Effectiveness of a Transfer Function Method for Evaluating Vibration Isolation Performance of Gloves When Used With Chipping Hammers

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ABSTRACT
Anti-vibration gloves have been used as personal protective equipment to reduce the exposure intensity of hand-transmitted vibration. Although a method based upon the measured transfer function has been recently proposed to predict the tool-specific anti-vibration performance of these gloves, its validity for real tool applications has not been sufficiently evaluated. In this study, the effectiveness of the proposed prediction method was examined using two typical vibration-attenuation gloves when used in conjunction with two different pneumatic chipping hammers. Six adult male subjects were employed in the experiments involving measurement of gloves transmissibility while operating the selected tools. A comparison of the measured vibration transmissibility with the predicted values revealed that the transfer function method provides a reasonably good prediction of the vibration isolation performance of the gloves. The differences between the predicted and measured mean values of the weighted transmissibility were surprisingly small. It is concluded that the transfer function method can serve as an effective and convenient approach for estimating the effectiveness of anti-vibration gloves when used with pneumatic chipping hammers. A pneumatic chipping hammer is considered to represent a critical case for the evaluation of the method because they are typical percussive tools that generate impact vibration. It is thus anticipated that the transfer function method may also be widely employed to predict anti-vibration glove performance when used with many other vibrating tools.

Key words: Hand-arm vibration, anti-vibration glove, chipping hammer, percussive tool, glove vibration isolation.

INTRODUCTION

Exposure to hand-transmitted vibration over extended durations may cause hand-arm vibration syndrome (HAVS). Gloves have been highly recommended as personal protective equipment to prevent cuts and abrasions, to keep workers' hands warm and dry, and to help maintain blood circulation to the hands and fingers.[1,2] Operators of powered hand tools have also used anti-vibration gloves, made with resilient materials or air bladders, to isolate or reduce transmitted vibration.[3-6] A reliable and convenient method is highly desired to assess the anti-vibration performance of the gloves when used with specific tools. Such a method would be a useful tool for quantifying the beneficial effect, for the proper selection and use of anti-vibration gloves, and for the further development of tool-specific anti-vibration gloves.

To date, the anti-vibration performance of such loves has been typically evaluated through laboratory measurements of the source and response vibrations along a single specific axis conducted under idealised excitations. Previous studies have employed varied vibration excitation spectra, such as swept sine or random white noise, and different measurement locations, such as the palm, back of the palm, fingers, carpal bone, and wrist.(7-12) A few studies on the hand-arm response to the glove worn while operating real tools have also been reported.(13-14) A few investigators have also studied the health effects of wearing vibration-attenuation gloves (15-16) The results of these studies vibration transmission and health effects.

In an effort to provide a uniform laboratory screening test method, the International Standard Organisation (ISO) has set forth a laboratory test method to assess the anti-vibration performance of these gloves.(17) The ISO method uses a palm adapter equipped with an accelerometer to measure the vibration transmitted at the hand-glove interface and an instrumented handle to measure the vibration input to the glove under controlled grip force (30 N). The handle is fixed on a single-axis shaker to provide axial vibration. The test also requires a push force (50 N), which is measured using a force plate or a force sensor installed between the shaker and handle. Three test subjects are required for measurement, where each subject completes two trials for each glove. The standardised test method requires the measurements to be taken with the test subject assuming a specific posture (forearm horizontal and parallel with the direction of vibration, and wrist angle between 0° and 40°). The standard assessment is based on the vibration transmissibility through the gloves under two vibration excitation spectra: (i) medium frequency (M) vibration spectrum in the 16-400 Hz range; and (ii) high frequency (H) vibration spectrum in the 100-1600 Hz range. A glove is considered to be an 'anti-vibration glove', when the transmissibility values measured under M- and H-spectra fall below 1.0 and 0.6, respectively. Although the standardised method has been widely used to assess the vibration isolation effectiveness of gloves, the method cannot predict exactly how much a glove will reduce the transmitted vibration when the glove is used with a specific tool under a particular operating condition. Owing to the considerable differences between the vibration spectra of most hand-held power tools and the idealised M- and H-spectra, the vibration isolation effectiveness of gloves are expected to be strongly dependent upon the type of tool used.(18)

The vibration isolation performance of a glove may depend upon many factors such as the characteristics of tool vibration (magnitude and frequency range), visco-elastic properties of the glove material, hand-arm postures, and magnitudes of hand coupling forces.(18) The evaluation of the performance would require measurements in the field under representative operating conditions (working material, posture, and coupling forces, etc.) or in the laboratory under representative vibration spectra and operating conditions. A US National Standard for glove evaluation (ANSI 3.40. 1989) (19) was designed primarily for field studies and is based on such a methodology. This standard requires two sets of vibration measurements on a tool handle and on the third metacarpal of the hand to establish: (a) the baseline "bare hand" (no glove) transmissibility, and (b) the vibration transmissibility with a "gloved hand," using the glove to be tested. The corresponding bare hand and gloved hand transmissibility values are then compared to assess the effectiveness of the glove. Application of this methodology, however, can pose considerable difficulties in the data analysis. These difficulties are mostly attributed to the inter- and intra-subject variations because of the complex interactions among the tool vibration, working conditions, coupling forces, and hand-handle-glove system dynamics. This may explain why very few studies(13,14) have employed such a methodology.

