11TH INTERNATIONAL CONFERENCE ON HAND-ARM VIBRATION

HOW TO ACCURATELY MEASURE BIODYNAMIC RESPONSES OF THE HAND-ARM SYSTEM

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Abstract

The biodynamics of the hand-arm system is an important part of the foundation for understanding hand-transmitted vibration exposure and its health effects. The objective of this study is to determine how the biodynamic response (BR) can be accurately measured. A modelling analysis of typical BR measurement systems coupled with a hand-arm system was performed. A new model of the hand-arm system was used. The flexibility of the handle and its fixture mounting were taken into account. This study found that the locations of the force sensors and accelerometer in the instrumented handle are critical to assuring the accuracy of the measurement. To increase the accuracy of the measurement at high frequencies, it is essential to maximize the stiffness of the instrumented handle.

1. Introduction

The biodynamics of the hand-arm system are an important part of the foundation for understanding hand-transmitted vibration exposure and its health effects [1, 2]. Reliable and accurate biodynamic data are required for understanding the biodynamics and conducting further analyses and applications. Dong et al. [3, 4] examined many sets of the reported driving-point biodynamic data and found that some of them are questionable or unrealistic. For example, some of the reported data imply that human hands or fingers subjected to high frequency vibration (>100 Hz) could behave like rigid bodies, that the hand-arm system may not exhibit resonance at frequencies up to or even beyond 100 Hz, or that the imaginary part of the apparent mass measured on a single hand could be close to or more than the entire body mass of the subject participating in the measurement. These physically unlikely implications suggest that there may be lack of a comprehensive understanding of biodynamic measurement processes.

As also indicated by Dong et al. [3, 4], some of the errant data and the computer models constructed using such data are included in ISO 10068 (1998) [5]. Other major problems with this standard include (i) none of the models included in this standard provide a reasonable simulation of the structure of the hand-arm system [6], and (ii) some of the models do not fit the experimental data [6]; this casts doubt on the optimization method used to determine the model parameters. These observations suggest that this standard needs some major revisions. To facilitate the revisions, it will be require that more reliable experimental data are generated. To generate such data, it is necessary to have a comprehensive understanding of the biodynamic measurement processes.

Dong et al. [3] have also conducted an experimental study to identify the major sources of the measurement errors. They found that at low frequencies (<25 Hz), significant measurement errors could stem from the phase difference between the accelerometer signal and the force sensor signal. Dynamic forces resulting from non-vibration-induced motions of the hand and arm could also cause large measurement errors in the low frequency range. This is because the input vibration magnitude could be very low at frequencies less than 10 Hz, and the vibration-induced dynamic force could be lower than the noise level [7]. At high frequencies (>100 Hz), major errors result from inappropriate or inaccurate cancellation of the handle mass [3]. At any frequency, significant rotation motions of the handle or non-uniform distribution of vibration may also result in large measurement errors. In such cases, the response at one part of the hand could cancel the response from another part of the hand; the summed response may not provide an accurate representation of the true response.

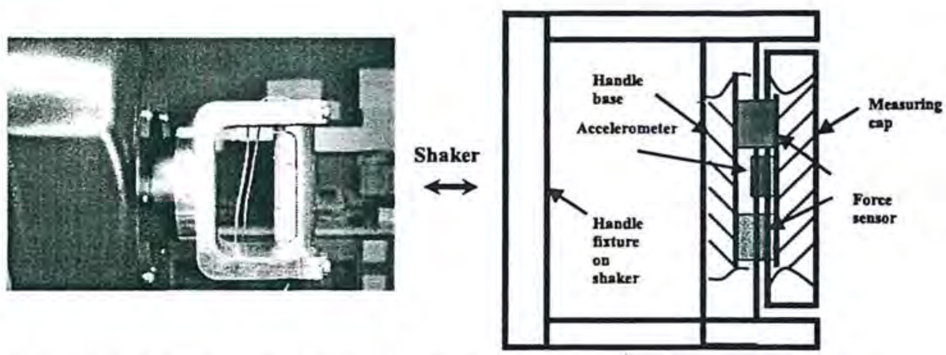
Whereas several practical methods have been proposed to identify and resolve these potential problems, some phenomena observed in the reported studies are not sufficiently understood [3]. For example, it was noticed that the accelerometer position could significantly affect the results. The accelerometer has been installed at different positions in many reported studies. It is very important to find which positions can provide the best measurements. It was also reported that a calibration mass attached to the handle can be reliably detected at frequencies close to the handle resonance point. If this can be verified, the currently established limitations of the measurement frequency range may be relaxed. It has also been reported that the hand coupling could significantly reduce the handle natural frequency and resonant magnitude. It remains an issue whether such influences could affect measurement accuracy. It is necessary to measure and control the grip force during BR measurement. A split instrumented handle is usually used for such a purpose. No modelling analysis has been reported as to how the dynamic response of the split handle could affect BR measurement accuracy. Furthermore, the handle could exhibit a significant bending motion at high frequencies. It is also unclear how such bending motions could affect the measurement.

