Establishment of One-axis Vibration Test System for Measurement of Biodynamic Response of Human Hand-arm System

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Abstract: Prolonged exposure to hand-arm vibration (HAV) due to use of hand-held power tools leads to an increased occurrence of symptoms of disorders in the vascular, neurological, and osteo-articular systems of the upper limbs called hand-arm vibration syndrome (HAVS). Biodynamic responses of the hand-arm system to vibration can be suggestive parameters that give us better assessment of exposure to HAV and fundamental data for design of low-vibration-exposure power tools. Recently, a single axis hand-arm vibration system has been installed in the Japan National Institute of Occupational Safety and Health (NIOSH). The aims of this study were to obtain the fundamental dynamic characteristics of an instrumented handle and to validate the performance and measurement accuracy of the system applied to dynamic response measurement. A pseudo-random vibration signal with a frequency range of 5–1,250 Hz and a power spectrum density of 1.0 (m/s²)²/Hz was used in this study. First the dynamic response of the instrumented handle without any weight was measured. After this measurement, the dynamic response measurement of the handle with weights mounted on the handle was performed. The apparent mass of a weight itself was obtained by using the mass cancellation method. The mass of the measuring cap on the instrumented handle was well compensated by using the mass cancellation method. Based on the 10% error tolerance, this handle can reliably measure the dynamic response represented by an apparent mass with a minimum weight of 2.0 g in a frequency range of 10.0 to 1,000 Hz. A marked increase in the AM magnitude of the weights of 15 g and 20 g in frequency ranges greater than 800 Hz is attributed not to the fundamental resonance frequency of the handle with weights, but to the fixation of the weight to the measuring cap. In this aspect, the peak of the AM magnitude can be reduced and hence should not be an obstacle to the biodynamic response measurement of the human hand-arm system. On the basis of the results obtained in this study, we conclude that this hand-arm vibration test system can be used to measure biodynamic response parameters of the human hand-arm system.

Key words: Single-axis vibration, Hand-arm vibration, Dynamic response, Apparent mass, ISO10068

Introduction

Biodynamic response (BR) parameters represented by apparent mass, mechanical impedance, apparent stiffness, etc. are effective indicators that describe the dynamic mechanical behavior arising in response to exposures to hand-transmitted vibration (HTV) in the human hand-arm system. Particularly, the mechanical impedance of the hand-arm system can be used as an effective parameter in estimation of vibration power transmission and absorption¹), and in the design of low-vibrating hand-held power tools²–⁴). Also, the mechanical impedance can be useful
in performing vibration transmissibility analyses of anti-vibration gloves\textsuperscript{5, 6}. The mechanical impedance has been recognized as one of the important factors for the better understanding of the vibration transmission behavior of the hand-arm system. In order to use this dynamic parameter as a potential indicator that estimates and predicts the health effects of HTV, research will have to elucidate the relationship between this parameter and the health effects of HTV.

There exist in the literature many sets of data on mechanical impedance of the hand-arm system, which show considerable differences with each other\textsuperscript{7, 8}. Indeed several data sets of the free mechanical impedance of the human hand-arm system at the driving point have been summarized in the international standard ISO 10068\textsuperscript{9,10}, and they considerably differ from each other even if measured under similar experimental conditions. Many of the differences reported among the mechanical impedances of the hand-arm system have arisen from imperfect control of experimental conditions, such as coupling force, individual posture differences, and vibration directions. However, the most fundamental and important problem to be considered for a better understanding of these differences observed in measures of the mechanical impedance of the hand-arm system, is the system instrumentation and algorithms for calculating the mechanical impedance. In this respect, it is essential to carefully examine the measurement system and minimize any potential problem that might cause serious and unacceptable errors in the measured data.

Recently a single-axis hand-arm vibration test system has been installed in the Japan National Institute of Occupational Safety and Health (NIOSH). This vibration test system can generate random and sinusoidal vibration along a single axis in frequencies up to 2,000 Hz, a range that fully covers the frequency range of 10 to 500 Hz required in the international standard ISO10068. If this hand-arm vibration test system can be applied with reliability to BR measurement of the human hand-arm system, BR data obtained by using this measurement system with the Japanese population under a set of representative work conditions will be a noteworthy contribution to revision of ISO10068. Thus, a thorough examination of the dynamic behavior of the measurement and test systems is the foremost task in the validation of the reliability of the measurement and the analysis of biodynamic responses.