As an alternative approach, the vibration isolation performance of a glove for a specific tool can be derived from the transfer function of the glove, which can be conveniently measured in the laboratory and applied to estimate the glove effectiveness for different tool vibration spectra. The ISO standard for the glove testing(17) recommends the reporting of the transfer function or the unweighted transmissibility as a function of frequency for the estimation of the tool-specific isolation performance of gloves when the tool vibration spectrum is available. Griffin[18] employed this method to demonstrate the nature of the tool-specific performance of gloves. In his study, the transfer function was attained from the idealised M- and H-spectrum excitations specified in the standard. Rakheja et al.[20] proposed the use of broadband random excitations to measure the transfer function of selected gloves. Their study also conducted laboratory evaluations of gloves under the vibration spectra of six different tools synthesised on a single-axis shaker test system. The comparison of measured and predicted data revealed reasonably good agreements. A similar prediction method has also been used by other investigators[21] for estimating the vibration isolation effectiveness of five different types of gloves when used with chain saws and grinders in the field. The predicted values, however, differ considerably from the measured data. This casts some doubts on the transfer function approach. Therefore, the validity of the predication method for real tool applications requires further evaluations.

The present study was designed to compare the predicted vibration transmissibility of the gloves with the measured data obtained while operating chipping hammers to assess the effectiveness of the transfer function approach.

2. METHODS AND MATERIALS

The vibration transmissibility is the ratio of the source acceleration measured on the chipping hammer handle to the response acceleration measured on a palm adapter inside a glove. In this study, the test setup specified in ISO 8662-2[22] for measuring the vibration emission of chipping hammers was employed to produce a repeatable and stable impact vibration. Figure 1 shows the basic test equipment setup for vibration measurement. The key feature of the test apparatus is the energy absorber. In accordance with the ISO standard,[22] the energy absorber is composed of a steel tube filled with hardened steel balls, which is firmly mounted on a rigid steel base secured to a concrete block. The apparatus is designed to provide a reproducible reaction dynamic force to an operating chipping hammer, while preventing the hammer from jumping. The chipping hammer's chisel bit is inserted into the top of the energy absorber to rest or impact against the steel balls.

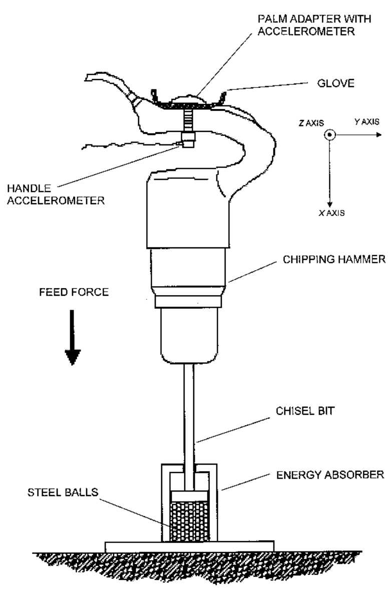


Figure 1 Basic Test Setup for the Measurement of Vibration Transmissibility of a Glove on a Chipping Hammer

A palm adapter equipped with a tri-axial piezoelectric accelerometer (PCB SEN026) was used to measure the vibration at the palm inside the glove. The 70 mm long adapter weighed 15 g, while its handle contact surface radius was 24 mm. These weight and dimensional values conform to the requirements outlined in the ISO-10819 standard.[17]

Two pneumatic chipping hammers were used in this study, weighing 6.6 kg and 6.9 kg, respectively. The supplied air pressure was regulated to 689 kPa (100 psi), as specified for these tools. The length of the chisel bit used in the test was approximately 30 cm. The handle vibration was measured using another tri-axial piezoelectric accelerometer (PCB 5611A), which was installed on a mounting block and secured to the handle with a hose clamp. A multi-channel data acquisition unit (B&K Type 2816) was used to collect the six acceleration signals from the two tri-axial accelerometers. The acquired vibration data were analyzed and expressed as the root-mean-square (rms) values of the accelerations in the 1/3-octave frequency bands.

Significant DC shifting of the piezoelectric accelerometer output usually occurs when measuring vibration on percussive tools if a mechanical filter is not used.[23], The application of a commercial mechanical filter (B&K, UA0059) was judged to be unsatisfactory to circumvent the difficulty associated with the DC shift of the accelerometer signals used in the present study. Consequently, a mechanical filter comprising a 3 mm thick elastomer was configured and wrapped around each tool's handle prior to accelerometer installation to act as a mechanical filter. The effectiveness of the elastomer layer and its effects on vibration transmissibility was assessed by comparing the accelerometer signals with that acquired using a laser vibrometer (PSV-300) to measure the tool handle vibration. The laser vibrometer signal was observed to be free from the DC shift. Four different subjects operated a chipping hammer with no gloves during these tests. Each subject employed a posture similar to that specified in the ISO-8662-2 chipping hammer handle vibrations test.[22] However, each subject placed his hands side-by-side on the tool handle and left a gap between the hands such that the laser beam could be pointed to the centre surface of the adapter in the dominant vibration direction, as shown in Figure 2. The raw velocity signal acquired from the laser vibrometer was captured by the data acquisition system and analysed concurrently with the signals acquired from the piezoelectric accelerometers on the handle and the adapter along the dominant direction (X-axis) only.

