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Measurement of biodynamic response of human hand–arm system

R.G. Dong*, D.E. Welcome, T.W. McDowell, J.Z. Wu

Engineering & Control Technology Branch, National Institute for Occupational Safety and Health (NIOSH), 1095 Willowdale Road, Morgantown, West Virginia 26505, USA

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Abstract

Biodynamics of the human hand–arm system is one of the most important foundations for understanding hand-transmitted vibration exposure and its health effects. Considerable differences among the reported data of the biodynamic response (BR) of the hand–arm system have been observed. A significant portion of the differences are believed to have resulted from instrumentation problems and/or computational algorithm errors. To help establish a reliable and accurate methodology for BR measurement, this study addresses the fundamental instrumentation issues. Specifically, the general theory of the driving-point BR is reviewed and summarized. An accurate mass cancellation method for BR measurement is identified and further developed. A set of methods is proposed to systematically examine and calibrate the BR measurement system. Based on the experimental results and theoretical analyses, several instrumentation and algorithm problems are identified. This study demonstrated that the instrumentation problems can be resolved or avoided by appropriately selecting the force and motion sensors, improving the structure design of the instrumented handle and fixture, using the frequency-domain method for the handle mass cancellation, and conducting the static and dynamic calibrations of the measurement system using the proposed methods. The information and knowledge presented in this paper can help to generate reliable experimental data in further BR studies.

1. Introduction

Prolonged, extensive exposure to hand-transmitted vibration and shock can cause various disorders and injuries that have been collectively labeled as hand–arm vibration syndrome (HAVS) [1,2]. Although the detailed mechanisms of these various HAVS components have not been precisely identified, it is clear that the onset and progression of the syndrome are associated with the vibration actually transmitted to the hand and arm. Therefore, it is very important to quantify the vibration-induced mechanical effects in order to establish the relationships between the mechanical input and the syndrome. Whereas it has been very difficult to directly measure and analyze the detailed mechanical effects such as dynamic stress, strain, and energy dissipation density within the highly complex hand–arm system, the biodynamic response (BR) —characterized by the apparent mass, mechanical impedance, and apparent stiffness (AS) measured at the hand-driving point — has been used as a practical and effective measure of the overall mechanical

*Corresponding author. Tel.: +1 3042856332; fax: +1 3042856265.
E-mail address: rkd6@cdc.gov (R.G. Dong).

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response of the system to excitation by vibration. Recent work has shown that the BR can be used to estimate the vibration power absorption density [3], biodynamic force [4], and stress [5]. The BR can also be used to study man–tool interaction [6], to develop test rigs and effective vibration isolators [7], and to perform anti-vibration glove evaluations [8,9]. Hence, BR is one of the most important foundations for understanding the mechanisms of the HAVS, for developing or improving standards for the measurement and risk assessment of hand-transmitted vibration exposure, and for advancing prevention methodologies [10,11].

As reviewed by Gurram et al. [12] and Dong et al. [13], the BR has been investigated under a wide range of vibration excitations and test conditions by many researchers. Based on some of these studies, the International Organization for Standardization (ISO) has set forth the ISO 10068 standard [14] for the determination of the mechanical impedance (MI) of the hand–arm system. Therein, recommended MI values and several biodynamic models of the system are described. This standard, however, has several deficiencies and limitations. For instance, the recommended values are not applicable beyond 500 Hz, which is not consistent with the requirements of the ISO standard for vibration measurement and assessment [15]. The ISO-recommended MI values apply only to males. The data are synthesized from selected studies [16–23], which only represent a few specific experimental conditions (e.g. frequency from 20 to 500 Hz, grip force in the 25–50 N range, and elbow angles close to 90°) [12]. A pushing action is essential in many tool operations, but only a few studies take into account the effect of the push force; hence, insufficient test data are available for standardization. Since the recommended MI values have such limitations, the applications of the recommended computer models that were established based on these MI data are limited. Furthermore, it is very difficult to construct a test rig using the ISO-recommended models that are based on these data [24]. Obviously, further investigations of the BR and its modeling are required.

Like the dynamic response of a mechanical structure, the BR of the hand–arm system reflects the mechanical properties of the hand–arm system. Such properties do not change with the variations of investigators or laboratories. However, although the studies selected for the ISO 10068 standard [14] used similar experimental conditions, the data still revealed considerable differences [12]. This is reflected by the wide envelope of the MI magnitude and phase values included in the standard. These considerable differences cast doubts on the accuracy and reliability of the data, as well as the models recommended in the standard. A reliable and accurate measurement methodology is required to assure the quality of the experimental data for the further development of the standard and its applications.

To assure the quality of the experimental data, it is necessary to carefully examine the instrumentation and the computational algorithms at the beginning of each experimental study. Some evaluation techniques are scattered in the scientific literature. However, few investigators have provided detailed reports regarding their instrumentation characteristics, systematic evaluations, and dynamic calibrations. While various measurement systems and computation algorithms have been used at different laboratories throughout the world, the general requirements of instrumentation, the system evaluation methods, and the experimental practices have not been seriously reviewed, examined, and documented. To fill these gaps, the specific aims of this study are as follows: (a) to review and summarize the basic theory for hand driving-point BR measurement, (b) to review and evaluate existing instrumentation practices, (c) to develop a systematic methodology for the calibration and evaluation of the measurement system, (d) to identify the major potential instrumentation problems by performing comprehensive examinations of a measurement system equipped with the instrumented handles developed at the National Institute for Occupational Safety and Health (NIOSH), and (e) to propose solutions to the identified problems. The overall goal of this study is to help establish a reliable and accurate methodology for further BR measurements.

2. Methods

2.1. Theory

The apparent mass (AM), the MI, and the AS are, respectively, defined as

$$AM = \frac{\tilde{F}}{\tilde{A}}, \quad MI = \frac{\tilde{F}}{\tilde{V}}, \quad AS = \frac{\tilde{F}}{\tilde{D}}, \tag{1}$$

where $\tilde{F}$, $\tilde{A}$, $\tilde{V}$, and $\tilde{D}$ are the dynamic force, acceleration, velocity, and displacement, respectively, at the hand–handle interface in the same vibration direction. The inverse forms of these three BR parameters are respectively termed accelerance (AC), mobility (MO), and receptance (RE) [25]. They are collectively called the frequency response function (FRF) and are widely used in investigations of engineering structure dynamics. The MO has also been occasionally used in the study of hand-transmitted vibration [26,27].

In the frequency domain, each of the BR parameters defined in Eq. (1) can be obtained by performing a transfer function- or transmissibility-like calculation. Specifically, they can be computed from

$$Z(\omega) = \frac{G_{\mathrm{fm}}(\omega)}{G_{\mathrm{mm}}(\omega)}, \tag{2}$$

where ω is vibration frequency in rad/s, $Z(\omega)$ represents any of the BR parameters, G_{fm} is the cross-spectrum of force and dynamic motion (either acceleration for AM, velocity for MI, or displacement for AS), and G_{mm} is the auto-spectrum of the motion.

While many investigators have used internally-developed programs, all of the computations can be easily performed using well-developed software packages that have been supplied with many commercial data acquisition systems (e.g. Brüel & Kjær PULSE™ systems). In the frequency domain, the results are generally complex; that is, each of the three response functions possesses real and imaginary components, which can be generally expressed as

$$Z(\omega) = Z_R(\omega) + Z_I(\omega)\mathrm{j}, \tag{3}$$

where $Z_R(\omega)$ and $Z_I(\omega)$ are the real and imaginary components of the BR, respectively, and $\mathrm{j} = \sqrt{-1}$.

These three BR parameters reflect different physical characteristics (effective mass, dynamic damping, and dynamic stiffness) of the hand–arm system. All three of these BR parameters, however, can be derived from each other. For example, if the MI is directly measured, the AM and AS can be simply calculated using the following formulae:

$$\mathrm{AM}(\omega) = \mathrm{MI}(\omega)/\mathrm{j}\omega \quad \text{and} \quad \mathrm{AS}(\omega) = \mathrm{MI}(\omega)\mathrm{j}\omega. \tag{4}$$

Hence, it is only necessary to measure one of the response parameters in the experiment. The MI has been most frequently measured and reported. These are probably the major reasons that only the MI values are recommended in ISO 10068 [14].

