 1998). The measures and criteria based upon TR_M and TR_H , therefore, cannot be relied upon for general assessment of isolation performance of the gloves or their beneficial effects. The vibration isolation performance of gloves for specific tools would require the measurements in the field under representative operating conditions (posture, and grip and feed forces) or in the laboratory under representative vibration spectra and operating conditions.

Owing to the complex nature of tool vibration and coupled hand–handle–glove system dynamics, the assessment methodology based upon either field or laboratory measurements would require repetitive measurements involving representative human subjects and test conditions under specific tool vibration spectra. Such measurement-based methodologies are also known to pose considerable complexities in the data analysis due to inter- and intra-subject variabilities (Hewitt, 1997). Alternatively, an estimate of the vibration isolation performance of the glove for a specific tool may be derived from the transfer function of the glove attained under a broad-band vibration spectrum of representative magnitude. Griffin (1998) computed the vibration transmissibility of

10 different gloves for 20 different tool spectra on the basis of the reported mean transmissibility characteristics of the gloves under a broad-band random vibration spectrum (Paddan, 1996; Paddan and Griffin, 1997). The validity of the methodology was examined for the M- and H-spectra alone, since no measurements were attempted under the vibration spectra of different tools. The comparisons of the estimated transmissibility values of different glove–tool combinations with those attained under M- and H-spectra revealed considerable deviations for specific tools.

In this study, the vibration isolation properties of two different gloves (air and visco-elastic) are estimated for six different tools from the mean measured transmissibility characteristics of the gloves under broad-band random excitations of two different magnitudes. The vibration spectra of the selected tools are synthesized in the laboratory and isolation properties of the gloves are evaluated for the specific tools. The measured vibration transmissibility characteristics of different glove–tool combinations are compared with the estimated values to demonstrate the validity of the proposed method. The results are discussed in view of the applicability of the transmissibility values derived under the standardized M- and H-spectra, and proposed broad-band spectrum, for specific tools.

2. Tool-specific glove vibration isolation

The vibration isolation performance of a glove is mostly affected by its frequency response characteristics defined under representative operating conditions. Owing to the nonlinear visco-elastic properties of the glove materials, the frequency response characteristics may further depend upon the nature of vibration excitation (magnitude and frequency range) and hand forces. The estimation of the tool-specific vibration isolation performance of a glove thus necessitates the determination of the frequency response function under a representative vibration excitation. Considering the glove as a single-input–single-output dynamic system, the power spectral density (PSD) of acceleration due to vibration

transmitted to a gloved hand may be derived from

$$S_A(f) = |H(jf)|^2 S_H(f), \quad (1)$$

where $j = \sqrt{-1}$. $S_A(f)$ and $S_H(f)$ are the PSD of acceleration due to vibration transmitted to the hand and of the tool handle, respectively, corresponding to frequency f , and $H(jf)$ is the complex frequency response function of the glove. The frequency response function of a glove can be conveniently evaluated from the acceleration excitation measured at the simulated handle and the response measured at the hand–glove interface (palm adapter), such that (Bendat and Piersol, 1986)

$$H(jf) = \frac{S_{HA}(f)}{S_H(f)}, \quad (2)$$

where $S_{HA}(f)$ is the cross-spectral density function of the handle and adapter accelerations.

Alternatively, the magnitude of vibration transmissibility of a glove is frequently defined in the $\frac{1}{3}$ -octave frequency bands by the ratio of rms acceleration of the adapter to that of the handle:

$$TR(f_i) = \frac{A_z(f_i)}{H_z(f_i)}, \quad (3)$$

where $TR(f_i)$ is the tool-specific acceleration transmissibility of the glove corresponding to centre frequency f_i of the third-octave band i . A_z and H_z are rms accelerations due to adapter and handle vibration corresponding to f_i , computed from

$$\begin{aligned} A_z(f_i) &= \left[\int_{f_l}^{f_u} S_A(f) df \right]^{1/2}, \\ H_z(f_i) &= \left[\int_{f_l}^{f_u} S_H(f) df \right]^{1/2}, \end{aligned} \quad (4)$$

where f_l and f_u are the lower and upper limits of the frequency band.

The overall frequency-weighted vibration transmissibility of a glove can be derived from

$$\begin{aligned} TR_w &= \sqrt{\frac{\sum_1^n W^2(f_i) A_z^2(f_i)}{\sum_1^n W^2(f_i) H_z^2(f_i)}} \\ &= \sqrt{\frac{\sum_1^n W^2(f_i) |H(jf_i)|^2 H_z^2(f_i)}{\sum_1^n W^2(f_i) H_z^2(f_i)}}, \end{aligned} \quad (5)$$

where $W(f_i)$ is the frequency weighting function defined in ISO-5349 (1986) and n is the number of $\frac{1}{3}$ -octave frequency bands considered.

The application of vibration spectra of a particular tool to Eqs. (3)–(5) can provide the tool-specific vibration transmissibility of the glove. Since the vibration spectra of different tools differ considerably in magnitudes and predominant frequency ranges, it is desirable to identify the frequency response characteristics of the glove over a broad range of frequency and magnitudes. The resulting $H(jf)$ could then be applied to estimate the vibration transmission performance of the glove for a class of power tools.

2.1. Vibration spectra of the selected tools

The vibration spectra of six different tools, reported by Griffin (1998), are examined in order to define an idealized broad-band vibration excitation for identification of $H(jf)$. The vibration spectra of the selected tools are also reproduced in the laboratory for measurement of glove performance and validation of the estimation methodology. The selected tools include a pneumatic chipping hammer, a nutrunner, an anti-vibration chainsaw, a pneumatic road breaker, a random orbital sander, and a riveter. The acceleration PSD of the selected tool handles are estimated from the reported rms acceleration spectra (Griffin, 1998) and presented in Fig. 1.

The figure also illustrates the acceleration PSD for the M- and H-spectra, as defined in ISO-10819 (1996). The figure clearly illustrates the significant differences between the vibration spectra of the selected tools and the idealized M- and H-spectra in terms of both the magnitudes and the predominant frequencies. While the predominant frequencies of vibration of the pneumatic chipping hammer, nutrunner and the random orbital sander could be considered to lie within the range of the M-spectrum, the corresponding magnitudes are considerably higher. Moreover, the vibration due to the pneumatic road breaker and nutrunner predominate in the lower frequencies (12.5–31.5 Hz). Although all the selected tools exhibit vibration in the range of H-spectrum, the magnitude of the H-spectrum vibration is generally higher.