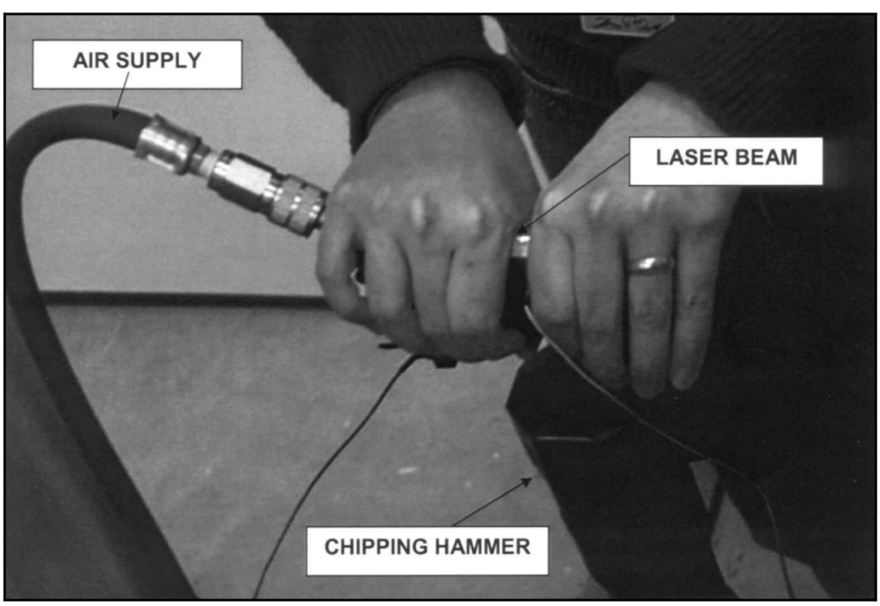


Figure 2 Verification of the Validity of the Vibration Measurement with Piezoelectric Accelerometers on the Chipping Hammer Using a Laser Vibrometer

The results of a previous study[24] indicate that it may not be necessary to simulate the grip and feed forces separately for the measurement of vibration transmissibility of gloves at the palm of the hand, and an equivalent feed force may be considered sufficient. To simplify the tool handle instrumentation and to allow the subjects to focus on the feed force control alone, the subjects were asked not to apply the grip force during the tests. Two levels of feed force (50 and 100 N), however, were used. These forces are comparable to those used in the transfer function measurement performed in the reported study.[20] A force measurement plate (Kistler Type 9286AA) was used to measure the applied feed force. Each subject stood on the force plate while operating the tool. A computer monitor displayed a strip chart depicting the applied feed force so the test subject could control the force to the desired level. Two different types of gloves (air and visco-elastic) that were marketed as anti-vibration gloves were employed in the study, which were identical to those used in the study reported by Rakheja et al. [20], such that the reported transfer functions could be directly applied in this investigation.

Six male subjects, with mean body mass of 87.3 kg and mean height of 1.83 m, participated in the study. The body mass of the participants varied from a minimum of 63.1 kg to a maximum of 112.2 kg, while the heights ranged from 1.68 m to 1.88m. After signing a required consent form and donning all the necessary personal protective equipment, each subject received brief training on the tool operation and was allowed to undertake trial runs for durations up to 10 minutes.

For this study, the test subjects were instructed to use the same posture as that specified in the ISO vibration emission test for chipping hammers.[22] Each subject stood on a platform and applied a downward push force on the tool handle. The platform height was adjusted for each subject to ensure proper posture and to maximize comfort. During the test, each subject wore a test glove on his dominant hand with the adapter held in the palm. In order to ensure that the feed force was applied through the centre of the adapter, the ungloved hand was placed on top of the dominant gloved hand as the subject applied the required feed force. The test subject's non-dominant hand also helped stabilise the tool. The tool's switch was fixed at the "on" position with an adhesive tape so that the subject could focus his attention on the tool operation and maintain a relatively constant feed force. A test assistant used a ball valve at the regulated air supply to control the tool's on/off operation during the test.

The sequence of the combinations of push forces and the gloves was randomised. The sequence of the hammers was also randomised among the six subjects. Three trials were completed for each test combination. Vibration data collection was initiated once the feed force was observed to be stable. The vibration in the standard emission test is usually stable, and the required minimum duration of the vibration measurement for each trial is only 8 seconds.[22] The measurement duration in the present study was extended to 15 seconds in an effort to enhance the reliability of the measurements. The test subjects usually took a one-minute rest between consecutive trials.