Another important BR parameter that has been frequently used in the study of hand-transmitted vibration is the vibration energy/power absorption (VPA) [28–30]. It is defined as

$$\mathrm{VPA} = |\tilde{F}||\tilde{V}|\cos(\varphi), \tag{5}$$

where φ is the phase angle between the vibration force and velocity. The VPA is the real part of cross-correlation function of the dynamic force and the vibration velocity [31]. Hence, it can be directly obtained by performing a cross-correlation calculation. The VPA can also be calculated indirectly using any other BR parameter and a motion parameter. This is proved as follows

$$\begin{aligned} \mathrm{MI} &= \frac{\tilde{F}}{\tilde{V}} = \frac{|\tilde{F}|\cos(\varphi) + \mathrm{j}|\tilde{F}|\sin(\varphi)}{|\tilde{V}|\cos(0) + \mathrm{j}|\tilde{V}|\sin(0)} = \frac{|\tilde{F}|\cos(\varphi) + \mathrm{j}|\tilde{F}|\sin(\varphi)}{|\tilde{V}|} \cdot \frac{|\tilde{V}|}{|\tilde{V}|} = \frac{|\tilde{F}||\tilde{V}|\cos(\varphi) + \mathrm{j}|\tilde{F}||\tilde{V}|\sin(\varphi)}{|\tilde{V}|^2} \\ &= \mathrm{Re(MI)} + \mathrm{j\,Im(MI)}. \end{aligned} \tag{6}$$

Hence,

$$\mathrm{VPA} = \mathrm{Re[MI]} \cdot |\tilde{V}|^2 = \mathrm{Re[MI]} \cdot \left|\frac{\tilde{A}}{\omega}\right|^2. \tag{7}$$

2.2. Mass cancellation

Obviously, it is necessary to measure the biodynamic force and vibration motion simultaneously in order to quantify the BR parameters. So far, an instrumented handle equipped with force and motion sensors has been the most reliable device for BR measurement. Because every instrumented handle has a certain amount of mass, the directly-measured dynamic force is a combination of the biodynamic force and the inertial force of the handle assembly. The effect of the handle mass must be cancelled to obtain the required BR data.

Based on a comprehensive sensor–structure model, it has been proven that the pure AC of a structure can be calculated from [25]

$$\mathrm{AC}(\omega) = \frac{\mathrm{Hm}_{\mathrm{pp}}(\omega)}{\mathrm{HI}_{\mathrm{pp}}(\omega) - m_1 \mathrm{Hm}_{\mathrm{pp}}(\omega)}, \tag{8}$$

where $\mathrm{Hm}_{\mathrm{pp}}$ is the total AC that results from the combined structure and measurement system response, m_1 is the effective mass on the sensor's sensing end, and $\mathrm{HI}_{\mathrm{pp}}$ is the measurement system's frequency response function, which is derived from the characteristics of the electronic measurement system: sensor, signal amplifier/conditioner, and data acquisition system (see Ref. [25, p. 227] for more details).

Using the conventional terminology for hand–arm vibration studies, we can define the following two functions:

$$\mathrm{AM}_{\mathrm{Hand}}(\omega) = 1/\mathrm{AC}(\omega), \quad \mathrm{AM}_{\mathrm{Total}}(\omega) = 1/\mathrm{Hm}_{\mathrm{pp}}(\omega), \tag{9}$$

where $\mathrm{AM}_{\mathrm{Hand}}$ is the pure AM of the hand–arm system, and $\mathrm{AM}_{\mathrm{Total}}$ is the total response directly obtained from the measurement of the test. Substituting Eq. (9) into Eq. (8), the formula for calculating the AM of the hand–arm system can be expressed as

$$\mathrm{AM}_{\mathrm{Hand}}(\omega) = \mathrm{HI}_{\mathrm{pp}}(\omega)\mathrm{AM}_{\mathrm{Total}}(\omega) - m_1. \tag{10}$$

If the hand is not coupled to the handle, $\mathrm{AM}_{\mathrm{Hand}}$ in Eq. (10) becomes zero. Hence, when testing the handle without hand coupling, the measured $\mathrm{AM}_{\mathrm{Total}}$ results solely from the response of the handle system. This is called handle AM ($\mathrm{AM}_{\mathrm{Handle}}$) in this study. Then, we have the relation

$$m_1 = \mathrm{HI}_{\mathrm{pp}}(\omega)\mathrm{AM}_{\mathrm{Handle}}(\omega). \tag{11}$$

Substituting Eq. (11) into Eq. (10), the general mass cancellation formula is expressed as

$$\mathrm{AM}_{\mathrm{Hand}}(\omega) = \mathrm{HI}_{\mathrm{pp}}(\omega)[\mathrm{AM}_{\mathrm{Total}}(\omega) - \mathrm{AM}_{\mathrm{Handle}}(\omega)]. \tag{12}$$

If the mass on the sensor's end can be precisely determined, $\mathrm{HI}_{\mathrm{pp}}$ can be computed from relation (11). While the mass at the ends of the handle, the motion sensor, and the connecting parts (e.g., screws) can be precisely determined before assembling the instrumented handle, it is very difficult to determine exactly how much the force sensors contribute to the total end mass without using a dynamic measurement approach. If the handle is sufficiently rigid, the sensor connections are sufficiently stiff, and the handle damping can be ignored, the mass at the end of the assembly can be modeled as a lumped mass on a spring–damper system that represents the elasticity and damping of the sensor element. If the excitation frequency is far below the resonant frequency of this 1-D system, the real part of the measured AM is theoretically approximately equal to the mass on the sensor's end, such that

$$\mathrm{HI}_{\mathrm{pp}}(\omega) = \frac{m_1}{\mathrm{AM}_{\mathrm{Handle}}(\omega)} \approx \frac{\mathrm{Real}(\mathrm{AM}_{\mathrm{Handle}}(\omega))}{\mathrm{AM}_{\mathrm{Handle}}(\omega)}. \tag{13}$$

Similarly, the mass cancellation formulas for calculating the other BR parameters, such as MI and AS of the hand–arm system, can also be derived. Their forms are basically the same as those expressed in Eq. (12). If the characteristics of the force and motion sensors, the signal conditioners, and the filters are good matches, the effect of a small signal phase difference can be ignored. In this situation, the instrument system FRF ($\mathrm{HI}_{\mathrm{pp}}$) approaches unity. Then, for the general BR calculation, the hand–arm system response can be simply computed from

$$Z_{\mathrm{Hand}}(\omega) = Z_{\mathrm{Total}}(\omega) - Z_{\mathrm{Handle}}(\omega). \tag{14}$$

This equation can be alternatively derived from the fact that the force seen by the force sensor is the vector summation of the force from the handle response and the force from the hand–arm response [32].

With the above-described principle, the effect of the handle mass can be canceled using either a time-domain method or a frequency-domain method. The time-domain cancellation can be achieved by using a special electronic circuit incorporated in the measurement system (e.g., Refs. [21,27]). The frequency-domain cancellation can be performed during data post-processing [32].

2.3. The BR measurement system used in this study

The experimental set-up used for the BR measurement in this study is illustrated in Fig. 1. The instrumented handle in the system was developed by NIOSH investigators, which is illustrated in Fig. 2. As shown in the figure, two accelerometers were installed in the handle to evaluate whether or not accelerometer location can affect BR measurements. The force sensors were used to measure both the quasi-static force for monitoring and controlling the grip/push force and the dynamic forces for BR calculations. After searching and testing several different types of sensors, we selected the piezoelectric sensor made by Kistler (Model #9212). The selected sensor not only has sufficient rigidity and acceptable sensitivity such that the handle has a high natural frequency, but it also has a low zero-drift for quasi-static force measurement. However, the zero-drift of the piezoelectric force sensor may not be acceptable for long-term (>5 min) exposure measurements. In such applications, we used two strain-gauge force sensors (Interface SML-50) in the handle, which did not show any significant zero-drift.

This instrumented handle can be used to separately measure the biodynamic responses distributed on the fingers and the palm of the hand [32]. When measuring the finger BR, the fingers are placed on the measuring cap while the hand applies a power grip on the handle. When measuring the palm BR, the handle is rotated 180° so that the palm can be placed on the measuring cap using the same hand grasp posture as that in the finger BR measurement. The total response of the entire hand–arm system is the summation of the responses measured at the fingers and the palm of the hand [32].

2.4. Static calibration

The static calibration of the force measurement system was performed with the instrumented handle installed in the handle fixture. Various dead weights were used as loads for the calibration. Each weight was suspended from the measuring cap using a loop of string sequentially placed at three different handle locations: at the middle of the handle and directly over each of the two force sensors.