The differences between the measured tools vibration and the recommended M- and H-spectra are further evaluated in terms of: the overall rms accelerations (unweighted, H_z ; and frequency-weighted, H_{zw}); 4-h energy-equivalent frequency-weighted acceleration, assuming 30 min daily exposure, $H_{zw}(4)$; and the probable number of years of exposure expected to produce episodes of finger blanching in 10% of the exposed population. The values of $H_{zw}(4)$ and years of exposure are computed in accordance with the ISO-5349 (1986). The results summarized in Table 1 reveal significant differences between the measured and recommended vibration spectra. Both the M- and

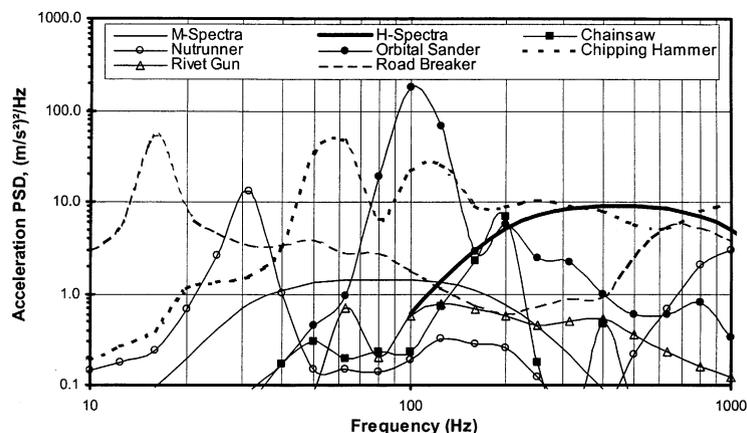


Fig. 1. Comparison of acceleration PSD spectra of tools vibration with the M- and H-spectra.

Table 1

Comparison of vibration characteristics of the selected tools with the recommended M- and H-vibration, and the selected broad-band vibration

Tool/spectra	RMS acceleration (m/s^2)		4-h equivalent vibration total value $H_{zw}(4)$	Years of exposure expected to produce symptoms in 10% of exposed population
	H_z	H_{zw}		
M	16.7	3.3	1.16	26
H	92.2	3.3	1.16	26
Chainsaw (antivibration)	22.6	2.3	0.81	37
Nutrunner	37.2	6.0	2.13	14
Riveter	19.3	1.6	0.55	54
Random orbital sander	87.3	12.5	4.43	7
Pneumatic chipping hammer	100.6	11.7	4.13	7
Pneumatic road breaker	60.8	16.6	5.87	5
Broad_M	36.6	4.5	1.60	19
Broad_H	63.8	7.9	2.79	11

H-spectra yield identical 4-h equivalent vibration total values (1.16 m/s^2) and total number of years (26) of exposure expected to produce symptoms in 10% of the exposed population. These values for the tools range from 0.55 to 5.87 m/s^2 and from 5 to 54 years, respectively.

2.2. Measurement of tool-specific glove vibration transmissibility

Owing to the significant differences in the frequency ranges of the M- and H-spectra and the tools vibration, broad-band vibration spectra (8–1600 Hz) of different magnitudes, referred to as Broad_M and Broad_H, are synthesized to derive the frequency response characteristics of the gloves as a function of the intensity of vibration. Fig. 2 illustrates a comparison of the standardized and broad-band spectra in the 10–1000 Hz frequency range. The overall rms accelerations, 4-h energy equivalent values and the number of years of exposure corresponding to the broad-band spectra are also summarized in Table 1.

The tool-specific vibration transmissibility characteristics of two different gloves are evaluated through laboratory measurements. The measured transmissibility characteristics are assessed in relation to those evaluated under the recom-

mended M- and H-spectra. The glove transmissibility attained under Broad_M and Broad_H excitations are used to examine the validity of the proposed estimation method. Two different gloves made of air pockets (Glove A) and visco-elastic material (Glove B) are considered for the laboratory evaluations. The vibration spectra of the selected tools and the broad-band excitations, presented in Figs. 1 and 2, are synthesized in the laboratory using an electro-dynamic vibration exciter (Unholtz Dickie S032). The experiments were performed using the method described in ISO-10819 involving three male subjects with hand sizes between 8 and 9, as estimated from EN 420 (1994).

An aluminum handle and a titanium palm adaptor were fabricated in accordance with the ISO-10819. The handle consisted of a three-axes accelerometer (Endevco-Isotron 35A), and an elastic force sensing structure with four strain gages to measure the subjects' grip force. The 70 mm long palm adaptor was fabricated with contact surface radius of 30 mm (weight = 15.7 g). A three-axes micro-machined accelerometer was installed within the adaptor to measure the vibration transmitted to the glove–hand interface, and to monitor and control its yaw misalignment with respect to axis of the source vibration (Dong

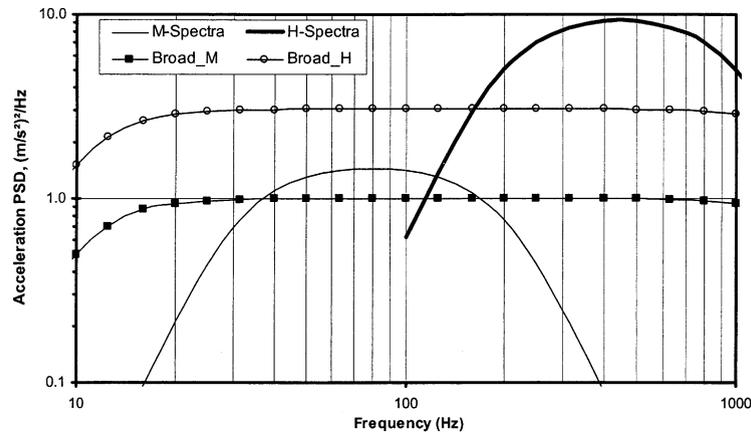


Fig. 2. Comparison of the broad-band vibration spectra with the M- and H-spectra.

et al., 2001). The instrumented handle was installed on a horizontally mounted vibration exciter and a resonance test was performed on the handle with and without the hand under excitations in the 10–1250 Hz frequency range. The results revealed the presence of handle resonance at a frequency above 1250 Hz.

