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Effectiveness of a new method (TEAT) to assess vibration transmissibility of gloves

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Abstract

A test method based upon total effective acceleration transmissibility (TEAT) is proposed to study the vibration isolation performance of anti-vibration gloves. The vibration transmission characteristics of three different gloves are investigated under predominantly axial vibration using the proposed method and the procedure outlined in ISO-10819 (Mechanical Vibration and Shock—Hand–Arm Vibration—Method for the Measurement and Evaluation of the Vibration Transmissibility of Gloves at the Palm of the Hand, International Standard Organization, Geneva, Switzerland, 1996). The measured data are systematically analyzed to illustrate the measurement and evaluation errors arising from misalignments of the response accelerometer within the palm-held adaptor, unintentional non-axial vibration caused by the vibration exciter and dynamics of the coupled hand–handle system. The degree of adaptor misalignment, estimated from the measured data, was observed to vary from 5.9° to 59.6°. Such variations could cause measurement errors in excess of 20%. The vibration transmission characteristics of selected gloves, evaluated using the proposed method, are compared with those derived from the standardized method to demonstrate the effectiveness of the TEAT approach. From the results, it is concluded that the TEAT method, based upon vector sums of both the source and response accelerations, can effectively account for the majority of the measurement errors, and yield more repeatable and reliable assessments of gloves.

Relevance to industry

Prolonged exposure to hand-transmitted vibration has been related to the possible occurrence of several health disorders by affecting the bones, joints, muscles and nervous system. The epidemiological studies show that millions of industrial workers are being exposed to hand vibration throughout the world. It is thus vital to develop improved methods for assessment of effectiveness of anti-vibration gloves. The proposed methodology could be applied to assess the effective vibration attenuation performance of anti-vibration gloves, and it could contribute towards developing an improved test method.

Keywords: Anti-vibration gloves; Vibration transmissibility; Assessment method; Hand–arm vibration; Total effective acceleration transmissibility; Vibration attenuation

1. Introduction

Prolonged exposure to power hand tools vibration transmitted to the human hands has been

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related to a series of disorders in the vascular, sensorineural and musculoskeletal structures of the hand–arm system (Pelmear and Wasserman, 1998; Gemme and Taylor, 1983). Although the relationship between such disorders and physical characteristics of vibration (frequency, magnitude and direction) is not yet known, it is generally agreed that onset of these disorders can be reduced through a reduction in magnitude of vibration transmitted to the hand. Anti-vibration gloves, made of air bladder or resilient materials, such as sorbothane, are often viewed as simple means to reduce the vibration transmitted to the hands. The vibration transmission characteristics of many conventional and anti-vibration gloves have been assessed using different laboratory-based objective test methods (Griffin et al., 1982; Gurram et al., 1994; Goeland Rim, 1987; Voss, 1996). It has been reported that the gloves provide attenuation of handle vibration at frequencies above 100 Hz, and they tend to amplify the handle vibration at frequencies below 100 Hz. Too thick or stiffer gloves can lead to impaired dexterity, blood circulation and performance rate (Brown, 1990; Muralidhar et al., 1999).

The earlier studies have used considerably different measurement methods and locations, such as palm, back of the palm, fingers, carpal bones and wrist (Griffin et al., 1982; Goel and Rim, 1987; Rens et al., 1987; Gurram et al., 1994; Strack et al., 1990; Chang et al., 1999; Kattel and Fernandez, 1999) to assess the vibration isolation performance of different anti-vibration gloves. The International Standard Organization (ISO) has defined a standardized laboratory method to measure and evaluate the vibration attenuation performance of the gloves (ISO-10819, 1996). The method utilizes an instrumented handle, capable of measuring the grip force and acceleration due to vibration along the Z_h-axis, mounted on a single-axis vibration excitation system capable of generating specified vibration. A light weight cusp-shaped palm-held adaptor containing a single-axis accelerometer oriented along the Z_h-axis is placed between the subjects' palm and the glove, while gripping the vibrating handle with specified arm posture (elbow angle $= 90 \pm 10^\circ$), and grip (30 ± 5 N) and feed forces (50 ± 8 N). The feed force is measured using either a force transducer installed between the handle and the vibration exciter or a force plate. The method requires continuous monitoring and control of the grip and feed forces by the test subject by displaying the measured signals to the subject. The method also defines two vibration excitation spectra, the medium (M-spectrum; 16–400 Hz) and high (H-spectrum; 100–1600 Hz) frequency spectra, considered to represent the vibration characteristics of different power tools. The frequency-weighted rms accelerations due to vibration measured at the handle and palm-held adaptor are computed using the weighting function defined in ISO-5349-1 (2001). The vibration transmissibility of the glove is evaluated as the ratio of the rms acceleration of the adaptor to that of the handle. A glove can be considered as 'anti-vibration glove', when the transmissibility under M- and H-spectra are below 1.0 and 0.6, respectively.

Although the basic methodology of the standard has been generally accepted, several fundamental deficiencies and technical problems have been identified (Voss, 1996; Griffin, 1997; Hewitt, 1998; Reynolds and Jetzeer, 1998). These include: (i) misalignment of the adaptor or the sensitive axis of accelerometer with respect to the axis of source vibration; (ii) source vibration along the non-axial directions caused by the hand feed force; and (iii) dynamic characteristics of the handle and adaptor structures.

In this study, a new method to assess the vibration isolation performance of gloves is developed through examining various solutions to the deficiencies and problems, which is presented in Section 2. The method is based upon total effective acceleration transmissibility (TEAT). The authors believe that it will better account for measurement errors associated with misalignments of the adaptor, and input vibration along the unintended directions. The effectiveness of the new method is then evaluated comprehensively through its application to the measurement and assessment of the vibration isolation performance of three anti-vibration gloves.

2. Development of the TEAT method

Laboratory studies involving the characterization of vibration transmission performance of gloves are invariably based upon measurement of the source and response vibration along a single specific axis. The laboratory test method outlined in ISO-10819 (1996) has been widely used to assess the vibration attenuation performance of gloves under axial (Z_h) vibration (Paddan, 1996; Griffin, 1997; Hewitt, 1998). The vibration transmission performance of the glove is usually evaluated as the unweighted transmissibility, T_1, and weighted transmissibility, $T_{1,w}$, which are calculated from

$$T_1 = \frac{A_Z}{H_Z}, \quad T_{1,w} = \frac{A_{Z,w}}{H_{Z,w}}, \tag{1}$$

where A_Z, and H_Z are the overall rms accelerations due to vibration measured at the palm-held adaptor and the handle, respectively, along the Z_a and Z_h directions shown in Fig. 1(a); $A_{Z,w}$, and $H_{Z,w}$ are the respective frequency-weighted rms accelerations derived from the weighting function defined in ISO 5349-1 (2001).