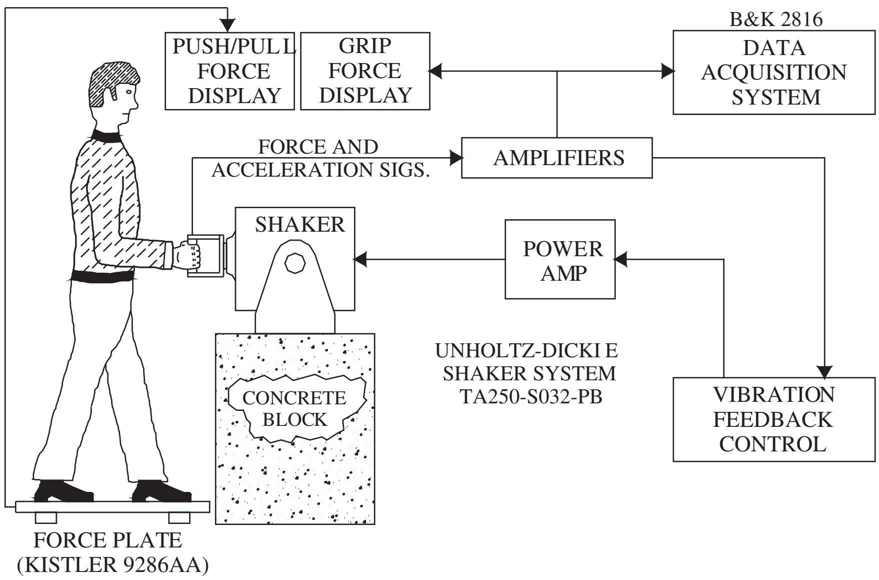

Fig. 1. Instrumentation set-up and typical subject posture for measuring biodynamic responses of the human hand–arm system.

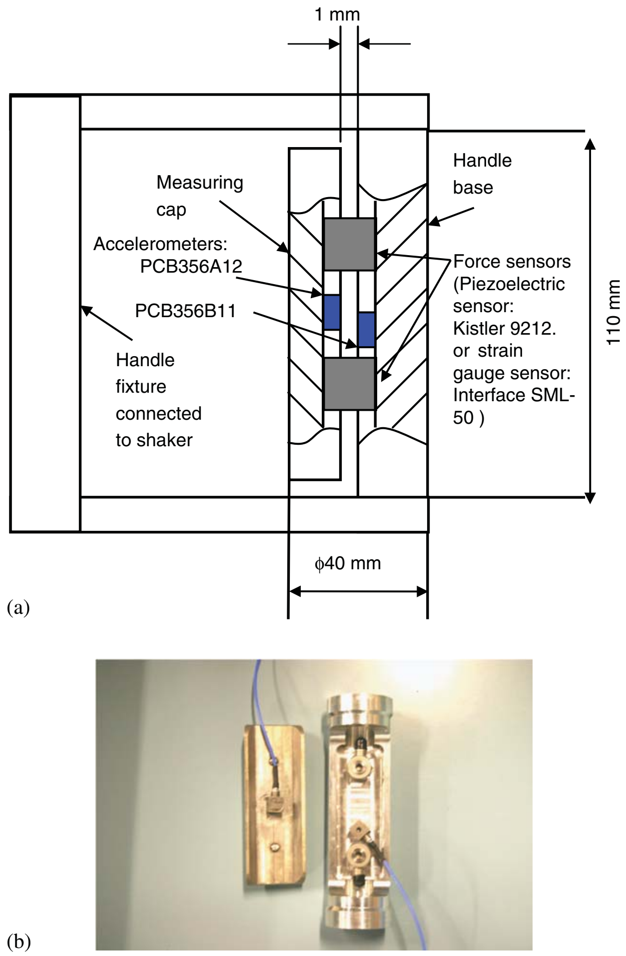

Fig. 2. NIOSH's instrumented handle: (a) a sketch of the handle; and (b) a picture of the handle. The measuring cap is made of magnesium and the other parts are made of aluminum. The accelerometers are attached to the measuring cap and handle base, respectively, using permanent adhesive.

2.5. Dynamic characterization of the instrumented handle and fixture

The frequency response functions of the handle–fixture system with and without a hand coupling were examined by applying a chirp excitation up to 3200 Hz (an uncontrolled sweep sinusoidal vibration). A scanning laser vibrometer (PSV 300 H) was used for the vibration measurements. With the hand coupled to the handle, a small plastic ring was used to provide clearance between the middle and ring fingers to allow the laser vibrometer's beam to strike and reflect from the handle surface. The response functions were used to determine the resonant frequencies of the system and the effect of hand coupling on the resonant frequencies.

Using a method similar to that reported previously [33], the scanning laser vibrometer was also used to examine the vibration distribution on the surface of the measuring cap subjected to a sinusoidal vibration (141 m/s^2 rms) at several high frequencies (1000, 1500, 2000, 2500, and 3000 Hz). The acceleration measured on the measuring cap was used to control the vibration for the test. This laser technique was also used to measure the relative motions at the shaker armature, handle fixture, handle base, and measuring cap. Based on these measurements, the modal shape of the entire structure was determined and used in follow-up improvements to the fixture design.

To examine the effect of hand coupling on vibration distribution, the vibration at each end of the measuring cap was also measured with the laser vibrometer. The measurement approach is shown in Fig. 3. Since the

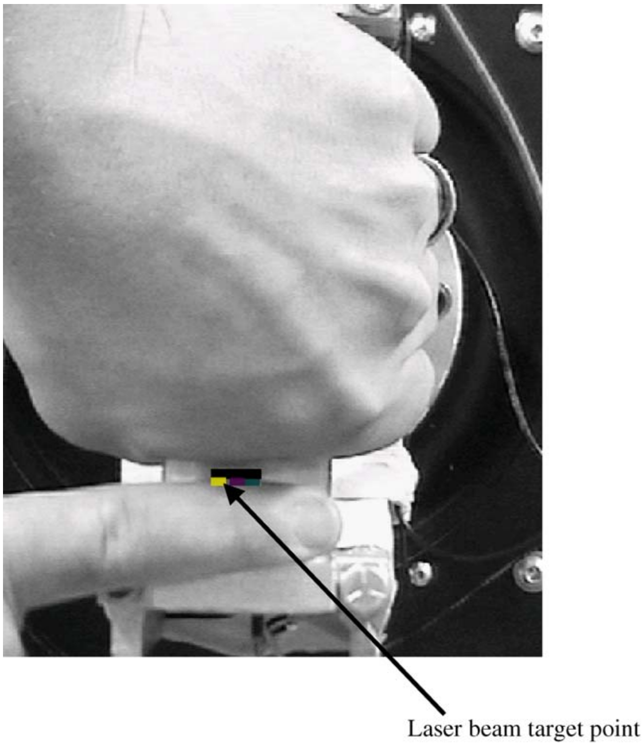

Fig. 3. Hand grip posture for examining the effect of hand coupling on the vibration distribution at the extreme ends of the measuring cap. The measurements were taken with one hand grasping the handle and the index finger of the other hand pushing against the edge of the measuring cap. The laser beam was aimed at the small gap between the grasping hand and the index finger.

edges of the palm are not normally in tight contact with the extreme ends of the measuring cap during a regular BR test, such an arrangement was considered to be an adequate representation of the normal hand-coupling condition.

2.6. Dynamic calibration and evaluation

Both a sinusoidal vibration and a broad-band random vibration were used to measure the AM of the measuring cap. In the sinusoidal excitation, a constant ISO-weighted acceleration ($10\,m/s^2$) [15] from 10 to 250 Hz and a constant unweighted acceleration ($141\,m/s^2$) from 250 to 2000 Hz were used in the experiment. In the random excitation, the effective frequency range was from 10 to 1250 Hz with a constant power spectrum density $\{(3.0\,m/s^2)^2/Hz\}$ from 16 to 1000 Hz.

Several small pieces of metal were used as calibration weights to conduct the dynamic calibration of the measurement system. The metal pieces were slightly bent so that they could be form-fitted to the cylindrical surface of the measuring cap. A small section of double-sided adhesive tape and a small rubber band were used to secure the metal pieces to the handle. The fastening force measured on the handle was approximately 30 N. In addition, a short section of electrical tape was also used for the smallest calibration weight. The calibration weights (including the adhesive tape and rubber band on the measuring cap) were 0.24, 0.68, 2.10, 3.10, 5.66, 9.30, 12.31, and 21.60 g. The weights were measured using a calibrated balance. Both the above-mentioned sinusoidal and random vibrations were used in the calibration tests.