Even though the accelerometers on the handle and the adapter were calibrated prior to their installation, the two accelerometer signals tend to be different due to differences in their installation locations and contributions due to the hand-handle interactions. A correction factor is often applied during the transmissibility calculations to account for such differences. For this purpose, additional tests were performed with each subject while operating the tool with the bare hand test. The measured data was utilised for the internal calibration of the two accelerometers. Furthermore, the axes of the two accelerometers were aligned with each other as closely as possible. The average ratios of the two unweighted accelerations in each axis across the entire 5 Hz-1500 Hz frequency range were used as correction factors to normalise the vibration measured on the tool handle during glove testing. The frequency-weighted rms accelerations were further computed using the weighting function specified in ISO 5349-1.[2] Finally, the measured vibration transmissibility of each glove was derived from the frequency-weighted rms accelerations in terms of total vibration and the transmissibility along a dominant vibration axis.

The total vibration transmissibility (MT_t) was calculated from

$$MT_t = \frac{\sqrt{A_{ax}^2 + A_{ay}^2 + A_{az}^2}}{\sqrt{A_{tx}^2 + A_{ty}^2 + A_{tz}^2}} \tag{1}$$

where A_{ax}, A_{ay} and A_{az} are the frequency-weighted rms values of acceleration components measured on the adapter along the three orthogonal directions, and A_{tx}, A_{ty} and A_{tz} are those measured on the tool handle. The measured transmissibility (MT_d) in the dominant axis was calculated from:

$$MT_d = \frac{A_{ax}}{A_{tx}} \tag{2}$$

The glove transfer functions used in this study were taken directly from a reported study[20], which were evaluated under a broadband random excitation, and with identical test setup and subject posture as specified in the current ISO 10819 standard[17]. The magnitude of the transfer functions of the two candidate gloves used in this study are presented in Figure 3. The figures show equivalent values of the feed forces, which were attained upon summations of the feed and the grip forces used in the reported study,[20] and matched closely with those used in the present study. Since the tests in the present study were performed with negligible grip force, the data reported for 50 N feed and 0 N grip forces was considered, while the reported data corresponding to 50 N grip and 50 N push forces was considered to represent an equivalent feed force of 100 N.

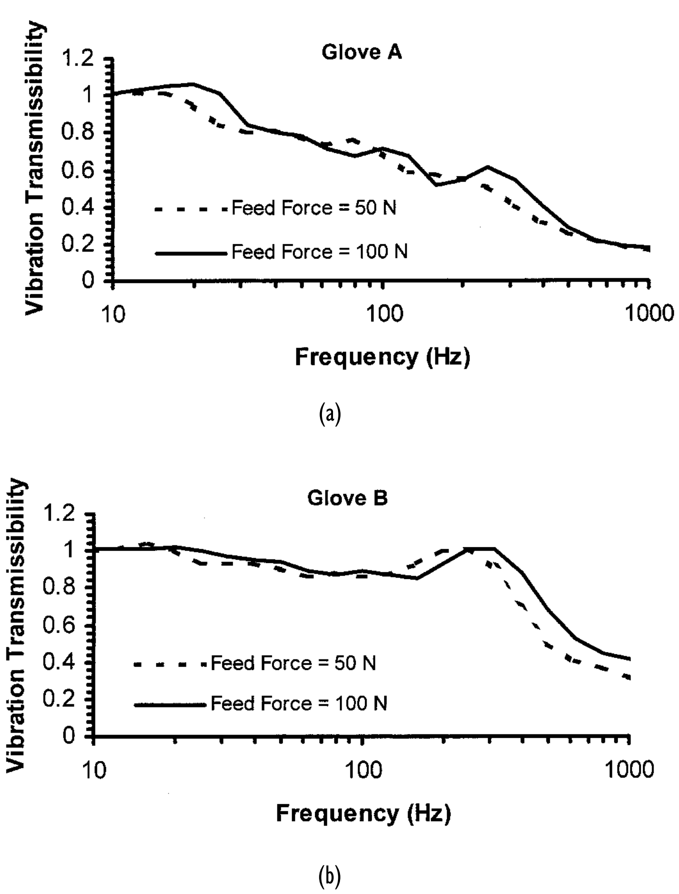


Figure 3 The Frequency Response Characteristics of the Two Transfer Functions

The selected transfer functions were applied to estimate the transmissibility of total vibration in the following manner:

$$ET_T = \sqrt{\frac{\sum_{i=1}^{3}\sum_{k=1}^{n} W^2(f_k)\, T_i^2(f_k)\, a_{ti}^2(f_k)}{\sum_{i=1}^{3}\sum_{k=1}^{n} W^2(f_k)\, a_{ti}^2(f_k)}} \quad (3)$$

where $T_i(f)$ is the frequency response characteristics of the selected glove as shown in Figure 3, $a_{ti}(f)$ is the unweighted rms acceleration measured on the tool handle corresponding to centre frequency f_k of the kth third-octave frequency band, and $W(f)$ is the corresponding weighting factor,[2] and i denotes the three axes of vibration, as shown in Figure 1. n is the number of the 1/3-band centre frequencies used in the calculation. The estimated transmissibility (ET_d) along the dominant vibration axis was computed from:

$$ET_d = \sqrt{\frac{\sum_{k=1}^{n} W^2(f_k)\, T_x^2(f_k)\, a_{tx}^2(f_k)}{\sum_{k=1}^{n} W^2(f_k)\, a_{tx}^2(f_k)}} \quad (4)$$

where $T_x(f)$ and $a_{tx}(f)$ are the transfer function and the unweighted rms acceleration measured on the tool handle along the direction of the dominant vibration, respectively, corresponding to the 1/3-band centre frequency f_k.