The aims of this study were (1) to examine the dynamic behavior of the instrumented handle and the measurement accuracy of the test system, (2) to validate the mass cancellation method used in this study to obtain dynamic response parameters, and (3) to examine the feasibility of using this test system for BR measurement of the human hand-arm system.

**Experimental Methods**

**Experimental apparatus**

Figure 1 shows the schematic signal flow diagram of the single-axis hand-arm vibration test system installed in the Japan NIOSH. An electro-dynamic shaker (VE-100S; IMV Corporation, Osaka, Japan) was set up to generate vibration along the \(Z_h\) direction.

An instrumented handle was fabricated following the design proposed by Dong et al.\textsuperscript{10} of the US NIOSH laboratory. The handle has a circular cross-section a diameter of 40 mm and an effective grip length of 100 mm, and it was connected to the shaker shaft so that the centerline axis of the handle is vertically oriented. This handle consists of the handle base and measuring cap, between which two piezoelectric single-axis force sensors (9212; Kistler Inc., Winterthur, Switzerland) are sandwiched along the centerline of the handle to measure the force acting between the base and measuring cap. Signals from these two force sensors are passed through a low-pass filter with a cut-off frequency of 5 Hz and are then summed up to obtain the total force acting on the measuring cap. Also an accelerometer (356A12; PCB Piezotronics, Inc., New York, USA) is secured to the center of the measuring cap to measure the vibratory acceleration of the handle in the \(Z_h\) direction.

**Dynamic response parameters**

Apparent mass is one the parameters that describe the dynamic responses (DR) of a mechanical system, and it can be defined as a function of the angular velocity \(\omega\) in the frequency domain. The apparent mass \(AM(\omega)\) is defined as follows:

\[
AM(\omega) = F(\omega)/A(\omega) \tag{1}
\]

In Eq.(1), \(F(\omega)\) and \(A(\omega)\) are the dynamic force and acceleration expressed in the complex frequency-domain, which are the parameters measured during experiments. Under random vibration, the \(AM(\omega)\) can be calculated by using the following equation:

\[
AM(\omega) = \frac{G_{fm}(\omega)}{G_{mm}(\omega)} \tag{2}
\]

where \(G_{fm}(\omega)\) denotes the cross-spectrum of force and acceleration and \(G_{mm}(\omega)\) the auto-spectrum of acceleration.

The apparent mass directly measured with an additional mass attached to the handle corresponds to the sum of the apparent mass of the handle itself and that of the added mass. The apparent mass due to the added mass is calculated based on the mass cancellation method pro-
posed by Dong et al.\textsuperscript{11}). Specifically, the apparent mass due to an additional mass $AM_w(\omega)$ can be obtained by subtracting the apparent mass of the handle $AM_{\text{handle}}(\omega)$ from the total apparent mass for the handle with the weight $AM_{\text{total}}(\omega)$:\textsuperscript{11)}

$$AM_w(\omega) = AM_{\text{total}}(\omega) - AM_{\text{handle}}(\omega) \quad (3)$$

Experimental procedure

The vibration signal used in this study was a pseudo-random vibration in the frequency range of 10 to 1,250 Hz with a flat power spectrum density (PSD) of 1.0 $(\text{m/s}^2)^2/\text{Hz}$, which corresponds to an acceleration magnitude of 35 m/s$^2$ (r.m.s.).

The dynamic force and acceleration in the $Z_h$ direction were measured at the measuring cap of the handle. The data gathering was performed with a data acquisition system (Type3109; Brüel & Kjær; Nærum, Denmark).

Prior to the experiments, preliminary measurements were performed to obtain the apparent mass of the handle without the additional mass. After these preliminary measurements, small pieces of metal were sequentially attached to the surface of the measuring cap with an adhesive tape and then the apparent mass of the handle with weights was measured. Eight pieces of metal with weights of 1, 2, 3, 4, 5, 10, 15, and 20 g respectively were used in this study.