While the dynamic calibration was performed with pure mass, the measurement system's capability to detect the responses of a single mass–spring system was also explored. A palm adapter that weighs 20 g was used to represent the lumped mass. The spring material consisted of a small section of bubble wrap with very little weight and damping properties. The bubble wrap was attached to the measuring cap with a small section of double-sided adhesive tape. The AM of the cap with the attached bubble wrap was first measured for mass cancellation. Then, the lumped mass was loaded on the bubble wrap with a rubber band. The effective mass of the rubber band lumped to the adapter was found to be approximately 1.6 g. Therefore, the total mass was approximately 21.6 g. The stiffness of the bubble wrap depends on the applied force and the effective contact area. For this study, the applied fastening force was approximately 50 N. The above-mentioned sinusoidal vibration was used in this test. The measured results were compared with theoretical predictions.

To evaluate the behavior of the instrumented handle under shear and bending loads, the handle-fixture assembly was installed on the shaker with the handle mounted horizontally. The measuring cap was then loaded in the vertical direction with a weight (10 N) suspended on nylon fishing line (1.5 m in length). By looping the fishing line around the measuring cap, the weight served as a pure shear force acting at the surface between the measuring cap and the handle base (refer to Fig. 2). Next, the loop was repositioned to create a combined shear force and bending moment acting on the measuring cap. Finally, a combined dynamic shear force and bending moment was also applied to the measuring cap by manually shaking the suspended weight in the vertical direction. It is estimated that the manually applied dynamic force was more than 50% of the weight as the weight was frequently released and allowed to drop during the manual shaking. The normal static force and the AM of the measuring cap were measured under all three loading conditions. The evaluation was performed by comparing the force and mass values measured with and without the shear force and bending moment.

2.7. Modeling

The soft tissues of the hand, especially at the palm in contact with the handle can be modeled as a spring–damping system. Furthermore, the bones and other tissues of the hand and arm can generally be considered as a lumped mass attached to the spring–damper system. Therefore, as a rough approximation, it is reasonable to model the hand–arm system in the z_h-direction as a single-degree-of-freedom system (1-D system) in a certain frequency range. This is supported by the fact that the hand–arm system's response has an obvious single resonance in the frequency range of 16–63 Hz [16–18,20,32–36], which is a fundamental characteristic of the 1-D system. Therefore, the 1-D model was used to help interpret and evaluate the basic characteristics of the experimental results.

3. Results

3.1. Static calibration

As examples, the static calibration results of the handle equipped with the piezoelectric force sensor are shown in Fig. 4. The handle equipped with both types of sensors showed excellent linear behavior. The regression lines for the three loading locations of the handle almost completely overlap each other. This means that the hand force measured with this handle is practically independent of the force loading position.

3.2. Frequency responses of the instrumented handles

Fig. 5 shows the frequency responses measured at the midpoint of the measuring cap with and without hand coupling on the handle equipped with the piezoelectric sensor. The responses were recorded at 4 Hz increments. The handle–fixture system had a fundamental resonant frequency of 1452 Hz, and a secondary resonant frequency of 2536 Hz. With the fingers positioned on the measuring cap, the resonant frequencies of the handle–fixture system were only marginally reduced, but the magnitudes of the resonant peaks decreased dramatically. The resonant peaks under the hand-coupling condition were less sharp than those without hand coupling. These observations suggest that hand coupling does not obviously increase the system's effective mass at such high frequencies, but the hand can absorb a significant portion of the vibration energy.

When the piezoelectric sensors were replaced with the strain-gauge sensors, the fundamental resonant frequency of the NIOSH handle was reduced to about 1000 Hz. The test system could not reach the designed random spectrum without a hand coupled on the handle.

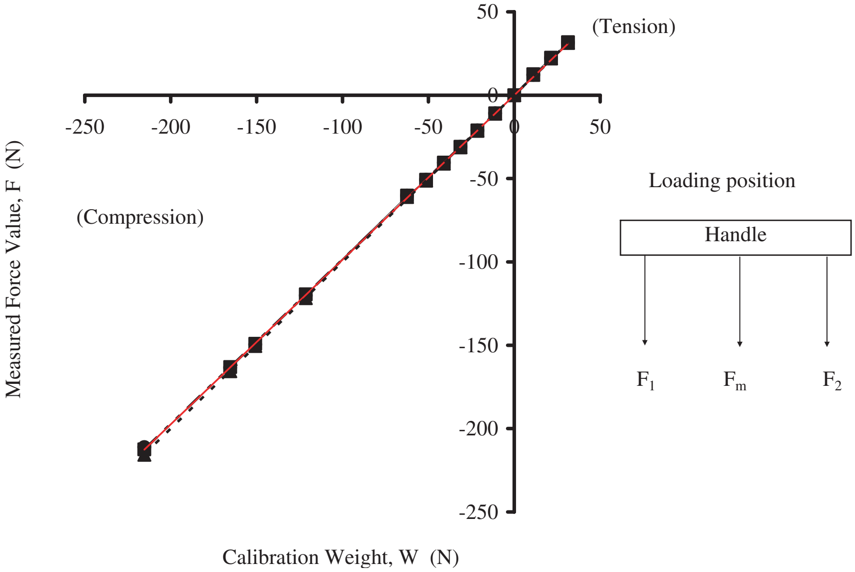

Fig. 4. Static calibration results obtained by loading the measuring cap at three locations: middle of the handle (F_m), over the two force sensors (F_1 and F_2). (◆, F_1; ■, F_m; and ▲, F_2). The trend lines for the three sets of data nearly overlap each other ($F_1 = 0.986\,W$, $R^2 = 0.9999$; $F_m = 0.9869$, $R^2 = 0.9999$; and $F_2 = 1.0002$, $R^2 = 0.9999$, in which R is the correlation coefficient).

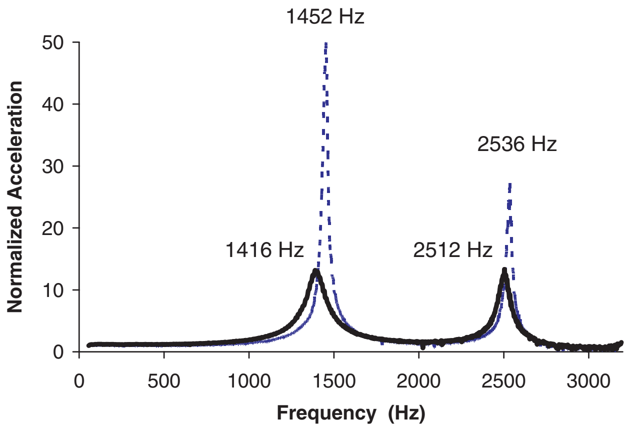

Fig. 5. Comparisons of the frequency responses of the handle measuring cap with and without hand coupling, and with an improved handle fixture (——, with hand coupled on the handle; and - - - -, without hand coupling).

3.3. Vibration distribution on the measuring cap without hand coupling

Fig. 6 shows the vibration distribution on the measuring cap along the axis of the handle equipped with piezoelectric force sensors. As can be seen, the cap did not display obvious bending (distribution difference $< 3\%$), and the vibration distribution is highly uniform at frequencies up to 1500 Hz. At 2000 Hz, however, the distribution difference reached 21% at the lower end of the cap, which seemed to result from the combined bending and tilting motions of the handle.

3.4. Effects of hand coupling on the vibration distribution

The acceleration ratio (R = acceleration with hand coupling/acceleration without hand coupling) is plotted in Fig. 7 for the handle with the piezoelectric force sensors. Except in the neighborhood of the fundamental

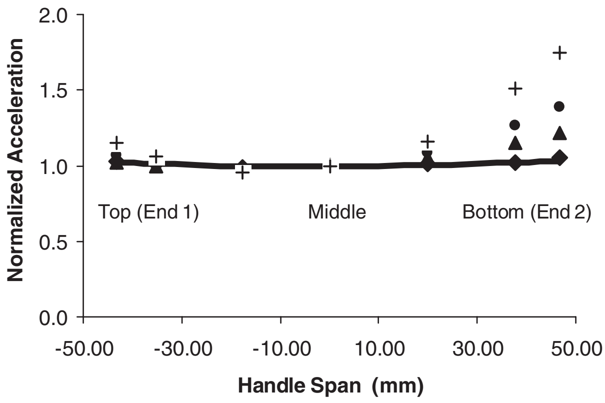

Fig. 6. Vibration distribution (normalized with respect to the mid-point) on the measuring cap along the center axis of the handle at different frequencies: +, 3000 Hz; ●, 2500 Hz; ▲, 2000 Hz; ◆, 1500 Hz; and ——, 1000 Hz.