2.1. Adaptor misalignment

The reported studies using ISO-10819 have identified a number of test errors and difficulties. The majority of the test errors have been attributed to misalignments between the adaptor and the direction of primary vibration excitation (Z_h), as illustrated in Fig. 1. The misalignment errors could arise from two sources: (i) poor orientation of the adaptor with respect to the axis of vibration excitation; and (ii) the geometry of the standardized adaptor and the handle. Of these two sources, poor adaptor orientation has been identified as the primary source of experimental errors. This is because adaptor orientation cannot be monitored or controlled during a test, since both the subject and the experimenter are unable to visualize the placement of the adaptor between the glove and the palm. The yaw movement of the adaptor (rotation about the shear axis, Y_h) with respect to the fixed handle, shown in Fig. 1(a), could exceed 40° during tests and yield measurement errors in excess of 20% (Hewitt, 1998). The ISO-10819 (1996) specifies that the radius of the curved adaptor should lie in the 22–30 mm range, which is larger than the 20 mm radius specified for the test handle. The adaptor thus has a tendency to rotate around the contact line on the handle in the $X_h - Z_h$ plane. The adaptor within the glove may also incur rotation in the $Y_h - Z_h$ plane, as shown in Fig. 1(b). This tilting of the adaptor becomes significant when the palm pad of a glove is thick or when a glove is either too tight or stiff. The degree of adaptor misalignment may thus differ for different types of gloves, and hand and glove sizes.

Two methods have been tried to control adaptor misalignment. The first method is based on the fact that the gloves are not expected to attenuate low-frequency vibration and the transmissibility should

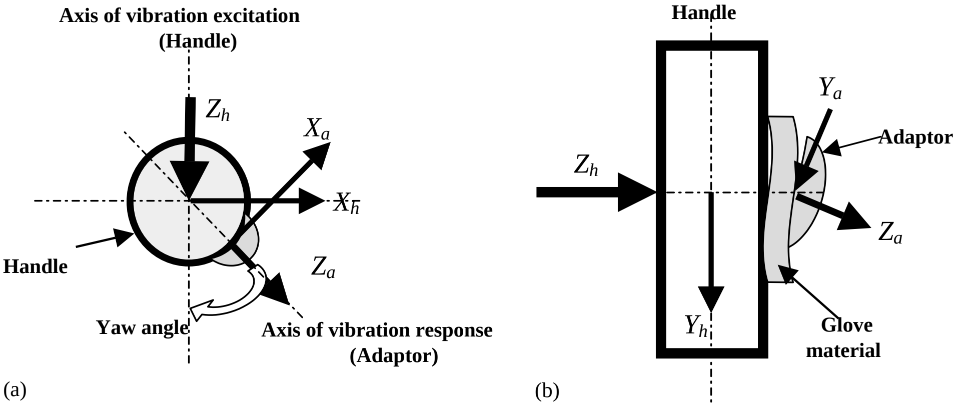

Fig. 1. Adaptor orientation with respect to axis of source vibration in: (a) $X_h - Z_h$; and (b) $Y_h - Z_h$ planes.

be unity at low frequencies. The misalignment of the adapter would result in a value lower than unity at such frequencies. The measured glove transmissibility is thus corrected by scaling the test data to achieve unity value at a frequency of 21 Hz (Paddan, 1996; Griffin, 1997). However the use of such scaling factor, based upon low-frequency vibration transmissibility, may introduce significant errors if unintended vibration would occur in the non-axial direction, which is observed in this study and presented in Section 2.2. Moreover, this method cannot be applied to the H-spectrum, which exhibits predominant vibration in the high-frequency range (100–1600 Hz). In the second method, the errors associated with misalignments could be minimized by adequately orienting the palm-adaptor. A simple approach employed by some researchers is to open the glove along the seam between the thumb and the forefinger so that the adaptor can be seen to ensure adequate alignment of the adaptor (Hewitt, 1998). The opening of a glove, however, may alter its configuration and vibration transmissibility characteristics.

An alternative method of controlling adaptor misalignment was proposed by the authors. A micro-machined miniature three-axis accelerometer was integrated within the standardized adaptor, as shown in Fig. 2(a), to measure the components of vibration along the three-orthogonal directions (X_a, Y_a and Z_a), as illustrated in Fig. 1. The vibration transmitted to the gloved hand, as measured by the adaptor was then evaluated in terms of the resultant vibration, and the unweighted transmissibility (T_2) and the weighted transmissibility ($T_{2,w}$) are computed from

$$T_2 = \frac{\sqrt{A_X^2 + A_Y^2 + A_Z^2}}{H_Z},$$
$$T_{2,w} = \frac{\sqrt{A_{X,w}^2 + A_{Y,w}^2 + A_{Z,w}^2}}{H_{Z,w}}, \qquad (2)$$

where A_X and A_Y are unweighted rms accelerations due to vibration measured by the adaptor accelerometer along the X_a- and Y_a-axis, respectively; $A_{X,w}$ and $A_{Y,w}$ are their corresponding weighted rms accelerations. This method can be used to resolve the misalignment problem but it cannot be used to deal with the non-axial vibration that is described in the following section.

2.2. Non-axial source vibration: handle–adaptor dynamics

The acceleration transmissibility, defined in Eq. (2), implies that the source vibration occurs along the Z_h-axis alone. While it is known that most tools transmit vibration to the hand along all the three axes, the single-axis electro-dynamic vibration exciters used in the laboratory may also transmit considerable vibration along the non-axial directions, when coupled with the human hand. The feed force imparted by the human subjects on the instrumented handle may not be of purely axial nature. The components of the feed force along the non-axial directions tend to impose side loads on the armature of the electro-dynamic

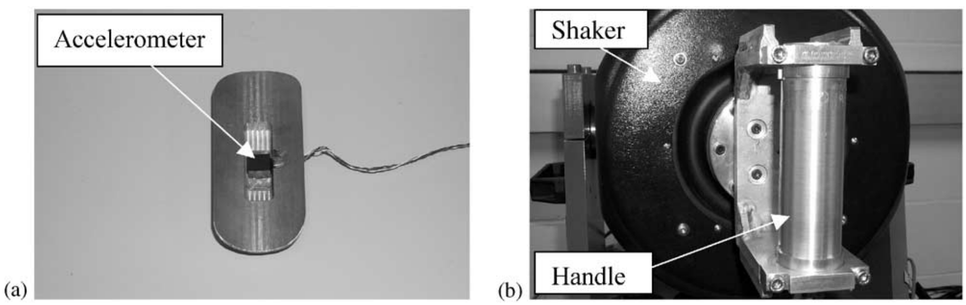

Fig. 2. Pictorial views of: (a) palm-adaptor; and (b) instrumented handle.

vibration exciter, resulting in considerable vibration along the X_h- and Y_h-axis.

