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A method for assessing the effectiveness of anti-vibration gloves using biodynamic responses of the hand–arm system

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Abstract

Anti-vibration gloves are widely used to help minimize hand–arm vibration exposure. In this study, an alternative method is proposed to assess the vibration isolation effectiveness of these gloves using the biodynamic responses of the bare- and gloved-hand–arm system exposed to vibration. The laboratory experiments were performed with a total of five human subjects using a typical anti-vibration air bladder glove subjected to a broad-band random vibration spectrum in conjunction with a specially designed instrumented handle. The measured data were analyzed to derive the biodynamic responses of the bare as well as gloved human hand–arm system in terms of the apparent mass and the mechanical impedance. The two biodynamic responses were applied to estimate the vibration isolation effectiveness of the glove. The validity of the proposed concept was examined by comparing the estimated vibration transmissibility magnitudes of the glove with those obtained using a palm adapter method. The comparison of the results suggests that the proposed method offers a good alternative for estimating glove vibration transmissibility. The measured data and the proposed method based upon the biodynamic responses were further used to investigate the effect of the palm adapter on the vibration transmissibility of the glove. The results suggest that the presence of the palm adapter between the subject's palm and the glove may not alter the basic trends in the transmissibility response, but it would affect the transmissibility magnitudes in the middle- and

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high-frequency ranges. A distinct advantage of the proposed method is that it eliminates the use of an adapter in assessing the vibration isolation effectiveness of the gloves.

1. Introduction

Extended exposure to vibration generated by power hand tools may cause a series of disorders in the vascular, sensorineural, and musculoskeletal systems of the hand and arm [1,2]. These disorders have been collectively defined as hand–arm vibration syndrome (HAVS) [3]. Gloves have been viewed as one method to help protect workers from HAVS. The vibration isolation effectiveness of anti-vibration gloves, however, remains unclear. A reliable assessment method is desirable to evaluate the isolation effectiveness of such gloves, to select tool-specific or task-specific gloves, and to further develop anti-vibration gloves.

The effectiveness of anti-vibration gloves can be judged by examining their influence in reducing the prevalence of HAVS in the workplace, as attempted by several investigators [4,5]. However, the diagnosis of HAVS remains a formidable task, and many factors may affect the experimental results. It is technically difficult, time-consuming, and expensive to reliably quantify the effectiveness of these gloves using such an approach. In addition, the effectiveness of anti-vibration gloves is vibration spectrum-specific [6,7], and it depends on the type of tool in use, the working condition, and the tool–hand coupling condition. The data obtained at one worksite may not be directly applicable to other worksites. Alternatively, temporal vibration effects such as vibrotactile temporal threshold shifts have been used to assist the assessment of the effectiveness of the anti-vibration gloves in laboratory studies [8,9].

The most efficient and least expensive approach to assess the effectiveness of these gloves is to measure the glove vibration transmissibility. The methodologies that have been used to measure the transmissibility can be divided into two basic groups: (1) on-the-hand measurement; and (2) at the hand–glove interface measurement or adapter method. Each group offers distinct advantages and limitations. Within the first group of methods, the assessments have been performed through the measurement of vibration transmitted to the fingernail, the knuckle, on the back of the hand, and at the wrist [10–15]. These methods formed the basis for the American National Standards Institute (ANSI) standardized test method [16] for assessing the vibration isolation performance of gloves. A major problem with this method is that the hand and the fingers themselves may amplify the source vibration at certain low frequencies, and may effectively attenuate some high-frequency components. The degree of amplification or attenuation depends on the magnitude and direction of the source vibration, hand–glove–tool handle coupling forces, and on individual characteristics of the hand and fingers. The mass of the motion sensor attached to the finger or hand skin for the vibration measurement may also alter the characteristics of vibration at the measurement location.

The second method uses a palm adapter equipped with a miniature accelerometer to measure the vibration transmitted to the hand–glove interface. The vibration transmissibility of the glove is computed from the acceleration values measured at the adapter and at the tool handle. The standardized ISO method [17] employs this approach and outlines the design requirements for the palm adapter. This approach has been widely used to determine the transfer functions of different gloves. The measured transfer functions have been further applied to predict the tool-specific vibration transmissibility of the gloves [6,7,18]. A critical concern with this method is that the insertion of the adapter between the palm and the glove may alter the contact conditions (area, pressure, and stiffness) and the impedance of the hand–arm system, and thus the glove vibration transmissibility. It has also been speculated that the mass of the adapter may also change the high-frequency transmissibility of the glove [6]. However, the contributions due to such factors have not yet been quantified.

This study proposes an alternate methodology to assess the vibration transmissibility of the gloves on the basis of the differences in the biodynamic responses of the hand–arm system with and without the glove. The primary advantage of the proposed method lies in the fact that it does not require the measurement of vibration transmitted to the hand or the hand–glove interface. The method offers a convenient alternative to quantify the vibration isolation performance of the glove without the use of the palm-held adapter. The specific aims of the present study are (1) to establish the mathematical or theoretical basis for the evaluation methodology, (2) to examine the validity of the proposed biodynamic response approach for determining the vibration transmissibility of gloves, and (3) to explore the effect of the palm adapter on the transmissibility of an anti-vibration air bladder glove.

2. Theory and experimental methods

2.1. Theory for the measurement of glove transmissibility

Fig. 1 shows an ideal model representation of the hand–glove–tool handle system, where the human hand–arm is represented by a continuous mechanical system. The glove material is represented by a mass-less spring–damper system, assuming that the mass of the material is partially lumped to the handle and the other part lumped to the hand. The vibration transmissibility of a glove (T_a) is defined as the ratio of the vibration measured at the hand–glove interface to that at handle–glove interface (vibration input into the glove), such that

$$T_a(\mathrm{j}\omega) = \frac{\ddot{z}_h(\mathrm{j}\omega)}{\ddot{z}_0(\mathrm{j}\omega)}, \tag{1}$$

where $\ddot{z}_h$ and $\ddot{z}_0$ are the accelerations due to vibration measured at the glove–hand interface and the tool handle surface, respectively, corresponding to excitation frequency ω, as shown in Fig. 1, and $\mathrm{j} = \sqrt{-1}$.