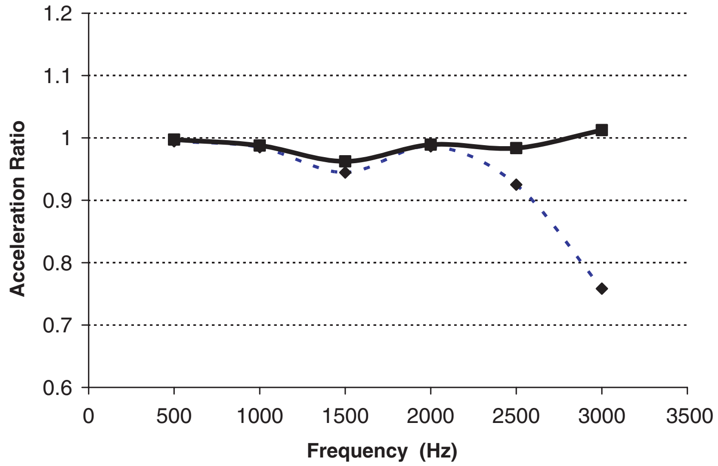

Fig. 7. Effects of hand coupling on vibration distribution at the two ends of the measuring cap as shown in Fig. 4 (acceleration ratio = acceleration measured with hand coupling/acceleration measured without hand coupling) (–■–, end 1 or upper end; and –◆–, end 2 or lower end).

resonant frequency, the data indicate that hand coupling has no significant effect on the vibration distribution at the two ends of the measuring cap for frequencies at or below 2000 Hz. In the neighborhood of the fundamental resonant frequency, the effect is approximately 5%. However, the influence of hand coupling on the distribution can be more than 10% at frequencies above 2500 Hz.

3.5. AM of the measuring cap

Fig. 8 shows the phase angle of the AM measured on a trial/first version of the NIOSH handle. Theoretically, the phase angle of the measuring cap should be close to zero because there is little damping and elasticity of the handle at the low frequencies. However, a large phase angle was observed, which increases with the reduction in frequency. Although the effect of the phase angle could be taken into account using Eq. (12) for the mass cancellation, the large phase angle suggests that the handle structure may have some problems and/or that the force sensor (Kistler 9212) and accelerometer (PCB 339B24) have different phase angles. Consequently, we improved the handle design by replacing the accelerometer with the one shown in Fig. 2, reducing the cap mass, and enhancing the connections of the two force sensors. This significantly improved the dynamic performance of the handle.

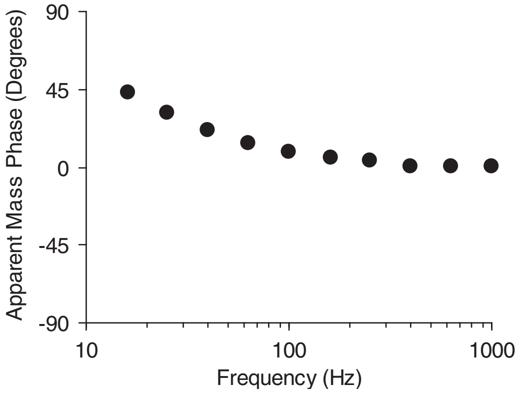

Fig. 8. Phase angle of the apparent mass measured on the trial/first version of NIOSH's instrumented handle.

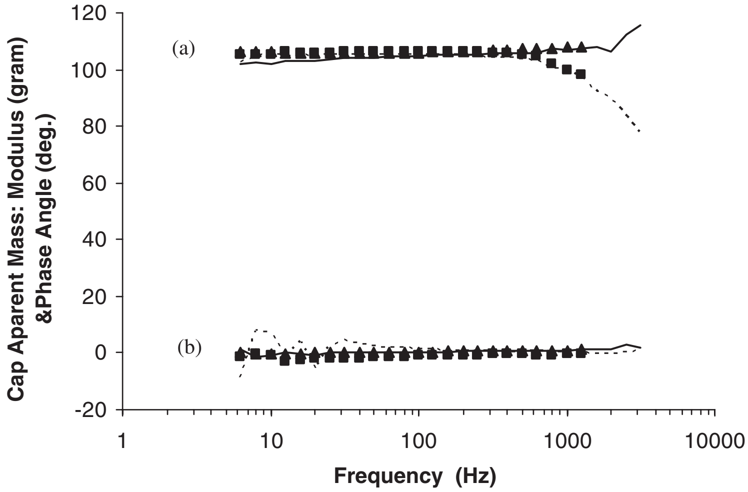

Fig. 9. The apparent mass values of the handle measuring cap calculated with the accelerations measured on the cap and the base under random and sinusoidal vibrations: (a) modulus; (b) phase angle (■, random vibration and accelerometer on base; ▲, random vibration and accelerometer on cap; - - - -, sinusoidal vibration and accelerometer on base; and ——, sinusoidal vibration and accelerometer on cap).

Fig. 9 shows the AM of the improved handle equipped with the piezoelectric force sensor. The AM values measured with a random vibration input are more consistent over the entire frequency range than those measured with sinusoidal vibration excitation. Up to 500 Hz, the magnitude or modulus calculated with the acceleration measured on the cap is very similar to that using the acceleration measured at the handle base. However, at higher frequencies, the magnitude calculated with the handle base acceleration decreases with an increase in frequency. Because the force used in the calculation remains unchanged, the acceleration measured on the handle base must be greater than that on the cap at the higher frequencies. Above 2000 Hz, the magnitude calculated with the measuring cap acceleration is higher than the average value. This is likely because there is more motion at the force sensors than at the middle of the handle. The additional motion at the force sensors likely results from the bending motion of the measuring cap at the very high frequencies (see Fig. 6).

As also shown in Fig. 9, the phase angle calculated with the acceleration measured at the base has a fairly large variation (-8° to 8°) at the lower frequencies ($\leqslant$ 25 Hz), which suggests that the FRF of the measurement system exhibits some small shifts from unity in this frequency range. The phase angle derived from the accelerometer on the measuring cap is much less variable, and its corresponding FRF can be treated as unity up to at least 2000 Hz. As also shown in this figure, the cap AM values (both magnitude and phase angles) in the neighborhood of the fundamental resonant frequency (1452 Hz) do not show any significant differences from the AM values obtained at the lower frequencies.

In the sinusoidal excitation, we observed that the force waveform produced by the piezoelectric sensor was significantly distorted at some low frequencies (<25 Hz), which resulted in the phase differences shown in Fig. 9. This phenomenon was not observed on the handle equipped with the strain gauge force sensor. As a result, this handle has a more consistent mass response and lower phase angle at the low frequencies than the handle equipped with the piezoelectric sensor. This may be because the strain gauge sensor is more sensitive than the piezoelectric sensor. However, the performance of the piezoelectric sensor handle at frequencies higher than 1000 Hz is better than that of the handle with the strain gauge sensor.

3.6. Dynamic calibration

As examples, the dynamic mass calibration values for the piezoelectric sensor handle measured with a random vibration excitation are shown in Fig. 10. As depicted in the figure, the measured mass values generally agree with the true mass values. The measured values for the largest mass (21.6 g) begin to exceed the true mass value at 630 Hz. This is probably because this mass started to exhibit some resonant response at such a frequency due to its relatively low attachment rigidity. The measurements with the smallest mass (0.24 g) reached the noise level and could not be reliably determined at frequencies less than 63 Hz.

Fig. 11 shows the calibration results measured at the least favorable attachment location (the bottom end in Fig. 6) using sinusoidal excitation. Similar to that observed in the random vibration calibration, the large mass (21.6 g) begins to exceed the true mass value at frequencies greater than 630 Hz. It becomes substantially higher at frequencies above 2500 Hz. The responses of the smaller mass (6.02 g) at frequencies up to 2000 Hz are very reasonable. Similar to the cap AM measurements, under the closed-loop-controlled vibration excitation, the system resonant frequency does not show an obvious influence on the measurements at either the middle or the lower end of the handle equipped with the piezoelectric sensors. To further investigate the resonance effect, sinusoidal excitation at each 1/12 octave-band center frequency from 1029 Hz to 2054 Hz was used. As expected, no resonance effect was observed; the data were very similar to those shown in Fig. 11.