The contributions of the hand–handle interactions to the non-axial vibration were investigated through measurement of source vibration along all three axes. An aluminum handle was fabricated in accordance with ISO-10819, which is shown in Fig. 2(b). The structure of the handle consists of a handle pipe, an elastic force sensing structure with four strain gages to measure the subjects' grip force, two handle caps attached to the pipe and the force sensing element, and a support structure that can be directly attached to the shaker table. The instrumented handle weighed 13 N. A tri-axial accelerometer was installed on the inner wall of the handle pipe structure. The same type of miniature micro-machined accelerometer (ENDEVCO, 35A-Z) was used on both the handle and adapter. The palm-adaptor (Fig. 2(a)) was fabricated with titanium and weighed 15.7 g, slightly larger than the recommended value of 15 g. Its contact surface radius was 30 mm, at the upper end of the recommended range. The instrumented handle was installed on a horizontally mounted vibration exciter (Unholtz Dickie S032). A resonance test was performed on the handle with and without the hand under excitations in the 10–1250 Hz frequency range.

Experiments were then performed to study the characteristics of non-axial source vibration caused by the hand feed force using 8 male subjects. The instrumented adaptor was placed in the palm of the subjects' hand, which was carefully aligned with the axis of vibration excitation. 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 $90 \pm 10°$. The vibration exciter was programmed to generate vibration corresponding to the M- and H-spectra defined in the ISO standard. The six acceleration signals from the handle and adaptor were amplified and analyzed using a multi-channel signal analyzer. The measurement setup is schematically shown in Fig. 3.

The measured data was analyzed to derive the rms-acceleration spectra of the handle and adapter vibration along the three translational directions. Fig. 4 illustrates the rms acceleration spectra of the handle and adaptor vibration, for one of the test subjects, corresponding to the M-spectrum. The results clearly show that the exciter produces vibration of considerable magnitudes along the X_h- and Y_h-axis, in the 20–315 and 16–500 Hz bands, respectively. The rms acceleration spectra (M-spectrum) of both the adaptor and the handle vibration along the axial direction are identical. The handle vibration along the Y_h-axis peaks near the 63 Hz band, while the spectrum of X_h-axis vibration is nearly uniform in the 20–200 Hz bands. The measured response at the hand–handle interface suggests that the X_h- and Z_h-axis vibration are directly transmitted to the hand, while the Y_h-axis (shear) vibration is attenuated at frequencies above 160 Hz. The tests performed with all the subjects revealed similar magnitudes of non-axial vibration under M-spectrum, which were not evident under the high frequency H-spectrum. The presence of such non-axial vibration can contribute to measurement errors, specifically when low and medium frequency excitations are involved, and therefore must be accounted for.

The presence of the non-axial source vibration can be primarily attributed to side loading of the exciter's armature caused by non-axial nature of the hand feed force. Additional experiments, with and without the human hand, were thus performed to study the contributions due to the hand, and dynamic response of the handle and adaptor system. In the first experiment, the adaptor was attached to the handle through an elastic band that was adjusted to realize a grip force in the order of 30 N. In the second experiment, the subject held the adaptor and the handle with specified grip force but negligible feed force. The measurements attained from both experiments revealed insignificant vibration along the X_h- and Y_h-axis. It was thus concluded that the hand feed force primarily causes the non-axial source vibration.

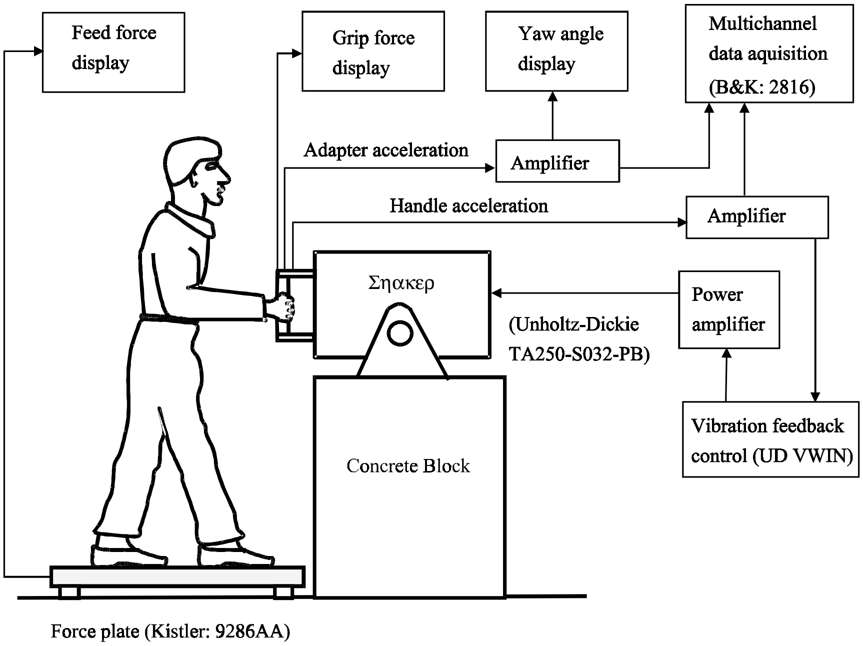

Fig. 3. Schematic of the glove transmissibility measurement and data acquisition system.