Therefore, the objectives of this study are to conduct a modelling analysis of a typical measurement system, to discuss the above-mentioned issues or questions, and to determine how the biodynamic response can be accurately measured.

2. Methods

Figure 1 shows a typical 1-D system used for measuring the driving-point biodynamic response of the hand-arm system exposed to vibration in one direction. As shown in figure 1b, the instrumented handle is composed of a measuring cap, a handle base, two force sensors sandwiched between the measuring cap and the base, and an accelerometer fixed on the measuring cap. The handle is fixed on the handle fixture that is connected to a shaker.

Figure 2 shows various sensor positions that have been used in the reported studies [e.g., 3,8,9]. Figure 3 shows the model of the device used in the analysis. The handle base, measuring cap, and fixture are assumed to be rigid. The flexibility and damping of the system are lumped to the connection points of the force sensors, and they are represented using linear spring and viscous damping elements.



(a) A pictorial view of the device (b) Configurations of instrumented handle

Figure 1 - A device used to measure the biodynamic response of hand-arm system (Notes: the handle can be installed in the fixture at any desired angular position. The measuring cap in (a) is used to measure the response at the fingers. At the position shown in (b), the response at the palm is measured. The total response of the hand-arm system is the summation of these responses [3, 10, 11]).

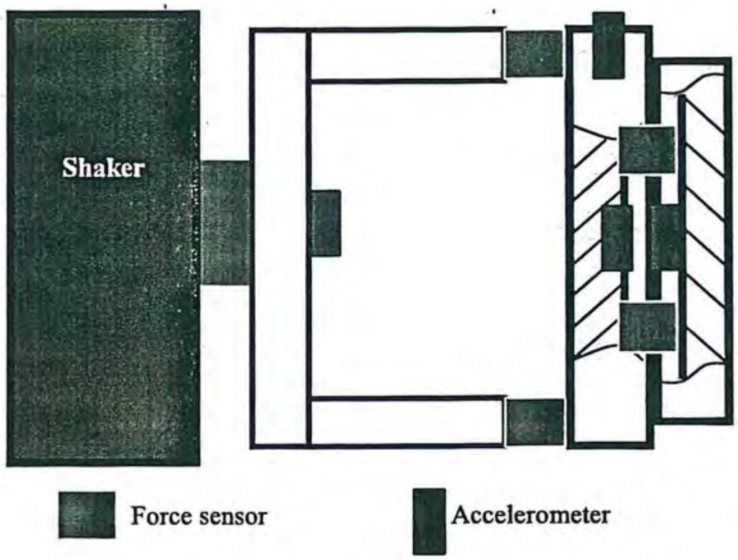


Figure 2 - Possible positions of the force and motion sensors for the measurement