A transducer positioned at the contact interface is required to directly obtain the vibration measurements. An adapter equipped with an accelerometer is generally used to measure the transmitted vibration at the hand–glove interface [17]. This technique is referred to as the adapter method in this study. If the local vibration measured on the surface of the hand (back of the palm, metacarpal bone, etc.) or the fingers would be the same as that measured at the hand–glove interface, the on-the-hand measurement methods would be comparable to the adapter method.

Many studies have investigated the biodynamic response characteristics of the human hand–arm exposed to vibration, which represent the force–motion behavior of the biological hand–arm system at the driving point, such as mechanical impedance, dynamic compliance and

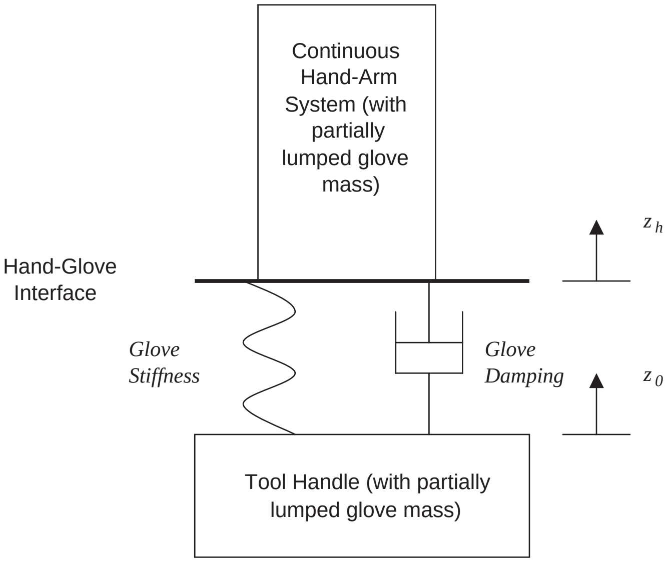

Fig. 1. A simple hand–glove–handle coupling model.

apparent mass [19,20]. The visco-elastic properties of a glove or glove material inserted between the vibration source and the human hand would alter the force–motion relationship for the human hand–arm, and thus the biodynamic response. The differences observed between the force-motion relationships of the hand–arm and the glove–hand–arm could provide an estimate of the vibration isolation behavior of a glove. The biodynamic responses of the hand–arm system with and without the glove could be expressed in terms of the apparent masses (AM) in the following manner:

$$\mathrm{AM}_{gh}(\mathrm{j}\omega) = \frac{F_{gh}(\mathrm{j}\omega)}{\ddot{z}_h(\mathrm{j}\omega)} \quad \text{and} \quad \mathrm{AM}_{uh}(\mathrm{j}\omega) = \frac{F_{uh}(\mathrm{j}\omega)}{\ddot{z}_0(\mathrm{j}\omega)}, \tag{2}$$

where AM_{gh} and AM_{uh} are the complex apparent mass functions of the hand and arm in contact with and without the glove, respectively, and F_{gh} and F_{uh} represent the dynamic forces measured at the driving point at the hand contact surface under gloved and ungloved conditions, respectively.

It is generally believed that the hand–arm behaves as a nonlinear system due to nonlinear dependence of the properties of the biological materials of the hand–arm system. Many studies, however, have also stated that the magnitude of the biodynamic response function is not greatly dependent upon the magnitude and type of vibration excitation in the range of excitation frequencies considered, and a number of lumped-parameter models with linear properties have been proposed [20–22]. Therefore, the change in the vibration magnitude due to the glove isolation effect should not greatly alter the apparent mass of hand–arm system, such that

$$\mathrm{AM}_{gh}(\mathrm{j}\omega) \approx \mathrm{AM}_{uh}(\mathrm{j}\omega). \tag{3}$$

From Eqs. (2) and (3), we obtain that

$$T_b(\mathrm{j}\omega) = \frac{F_{gh}(\mathrm{j}\omega)}{F_{uh}(\mathrm{j}\omega)} \approx \frac{\ddot{z}_h(\mathrm{j}\omega)}{\ddot{z}_0(\mathrm{j}\omega)}, \tag{4}$$

where T_b is the vibration transmissibility that can be estimated from the biodynamic response approach. Eq. (4) suggests that the vibration transmissibility of the glove can be expressed as the ratio of the dynamic contact forces measured with the gloved and ungloved hands.

Letting $\mathrm{AM}_{g0}(\mathrm{j}\omega) = F_{gh}(\mathrm{j}\omega)/\ddot{z}_0(\mathrm{j}\omega)$ be the apparent mass of the coupled hand–arm–glove system measured at the glove driving point or handle contact surface, the force ratio in Eq. (4) can be expressed as the ratio of the apparent mass responses:

$$T_b(\mathrm{j}\omega) = \frac{F_{gh}/\ddot{z}_0}{F_{uh}/\ddot{z}_0} = \frac{\mathrm{AM}_{g0}(\mathrm{j}\omega)}{\mathrm{AM}_{u0}(\mathrm{j}\omega)}, \tag{5}$$

where AM_{u0} represents the apparent mass due to the ungloved hand–arm system directly in contact with a vibrating handle. Further, it can be derived that

$$T_b(\mathrm{j}\omega) = \frac{F_{g0}/\ddot{z}_0}{F_{uh}/\ddot{z}_0} = \frac{F_{gh}/(\mathrm{j}\omega\dot{z}_0)}{F_{uh}/(\mathrm{j}\omega\dot{z}_0)} = \frac{\mathrm{MI}_{g0}(\mathrm{j}\omega)}{\mathrm{MI}_{u0}(\mathrm{j}\omega)}, \tag{6}$$

where MI_{g0} and MI_{u0} represent the corresponding driving-point mechanical impedance functions measured with and without a glove, respectively. Similarly, the transmissibility can also be expressed as a ratio of the dynamic compliance. These equations form the theoretical basis of the biodynamic methodology proposed in this study.