2.3. Total effective acceleration transmissibility

The measurement uncertainties associated with both the adaptor misalignment and non-axial source vibration could be effectively minimized by considering the TEAT of the glove, defined as

$$TEAT_{\mathrm{u}} = \sqrt{\frac{A_X^2 + A_Y^2 + A_Z^2}{H_X^2 + H_Y^2 + H_Z^2}},$$

$$TEAT_{\mathrm{w}} = \sqrt{\frac{A_{X,\mathrm{w}}^2 + A_{Y,\mathrm{w}}^2 + A_{Z,\mathrm{w}}^2}{H_{X,\mathrm{w}}^2 + H_{Y,\mathrm{w}}^2 + H_{Z,\mathrm{w}}^2}}, \tag{3}$$

where $TEAT_{\mathrm{u}}$ and $TEAT_{\mathrm{w}}$ are the unweighted and weighted transmissibility, respectively; H_x, H_y and H_z are rms accelerations due to handle vibration along X_{h}-, Y_{h}- and Z_{h}-*axis, respectively,* and $H_{x,\mathrm{w}}, H_{y,\mathrm{w}}$ and $H_{z,\mathrm{w}}$ are their corresponding weighted rms accelerations. The effectiveness of the TEAT measure in reducing the errors resulting from misalignment of the adaptor in the $X_{\mathrm{h}}-Z_{\mathrm{h}}$ plane and non-axial source vibration were investigated by placing the adaptor on the handle at several different yaw angles, as defined in Fig. 1(a). The experiments involved one male subject and different orientations of adapter with yaw angles ranging from 0° to 50°. The subject gripped the handle with the specified grip force with his bare-hand and imparted the desired feed force, while the exciter was operated to generate the M- or H-spectra of vibration. The three-axis accelerations of the handle and adaptor were recording for each measurement, which lasted for approximately 30 s. The measurements were repeated three times, and the measured data was analyzed to derive the acceleration transmissibility based upon standardized method (T_1), vector sum of response acceleration (T_2) and $TEAT_{\mathrm{u}}$.

Fig. 5 illustrates the mean transmissibility responses derived under the M-spectrum as a function of the misalignment or yaw angle. The results clearly show that the vibration transmissibility (T_1) of the bare-hand–adaptor–handle system, derived using standardized method, approaches values considerably smaller than 1.0 as the misalignment increases (Fig. 5(a)). The results suggest that a misalignment in the order of 40° could yield measurement errors in excess of 20% in majority of the frequency range. This observation is also supported by the findings

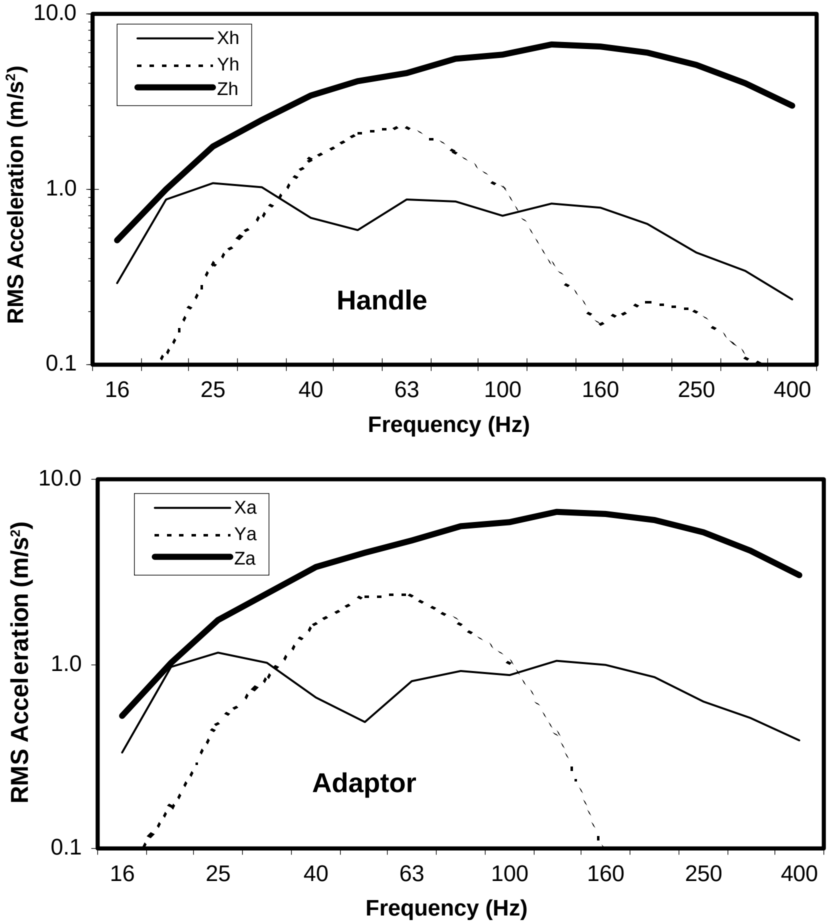

Fig. 4. Root mean square acceleration spectra of axial and non-axial vibration measured at the handle and adaptor.

reported by Hewitt (1998). Although the gloves are not expected to attenuate or amplify low-frequency vibration, many studies have reported vibration transmissibility values for gloves to be less than unity at low frequencies (Griffin, 1997; Paddan, 1996). The amplification/attenuation of vibration at higher frequencies is attributed to the properties of the gloves. The results derived for the bare-hand, illustrated in Fig. 5(a), suggest that the low transmissibility at lower frequencies is most likely caused by adaptor misalignment.

The application of vector sum of the response acceleration, on the other hand, yields vibration transmissibility (T_2) considerably larger than unity at frequencies below 80 Hz (Fig. 5(b)). This is attributed to contributions due to source vibration along the shear (Y_h) and compression (X_h) directions. The application of the TEAT approach yields nearly unity transmissibility in the entire frequency range, irrespective of the adaptor yaw angle or misalignment, as shown in Fig. 5(c). From the results, it is concluded that majority of the measurement errors are caused by the misalignment. The non-axial source vibration could also yield considerable errors at low frequencies (below 80 Hz), but relatively small errors at higher frequencies (in the order of 5–10%). Their contributions under H-spectrum tend to be negligible. These measurement errors could be either eliminated or minimized by using the proposed