3. RESULTS

Figure 4 illustrates the acceleration spectra of several data samples acquired from the laser vibrometer, and the handle and adapter accelerometers during the calibration tests. The figures also illustrate the permitted exposure limits recommended in the current ANSI standard[25] for assessment of the hand-transmitted vibration. As can be seen, the laser vibrometer measurements and those obtained from the two piezoelectric accelerometers show very good agreement at the centre frequencies greater than 25 Hz. However, there are apparent differences in the vibration measurements in the low frequency range (< 25 Hz). DC shifting of the piezoelectric accelerometer signals most likely causes these differences. These observations suggest that measurements made with conventional accelerometers on both the adapter and the handle are valid for frequencies greater than 25 Hz.

As examples, Figure 5 illustrates comparisons of a group of the measured and estimated acceleration spectra along the dominant axis measured with one of the subjects. As can be seen (Figs. 5-1 to 5-4), the estimated values in the 31.5 to 1,250 Hz frequency range corresponding to 100 N feed force trials are quite close to the corresponding measured values obtained during the experiment. The results, however, exhibit differences between the magnitudes of accelerations measured on the palm adapter and on the handle in the low frequency range (<25 Hz), particularly with those measured on Tool B. These differences are most likely attributed to the above-mentioned DC shifting of the low frequency signals acquired from the tool handle accelerometer. The results shown in Figure 5 demonstrate that while the DC shifting of the handle accelerometer signals remained relatively constant during glove testing, the adapter accelerometer signals were improved when the gloves were used. This is because the glove materials attenuate much of the high frequency vibration and thus effectively reduced the DC shifting. Consequently, the reductions in DC shifting due to glove use would be misinterpreted by the transmissibility calculation as vibration attenuation, and this would lead to overestimations of glove effectiveness. In some cases, the overestimations would be quite significant if the lower frequency data were included in the transmissibility calculations. In order to minimise the potential error due to DC shifting of the accelerometer signals, the transmissibility values were computed from the acceleration spectra in the 31.5 Hz to 1250 Hz frequency range in the present study.

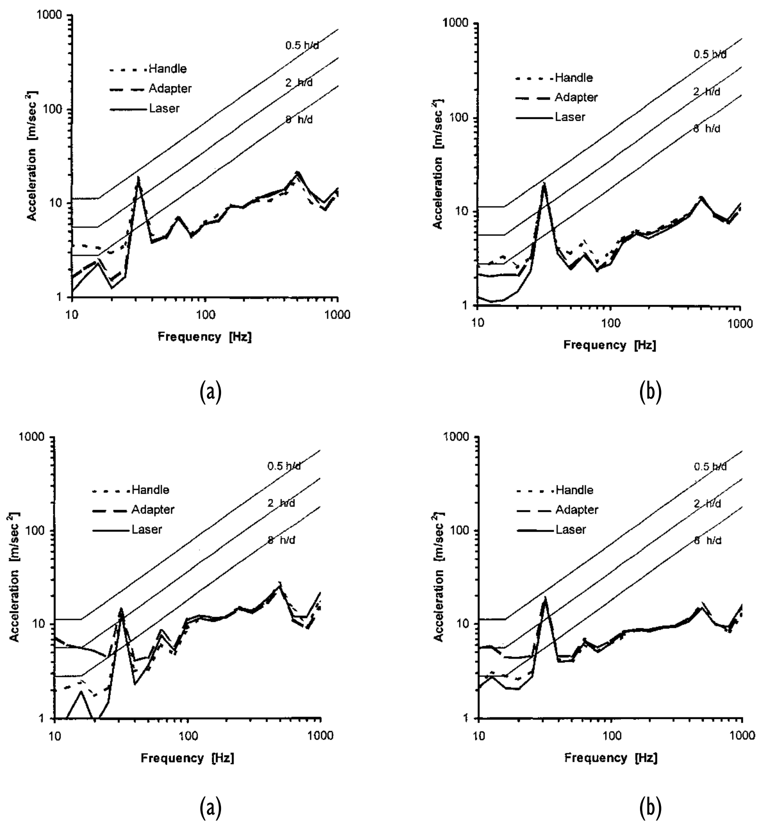
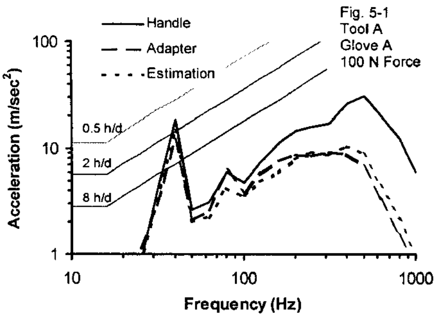


Figure 4 Measured Accelerations on the Handle and Palm Adapter Compared with Readings from a Laser Vibrometer

The estimated and measured vibration spectra corresponding to 50 N feed force trials (Figs. 5-5 to 5-8) reveal similar basic trends in the middle frequency range (31.5 to 100 Hz). Large differences between the estimated and measured values of rms accelerations, however, are evident in the high frequency range (>100 Hz). The predicted values underestimate the isolation effectiveness of the gloves in the high frequency range. The results derived from the data acquired from other test subjects also revealed trends similar to those shown in these figures.