2.2. Experimental methods

As indicated in Eqs. (5) and (6), the quantification of the biodynamic responses such as the mechanical impedance and the apparent mass at the driving point requires measurement of the driving-point force and motion (velocity or acceleration) at the handle. To achieve these measurements, a special instrumented handle has been developed and used in this study, as illustrated in Fig. 2. The handle structure consists of two parts: the aluminum handle base and the magnesium measuring cap. Two piezoelectric single-axis force sensors (Kistler 9212) are sandwiched between the two parts along the centerline of the handle to measure the static and dynamic hand–handle coupling forces. The handle acceleration is measured using an accelerometer (PCB 356A12) positioned on the measuring cap at the center point of the handle. The handle could be installed on a vibration exciter fixture at any angle in the horizontal plane, which enables it to measure biodynamic responses at any desired orientation. In the present study, the handle was oriented such that the measuring cap was in line with the vibration direction. Each subject was advised to place his palm on the measuring cap to acquire the biodynamic response of the hand–arm with and without the glove.

The dynamic behavior of the instrumented handle is critical to the measurement of the biodynamic responses. To assure the accuracy and reliability of the measurement, a methodology has been developed to examine the behavior of the handle [23]. Briefly, this methodology employs a scanning laser vibrometer (PSV-300) to determine the handle resonance and the vibration distribution pattern on the surface of the handle base and on the measuring cap without human

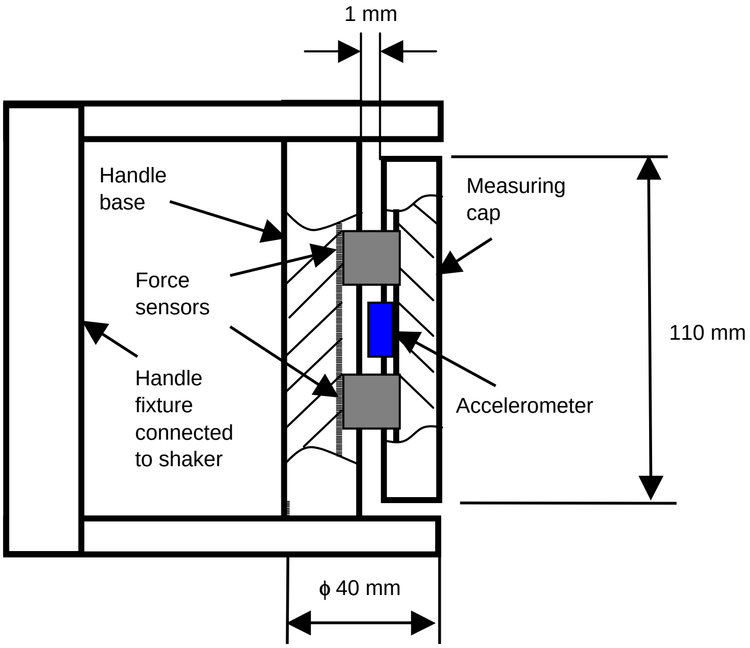

Fig. 2. An instrumented handle for the measurement of biodynamic responses of the hand–arm system at the hand driving point.

hand coupling. The results demonstrated that the handle used in this study was sufficiently stiff for the purposes of the study. Its fundamental resonant frequency was determined to be 1452 Hz.We observed that the resonance could be effectively controlled using the random vibration program used in this study. The variation in the magnitude of vibration distributed along the handle centerline on the measuring cap at 1000 Hz was observed to be less than 3%. This variation decreased with a decrease in frequency within the frequency range used in the study (16–1000 Hz). The mass of the measuring cap plus the accelerometer was found to be 90 g. The effective mass of the cap, force sensors and installation screws calculated using the measured acceleration and the dynamic force (apparent mass) was determined to be 110 g, as expected. The apparent mass response under a broad-band random excitation in the 16–1000 Hz frequency range revealed variations in the magnitude of less than 3 g. These performance features suggest that the handle used in this study can provide reasonably good measurements of the biodynamic responses of the human hand–arm system in the frequency range up to 1000 Hz.

The instrument setup and the subject posture used in this study are illustrated in Fig. 3, which is similar to that recommended in ISO 10819 [17] for glove testing. The measured force and acceleration signals were conditioned using a charge amplifier (Kistler Type 5010B) and then fed into a signal acquisition and analyzer (B&K Type 2816). The data were analyzed to determine the apparent mass and the driving-point impedance in the 1/3 octave frequency bands upon time integration of the acceleration signals. A vibration test system (Unholtz-Dickie TA250-S032) was employed to generate a broad-band random vibration with a flat power spectral density (PSD) value of 3.0 $(m/s^2)^2/Hz$ in the frequency range of 16–1000 Hz.The instrumented handle was fixed on the system's shaker using a specially designed handle fixture with its long axis oriented vertically as specified in the ISO standardized glove test method [17].

A 50 N push force was applied to the instrumented handle during the experiment. The push force was measured using a force plate (Kistler 9286AA) and displayed to the subject as a strip chart on a computer monitor. The force plate measurement was verified using the quasi-static component of the force measured with the two force sensors installed in the instrumented handle depicted in Fig. 2. For the purposes of this study, a commercially available air anti-vibration glove was used. The back of the glove was cut off, and the palm-side of the glove and its air bladder were attached to the instrumented handle using a double-sided adhesive tape. With the glove's air bladder fully inflated, the electrical tape was used to further secure the glove to the handle in order to avoid uncertainty in the biodynamic response measurements. A magnesium palm adapter, weighing 12 g and equipped with an accelerometer (Endevco M35), was also used to measure the transmitted vibration in accordance with the current ISO 10819 standard [17]. In order to validate the measurement concept proposed in this study, the palm adapter was centered on the handle in line with the vibration direction and secured to the glove with electrical tape.