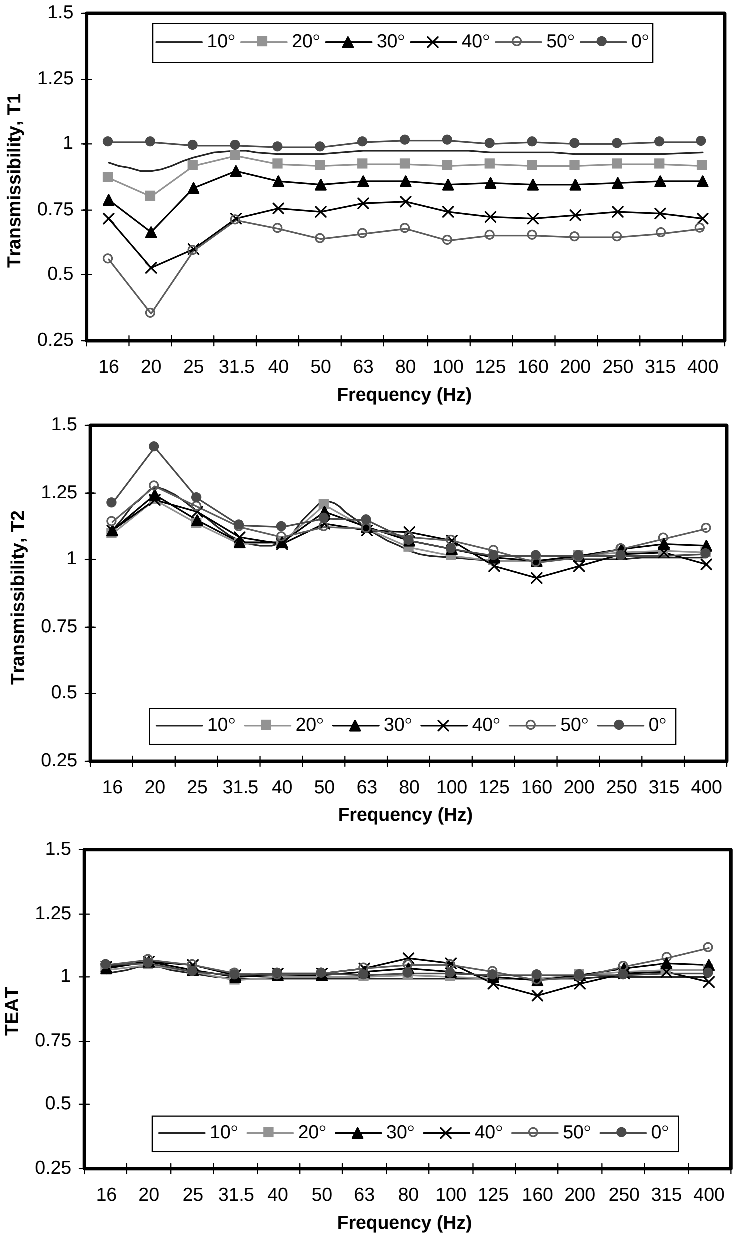

Fig. 5. Vibration transmissibility characteristics of the hand–adaptor–handle system evaluated using different methods.

TEAT measure. The use of TEAT approach not only minimizes the potential errors caused by the geometric issue, it also permits the assessment of effectiveness of the glove under combined axial, shear and compression axes, as expected from the actual tools.

The overall rms accelerations due to handle and source vibration, and the unweighted transmissibility values are also evaluated for the M-spectrum and summarized in Table 1, as a function of the yaw angle. The results clearly illustrate that the TEAT measure yields nearly unity transmissibility,

Table 1
Overall rms accelerations and unweighted vibration transmissibility of the hand–handle system for different adaptor yaw angles (M-spectrum)

Yaw angle (°)	Overall rms acceleration (m/s^2)						Transmissibility			Cosine (angle)
	H_X	H_Y	H_Z	A_X	A_Y	A_Z	T_1	T_2	$TEAT_u$	
0	3.05	4.18	17.19	3.14	4.37	17.37	1.01	1.06	1.017	1.000
10	1.83	4.36	17.23	4.33	4.39	16.69	0.97	1.03	0.996	0.985
20	1.69	4.04	17.09	7.14	4.07	15.71	0.92	1.04	1.005	0.940
30	1.65	3.94	17.21	9.69	3.99	14.66	0.85	1.05	1.016	0.866
40	1.86	3.25	17.00	11.75	3.31	12.55	0.74	1.03	1.000	0.766
50	1.71	3.51	16.88	13.60	3.51	11.01	0.65	1.06	1.03	0.643

as would be expected for the bare-hand. The T_1 and T_2 values tend to be lower and higher, respectively, as illustrated in Fig. 5. The results show only minimal variations (<2.1%) in handle acceleration along the axial direction (H_Z) with variations in the yaw angle, while the adapter acceleration component A_Z decreases. The cosine of the yaw angle closely describes the ratio of the two axial accelerations (T_1), as evident from Fig. 1(a) and the results presented in Table 1.

The Y_h-component of the handle vibration shows a decreasing trend with increase in the yaw angle. The magnitude of X_h-component (H_X) of handle vibration is considerable when adapter is aligned with the axial direction, but decreases considerably when yaw angle is increased to 10°. The magnitude of H_X tends to vary only slightly with further increase in the yaw angle. Such variations in magnitudes of H_X and H_Y are most likely attributed to the properties of the coupled hand–adaptor–handle system and its effect on the pushing tendency of the hand, magnitudes of resulting side-loads, and variations in moments induced by the hand–adaptor push force. Further investigations are perhaps desirable to gain insight into the contributions of the standardized adaptor to the dynamic behavior of the coupled hand–handle system.

3. Measurement and assessment of anti-vibration properties of gloves

The effectiveness of the proposed TEAT approach in assessing the vibration transmission characteristics of different anti-vibration gloves was examined through laboratory measurements. The vibration responses of three different gloves were assessed using the proposed TEAT and standard (ISO-10819, 1996) methods. The experiments were performed with 8 male subjects, using the procedure described in the standard and Section 2.2. The signal analyzer was configured to display the transfer function (magnitude and phase) and coherence of the measured accelerations along the axial direction (Z_a and Z_h). The experiment was rejected when coherence was below 0.95 for the gloved hand and when the phase response exceeded ±5° for the bare-hand.

Three different anti-vibration gloves were selected for the study. These included a relatively thick air glove (glove A), a thinner air glove (glove B) and a gel-filled glove (glove C). Each test subject performed the standard bare-hand and gloved-hand tests under both the M- and H-spectra. Each experiment was repeated three times and the data was examined for repeatability, while the order of the gloves was randomized. Each subject was trained for 5–10 min prior to the formal test. Each subject was also advised to position the adaptor along the axial direction to his best ability, while maintaining the desired posture, and grip and feed forces. The subjects, in general, showed a tendency to bend their wrist in an attempt to align the adaptor and exert the desired feed force. The posture of the hand and forearm of each subject was thus continually monitored during the test, and the subject was advised to correct the posture, when required.