3.7. Dynamic evaluation

The results of applying the single mass–spring system to the handle (dynamic evaluation) are shown in Fig. 12. Although the bubble wrap can exhibit some nonlinear behaviors, the measured data fit the predictions

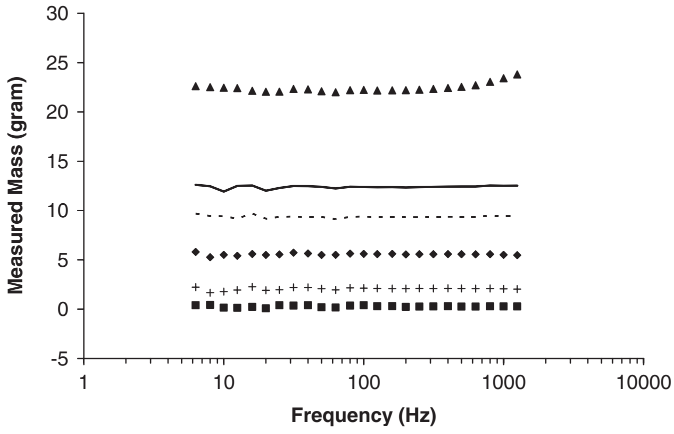

Fig. 10. Samples of dynamic calibration results under the broad-band random vibration: ■, 0.24 g; +, 2.10 g; ◆, 5.66 g; - - - -, 9.30 g; ——, 13.31 g; ▲, 21.60 g.

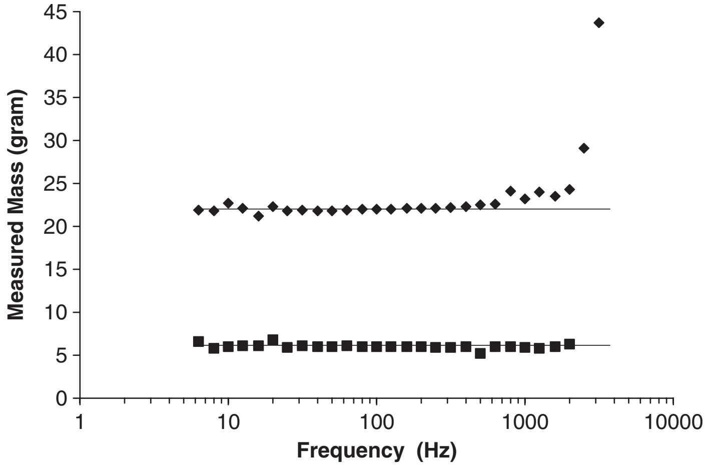

Fig. 11. Samples of dynamic calibration results measured at the least favorable attachment location (bottom end) on the measuring cap using the sinusoidal vibration: ——, reference line; ■, 6.02 g; and ◆, 21.0 g.

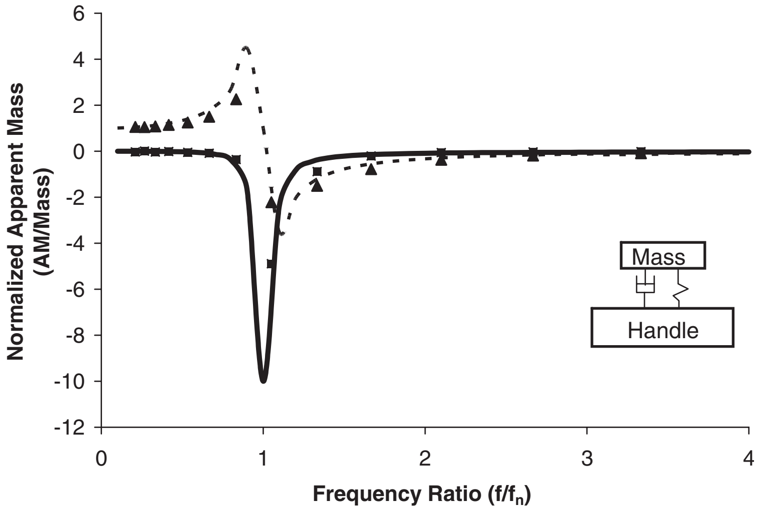

Fig. 12. Dynamic evaluation results with a single-degree-of-freedom system (mass = 21.6 g; the spring–damper system was simulated using a section of bubble wrap; the measured resonant frequency $f_n = 300$ Hz) (■, measured imaginary part; ▲, measured real part; ——, theoretical imaginary part; and - - - -, theoretical real part).

of the theoretical model very well. Although the responses at the high frequencies are very small, they were still detected with fairly good accuracy. Also as expected, the curve fit indicates that the bubble wrap provides little damping. These observations further suggest that this system can provide very reasonable measurements.

3.8. Effect of shear force and bending moment

There are inconsequential differences (<0.1%) between the data measured with and without the application of shear force and bending moment under all the static and dynamic tests performed on the NIOSH handle. This indicates that the force sensors are very stiff. Thus, the applied shear force and bending moment have negligible effects on the measurements with this NIOSH handle.

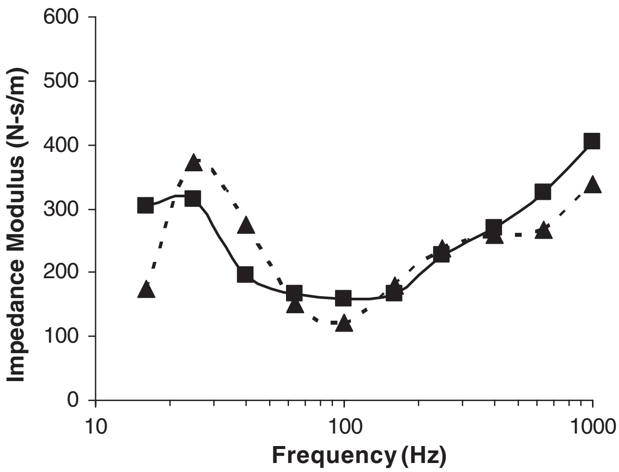

Fig. 13. Comparison of the mechanical impedance data measured using two different versions of an instrumented handle (–■–, trial version with a large phase angle; –◆–, improved version with a small phase angle).

3.9. Samples of BR data

Fig. 13 shows the comparison of the MI data measured with the preliminary and improved versions of the NIOSH handle equipped with the piezoelectric sensor. Eq. (14) was used in the mass cancellation. Obviously, without taking into account the phase angle between the force and acceleration signals observed on the preliminary version of the handle, a large error could be introduced into the measurement at frequencies less than 50 Hz.

3.10. Modeling results

Fig. 14 shows a comparison of the experimental data and the theoretical predictions. The theoretical results demonstrate that the resonant peak of the MI magnitude corresponds to a zero phase angle if the system exhibits no damping. The zero phase angle shifts to a higher frequency as the damping ratio is increased. The hand–arm system must exhibit significant damping. Hence, the zero phase angle of the hand–arm MI response should generally correspond to a higher frequency than the magnitude peak location. Our experimental data are generally consistent with this theoretical prediction.

4. Discussion

Fig. 15 shows three sets of BR data of the hand–arm system, which were manually digitized from the figures in the published articles [21,37,38]. These data were measured in the z_h-direction (along the forearm). The data in Fig. 15(a) are the average values of the three-subject data reported by Miwa [37]. The sinusoidal and random excitations generated similar responses in the Gurram et al. study [21]. Hence, the data shown in Fig. 15(b) are representative of their reported data in either case. Fig. 6 of the article written by Burström and Lundström [38] is larger and clearer than other figures in that article. Hence, the data in Fig. 15(c) were digitized from this figure. If we would use these data to predict the mechanical stress and potential medical effects of the vibration exposure and to develop prevention methods, we would end up with contradicting conclusions and prevention strategies. Miwa's data reflect the resonant feature of the hand–arm system well, but such a critical feature cannot be found in the other sets of data. This suggests that the data reported by Miwa 40 years ago (in 1964) [37] are more reasonable than those reported 10 years ago (in 1994) [21,38], although technologies have significantly advanced in the last 20 years. This suggests that the basic technologies for the BR measurement at the hand driving point have been available for a long time, but they might not have