The experiments were performed with five healthy male subjects with no previous work exposure to vibration. Their hand sizes are listed in Table 1. The arm posture used in this study was the same as that specified in the ISO standardized glove test method [17] and depicted in

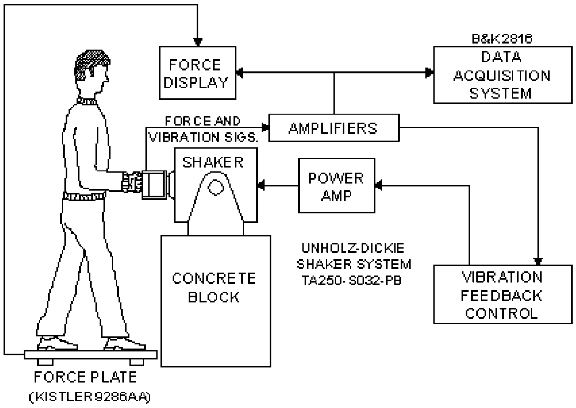

Fig. 3. Experimental setup.

Table 1
Hand size of the test subjects

Subject #	Hand size (EN420)
1	10
2	9
3	10
4	8
5	9

Fig. 3. Briefly, each subject was instructed to stand upright on the force plate in front of the shaker with his elbow angled at 90°. The force-plate height was adjusted to enable the subject to keep his forearm horizontal while maintaining the proper elbow angle. With this hand–arm posture, the vibration was delivered to the handle in the z_h-direction in the biodynamic coordinate system [24]. Unlike the conventional test method, the subjects in the present study did not grasp the handle. Instead, only the heel of the palm was in contact with the adapter, as illustrated in Fig. 4. The measurement method permitted simultaneous measurements of the biodynamic response and the vibration transmissibility.

The experiments were performed under four different test conditions involving the gloved and ungloved hand with and without the adapter, as summarized in Table 2. Two of the conditions involved the use of the palm adapter in order to examine the validity of the proposed methodology and to study the contributions due to adapter. The other two conditions involved the measurement of biodynamic responses of the ungloved and gloved hand in the absence of the adapter to estimate the glove transmissibility using the proposed methodology. The ungloved test condition was realized by fully deflating the air bladder of the glove, which was made of a lightweight and very thinfilm elastic material. The glove's air pump and check valve system allowed for easy inflation and deflation of the air bladder.

For each test condition, four different trials were performed in sequence for each subject. The sequence of the two groups and the subgroups within each group (Table 2) was randomized among the subjects. The subjects wore normal office clothes without jackets. Prior to the tests, the

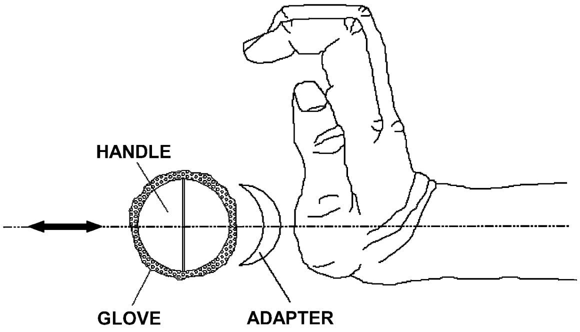

Fig. 4. The hand posture in relation to the hand, adapter, glove, and handle.

Table 2
Study conditions

Group	Subgroup	Test condition	Trials
1	I	Deflated glove with adapter	4
	II	Inflated glove with adapter	4
2	I	Deflated glove without adapter	4
	II	Inflated glove without adapter	4

test procedure was explained to each subject, and each subject was advised to read and sign a consent form. Each subject was asked to stand on the force plate adjusted to an appropriate height, and to apply the required push force (50 N) with the heel of his palm to either the vibrating handle or to the adapter, depending on the test condition. When the push force was stable at the required level, the investigator recorded the test data for a period of 30 s. The subject was then advised to relax for 1 min before performing the next trial.

2.3. Data analysis

The dynamic responses of the measuring cap–glove system and the biodynamic responses of the hand–arm system and the adapter–hand–arm system are required for the evaluation of the glove transmissibility and for exploring the effects of the palm adapter. The responses of the measuring cap–glove system are measured directly via the instrumented handle without hand coupling. An inertial correction was performed on the biodynamic responses of the gloved and ungloved hand–arm with and without the adapter using the measured apparent mass or mechanical impedance response of the measuring cap–glove system. The corrected biodynamic responses were applied to obtain the vibration transmissibility values (T_b) using Eq. (5) under both inflated and deflated glove conditions. The vibration transmissibility of the inflated glove (T_a) was also evaluated using Eq. (1).

A one-way repeated-measures analysis of variance (ANOVA) was performed to determine if the differences between the transmissibility values obtained from the adapter method and the biodynamic method were statistically significant. A paired *t*-test (two tails option) was also used to detect the significance of the difference between the transmissibility values corresponding to the center frequency of each 1/3 octave band. The correlation between the results attained from the two methods was further examined. One-way ANOVA was also performed to evaluate the significance of the palm adapter on the transmissibility derived from the biodynamic response approach (T_b). Pursuant to the results of the ANOVA, a paired *t*-test (two tails option) was undertaken to detect potential significant differences at each center frequency.

3. Results

The vibration transmissibility characteristics of the inflated glove were derived from the measured biodynamic response functions in terms of apparent mass data and the driving-point mechanical impedance, using Eq. (5). As expected, the two functions resulted in almost identical transmissibility responses. The results attained from the apparent mass function alone are thus presented and discussed.