4. Data analysis and results

The measured acceleration signals were analyzed to derive true and frequency-weighted rms accelerations corresponding to $\frac{1}{3}$-octave band center frequencies and overall rms accelerations. The data acquired from three different trials performed on each glove–subject combination were analyzed to derive the mean and standard deviation values. The vibration transmission characteristics of the selected gloves are evaluated using the method outlined in the standard ($T_{1,w}$) and the proposed TEAT approach. The vibration transmissibility values of the gloves derived from Eqs. (1) and (3) are normalized with respect to that of the bare-hand. The means and standard deviations of the vibration transmissibility values for each glove–subject combination, computed from the two methods under M- and H-spectra, are summarized in Tables 2 and 3. For clarity the subjects are identified by numbers (1–8), which do not reflect the order of the subjects employed in the test.

The results show that the mean transmissibility values derived from the TEAT approach are higher than those evaluated from the standardized method, irrespective of the glove–subject combination and the excitation spectrum. The geometric misalignment of the adaptor within a glove results in magnitude of vector sum of vibration response higher than its axial (Z_a) component alone and thus a higher value of transmissibility. The TEAT method also yields lower values of intra- and inter-subject variations, as evident from the corresponding lower values of standard deviations. It has been widely reported that the vibration transmissibility values of gloves exhibit standard deviations in the order of 5–6%, when the adaptor is carefully aligned with the direction of vibration, and the measurement repeatability may deteriorate considerably with adaptor misalignments (Hewitt, 1997, 1998). Since the TEAT method is based upon the vector sum of vibration, it yields considerably lower values of intra- and inter-subject variabilities caused by variations in the adaptor alignment. The results show that the standard deviations associated with the $TEAT_w$ values are generally more than 40% lower than those associated with transmissibility derived from the standardized method ($T_{1,w}$). The measurements performed under H-spectrum, however, yield relatively higher values of standard deviations for both methods. This tendency has also been reported by Hewitt (1997). The standard deviations of the mean values of $TEAT_w$ are in the order of 3% for M-spectrum and generally $<7\%$ for the H-spectrum, irrespective of the glove considered in this study.

On the basis of the overall mean values and the criterion specified in ISO-10819 (1996), the gloves ‘A’ and ‘B’ could be classified as anti-vibration gloves ($T_{1,w}<1.0$ for M-spectrum and $T_{1,w}<0.6$ for H-spectrum). The glove ‘C’, however, does not satisfy the specified criterion under H-spectrum. The consideration of overall mean values of $TEAT_w$ in conjunction with the specified criterion, on the other hand, suggests that the glove ‘B’ also does not satisfy the criterion under H-spectrum (overall mean and standard deviation = 0.66, 0.065), while the glove ‘A’ marginally meets the requirement (overall mean and standard deviation = 0.59, 0.061). The results further show that acceptance or rejection of a glove is strongly dependent upon the subjects considered for the test due to relatively high values of inter-subject variabilities. The current standard recommends the use of 3 subjects with hand sizes within a specified range. From the mean values of $T_{1,w}$, it is apparent that glove ‘B’ would be rejected under H-spectrum if subjects 1, 3 and 6 were considered, and accepted when the sample size included either all the 8 subjects or three of the remaining subjects. On the basis of $TEAT_w$ values, the glove ‘A’ would also be rejected for the H-spectrum, when subjects 1, 3 and 5 are included in the sample. The glove ‘C’, although acceptable on the basis of overall values for the M-spectrum, may also be rejected when $TEAT_w$ values are considered for a sample including subjects 6 and 7.

4.1. Estimation of adaptor misalignment in the $X_h - Z_h$ plane

The misalignment of the adaptor with respect to the dominant vibration direction can be

Table 2
Comparison of vibration transmissibility (mean and standard deviation) of different glove–subject combinations, as computed from different methods (M-spectrum)

Glove	Subject	Vibration transmissibility					
		$T_{1,w}$		$TEAT_w$		$\bar{\alpha}$ (degrees)	$T_{CF,w}$
		Mean	Stdev.	Mean	Stdev.	Mean	Mean
A	1	0.72	0.10	0.83	0.04	27.8	0.82
	2	0.85	0.01	0.87	0.02	15.3	0.88
	3	0.80	0.03	0.90	0.01	21.8	0.86
	4	0.79	0.03	0.87	0.03	18.8	0.84
	5	0.86	0.02	0.90	0.02	13.7	0.89
	6	0.83	0.05	0.88	0.04	14.8	0.86
	7	0.71	0.11	0.92	0.04	37.7	0.90
	8	0.79	0.01	0.87	0.01	17.6	0.83
Ovearll	Mean	0.80		0.88		20.9	0.86
	Stdev.	0.054		0.028		8.2	0.03
B	1	0.79	0.09	0.88	0.02	27.7	0.89
	2	0.84	0.01	0.88	0.02	19.4	0.89
	3	0.85	0.03	0.92	0.01	18.6	0.89
	4	0.83	0.07	0.91	0.04	19.0	0.88
	5	0.85	0.02	0.90	0.01	15.8	0.88
	6	0.85	0.02	0.90	0.03	20.7	0.90
	7	0.69	0.12	0.95	0.01	42.7	0.93
	8	0.77	0.14	0.90	0.01	29.5	0.88
Ovearll	Mean	0.81		0.90		24.2	0.89
	Stdev.	0.057		0.024		8.8	0.017
C	1	0.87	0.03	0.94	0.01	15.9	0.90
	2	0.92	0.01	0.92	0.01	7.6	0.92
	3	0.92	0.01	0.98	0.01	11.0	0.94
	4	0.95	0.02	0.97	0.04	15.1	0.98
	5	0.94	0.01	0.96	0.02	11.9	0.96
	6	0.96	0.02	1.00	0.02	11.9	0.98
	7	0.79	0.10	1.03	0.05	28.3	0.90
	8	0.90	0.05	0.99	0.05	15.7	0.93
Ovearll	Mean	0.901		0.97		14.7	0.94
	Stdev.	0.055		0.032		6.2	0.032

estimated from components of the measured adaptor acceleration. Referring to Fig. 1(a), the instantaneous adaptor misalignment in the X_h-Z_h plane (yaw angle) can be estimated from the acceleration components measured along the X_a- and Z_a-axis. An estimate of the mean value of the yaw angle can be conveniently derived from the true values of the overall rms accelerations, such that

$$\bar{\alpha} = \tan^{-1}\left[\frac{A_X}{A_Z}\right] - \bar{\alpha}_0, \quad (4)$$

where A_X and A_Z are the unweighted rms accelerations of the adaptor along X_a and Z_a directions, respectively. $\bar{\alpha}$ is the average yaw angle and $\bar{\alpha}_0$ represents the offset value of the