The instrumented adaptor was placed in the palm of the subjects' hand, inside a selected glove. Each subject was asked to grip the instrumented handle with his dominant right hand with a grip force of 30 ± 5 N. A force plate was also used for the subject to exert a feed force of 50 ± 8 N, as outlined in ISO-10819 (1996). Each subject was asked to stand upright on a force plate with his forearm directed along the dominant axis of vibration (Z_h). The subjects were also asked to monitor and adjust their grip and feed forces through the visual displays of the force signals, sampled at a rate of 1 sample/s. The elbow did not touch the body and formed an angle of approximately $90 \pm 10^\circ$. The vibration exciter was operated to generate the selected vibration spectra. The ratio of adapter lateral acceleration (A_x) to its vertical acceleration (A_z) was sampled and displayed to the subject to monitor and control the adapter yaw misalignment, while maintaining the specified arm and wrist posture (Dong et al., 2001). The measurements were performed with barehand and the two gloves under the excitations corresponding to M-, H-, Broad_M, Broad_H and

selected tools spectra. The source and response vibration characteristics of each glove–spectra combination were measured three times for each subject. The trial, glove and excitation spectrum were selected in a random fashion, while the test subject was allowed to relax for 4–5 min between the consecutive tests. The mean adapter acceleration ratio was recorded for each measurement, and the transmissibility derived from the measured data was corrected for the yaw misalignment in the following manner (Dong et al., 2001):

$$T_C(f_i) = \frac{TR(f_i)}{\cos(\alpha)}, \quad T_{Cw} = \frac{TR_w}{\cos(\alpha)}, \quad (6)$$

where T_C and T_{Cw} are the corrected unweighted and frequency-weighted acceleration transmissibility, respectively, and α is the mean yaw angle of the adapter with respect to the direction of axial handle vibration, which is determined from the adapter acceleration ratio:

$$\alpha = \tan^{-1} \left[\frac{A_x}{A_z} \right] \quad (7)$$

3. Results and discussions

3.1. Tool-specific acceleration transmissibility

The acceleration transmissibility values of the gloves subject to different excitations are evaluated

from the measured data using Eqs. (3)–(6). The mean and standard deviations of the corrected values of transmissibility acquired for the three subjects and three trials are summarized in Table 2. The table also summarizes the rms accelerations due to synthesized handle vibration (H_z and H_{zw}). A comparison of the unweighted values of measured handle acceleration with the target values (Table 1) shows error below 3% for the recommended and broad-band excitations. The synthesized excitation corresponding to the nutrunner, however, is approximately 14% lower than the unweighted target value. This is attributed to relatively low levels of the tool vibration in the majority of the frequency range (50–500 Hz). Consequently, the corresponding error in the weighted accelerations is in the order of 3%. The synthesized spectrum for the chainsaw reveals errors in the order of 11% and 4.5% in the unweighted and weighted values, respectively. The synthesized spectra corresponding to orbital sander and the road breaker also revealed errors in the orders of 7% and 8% for the unweighted and weighted values, respectively, due to their high magnitude peaks near 100 and 30 Hz, as shown in Fig. 1. Low-frequency components of vibration due to these tools yield considerable errors in the frequency-weighted values of rms acceleration.

The measured data were analysed to derive the mean acceleration transmissibility for each subject–glove–spectra combination. The measure-

ments revealed intra-subject variations ranging from 0.8% to 18.3% for all the glove–spectra combinations. The intra-subject variations for the air glove (A) were observed to be considerably higher than those for the glove B, specifically under excitations with lower magnitudes in the low-frequency bands (H-spectra, chainsaw and riveter). The mean and standard deviation of the means were then evaluated for each glove–spectra/tool combination, which are summarized in Table 2. The results under the M- and H-spectra were evaluated in the 16–400 and 100–1600 Hz frequency ranges, while those for the broad-band and tools spectra are computed over the 10–1000 Hz range.

From the results, it is apparent that glove A provides superior attenuation of vibration for all the tools/spectra, when unweighted values are considered. The vibration attenuation provided by glove B is considerably less. The degree of isolation of both the gloves, however, deteriorates significantly when frequency-weighted values of the transmissibility are considered. This is attributed to the tendency of the gloves to amplify the vibration in the lower frequency bands, where the weighting factor is nearly unity. Both the gloves satisfy the criterion ($T_{Cw} \leq 1$) for the M-spectrum, while glove A alone satisfies the criterion ($T_{Cw} \leq 0.6$) for the H-spectrum. The results further suggest that the mean acceleration transmissibility values attained for the recommended M- and

Table 2
Mean measured acceleration transmissibility of gloves

Tool/spectra	RMS acceleration (handle) (m/s ²)		Acceleration transmissibility (Mean, SD)			
	H_z	H_{zw}	Glove A		Glove B	
			T_C	T_{Cw}	T_C	T_{Cw}
M	16.9	3.4	0.69, 0.068	0.80, 0.084	0.85, 0.095	0.88, 0.067
H	89.7	3.3	0.39, 0.018	0.57, 0.030	0.64, 0.062	0.87, 0.051
Chainsaw	20.1	2.2	0.66, 0.043	0.78, 0.035	0.90, 0.074	0.93, 0.056
Nutrunner	31.8	5.8	0.40, 0.054	0.96, 0.036	0.54, 0.054	0.98, 0.052
Riveter	19.5	1.6	0.56, 0.027	0.81, 0.040	0.77, 0.050	0.93, 0.058
Orbital sander	80.8	11.5	0.65, 0.064	0.68, 0.082	0.75, 0.126	0.77, 0.132
Chipping hammer	95.4	11.6	0.51, 0.052	0.78, 0.084	0.70, 0.068	0.85, 0.076
Road breaker	64.6	15.2	0.50, 0.052	1.04, 0.018	0.57, 0.046	1.03, 0.024
Broad_M	37.3	4.7	0.38, 0.022	0.94, 0.008	0.64, 0.036	0.97, 0.011
Broad_H	64.5	8.2	0.41, 0.029	0.93, 0.028	0.62, 0.040	0.97, 0.013

H-spectra do not serve as good indicators of vibration attenuation performance of gloves for the selected tools. The frequency-weighted acceleration transmissibility of glove A varies from 0.57 under the H-spectrum to 1.04 for the road-breaker vibration spectrum, while those for glove B range from 0.77 for the orbital sander to 1.03 for the road breaker. Both the gloves yield higher transmissibility under low-frequency excitations, such as road breaker and nutrunner with predominant excitation in the 16 Hz and 31.5 Hz bands, respectively, and lower transmissibility under high-frequency excitations, such as H-spectrum, orbital sander and chipping hammer. The results also reveal relatively wide variations in standard deviations of the measured data, ranging from 0.9% to 17%, similar to those reported in other studies (Hewitt, 1997, 1998; Griffin, 1998). The magnitudes of unweighted acceleration transmissibility of the gloves attained under broad-band excitations are comparable to those evaluated for the H-spectrum, while low-frequency components of broad-band vibration yield considerably higher values for the frequency-weighted transmissibility. The results obtained for the broad-band spectra further suggest negligible effect of the magnitude of excitations considered in this study.