The apparent mass of the measuring cap–glove system without the human hand was initially measured with both inflated and deflated glove conditions under the broad-band vibration spectra in the 16–1000 Hz frequency range. The apparent mass magnitude and phase responses of the handle cap with the inflated and deflated bladder are presented in Fig. 5. It is evident that the apparent mass measured with the deflated glove remains nearly constant with mean magnitude of 125 g and a mean phase angle of less than 2°. The peak magnitude of 127 g occurs near 200 Hz. The apparent mass response of the cap with the inflated glove reveals constant magnitude and

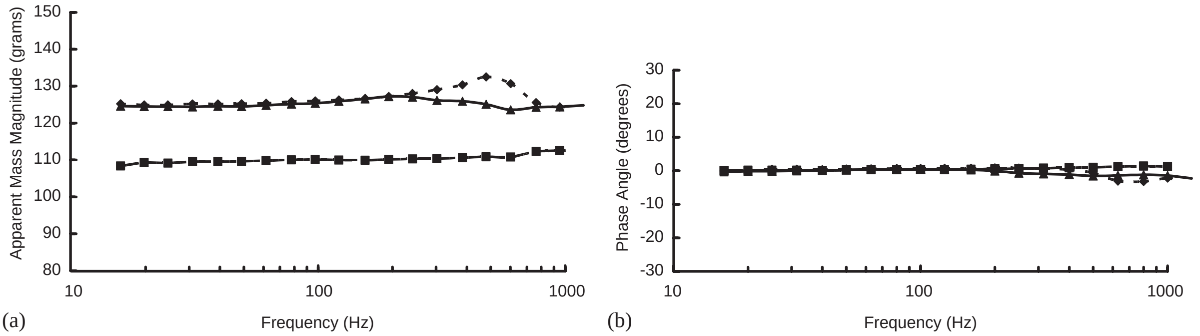

Fig. 5. Apparent mass values of the measuring cap and the glove measured with inflated and deflated glove conditions: (a) magnitude; (b) phase angle (—▲—, measuring cap and deflated glove; –■– –, measuring cap; - -◆- -, measuring cap and inflated glove).

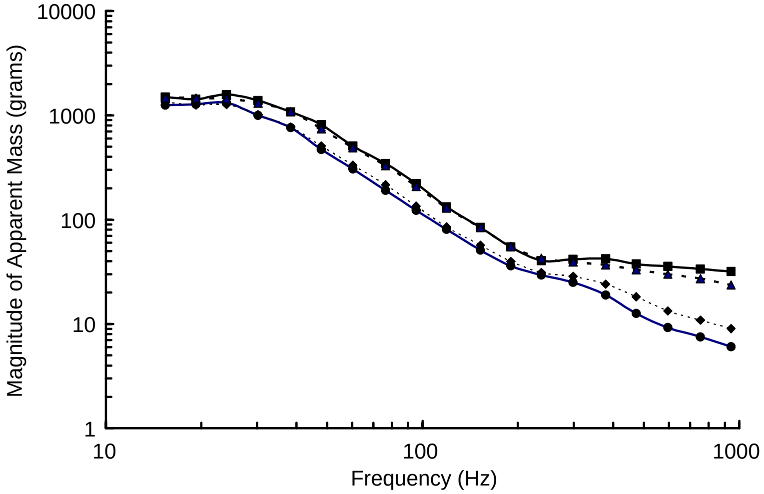

Fig. 6. Apparent mass values measured under four different test conditions (—■—, adapter–hand–arm on deflated glove; —●—, adapter–hand–arm on inflated glove; - -▲- -, hand-arm on deflated glove; · · · · ◆ · · · ·, hand–arm on inflated glove).

phase up to 300 Hz and a slight magnitude peak near 500 Hz, while the phase angle remains below 6°. The mean magnitude response was 126 g with peak value of 133 g near 500 Hz. Considering that the apparent mass magnitude of the measuring cap alone is approximately 110 g, as shown in the figure, the results suggest that the mass due to the glove bladder is in the order of 15 g. Owing to relatively small variations in the apparent mass responses of the cap with deflated and inflated gloves, the data attained with the deflated glove are applied to those measured with the human hand and arm to perform the inertial correction.

Fig. 6 shows, as an example, the apparent mass magnitude responses of the coupled hand–arm and the glove corresponding to each of the four test conditions listed in Table 2. The results show nearly constant magnitude in the 16–31.5 Hz range, irrespective of the test condition, suggesting mass-like behavior of the coupled system. Considerable attenuations in the magnitude responses are observed at frequencies above 31.5 Hz. At frequencies above 250 Hz, the magnitude response of the hand–arm with the deflated glove again assumes a nearly constant value. The magnitude response of the hand–arm with the inflated glove is observed to be considerably lower than that with the deflated glove in the entire frequency range, starting at 31.5 Hz.The results further show that the presence of the palm adapter has only little effect on the magnitude response attained with the deflated glove, but it is quite noticeable with the inflated glove at frequencies above 31.5 Hz.

The vibration transmissibility magnitudes of the glove derived from the adapter method (T_a) and the proposed biodynamic response method (T_b) for each of the five subjects are shown in Fig. 7 together with the mean values. The results show similar trends in the transmissibility responses attained from the two methods. The deviation between the two transmissibility magnitudes at a given frequency is considerably lower than the inter-subject variability. This observation is confirmed by the statistical analyses. The results of the ANOVA ($F< 0.001$,