The mean values of frequency weighted rms acceleration due to the vibration along the dominant axis (X-axis) and the total rms acceleration (vector summation of the accelerations in the three orthogonal axes) measured with each subject in the experiment, together with their standard derivations (STD) and coefficients of variation (CV), are summarised in Table I. The peak value of CV for the total vibration measured on the tool handles is 10.1%, which suggests that the vibration generated on the tools handle was fairly consistent across the subjects. The results in this table also show that the average difference between the rms accelerations derived from vibration along the dominant axis and the total acceleration is in the range of 5% to 9%, which would imply that the ratio of the vibration in the two non-dominant axes versus that in the dommant axis ranged from 0.33 to 0.45.

The mean values of acceleration transmissibility of gloves derived from the dominant axis vibration are summarised in Table II, while those computed from the total vibration appear in Table III. The inter-subject variations with Glove A are generally observed to be greater than those with Glove B. Similar variations were also observed in the reported study on the basis of shaker-based evaluations.[20] The mean value of the coefficient of variation for the total vibration transmissibility corresponding to 100 N feed force trials is in the order of 8.6% with a maximum of 11.1%. For the 50 N feed force trials, the average coefficient of variation is 12.3% with a maximum of 17.1%.



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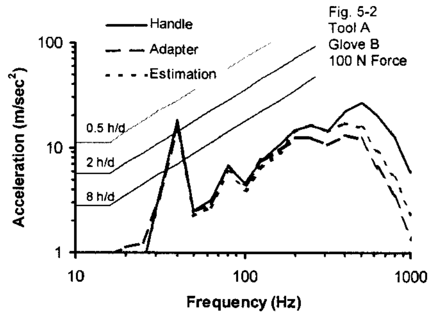

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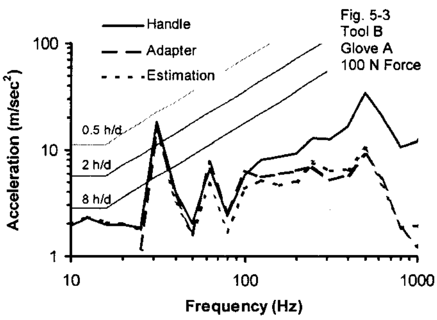

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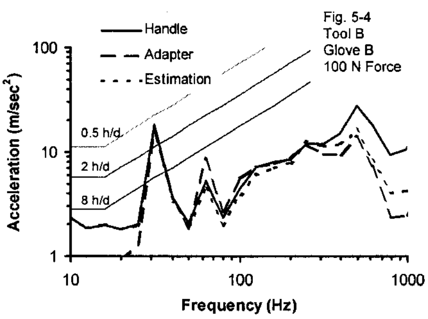

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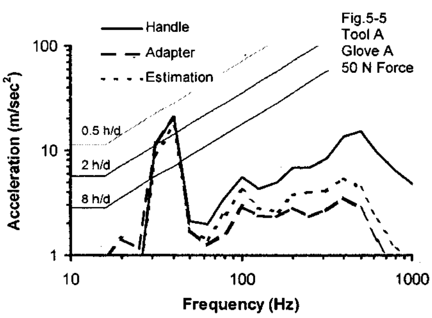

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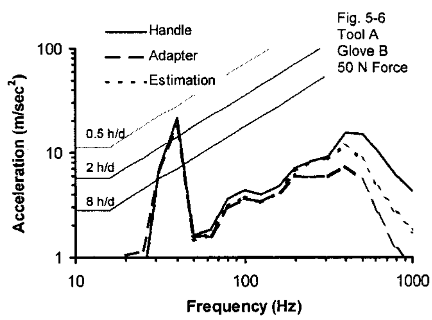

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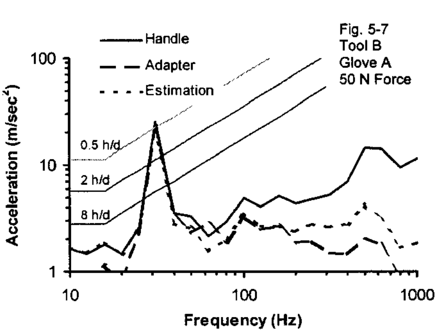

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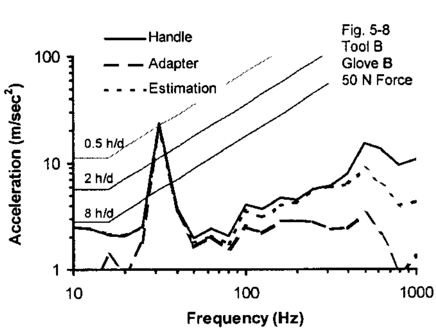

(5.8)

Figure 5 Samples of Measured and Estimated Acceleration Spectra in the Dominant Axis for One Test Subject