3.2. Frequency response function of the gloves

The vibration isolation effectiveness of the gloves is strongly affected by the nature of vibration excitation, specifically the predominant frequencies, and the frequency weighting, as is evident from the results summarized in Table 2. The vibration isolation performance of a glove is further dependent upon its frequency response characteristics, which are influenced by the visco-elastic properties of the isolating materials. Considering that the vibration spectra of different tools predominate over a wide frequency range, it is perhaps essential to identify the frequency response characteristics over a wide frequency range. Moreover, the frequency response characteristics of a glove may also depend upon the magnitude of vibration due to nonlinear material properties.

The frequency response characteristics of the two gloves coupled with the hand are evaluated from the measured data acquired from three subjects under Broad_M and Broad_H spectra, using Eqs. (3) and (6). The data acquired for the three subjects revealed intra-subject variations in the 1.7–7.5% range, which are considerably smaller than those attained under different tools spectra. The mean values of the frequency response characteristics of the two gloves, evaluated in terms of the acceleration transmissibility in the 10–1000 Hz frequency range, are presented in Fig. 3. The two gloves yield considerably different frequency response characteristics, and similar primary resonant frequencies. The air glove (A) yields a peak transmissibility of 1.05 near 16 Hz under both magnitude spectra, while glove B made of visco-elastic materials yields a peak transmissibility of 1.04 near 16 Hz under both the spectra. The frequency response characteristics of glove A reveal superior vibration isolation at frequencies above 25 Hz with peaks occurring near 100 and 250 Hz. Glove B yields a peak of considerable magnitude near 250 Hz, as shown in the figure. It tends to amplify the handle vibration slightly in the vicinity of 250 Hz, while glove A continues to provide effective attenuation (isolation = 41%) near this frequency. The frequency response characteristics of both gloves exhibit peaks near 100 and 250 Hz, which may be attributed to the biodynamic behaviour of the human hand and arm.

The results attained for the two gloves suggest that under the specified grip (30 ± 5 N) and feed (50 ± 8 N) forces, the frequency response characteristics are relatively insensitive to the magnitude of broad-band vibration excitation considered in this study. While glove B yields nearly identical values of transmissibility under both the spectra, glove A yields slightly better attenuation under Broad_M excitation in the 40–300 Hz range. The peak difference between the magnitudes of transmissibility attained under the two spectra is in the order of 10%, well below the inter- and intra-subject variabilities observed from the measured overall acceleration transmissibility under different tools spectra. The frequency response characteristics of each glove can thus be represented by

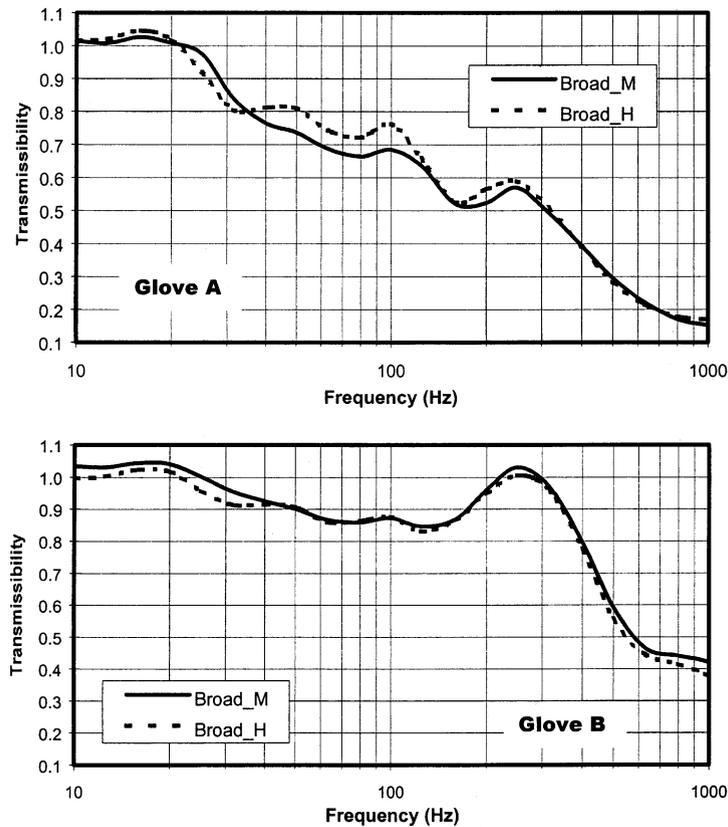


Fig. 3. Frequency response characteristics of the glove–hand combinations under broad-band vibration excitations of different magnitudes.

the mean values of the transmissibility magnitudes as shown in Fig. 4.

3.3. Influence of grip and feed forces

The variations in the feed and grip forces may alter the effective energy restoring and dissipating properties of the glove materials, and thus the frequency response characteristics. The frequency response characteristics of the selected gloves are thus measured under different magnitudes of controlled grip and feed forces, and Broad_M and Broad_H spectra. The effect of variations in the forces, however, is studied independently by varying either grip or feed force during a test. The measurements were initially performed with three subjects and three different magnitudes of mean grip force (10, 30 and 50 N), while the feed force

was held constant near 50 N. The subsequent measurements were performed under three different magnitudes of feed force (10, 30 and 50 N), while the grip force was held constant near 30 N. The subjects were permitted the tolerances of ± 5 and ± 8 N, respectively, for the grip and feed forces, as recommended in ISO-10819. A total of three measurements were performed for each subject, glove, grip, feed and excitation combination, and the data were analysed to derive the mean transfer function as a function of the grip force, feed force and the excitation magnitude. The measurements revealed relatively little effect of the magnitude of vibration excitation, as observed in Fig. 3.