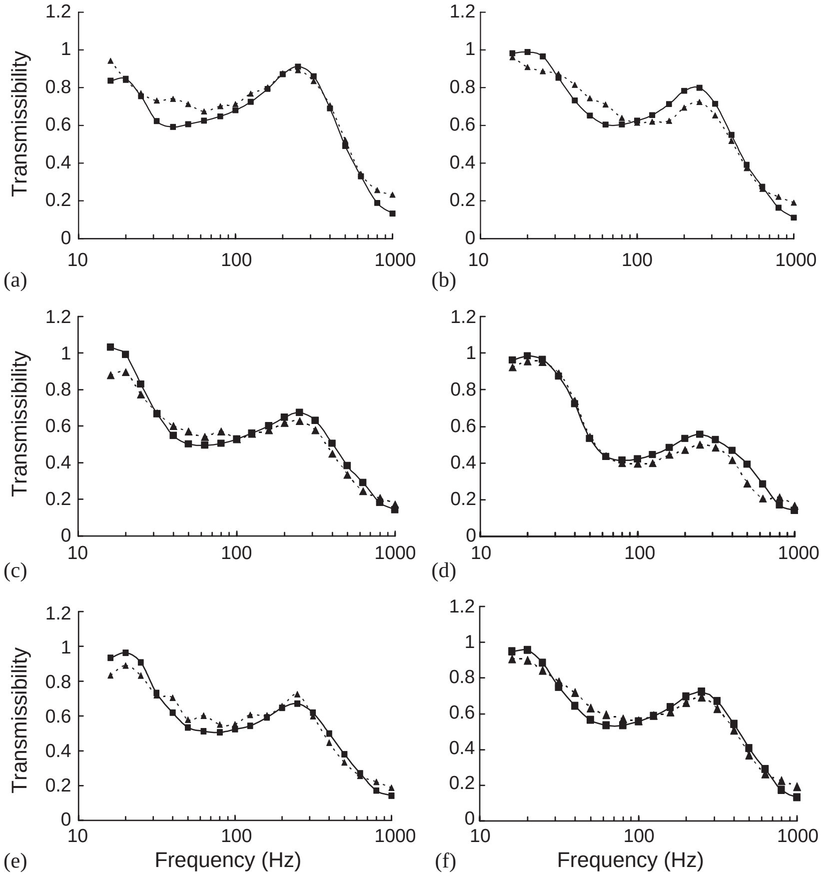

Fig. 7. Comparison of the transmissibility values evaluated with the adapter method (T_a) and with the biodynamic response method (T_b): (a) subject 1; (b) subject 2; (c) subject 3; (d) subject 4; (e) subject 5; (f) average of all subjects (—■—, adapter method; - -▲- -, biodynamic method).

$p = 0.981$) strongly suggest that the difference between the two methods cannot be reliably identified on the basis of the data attained for the five subjects considered in the study. The paired t-test also suggests that the differences between the mean transmissibility values are not reliably significant ($p > 0.050$) at 16, 25, 31.5, 80, 100, 125, 160, 200, 250, 400, 500, and 630 Hz, which are two-thirds of the 1/3 octave-band center frequencies from 10 to 1000 Hz.

A reasonable correlation between the two groups of data is a necessary condition to assure the consistency of the results obtained from the two different methods. The correlation between the two data sets is shown in Fig. 8. The Pearson correlation factor (R-value) is 0.965 and highly reliable ($p < 0.001$). The correlation function yields the linear slope of 0.989, and suggests strong correlation between the data from the two methods.

Fig. 9 illustrates a comparison of the transmissibility magnitudes (T_b) derived from the apparent mass functions attained with and without the adapter for all five subjects together with the mean values. In the tests without the adapter, the handle–glove–hand coupling relationship used in the experiment was similar to that shown in Fig. 4 with the adapter removed. While the results show comparable trends in the transmissibility magnitudes attained from both test conditions, considerable deviations in the magnitudes can be observed between the two responses in almost the entire frequency range. The analysis of variance (ANOVA) performed on the two groups of data suggests that the difference between the two methods is reliably significant ($F = 9.71$, $p = 0.002$). The paired t-test indicates that the difference between the mean transmissibility values is reliably significant ($p < 0.050$) at 1/3 octave-band center frequencies higher than 40 Hz, except at 125 Hz ($p = 0.051$) and 160 Hz ($p = 0.068$), at which the difference is also suggestively significant. Overall, these observations and analyses indicate that the transmissibility responses in the absence of the adapter are consistently and significantly higher than those obtained with the palm adapter at frequencies higher than 40 Hz.

The percentage of the adapter mass in relation to the mean apparent mass of the adapter–hand–arm system with the deflated glove (bare hand simulation) was derived, as shown

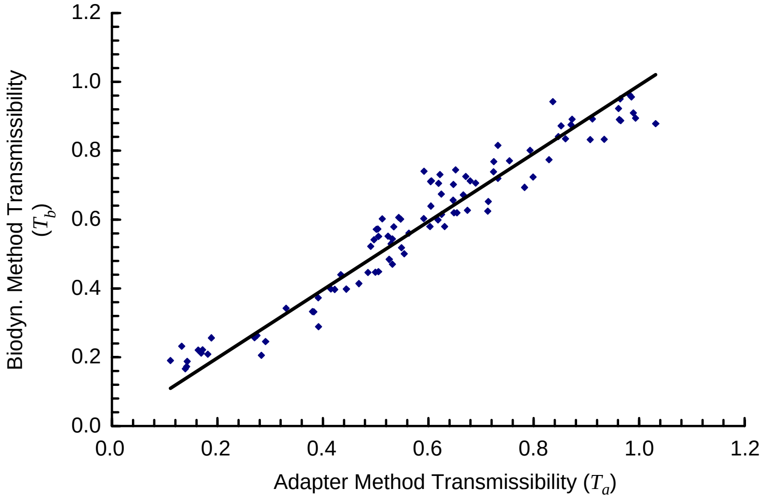

Fig. 8. Correlation between the transmissibility values evaluated from the adapter method (T_a) and the biodynamic method (T_b). $T_b = 0.989\ T_a$; R (correlation factor) = 0.965.