Table 1: Dominant Axis and Total Vibration Measurements

Measured Vibration (m/sec^2)		Tool A				Tool B			
		Glove A		Glove B		Glove A		Glove B	
		100N	50N	100N	50N	100N	50N	100N	50N
Mean	Dominant Axis	8.93	10.28	8.63	10.07	11.26	12.47	10.64	12.21
	Total	9.72	10.74	9.39	10.49	11.78	12.72	11.29	12.46
Standard Deviation	Dominant Axis	0.737	0.502	0.443	0.401	0.693	1.119	1.165	1.085
	Total	0.739	0.653	0.595	0.378	0.700	1.051	1.139	1.075
Coefficient of Variation	Dominant Axis	0.083	0.049	0.051	0.040	0.062	0.090	0.109	0.089
	Total	0.076	0.061	0.063	0.036	0.059	0.083	0.101	0.086

Table 2: Dominant Axis Vibration Transmissibility Values

Dominant Axis Vibration Transmissibility		Tool A				Tool B			
		Glove A		Glove B		Glove A		Glove B	
		100N	50N	100N	50N	100N	50N	100N	50N
Mean	Measured	0.70	0.74	0.88	0.86	0.82	0.83	0.99	0.91
	Estimated	0.78	0.80	0.94	0.93	0.83	0.80	0.96	0.93
	Difference	0.08	0.06	0.06	0.07	0.01	0.03	0.03	0.02
Standard Deviation	Measured	0.080	0.125	0.051	0.070	0.087	0.152	0.120	0.132
	Estimated	0.012	0.001	0.004	0.001	0.008	0.003	0.006	0.002
Coefficient of Variation	Measured	0.114	0.168	0.058	0.081	0.105	0.183	0.121	0.145
	Estimated	0.015	0.002	0.005	0.001	0.010	0.004	0.006	0.003

Table 3: Total Vibration Transmissibility Values

Total Vibration Transmissibility		Tool A				Tool B			
		Glove A		Glove B		Glove A		Glove B	
		100N	50N	100N	50N	100N	50N	100N	50N
Mean	Measured	0.78	0.78	0.88	0.90	0.83	0.84	0.97	0.92
	Estimated	0.77	0.80	0.94	0.93	0.81	0.79	0.95	0.92
	Difference	0.01	0.02	0.06	0.03	0.02	0.05	0.02	0.00
Standard Deviation	Measured	0.062	0.112	0.044	0.040	0.085	0.143	0.108	0.124
	Estimated	0.011	0.001	0.004	0.001	0.008	0.003	0.006	0.002
Coefficient of Variation	Measured	0.081	0.143	0.050	0.044	0.102	0.171	0.111	0.134
	Estimated	0.014	0.002	0.005	0.001	0.010	0.004	0.007	0.002

The results show reasonably good agreements between the estimated and measured vibration transmissibily values for both gloves irrespective of the tool and method used. For the 100 N feed force trials, the average difference of the transmissibility is only 0.028 with a maximum of 0.06. The 50 N feed force trials reveal even smaller differences; the mean deviation being in the order of 0.025 with a maximum of 0.05. The differences in the mean dominant-axis transmissibility values (Table II), however, are slightly larger than those observed for the total vibration (Table III).

DISCUSSION

The vibration isolation performance of a glove is tool- or excitation spectrum-specific. For example, Glove A can reduce the transmitted vibration by approximately 20% when used with the chipping hammers as shown in Table III but it may provide little attenuation when used with other types of tools that produce lower-frequency vibration, such as a tamper with dominant vibration components at frequencies less than 20 Hz. The commercially available anti-vibration gloves are generally more expensive than most of the conventional work gloves, while some of the anti-vibration gloves may interfere with the workers' ability to perform their tasks because of dexterity and grip strength losses.[7,8] There may be better options if gloves are used primarily for keeping the hands warm, preventing cuts and abrasions, or to protect hands from chemical effects. The evaluation of effectiveness of anti-vibration gloves for specific tools and working conditions thus forms an important task that would permit the selection of optimal or near optimal gloves and thereby reduce the potential health risks associated with the vibration exposure. The transfer function method offers a convenient tool for estimating the effectiveness of gloves for specific tool vibration spectra.

The magnitude of feed force or equivalent feed force imparted by the operator through the glove seems to have a great influence on the glove transmissibility in the high frequency range. In the lower feed force trials (50 N), the high impact loads in the fundamental frequency range (31.5 to 40 Hz) have the tendency to separate the hand and/or palm adapter from the tool handle. This could significantly reduce the transmissibility in the high frequency range (>100 Hz) but marginally increase it in the low frequency range. This separation also destabilises the hand-to-handle coupling, which contributes to relatively higher values of coefficients of variation that were observed for the 50 N trials. Considering that the weighting filter attenuates the high frequency vibration most significantly[2], the great underestimation in the high frequency range could be mostly made up by the marginal overestimation in the low frequency range. When based on weighted acceleration transmissibility, as recommended in the current glove assessment standard,[17] the transfer function method seems to provide a reasonably good estimation of the transmissibility value.