Figs. 5 and 6 illustrate mean acceleration transmissibility of the selected gloves at the third-octave band centre frequencies, as functions of

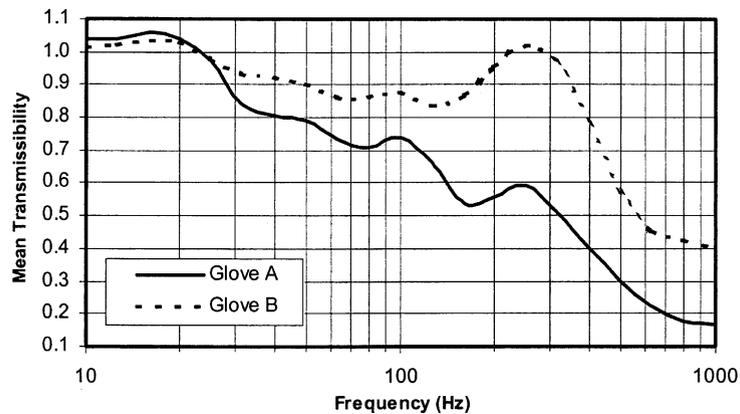


Fig. 4. Mean acceleration transmissibility of the gloves attained under Broad.M and Broad.H excitation spectra (grip force = 30 ± 5 N, feed force = 50 ± 8 N).

grip and feed forces, respectively. The transfer functions for both the gloves indicate notable dependence on both the grip and feed forces at frequencies above 250 Hz. Light grip and feed forces tend to lower the primary resonant frequency of the gloves, which appears to be quite evident for Glove A. An increase in grip force tends to amplify vibration in the lower frequency bands for Glove A, while the effect on transmissibility of Glove B in the same frequency bands is relatively small. The variations in the grip force yield more pronounced effect on the secondary resonant frequency (near 250 Hz) of both the gloves, resulting in lower frequency with a light grip force. The variations in the feed forces also yield similar effect on the vibration transmissibility, as shown in Fig. 6. From the results, it is apparent that both the grip and feed forces affect the frequency response characteristics of the gloves, specifically at frequencies above 250 Hz. The effect, however, may be considered to be relatively small at lower frequencies. The contributions due to variations in grip and feed forces may vanish when the frequency weighting (ISO-5349, 1986) is applied. On the basis of the weighted glove transmissibility, Paddan (1996) concluded that variations in the grip force affect the glove transmissibility only marginally.

The mean transfer functions of gloves, presented in Fig. 4, are thus considered valid for magnitudes of grip and feed forces in the vicinity of 30 and

50 N. Owing to the expected considerable variations in the grip and feed forces during tool operation, the mean transfer functions may be considered valid for excitation frequencies below 250 Hz. Considering that the frequency weighting tends to diminish the contributions due to variations in forces, the mean transfer functions are considered to be valid for estimation of frequency-weighted isolation effectiveness.

3.4. Validity of the estimation method

The acceleration response characteristics of the selected gloves (A_z and A_{zw} , at the hand–glove interface) are estimated from the mean frequency response function of the glove (Fig. 4) and Eqs. (1) and (4) in conjunction with the handle vibration spectra of different tools. The acceleration response measured at the palm adapter under synthesized vibration excitations of different tools are also analysed to compute the rms acceleration spectra in the broad frequency range. The estimated and measured rms acceleration response spectra are compared for each of the selected tools vibration to demonstrate the validity of the proposed method. The overall values of the frequency-weighted and unweighted rms accelerations, and the glove transmissibility are further evaluated from the measured and estimated responses, and compared in Tables 3 and 4, respectively.

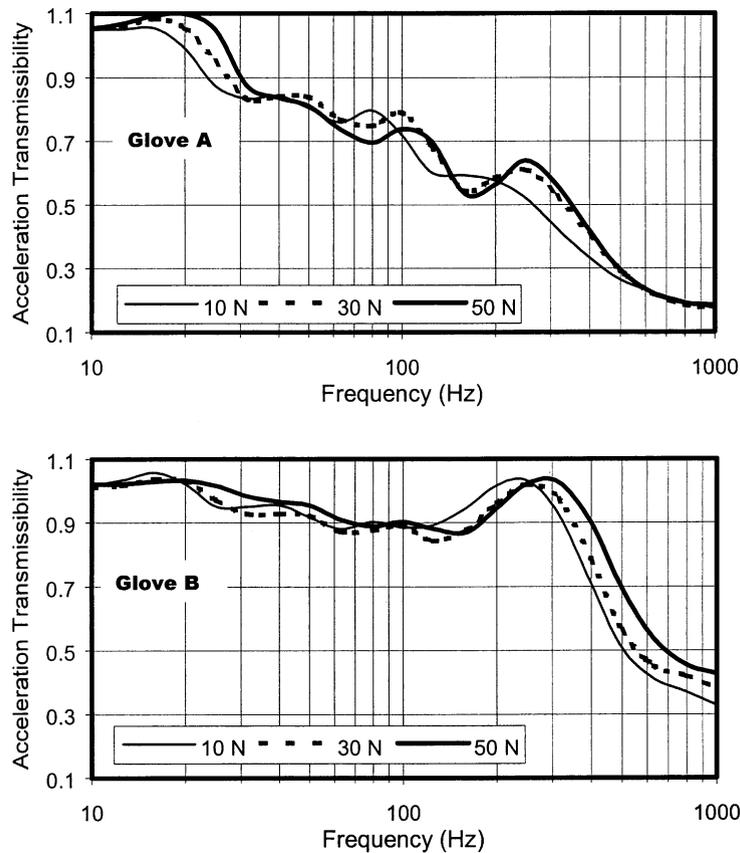


Fig. 5. Effect of grip force on the frequency response characteristics of the gloves (feed force = 50 N).

Fig. 7 illustrates comparisons of the estimated and measured rms acceleration response spectra under the standardized M- and H-excitations. The comparisons of the results attained under different tools vibration are presented in Figs. 8 and 9. The figures also illustrate the rms acceleration spectra of the synthesized handle vibration or the M- and H-spectra. The response and excitation spectra corresponding to M- and H-excitations are illustrated in the 16–400 and 100–1000 Hz frequency ranges, respectively (Fig. 7), while those corresponding to different tools are presented in the 10–1000 Hz frequency range (Figs. 8 and 9). The measured acceleration spectra represent the mean of the data acquired with three subjects and three trials per subject. The results, in general, show reasonably good agreements between the estimated and measured spectra for the different

handle vibrations considered in the study, with considerable deviations for glove A under some of the excitation spectra (H, chainsaw and riveter). The spectra of the estimated acceleration response agree very well for glove B, irrespective of excitation spectra. Glove B provides attenuation of handle vibration at frequencies above 315 Hz for majority of the spectra, with the exception of the chainsaw, orbital sander and the M-spectrum. It tends to amplify the M-spectrum vibration above 250 Hz, and provides only minimal attenuation of chainsaw and orbital sander vibration. Glove A, on the other hand, yields attenuation of vibration at frequencies above 50 Hz for majority of the spectra.