Results

Figure 2 shows the AM magnitude and the AM phase responses measured for the instrumented handle without the weights. The AM magnitude of the handle showed good agreement with the real handle mass of 101.6 g. Differences between the AM magnitude and the real handle mass were less than 3% of the real mass at every one-third octave band center frequency. The AM phase angle of the handle was nearly zero throughout the entire vibration frequency range; the average and standard deviation of the AM phase angle were $-0.091$ and $\pm 0.129$ degrees, respectively.

Figure 3 shows the AM magnitude and the AM phase angle measured for each weight mounted on the measuring cap. The AM magnitude of each weight showed good agreement with the actual mass of the weight in the frequency range of 10–800 Hz. In contrast, at frequencies greater than 800 Hz, the compensated AM magnitude of the weight was greater than the real mass of the weight. With an increase in the additional mass attached to the handle, this tendency was more evident. Except for some small discrepancies observed in the case of the AM phase angle of 1 g and 20 g additional masses, the AM phase angle of each weight was nearly zero degrees in the frequency range of 10–800 Hz. In contrast, the AM phase angle of each weight showed negative values up to $-11.3$ degrees at frequencies greater than 800 Hz.
Errors obtained by subtracting the real mass of each weight from the AM magnitude are shown as a function of frequency in Fig. 4. At frequencies less than 800 Hz, the maximum measurement error was 1.2 g observed for a weight of 20 g at 500 Hz. In contrast, in the frequency range of 800–1,000 Hz, the maximum measurement error was 3.9 g was observed for a mass of 20 g at 1,000 Hz. The maximum error was 25.1%, for a low mass of 1 g at 10 Hz. The maximum error for the remaining masses was less than 10%.

Discussion

The reliability and measurement accuracy of the instrumented handle secured to a single-axis hand-arm vibration test system was verified for applications in dynamic response measurement. The AM magnitude of the handle without weights showed fairly good agreement with the real mass of the handle within an error of ± 3% in the frequency range of 10–1,000 Hz. The AM phase angle obtained was nearly zero with a standard deviation of ± 0.129 degrees in the same frequency range. Ideally, the AM magnitude of the handle should coincide with the real handle mass while the AM phase angle of the handle should be zero, and our results suggest that the instrumented handle, including the mountings of the measuring cap, force sensors, and the accelerometer, will accurately measure the dynamic response in the 10–1,000 Hz fre-
quency range.

The mass effects of the instrumented handle were successfully cancelled by using the mass cancellation method. The effectiveness of the measurement system and the mass cancellation algorithm were further validated through measurements of small additional masses in the range of 1 to 20 g. The AM magnitude of each weight mounted on the measuring cap was observed to be fairly consistent with the real mass of each additional weight in the frequency range of 10–800 Hz. In contrast the AM magnitude of the unweighted handle increased with increase in vibration frequency resulting in overestimation of the handle mass at frequencies higher than 160 Hz, and underestimation of the handle mass at frequencies below 160 Hz. The maximum error was observed to be less than 10% for masses greater than 2.0 g. Therefore these results suggest that, based on a 10% error tolerance, the instrumented handle can reliably measure the dynamic responses represented by apparent masses greater than 2.0 g in the entire frequency range considered in this study.

A marked increase in the AM magnitude at frequencies greater than 800 Hz was observed to occur with higher added masses. In the preliminary experiments performed to examine the dynamic behavior of the handle, the fundamental resonance frequency of the handle without any coupling was observed to be approximately 1,450 Hz. In contrast, the handle coupled with the human hand fingers showed a lower fundamental resonance frequency, approx. 1,415 Hz. The total weight of the fingers excluding the thumb being approximately 220 g, the fundamental resonance frequency of the handle with weights of 15 g or 20 g mounted on the handle ought to be reduced to somewhere between 1,450 and 1,415 Hz. Thus we stress that the increased AM magnitude observed, particularly for weights of 15 g and 20 g, at frequencies greater than 800 Hz is attributable to other potential reasons.

One possible reason for the increase in the AM magnitude of weights of 15 g and 20 g observed at frequencies greater than 800 Hz is related to the fixation of the weights to the measuring cap. In this respect, the error is not expected to contribute to errors in the biodynamic response measurements of the human hand-arm system.

(3) On the basis of the results obtained in this study, this hand-arm vibration test system can be effectively used to measure biodynamic response parameters of the human hand-arm system under single-axis vibration.

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References