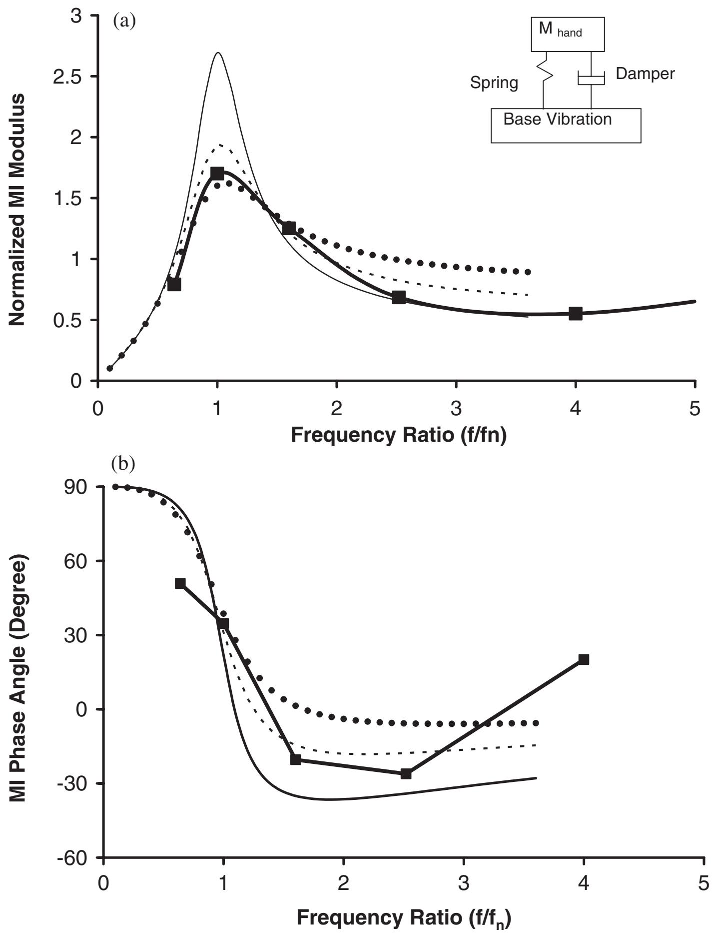

Fig. 14. Comparisons of modeling results and experimental data: (a) normalized modulus {$= \mathrm{MI}/(2\pi f_n M_{\mathrm{hand}})$, in which the resonant frequency (f_n) = 25 Hz and the hand–arm mass (M_{hand}) = 1.4 kg}; (b) phase angle {——, ξ (damping coefficient) = 0.2; - - - -, ξ = 0.3; ● ● ●, ξ = 0.4; –■–, experimental data}.

always been appropriately applied. The results of this study may help understand the instrumentation issues and advance the measurement techniques.

4.1. BR evaluation approaches

In many previous studies [e.g., 21,22,27], the velocity required for evaluating the MI or power absorption was calculated using the directly measured acceleration. If the sampling rate is sufficiently high and/or an appropriate algorithm or circuit is used, the possible error due to a numerical or electronic integration process may be negligible. However, there is no guarantee. The integration process can be avoided if the AM is evaluated first, and the other BR parameters are calculated using the relationships expressed in Eqs. (4) and (7). This may help increase the reliability and accuracy of the measured data.

4.2. Measurement of applied grip force

The BR of the hand–arm system is generally a function of applied forces [32,34–36]. It is important to measure and control the applied forces in the BR measurement. If the grip force measurement is not independent of the hand grip location on the handle, as observed in a previous study [33] (see Fig. 16), the applied grip force may not be consistently controlled among testing subjects or test trials. This is because the

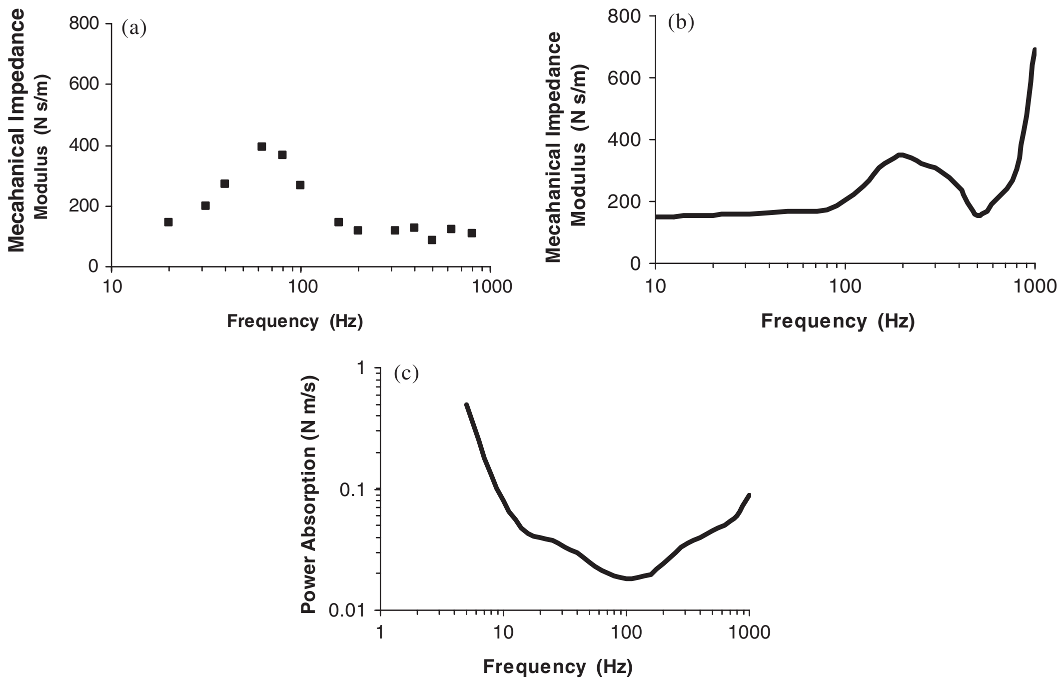

Fig. 15. Comparisons of three sets of reported data: (a) mechanical impedance modulus reported by Miwa [37]; (b) mechanical impedance modulus reported by Gurram et al. [21]; and (c) vibration power absorption (VPA) reported by Burström and Lundström [38], the shape of which is the same as that of the MI real part.

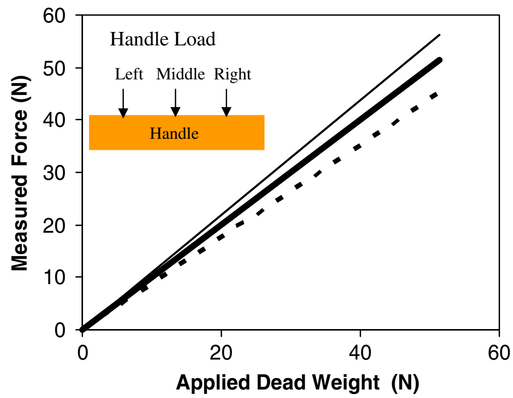

Fig. 16. Effect of loading locations on the static calibration results for the instrumented handle recommended in ISO 10819 (1996) [40]: ——, at the middle of the handle; ——, $\frac{1}{4}$ distance from the right end; and - - - -, $\frac{1}{4}$ distance from left end of the measuring cap.

exact grip locations and force distributions on the handle could vary in the experiment. The uncertainty of the applied force measurement on some instrumented handles may be one of the sources of the observed data variations.

4.3. Appropriate method for handle mass cancellation

It has been well understood that at high frequencies ($\geqslant$500 Hz), only the soft tissues close to the contact surface can be effectively involved in the biodynamic response. Hence, the impedance of the hand–arm system is usually less than 400 N s/m (see Fig. 13) or the AM is usually less than 127 g at 500 Hz [32,34,36,37]. However, a few studies reported that the impedance of the hand-arm system could be more than 1500 N s/m at

500 Hz [22], which means that the AM would be more than 477 g. Instrumented handles generally weigh more than 200 g. The reported impedance values suggest that the handle or handle–fixture mass might not have been sufficiently cancelled (or not cancelled at all) in some of the reported studies.

For unknown reasons, the time-domain method for handle mass cancellation was generally used for BR measurements of the hand–arm system before Dong et al. proposed to use the frequency-domain method several years ago [39]. Unfortunately, the time-domain approach may not be the best choice. First, although the additional required circuitry can be relatively simple, it does increase the complexity of the measurement system. Second, the additional elements may also introduce an additional phase shift and potential circuit errors into the measurement system. Most critically, as shown in Fig. 9, the effective handle mass may vary with the type of vibration and its characteristics (magnitude and frequency). Such variations can be taken into account by adjusting the circuit parameters for each magnitude under each frequency if a discrete sinusoidal vibration is used in the test. It is, however, very difficult to compensate for such variations when random, swept sine, and tool vibration spectra are used in the experiments. This might be one of the major sources of error in the high frequency range data reported in the previous studies. On the other hand, calculations made with the frequency domain method (expressed in Eq. (12) or Eq. (14)) can be easily performed in the course of the measurement or during the post-processing of the data using a simple program or routine. The variation of the effective handle mass as a function of frequency can be easily taken into account in such a computation. For these reasons, the frequency domain approach is superior.

4.4. Effects of vibration distribution on the handle

No matter which method is used, the validity of the mass cancellation is based on the assumption that the handle's response will be the same whether it is measured with or without hand coupling. As observed in our previous study [33], the handle recommended in ISO 10819 (1996) [40] responds dramatically differently with and without hand coupling; probably because this handle is not sufficiently rigid, and its natural frequency is only about 150 Hz. We also observed that the shaker control system will reach the designed random spectrum more efficiently with a hand coupled to the handle. This suggests that vibration characteristics of the test system are generally different with and without a hand holding the handle. It is simply a matter of controlling these differences to reduce mass cancellation errors.