A comparison of frequency-weighted and unweighted values of the response accelerations (A_z and A_{zw}), presented in Table 3, also reveals

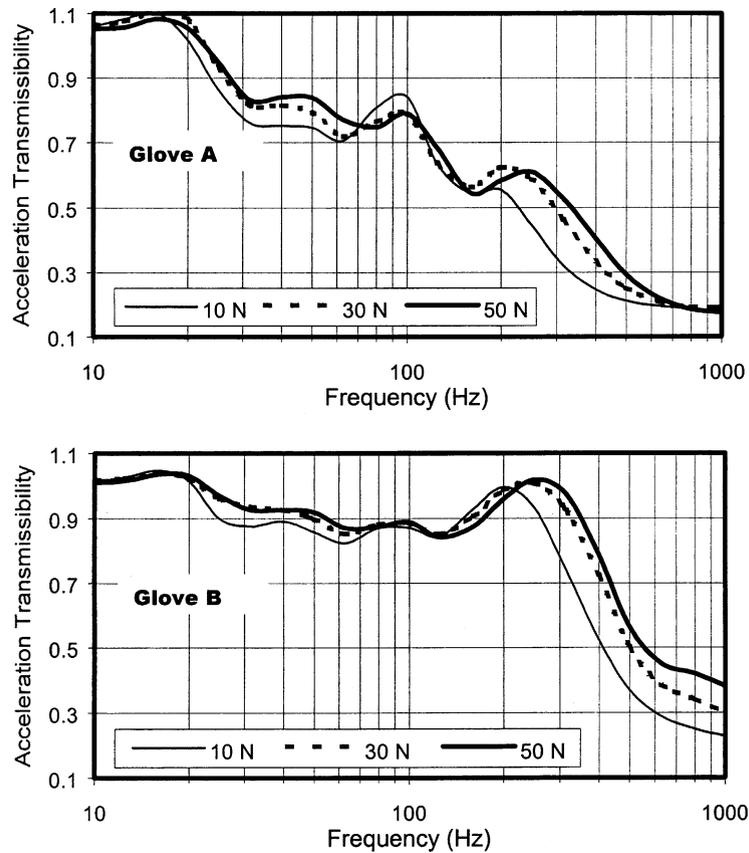


Fig. 6. Effect of feed force on the frequency response characteristics of the gloves (grip force = 30 N).

Table 3
Comparison of measured and estimated overall response accelerations of the gloves

Tool/spectra	Glove A						Glove B					
	Acceleration, A_z (m/s^2)			Acceleration, A_{zw} (m/s^2)			Acceleration, A_z (m/s^2)			Acceleration, A_{zw} (m/s^2)		
	Measured	Estimated	% error	Measured	Estimated	% error	Measured	Estimated	% error	Measured	Estimated	% error
M	11.51	11.17	2.9	2.68	2.71	1.0	15.16	15.16	0.0	3.03	3.06	1.2
H	32.90	29.48	10.4	1.80	1.68	6.7	54.81	55.26	0.8	2.79	2.77	0.7
Chainsaw	12.44	11.35	8.8	1.62	1.54	5.2	17.46	18.10	3.7	1.95	2.00	2.6
Nutrunner	11.83	11.44	3.4	5.43	5.12	5.6	17.04	17.21	1.0	5.56	5.50	1.2
Riveter	10.65	9.26	13.1	1.24	1.09	12.1	14.80	14.47	2.2	1.43	1.38	3.3
Orbital sander	52.05	53.56	2.9	7.97	8.04	0.9	67.17	68.53	2.0	9.72	9.85	1.3
Chipping hammer	48.27	45.61	5.5	9.18	8.62	6.2	64.65	68.82	6.5	9.58	10.07	5.1
Road breaker	26.17	24.48	6.5	15.00	15.24	1.6	37.71	36.12	4.2	14.45	15.25	5.5

generally good agreements between the estimated and measured values, with the exception of those attained for glove A under the spectra mentioned

above. The estimated values of overall acceleration transmissibility also reveal similar agreement with the measured values, as illustrated in Table 4. For

Table 4
Comparison of measured and estimated overall transmissibility values of the gloves

Tool/spectra	Glove A						Glove B					
	Transmissibility, T_C			Transmissibility, T_{Cw}			Transmissibility, T_C			Transmissibility, T_{Cw}		
	Measured	Estimated	% error	Measured	Estimated	% error	Measured	Estimated	% error	Measured	Estimated	% error
M	0.69	0.67	0.80	2.9	0.79	1.0	0.85	0.85	0.0	0.88	0.89	1.2
H	0.39	0.35	10.4	0.57	0.52	6.7	0.64	0.65	0.8	0.87	0.86	0.7
Chainsaw	0.66	0.60	8.8	0.78	0.74	5.2	0.90	0.92	3.7	0.93	0.95	2.6
Nutrunner	0.40	0.39	3.4	0.96	0.91	5.6	0.54	0.54	1.0	0.98	0.96	1.2
Riveter	0.56	0.49	13.1	0.81	0.71	12.1	0.77	0.75	2.2	0.93	0.90	3.3
Orbital sander	0.65	0.67	2.9	0.68	0.69	0.9	0.75	0.77	2.0	0.77	0.78	1.3
Chipping hammer	0.51	0.48	5.5	0.78	0.74	6.2	0.70	0.75	6.5	0.85	0.89	5.1
Road breaker	0.50	0.47	6.5	1.04	1.05	1.6	0.57	0.55	4.2	1.03	1.09	5.5