A comparison of the results presented in Tables II and III suggests that the differences between the estimated and measured values of transmissibility derived from the dominant axis vibration are generally greater than those based upon the total vibration. It can also be seen that the coefficient of variation for the transmissibility in the dominant axis is always greater than that for the total vibration. This is largely attributed to the inability of the subject or investigator to keep the adapter aligned with the handle accelerometer during the testing, a factor which is markedly mitigated when the vector-sum (total) vibration is considered. This suggests that the total vibration method is more robust and tends to correct for the possible adapter misalignment errors. Overall, the intra- and inter-subjects variations shown in Table III for both feed forces are generally within the range of the reported study,[20] and less than that of the inter-laboratory results of the ISO-10819 standard test that was performed using a well-controlled vibration test system. Therefore, the estimation methodology based on the total vibration evaluation is generally acceptable.

Theoretically, the transfer function method would be considered valid for a linear system. Anti-vibration gloves are usually made from materials with non-linear stiffness and damping properties that could further depend upon the variations in the grip and feed forces. The application of the transfer function assumes that gloves materials can be considered to possess quasi-linear visco-elastic properties, that would be considered valid in the vicinity of a specific working feed force, provided that the glove deformation lies within the linear range (absence of loss of contact and material bottoming). The impact vibration generated by the percussive tools may cause larger compression and/or shear glove deformations than those caused by non-impact tools or by the shaker-simulated vibration test. Hence, the validation of the transfer function method for percussive tools such as the chipping hammers is critical for its general application. As discussed above, the results clearly revealed the non-linear effects of the impact vibration on the transmissibility in different frequency ranges when a low coupling force was used. However, the overall effects of the non-linear glove properties on the transmissibility were not substantial. The proposed transfer function method can thus be considered as an effective methodology for estimating the tool-specific glove transmissibility.

Previous glove studies [13,21] with real tools at workplaces reported that the standard derivation (SD) of the glove transmissibility is generally more than 20%. The variability of the data obtained in the present study is considerably lower. This reduced variability is likely due to the improved tool vibration repeatability provided by the use of the ISO standardised chipping hammer test set-up and the controlled push forces and working posture. However, it should be noted that the magnitude of vibration observed at the test station might not be fully representative of that observed in the field. It has been reported that the energy absorber produces lower levels of tool handle vibration than that encountered during actual field use.[26] In the present study, the vibration magnitudes measured on the chipping hammer handles were in the range of 9.56-12.59 m/s^2, which were also lower than the mean value (16 m/s^2) of vibration measured on several other chipping hammers previously reported.[26] The vibration along the non-dominant directions in such a test may not be as high as those observed in the field either. These are the major weaknesses of the standardised ISO chipping hammer test but these issues are not critical for the purposes of this study. The stability and repeatability with the test setup made the test data manageable and consistent for reliable assessment of the method.

In fact, the magnitudes of vibration on both chipping hammers were about 12 m/s^2, which were high enough to trigger certain action levels for vibration exposure.[25,27] The critical peak values shown in Figures 4 and 5 suggest that the tested tools could only be used for 0.5 to 1 hour/day according to the ANSI standard.[25] The vibration magnitudes measured in this study are also comparable to those associated with other percussive tools such as pavement breakers and electric hammers.[28,29] Compared with the vibration generated by many non-percussive tools, the magnitudes of vibration produced by the two chipping hammers in this study are relatively higher. Hence, the reasonable agreement between the estimated and measured results on the chipping hammers suggests that the transfer function method may also be applicable to many other powered hand tools.

In many real working conditions, many tools may transmit vibration of considerable magnitudes along all the three directions. In such cases, a significant difference between the tangential and compression transfer functions may exist and would have a greater impact on the total transmissibility. While the transmission of tangential vibration has been investigated,[30] the contributions due to different compression and tangential characteristics have not been reported. Further studies on the tangential transfer function and the validity of the transfer function method in comparable multi-axis vibration environments would thus be needed.

5. CONCLUSIONS

During this study, two chipping hammers were employed to examine the merits of a transfer function method for estimation of anti-vibration glove performance when used with real tools. Two typical vibration-attenuating gloves available on the market were tested using six adult male subjects. A comparison of the measured and estimated values of vibration transmissibility of the gloves revealed that the transfer function method underestimated the effectiveness of the glove at higher frequencies (>100 Hz) but marginally overestimated it at lower frequencies when a low feed force (50 N) was applied. However, the estimation was very reasonable when a higher magnitude feed force (100 N) was used because the hand was better coupled with the glove and the tool handle. The difference between the mean values of the estimated and measured frequency-weighted transmissibility was surprisingly small in most cases. The inter-subject variation of the results was within the range of those reported in studies that were performed under laboratory test conditions with well-controlled vibration sources. It is therefore concluded that the transfer function method is basically acceptable for estimating the palm vibration isolation effectiveness of the gloves when used with chipping hammers. Since a chipping hammer represents a critical case for the evaluation, it is anticipated that the transfer function method may also be widely used to predict the anti-vibration effectiveness of gloves when used with many other tools. Tool-specific glove performance information can be used to estimate the potential benefits of glove use and to help in the selection of appropriate gloves for particular tools and working conditions.

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