With the fundamental resonant frequency up to 1495 Hz, the handle used in the present study does not show significant coupling effects at frequencies less than 1000 Hz. The closed-loop control also made it possible to effectively control the response in the resonant frequency region, and the calibration measurement up to 2000 Hz was still fairly reasonable (see Fig. 11). Whereas it was difficult to realize the random spectrum on the handle equipped with the strain gauge sensors, the spectrum was easily achieved with the piezoelectric sensor handle. These observations suggest that the instrumented handle should be made as rigidly as possible to reduce the hand coupling effect. These observations also suggest that the handle equipped with the strain gauge sensors may not be suitable for measuring high frequency responses.

Undesired rotational or side motions may occur on some shakers [41]. The unsymmetrical distribution of vibration at the very high frequencies (>2000 Hz) along the handle axis shown in Fig. 6 may result from such motions. Such motions may be amplified if the handle–fixture assembly's center of mass and the applied push/pull force are not acting on or along the shaker's centerline. As also shown in Fig. 6, the bending motions of the handle and fixture may also affect the vibration distribution. It is speculated that a severely uneven vibration distribution could significantly affect the measurement results, because in such a situation, the motion measured at one point on the handle or fixture cannot be representative of the motion at every point on the hand–handle interface. This is another potential error source.

The BR data shown in Fig. 15(b) were measured using an unsymmetrical (cantilever-like) handle–fixture structure [21]. With the same material, size, and weight, such a structure is usually less rigid than the symmetrical structure (e.g., the handle and fixture in Fig. 2). Therefore, it is more problematic in terms of vibration distribution. The trends of the data measured with this handle are dramatically different from those shown in Figs. 13 and 15(a) and those reported in many other studies that used symmetrical handle–fixture structures in the experiments (e.g., Refs. [17,34]). Without examining the distribution of the vibration on such an unsymmetrical handle–fixture structure and calibrating the dynamic measurements at different locations on the handle, this set of data cannot be trusted. Unfortunately, such data were used to synthesize the ISO-recommended MI values and construct the recommended computer models [12,14]. This further suggests that the ISO-recommended values and computer models should be re-examined, and a revision of the standard should be made when more reliable experimental data are available.

The vibration values measured on the shaker armature, the handle fixture, handle base and the measuring cap indicate that the majority of the resonant motion on the handle–fixture used in the present study results from the bending of the handle base and the relative displacement at the force sensor connections. It is difficult to further enhance the sensor connections and sensor behaviors. However, it is possible to strengthen the handle–fixture connection and increase the resonant frequency of the handle base. Based on these considerations, we have further improved our handle fixture design, which increased the resonant frequency of the piezoelectric sensor handle to 1924 Hz.

4.5. Potential errors at high frequencies

At frequencies above 100 Hz, the distribution of hand-transmitted vibration is mainly limited to the hand, and the amount of tissue involved in the response is considerably smaller than that at lower frequencies. At 1000 Hz, the AM of the fingers could be less than 10 g and the AM of the entire hand–arm system could be less than 20 g [32].These values are usually much less than the tare mass of the measurement device. In the majority of the reported studies, the dynamic force of the entire hand–arm system was measured either at the connection point between the handle fixture and the shaker armature (e.g., Refs. [21,27]) or at the handle end points connected to the handle fixture. As mentioned above, the handles used in the majority of the reported studies likely weighed more than 200 g. The handle–fixture assembly likely weighed more than 500 g. Such high tare values make it very difficult to measure the BR response accurately at the high frequencies. This provides an explanation as to why the reported BR data in the high frequency range (>500 Hz) were dramatically different [12,13] (also see Fig. 15). To reduce the tare mass, the force sensors should be located as closely as possible to the driving point, and the measuring cap should be as light as possible without significantly reducing the rigidity of the handle. The results of this study also demonstrated that the motion sensor should also be installed as close as possible to the driving point to reduce the inconsistency between the measured motion and the motion input to the hand. The NIOSH handle was designed based on these concepts, and it should be less problematic than many other reported instrumented handles.

4.6. Potential errors at low frequencies

At frequencies lower than 40 Hz, the major potential problems identified in this study are signal phase differences (see Figs. 8 and 13), limited sensitivity of the measurement system (see Fig. 10), and signal noise. It is better to select the appropriate force and motion sensors that have no significant phase difference ($<5^\circ$) than to correct the phase effect using Eq. (12) for the mass cancellation. There is a trade-off between the sensitivity and rigidity of the instrumented handle. Depending on the purpose of the study, different sensors may be used. Because of the limitation of shaker travel distance and frequency weighting considerations, the vibration used in many experiments at the low frequencies is usually fairly low. The potential for noise in both the motion and force signals may cause significant errors and requires special attention.

One study used a constant-velocity (14 mm/s) sinusoidal sweep excitation from 4 to 1000 Hz to measure VPA [38]. The acceleration for such a velocity at 4 Hz is only 0.35 m/s^2. The dynamic force generated at such a vibration level could be close to the noise level of the sensors. Furthermore, the involuntary shaking and movements of the hand and arm in the grip and push actions could also cause unexpected dynamic force at such low frequencies [37]. Together with effects of the possible phase difference between the motion and force sensors, the noise in the force signals could lead to a great overestimation of the BR. As shown in Fig. 15(c), the VPA at 5 Hz seems more than 0.45 N m/s. Calculated using Eqs. (4) and (7), the real part of the impedance is 2296 N s/m and the imaginary part of the AM is 73.1 kg. This is obviously unrealistic because the average weight of the ten subjects used in the reported study was only 63.7 kg [38]. As a result, the frequency weighting derived from this set of VPA data could not be used to explain any vibration-induced sensation or medical effect [42]. This further demonstrates the importance of addressing fundamental instrumentation issues.

4.7. General data interpretation and debugging

It is common knowledge that the MI phase angles are 90° for a pure mass, 0° for pure damping, and −90° for a pure spring [16]. The human hand–arm system can be modeled as a complex mass–spring–damping system in each vibration direction [14]. Hence, its dynamic behavior is generally a combination of all of these physical component responses. Which one of these three factors plays the dominant role in the BR depends primarily on the vibration frequency. In any case, however, the power absorption cannot be negative or the imaginary part of the AM can never be positive at any frequency. The zero-phase angle should usually occur at a frequency higher than that of the peak magnitude of the fundamental resonance (see Fig. 14).

In addition to using the basic theory to analyze the data as demonstrated in the last example, basic knowledge of mechanical systems can also be used to identify some obviously unusual data in an experiment. For example, the phase angles of MI presented in one published article [43] are generally near 90° at frequencies above 500 Hz (up to 1250 Hz); and in the y_h-axis (as defined in ISO 5349-1 [15]), the largest phase angle is reached at frequencies as low as 100 Hz. A near-90° phase angle was also reported in another study [44]. At such large phase angles, the vibration power absorption is near zero, although a constant-velocity vibration could be used, as reported in another study [45]. These observations imply that the hand–arm systems of the subjects exhibited almost pure mass behaviors, like a rigid rock or a piece of steel, at these intermediate and/or high frequencies. This is questionable because the finger or hand's soft tissues are the major materials involved in the vibration response at such frequencies, and these soft tissues cannot behave in such a manner. As evidenced from the fact that the hands can effectively suppress the handle resonance [33] and quickly absorb the vibration on a ringing bell, human hands usually display good damping at the high frequencies, which is also shown in the present study (see Fig. 5). Such large phase angles may have resulted from insufficient mass cancellations of the measuring cap and/or handle. A second possibility is that the subjects wore rings on their fingers during the experiment. Another possibility is that some testing subjects may have had fairly rigid layers of callous on the glabrous skin of the hand. Hence, in addition to examining the instrumentation and computational algorithms, these hand conditions should also be examined when such an unusual large phase angle is observed in the experiment.

5. Conclusions

Considerable differences among the reported data of biodynamic responses of the human hand–arm system are observed. Some of the reported data are obviously questionable. We believe that a significant portion of these differences are likely the result of instrumentation and data processing problems. The results of this study confirmed that inappropriate instrumentation and insufficient mass cancellation are among the major sources of error in the BR measurement. The use of the methods demonstrated in this study for instrumentation calibration and evaluation can help identify and correct many potential problems, improve the design of handle–fixture structures, and debug data errors. Hence, this study may help establish a reliable and accurate methodology for future BR measurement.

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