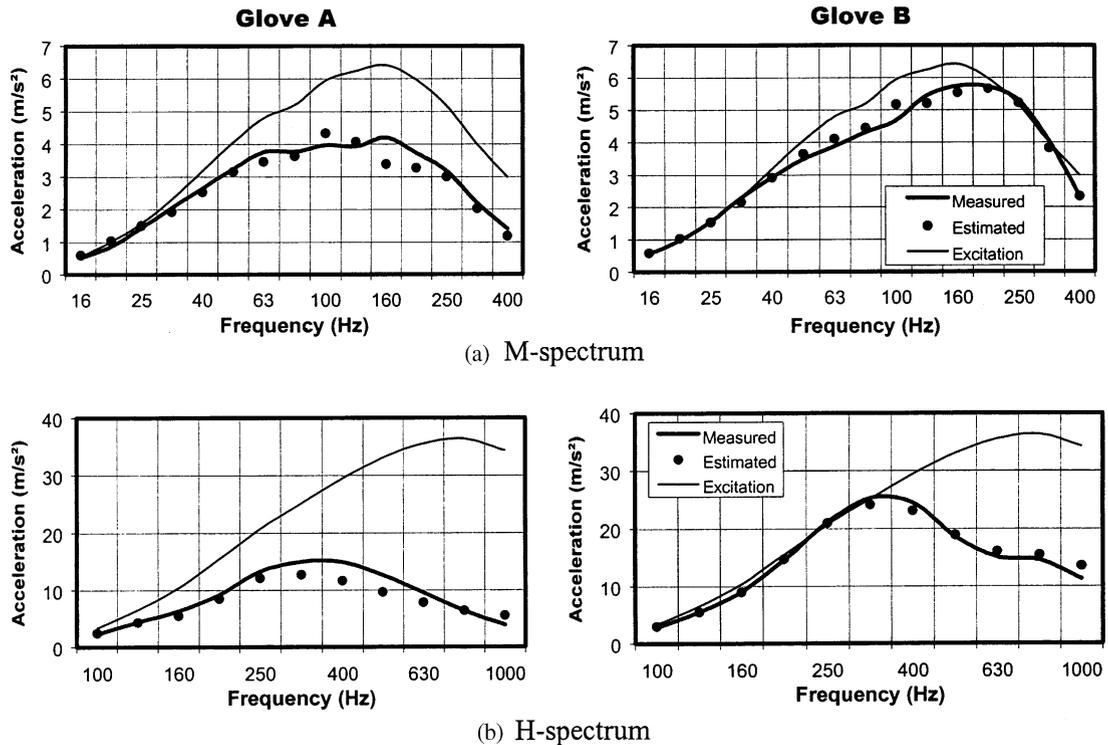


Fig. 7. Comparison of measured and estimated acceleration response of the gloves under M- and H-spectra.

glove B, deviations between measured and estimated unweighted values of A_z and T_C are $<7\%$ for all the excitation spectra, while the deviations in weighted values are even lower ($\leq 5.5\%$). The deviations between the unweighted and weighted

estimated and measured values for glove A are below 6.5% , when the data for the H-spectrum, chainsaw and riveter are excluded. The results show errors between estimated and measured unweighted values in the order of 10.4% under

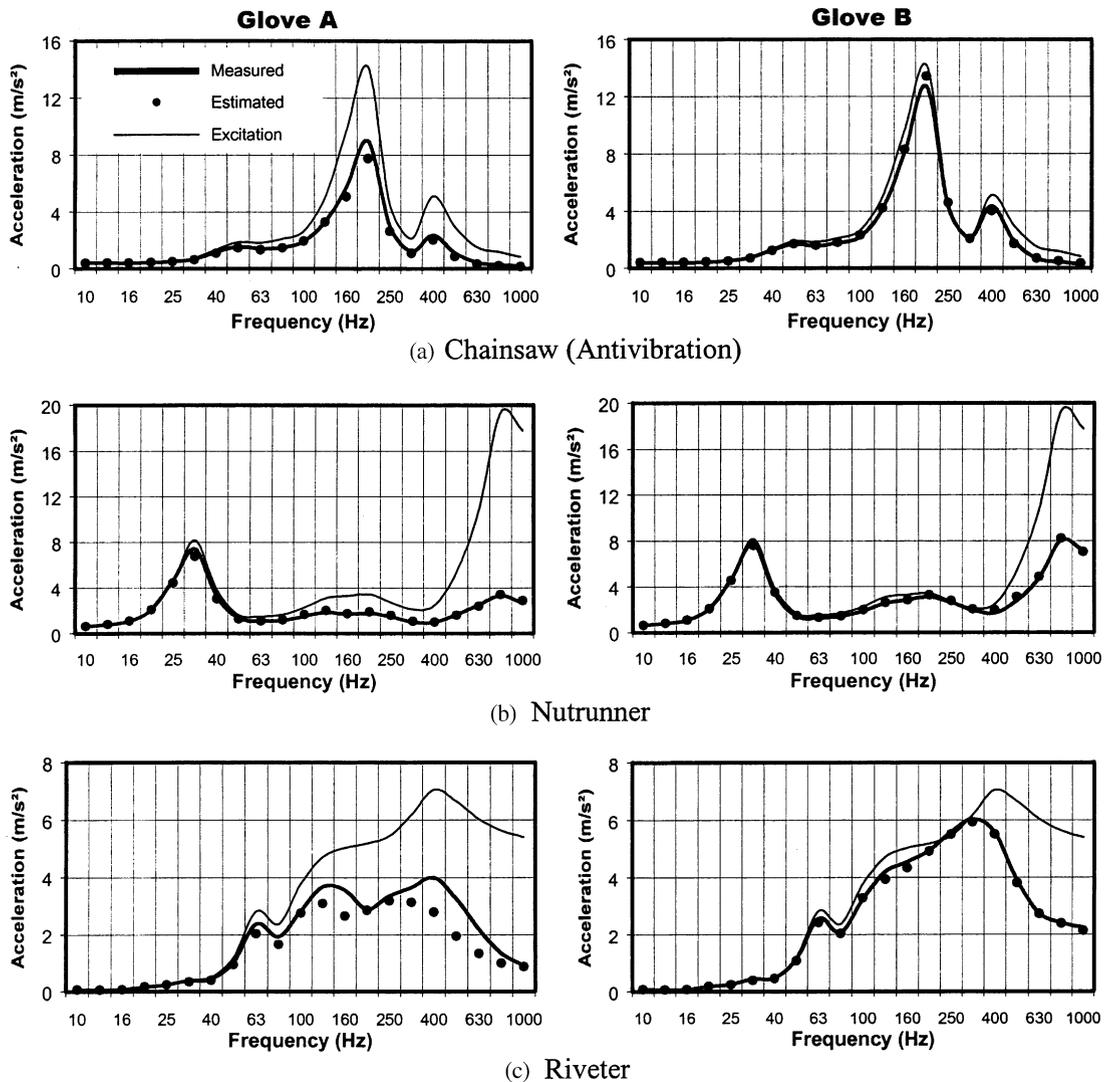


Fig. 8. Comparison of measured and estimated acceleration response of the gloves under synthesized handle vibration of: (a) chainsaw (antivibration); (b) nutrunner; and (c) riveter.

H-spectrum, 8.8% under chainsaw excitation and 13.1% under the riveter excitations. The corresponding errors in the frequency-weighted values are considerably smaller for the tools excitations. The excitations due to these spectra (H, chainsaw and riveter) consist of very low magnitude vibration in the lower frequency bands (below 60 Hz), as shown in Fig. 1. The measured data corresponding to these excitations revealed considerable variations in the subjects' grip and feed forces, and

intra-subject variations as high as 18.3%. The deviations between measured and estimated spectra are thus attributed to large intra-subject variations associated with the measured data.