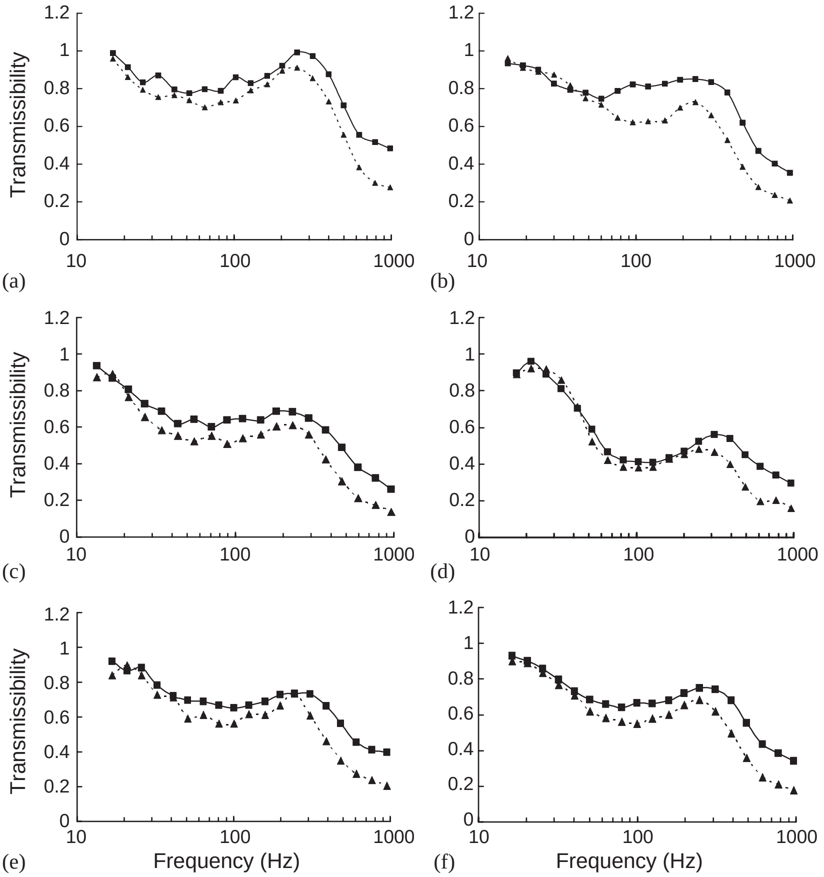

Fig. 9. Comparison of the transmissibility values evaluated from the biodynamic method with and without the adapter: (a) subject 1; (b) subject 2; (c) subject 3; (d) subject 4; (e) subject 5; (f) average of all subjects (—■—, without adapter; - -▲- -, with adapter).

in Fig. 10, together with the percentage difference between the transmissibility values measured with and without the adapter. As it can be seen, the percentage difference in transmissibility generally increases with an increase in the percentage of the adapter mass. At high frequencies (>250 Hz), the adapter mass accounted for more than 25% of the apparent mass of the adapter–hand–arm system, and the transmissibility difference was generally found to be more than 50%.

4. Discussion

A methodology for assessing the effectiveness of anti-vibration gloves was developed and evaluated in this study. This method is based on the biodynamic responses of the hand–arm system measured with and without a glove. A primary advantage of the proposed biodynamic

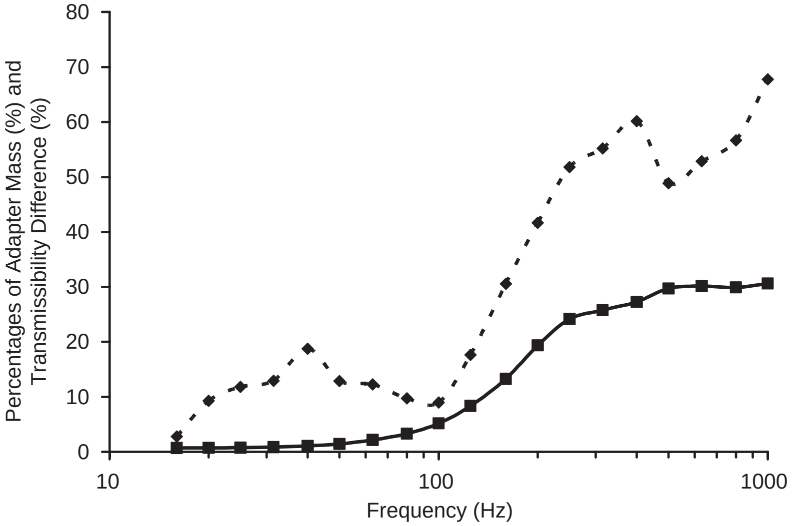

Fig. 10. The percentage of the adapter–hand–arm system apparent mass attributed to the adapter alone and the average percentage difference between the transmissibility values measured with and without the adapter (—■—, adapter mass; --▲--, transmissibility difference).

function approach is that it does not require measurement of vibration transmitted through the glove or to the hand, which poses some complexities and could introduce measurement errors. This eliminates the need for the palm adapter to measure the vibration transmitted to the glove–hand interface and to the hand–arm system as recommended in the current standard [17], and makes it possible to evaluate the transmissibility of a glove without any "third party" interference. The proposed biodynamic response approach could thus serve as a reliable and accurate measurement methodology for assessing the isolation effectiveness of anti-vibration gloves.

The transmissibility values obtained from the biodynamic response method generally agreed reasonably well with those derived from the standardized adapter method under equivalent test conditions. It is possible that their differences would be determined to be statistically significant if a sufficiently large number of subjects were used in the experiment. Many factors could potentially contribute to these differences. For example, the hand–arm system may not behave exactly as a linear system; some errors may exist in the estimates of the glove and the measuring cap apparent masses; the single-axis acceleration measured on the adapter may not truly reflect the dynamic motions of the adapter; variations in the hand posture may exist during measurements with the bare and the gloved hands. Therefore, it is anticipated that there would be some differences between the data obtained from these two principally different measurement methods. The observed differences, however, would most likely not alter the fundamental patterns of the transmissibility response. The deviations in the transmissibility magnitudes attained from the two methods are also generally much smaller than the inter-subject differences, and would be acceptable for practical engineering applications. These observations suggest that the proposed biodynamic response approach is feasible for practical applications.