Table 3
Comparison of vibration transmissibility (mean and standard deviation) of different glove–subject combinations, as computed from different methods (H-spectrum)

Glove	Subject	Vibration transmissibility					
		$T_{1,\mathrm{w}}$		$TEAT_{\mathrm{w}}$		$\bar{\alpha}$ (degrees)	$T_{CF,\mathrm{w}}$
		Mean	Stdev.	Mean	Stdev.	Mean	Mean
A	1	0.57	0.01	0.68	0.03	31.6	0.67
	2	0.49	0.02	0.54	0.02	15.3	0.51
	3	0.52	0.07	0.65	0.06	35.1	0.63
	4	0.48	0.02	0.56	0.03	26.1	0.53
	5	0.51	0.04	0.62	0.05	28.9	0.58
	6	0.52	0.05	0.57	0.04	9.5	0.53
	7	0.31	0.09	0.49	0.06	46.1	0.45
	8	0.45	0.02	0.59	0.03	35.7	0.56
Ovearll	Mean	0.48		0.59		28.5	0.56
		0.076		0.061		11.7	0.069
B	1	0.64	0.04	0.70	0.02	20.7	0.68
	2	0.53	0.02	0.60	0.02	22.6	0.57
	3	0.66	0.10	0.78	0.07	15.9	0.69
	4	0.53	0.08	0.60	0.06	27.2	0.60
	5	0.55	0.03	0.64	0.02	25.9	0.61
	6	0.61	0.08	0.66	0.04	17.5	0.63
	7	0.31	0.11	0.60	0.05	59.6	0.61
	8	0.55	0.05	0.70	0.03	37.3	0.69
Ovearll	Mean	0.55		0.66		28.3	0.64
		0.108		0.065		14.3	0.047
C	1	0.90	0.02	0.91	0.02	7.80	0.91
	2	0.83	0.05	0.84	0.05	4.30	0.83
	3	0.73	0.06	0.77	0.05	11.50	0.75
	4	0.82	0.06	0.84	0.05	6.30	0.83
	5	0.84	0.07	0.89	0.06	7.90	0.84
	6	0.87	0.03	0.90	0.03	5.90	0.88
	7	0.49	0.07	0.72	0.01	31.80	0.57
	8	0.83	0.04	0.88	0.01	6.30	0.84
Ovearll	Mean	0.79		0.84		10.2	0.81
		0.131		0.068		9.0	0.104

acceleration ratios corresponding to a zero yaw angle obtained from the bare-hand tests.

The above equation provides an estimate of the average yaw angle, assuming that the X_a-component of acceleration arises only from the geometric misalignment in the $X_h - Z_h$ plane. This component of acceleration, however, may be affected by many other factors, such as misalignment in the $Y_h - Z_h$ plane that may be considerable in case of thick or stiff gloves (Fig. 1(b)), and magnitudes of source vibration along the X_h- and Y_h-axis. Considering that misalignments in the $X_h - Z_h$ plane are the primary source of test errors, an estimate of the yaw angle can provide essential information leading to meaningful interpretation of the results and a convenient correction factor to account for the misalignment-induced errors.

Eq. (4) is solved using the rms values of the measured components of the adaptor acceleration to estimate the average yaw angles. The mean values of the estimated yaw angles derived for each glove–subject combination under M- and H-spectra are summarized in Tables 2 and 3, respectively. The average yaw angle ranges from 9.5° to 37.7° for glove 'A', from 15.8° to 59.6° for glove 'B', and from 5.9° to 31.8° for glove 'C'. The mean values of the average yaw angles for gloves 'A' and 'B' range from 20.9° to 28.5°, while those for glove 'C' range from 10.2° to 14.7°. The standard deviations of the means are excessive, ranging from 36% to 88%. This can be directly attributed to the difficulties experienced by the subjects in aligning the adaptor, and lack of repeatability. Majority of the subjects felt that the middle of the palm provides the most stable position for the adaptor. This position, however, results in considerable degree of misalignment in an excess of 40°. In order to achieve adequate orientation of the adaptor, the adaptor had to be positioned near the base of the thumb. The subjects considered this position not only uncomfortable but reported that it had a tendency to slide towards the middle of the palm. A further examination of the estimated yaw angles reveals that the data acquired for subject 7 yields relatively high values, irrespective of the glove and excitation spectrum, and can be considered as an outlier. The exclusion of this data resulted in mean values in the 7.1–26° range with standard deviation ranging from 24% to 38%.

4.2. Misalignment correction factor

From the geometry, shown in Fig. 1(a), the cosine of the yaw angle can serve as a convenient correction factor to account for the experimental errors caused by misalignment in the $X_h - Z_h$ plane. The application of this correction factor to the acceleration transmissibility measured using the standard method ($T_{1,w}$) could yield a better assessment of the glove transmissibility in the following manner:

$$T_{CF,w} = \frac{T_{1,w}}{\mathrm{Cos}\,\bar{\alpha}}, \tag{5}$$

where $T_{CF,w}$ is the corrected acceleration transmissibility of the glove.

The corrected values of the transmissibility, derived from Eq. (5) and the estimated yaw angles, are also summarized in Table 2 and 3, respectively, for the M- and H-spectra. The results clearly show that the corrected values are considerable larger than the $T_{1,w}$ values and only slightly smaller than the $TEAT_w$ values for all the glove–subject combinations. The inter-subject variations associated with $T_{CF,w}$ are also considerably smaller than those associated with $T_{1,w}$. These results suggest that the misalignments in the $X_h - Z_h$ plane form the major source of error, while the contributions due to other factors are relatively small.

5. Discussions

The test methodology outlined in ISO-10819 (1996) appears to be based on the ideal adaptor orientation, and an assumption that the non-axial components of vibration at the hand–glove interface and simulated handle are negligible. All the test subjects considered the most stable and comfortable position of the cusp-shaped adaptor is the middle of the palm. This position, however, represents a significant yaw rotation of the adaptor (with an excess of 40°) with respect to the direction of the intended source vibration, which can lead to errors larger than 20%. The subjects were, however, required to position the adaptor near the base of the thumb to achieve adequate alignment, a position considered to be uncomfortable and unstable. The adaptor tends to slide towards the more stable position, middle of the palm, resulting in components of vibration along the unintended non-axial directions and poor repeatability of results in terms of $T_{1,w}$. This is also evident from the average yaw angles estimated from the measurements, which ranged from 5.9° to 59.6°. The lack of consideration of non-axial components of adaptor vibration in the standardized assessment method could yield a considerably lower value of acceleration transmissibility coupled with large inter- and intra-subject variabilities, and may lead to erroneous conclusions regarding anti-vibration capability of a glove.