4. Conclusions

A methodology to estimate the tool-specific vibration isolation effectiveness of antivibration

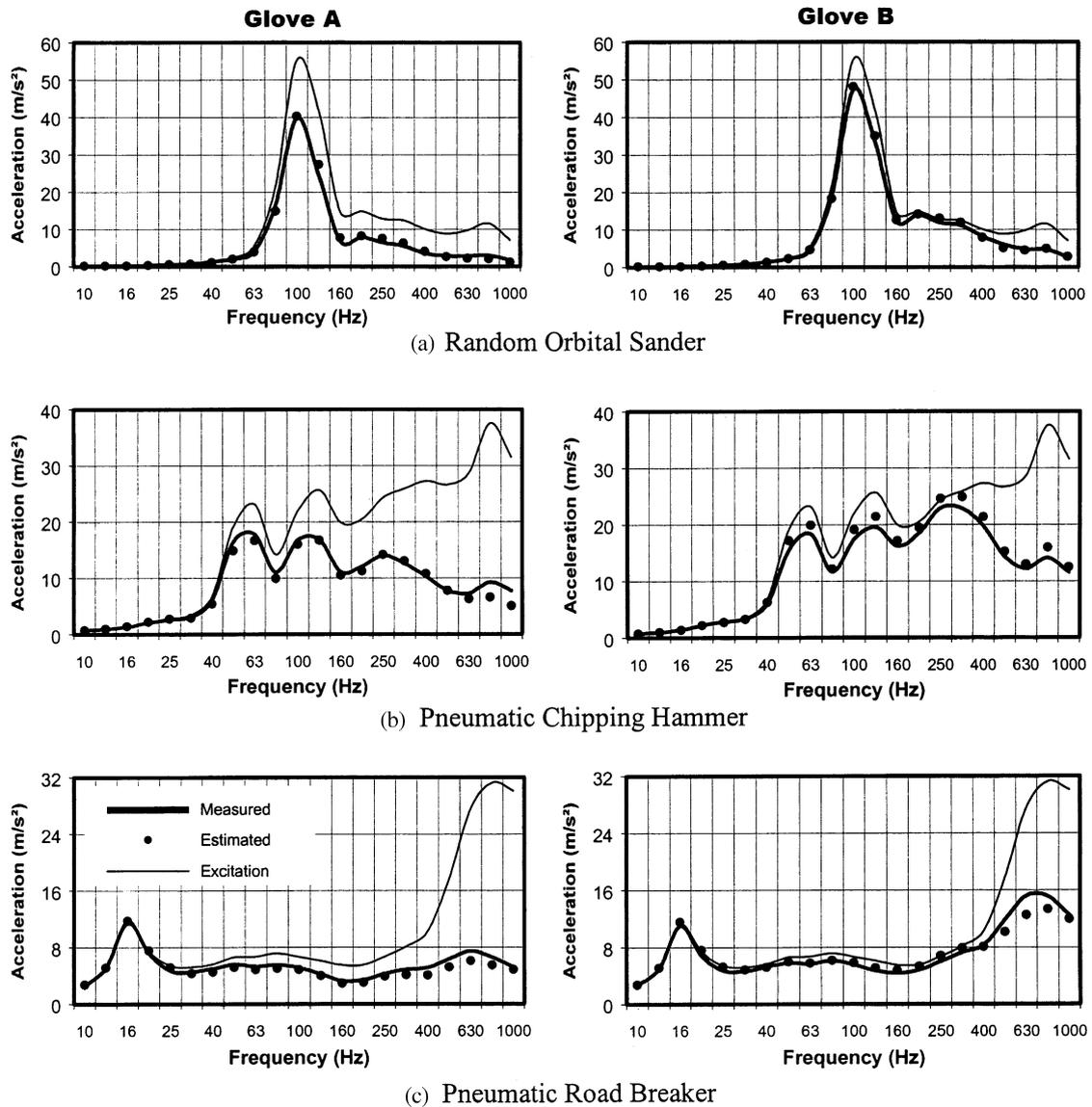


Fig. 9. Comparison of measured and estimated acceleration response of the gloves under synthesized handle vibration of: (a) random orbital sander; (b) pneumatic chipping hammer; and (c) pneumatic road breaker.

gloves is proposed on the basis of the frequency response characteristics of the gloves. The handle vibration spectra of six different tools are synthesized in the laboratory and attenuation performance of two different gloves are evaluated under the tools vibration, and the M- and H-spectra defined for assessment of antivibration perfor-

mance of gloves in ISO-10819 (1996). The measurements are performed with three male subjects in the laboratory using the method outlined in the standard. From the comparison of the tools vibration spectra with the standardized medium (M) and high (H) frequency spectra, it is concluded that the recommended spectra do not

characterize the vibration characteristics of most of the tools considered. Consequently, the vibration isolation effectiveness of a glove for a specific tool cannot be evaluated using the acceptance criteria defined in the standard, i.e., the overall frequency-weighted acceleration transmissibility to be below 1.0 and 0.6 under the M- and H-spectrum, respectively. The mean acceleration transmissibility values derived from the measured data tend to vary considerably for different excitations. The frequency-weighted acceleration transmissibility values lie in the 0.57–1.04 range for glove A and 0.77–1.03 for glove B, depending upon the nature of excitation. It is thus concluded that the tool-specific vibration isolation performance of a glove cannot be derived from the standardized M- and H-spectra.

It is proposed that the isolation effectiveness of a glove should be evaluated from its frequency response characteristics and a representative tool vibration spectrum. The frequency response characteristics of the selected gloves are thus characterized under broad-band vibration excitations of two different magnitudes, and different magnitudes of the grip and feed forces. The results suggest that the frequency response characteristics of the gloves are relatively insensitive to the magnitude of vibration but strongly dependent upon the visco-elastic properties of the glove material. The variations in the grip and feed forces also influence the fundamental frequency, resonant transmissibility and high-frequency vibration isolation property of the glove. The application of frequency-weighting, however, would diminish the effect of the grip and feed forces on the high-frequency isolation characteristics. The mean measured frequency response characteristics of the gloves are thus defined from the data acquired for the recommended values of grip (30 N) and feed (50 N) forces.

The validity of the proposed estimation methodology is demonstrated by comparing the estimated response acceleration spectra, and overall response acceleration and acceleration transmissibility values with the mean measured responses. The comparisons revealed reasonably good agreements between the measured and estimated values for majority of the handle vibration spectra

considered in the study. The deviations between the predicted and measured transmissibility values are within 9% for majority of the glove–spectra combinations, well within the intra- and inter-subject variabilities. The results revealed deviations as high as 13.1% for the air glove under excitations with relatively low magnitude vibration in the low-frequency range. Such high magnitude errors are attributed to relatively large intra-subject variations, in the order of 18%, associated with the measurements under this spectra.

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