The results of this study also clearly demonstrated that the adapter could significantly reduce the vibration transmissibility of the air glove under a 50 N push force. In principle, the adapter mass alone could only measurably affect the high frequency response. This is because the adapter mass (12 g in this case) is much less than the effective hand–arm mass in the low-frequency range, but the two effective masses would be comparable in the high-frequency range. This explains that the difference between the transmissibility values roughly increases with the increase of the percentage of the adapter mass in the system, as shown in Fig. 10.

The data in Fig. 10 further show that at frequencies below 100 Hz the adapter mass is less than 5% of the total apparent mass, while the transmissibility difference is more than 10% at certain frequencies between 25 and 100 Hz, which is statistically reliable at frequencies higher than 40 Hz ($p < 0.05$). As further evidenced from the figure, the differences between the transmissibility values are not exactly proportional to the percentage of the adapter mass in the system, but varies greatly with the frequency. This suggests that the effects of the adapter on the hand–arm system responses and the transmissibility are dynamic and complex. The transmissibility difference may not be attributed solely to the adapter's mass. Other factors contributing to the transmissibility differences may include the effects of the coupling force concentration and the changes to the geometry of the hand contact.

In performing a typical glove test as specified in ISO 10819 [17], the gloved hand grasps a handle with the adapter positioned inside the glove at the palm. With such a coupling, a portion of the hand force applied to the palm side of the handle may bypass the adapter. The percentage of the hand force applied to the adapter varies with the hand size and the actual location of the adapter at the palm. In the present study, the entire hand force was imparted on the adapter. Thus, the effect of the adapter on transmissibility may be more pronounced in this study than it would be in an experiment utilizing the ISO recommended hand grip condition. The results of this study also show that the adapter did not greatly alter the fundamental pattern of the transmissibility response curve, but considerable deviations in the transmissibility magnitude were observed in the middle- and high-frequency ranges. After applying the frequency weighting specified in the ISO-5349 [24] for the risk assessment of hand–arm vibration exposure, the deviations in the transmissibility magnitudes in the intermediate- and high-frequency ranges would be greatly suppressed. Therefore, the adapter method specified in the ISO standard may be acceptable for glove screening tests when glove performance judgments are based on weighted acceleration transmissibility. However, when unweighted transmissibility measurements are desired, for example, when evaluating a glove's shock attenuation performance, the adapter method may not provide accurate results. The results of this study suggest that the standardized adapter method generally underestimates the transmissibility or overestimates the effectiveness of the gloves, especially in the high-frequency range.

Decreasing the thickness of the adapter would reduce both the adapter mass and the palm force concentration effect and thus its effect on the glove vibration transmissibility. The development of a smaller miniature accelerometer could also improve the reliability of the adapter method. While reducing the size of the adapter can also reduce its mass, it could yield higher concentration of the palm force in a smaller localized area if the thickness of the adapter would not be reduced. The vibration transmissibility measured with a smaller adapter may only be used to represent the isolation effectiveness in a more localized area.

A major assumption in the current ISO 13753 standard [25] for evaluating the transmissibility of glove materials is that the mass of the glove material is negligible. The results of this study suggest that this assumption may only be acceptable when evaluating the vibration isolation effectiveness in a certain frequency range (less than 100 Hz). As mentioned above, the apparent mass of the glove measured in this study is about 15 g, which is comparable to that of the adapter. The percentage of the glove mass relative to the apparent mass of the hand–arm system would be similar to that of the adapter mass, as shown in Fig. 10. Consequently, ignoring the glove mass when using the biodynamic response approach would likely lead to the underestimation of glove effectiveness. The application of the biodynamic approach necessitates the consideration of the apparent mass, especially at frequencies above 100 Hz. This perhaps represents the major challenge when applying the proposed biodynamic approach. The method for estimating glove mass used in this study may not be perfect for a general glove test, but it offers one possible solution. Without considering the glove mass, the estimated effectiveness of the glove would generally be on the conservative side, while the effectiveness evaluated with the adapter method could be on the opposite side.

In addition to maintaining the original hand–handle coupling relationship and avoiding the need for direct measurement of the transmitted vibration, the biodynamic method proposed in this study also offers another advantage: it can be used to assess both local and global (overall) isolation behaviors of gloves. The adapter and the on-the-hand methods can only be used to measure local transmissibility or the transmissibility at a specific location. The instrumented handle design shown in Fig. 2 can be used to separately measure the biodynamic responses at the fingers and at the palm of the hand. Impedance heads or similar devices can also be used to measure local biodynamic responses [e.g. 26,27] for estimating the local transmissibility. The measurements of the biodynamic responses of the entire hand–arm system have been studied by many investigators [e.g. 28,29], which can be used to evaluate the overall transmissibility of anti-vibration gloves.

5. Conclusions

An alternative methodology for assessing the vibration transmissibility characteristics of anti-vibration gloves was proposed and evaluated in this study. This methodology is based on the measurement of the biodynamic responses of the hand–arm system at the driving point, when exposed to handle vibration. The results of this study demonstrate the validity of the proposed methodology, which can be effectively applied for evaluating the effectiveness of these gloves. The results also suggest that the use of the palm adapter specified in the current ISO 10819 standard can considerably influence the transmissibility of an air bladder anti-vibration glove. A distinct advantage of the proposed biodynamic response approach is that the glove transmissibility can be determined without measuring the vibration transmitted to the hand–glove interface or the hand. Thus, the true effectiveness of the glove can be estimated in the frequency range of concern for hand–arm vibration exposure assessments. Another advantage is that this approach could be used to determine both the local and the overall vibration attenuation performance of a glove. Even though the study only evaluated the validity of the proposed methodology using the air bladder anti-vibration glove, this methodology should be generally applicable to any other types of anti-vibration gloves.

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