Theoretically, the proposed method based upon TEAT minimizes the 'leakage' of the translational components of vibration, including the non-axial components of the source vibration, in evaluating the anti-vibration performance of a glove. The proposed method thus allows for assessment of the gloves independent of the geometric relationship between the adaptor and the handle, and direction of the source vibration. The results presented in Tables 2 and 3 clearly illustrate the effectiveness of the proposed method, irrespective of the glove–subject combination and excitation spectrum considered in this study. The appropriate consideration of the geometric relationship in the proposed method enhances the repeatability and reliability of the assessment, as evident from considerably lower values of associated standard deviations, and thus the inter- and intra-subject variations. The consideration of geometric factors in the proposed method forms its major potential benefit. The subject could be allowed to place the adaptor in a comfortable position, independent of the direction of source vibration, and thereby eliminating the need for training of test subjects. The proposed method could be applied to study the anti-vibration performance of gloves under multi-axes vibration (axial, shear and compression). The method may thus be applied for field assessment of anti-vibration gloves, while operating typical hand tools.

The electro-magnetic vibration exciters, commonly employed in laboratory studies of hand–arm vibration, generate non-axial vibration components under applications of side loads (Harris, 1996). The feed force exerted by the human hand on the exciter often causes side-loading of the armature. The magnitude and frequency contents of non-axial vibration may depend upon the degree of side load and design of the exciter, specifically the armature mounts. The measurements performed in this study revealed considerable magnitudes of low frequency vibration along the X_h- and Y_h-axis, while their dependency on the hand–handle interactions and adaptor position needs to be explored. The magnitudes of high-frequency vibration along these directions, however, were insignificant. The assessment of gloves in the laboratory thus necessitates appropriate consideration of the non-axial source vibration. Furthermore, the moment induced by the off-centered loading may also cause angular vibration of the handle. The laboratory assessments of anti-vibration gloves, in-general, necessitate careful considerations of additional factors, such as minimal length of the handle fixture along the vibration direction to minimize the moments, handle design and hand positioning to minimize the side-loads. The consideration of above factors, however, is not critical when the assessments are based upon the total effective vibration (TEAT).

Although the proposed method can effectively account for errors caused by misalignments in both the X_h-Z_h and Y_h-Z_h planes, and non-axial source vibration, the results of the study suggest that the major errors arise from the X_h-Z_h plane misalignment. The degree of misalignment can be estimated from the X_a-component of the adaptor acceleration. The application of a simple correction factor based upon the estimated yaw angle can effectively account for the X_h-Z_h plane misalignment errors. The estimated yaw angle can further serve as a feedback to the test subject to monitor and control the adaptor position during a test. The instantaneous yaw angle of the adaptor can be estimated from the time ratios of X_a- and Z_a-components of the adaptor acceleration, such that

$$\alpha_{t+\Delta t} = \tan^{-1}\left[\frac{\int_0^{t+\Delta t} a_x^2\,\mathrm{d}t}{\int_0^{t+\Delta t} a_z^2\,\mathrm{d}t}\right] - \alpha_0, \tag{6}$$

where t is the time, Δt is the time interval considered for refreshing the yaw angle display for the subject, α_0 is the off-set value corresponding to zero yaw angle obtained from the bare-hand test, and a_x and a_y are instantaneous values of measured adapter accelerations along X_a- and Y_a-axis, respectively. In this study, a Labview program was developed to solve Eq. (6) at time intervals of 1 s. While the estimated yaw angle was recorded, it was not displayed to the test subject. A comparison of the yaw angles derived from Eqs. (3) and (6) revealed excellent agreement between them.

The acceleration transmissibility characteristics of the gloves, irrespective of the evaluation method, reveal relatively higher values of intra- and inter-subject variations under H-spectrum excitations. This has also been reported in other studies (Hewitt, 1997, 1998). The high standard deviations under high-frequency excitations may be partly attributed to the dynamic behavior of the handle. Preliminary measurements performed on the surface of the standardized handle with clamped end conditions revealed bending deflections of the contact surface at excitation frequencies above 500 Hz, which results in uneven distribution of vibration along the span of the handle. The position of the hand on the handle may further alter the distribution of vibration at the handle surface, resulting in possible variations in the measurements. The dynamics due to the handle alone, however, are expected to cause only slight errors when compared to those caused by adaptor misalignment.

6. Conclusions

Based on the results and observations from this study, it is concluded that:

- Assuming the hand–arm posture specified in the glove test standard, the test subjects tend to position the adaptor near middle of the palm, which results in considerable misalignment of the hand adaptor. The average yaw angle between the central axes of the handle and the adapter range from 10° to 28°, depending upon the design of the glove and individual characteristics.
- The adaptor yaw misalignment is the major factor that contributes to significant errors in the measured glove transmissibility. The high values of intra- and inter-subject variations, primarily attributed to adaptor misalignment, lead to poor repeatability of the measured transmissibility.
- The electro-magnetic vibration exciters, in general, cause considerable magnitudes of non-axial vibration due to side-loads imposed by non-axial nature of the hand feed force. The presence of non-axial vibration also forms another important source of measurement errors for vibration analysis of gloves, specifically under low-frequency excitations.
- The measurement and analysis of the three translational components of source and response vibration provides comprehensive information leading to identification of primary error sources and means to account for their contributions.
- The proposed TEAT method eliminates the 'leakage' of vibrations that occur along the unintended directions, and thus effectively accounts for geometric misalignment and possible side vibration. The test results obtained for the bare-hand and the gloved hand clearly show the effectiveness of the proposed method.
- The TEAT approach yields nearly unity value of transmissibility of the bare-hand–handle system in the entire frequency range, irrespective of the adaptor orientation and side-loads. The transmissibility values derived from the standardized test method are generally below 1.0 and tend to be considerable lower when adaptor yaw angle increases.
- The adequate consideration of the geometric misalignments in the TEAT approach results in considerably lower values of intra- and inter-subject variations, and thus enhances the repeatability and reliability of assessment of anti-vibration capabilities of gloves.
- An examination of translational components of adaptor acceleration provides an effective estimate of the degree of misalignment in terms of the average yaw angle. The estimated yaw angle further provides a simple correction factor, which when applied to the transmissibility values derived from the standardized method reduce the error contributions due to misalignment in the $X_h - Z_h$ plane.

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