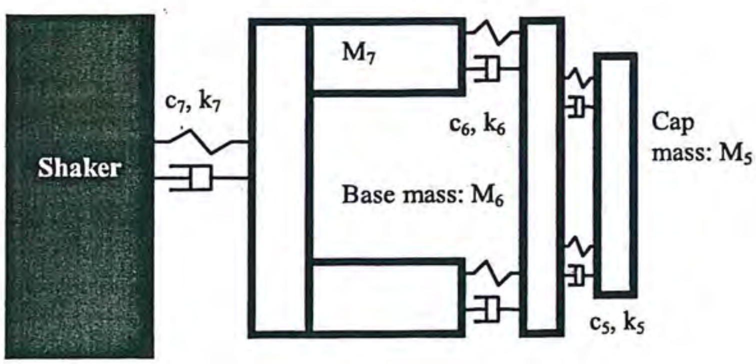


Figure 3 - A lumped parameter model of the measurement device

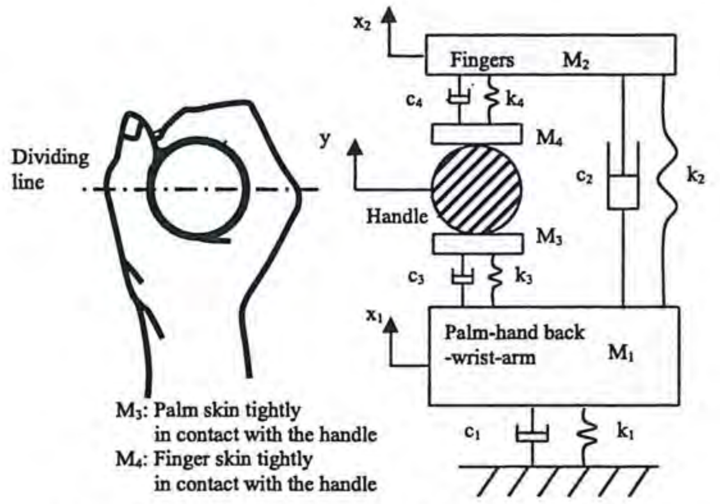


Figure 4 - A 4-DOF model of the hand-arm system [11]

Figure 4 shows a 4-DOF model developed by Dong et al. [11]. The model parameters determined from the experimental data measured under a combined action of 50 N grip and 50 N push are used in this study [11]. Assembling this model with the device model shown in figure 3, we obtain the combined system model shown in figure 5.

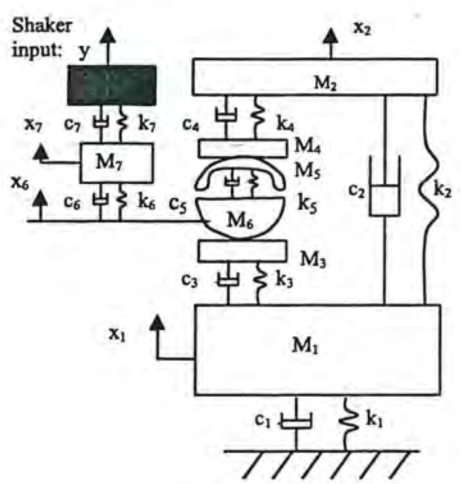


Figure 5 - A model of the measurement device coupled with a hand-arm system

The equations of motion of the model subjected to shaker excitation y(t) are expressed in the matrix form as:

$$[M]\{\ddot{q}\}+[C]\{\dot{q}\}+[K]\{q\}=\{F\} \tag{1}$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{F\}$ is the force vector and $\{q\}$ represents the vector response coordinates. The parameters of the model are listed in table 1.

Table 1 - Model parameters

Parameter	Value (kg)	Parameter	Value (N/m)	Parameter	Value (N·s/m)
M1	1.414	k1	4,206	c1	86
M2	0.082	k2	6,523	c2	38
M3	0.027	k3	58,555	c3	118
M4	0.014	k4	207,964	c4	121
M5	0.105	k5	8,739,413	c5	19
M6	0.240	k6	34,957,652	c6	19
M7	1.200	K7	100,000,000	c7	100

The equations of motion are solved to derive biodynamic forces acting at the connection points and the accelerations of mass elements of the model. Then, the mechanical impedance (Z_{ik}) is calculated using the force at i^{th} point (F_i) and the acceleration of the k^{th} part (A_k) is calculated from:

$$Z_{ik}(j\omega)=F_i(j\omega)/V_k(j\omega)=F_i(j\omega)\cdot j\omega/A_k(j\omega) \tag{2}$$

where $j=\sqrt{-1}$, and ω is the excitation frequency. The impedance values were calculated using the forces and accelerations measured at different locations. The mass cancellation process [3] was also included in the simulation.

3. Results and Interpretations

3.1 Simulation of measuring cap method

In the studies reported by Dong et al. [e.g., 3, 10], the biodynamic response was measured using the measuring cap method shown in figure 1. This method was simulated in this study. For comparison, the 'accurate' solution is shown in figure 6, which is the mechanical impedance of the entire hand-arm system directly calculated from the model shown in figure 4 [10]. When the dynamic force (F_5) on c_5 and k_5 and the acceleration (A_5) of M_5 are used, the simulated response is almost identical to the accurate solution shown in figure 6. The theoretical basis is explained as follows.

For the model shown in figure 5 (with fingers positioned on the measuring cap and the palm on the handle base), the accurate response (Z_{Hand}) can be calculated from:

$$Z_{Hand} = Z_{Fingers} + Z_{Palm} = (F_4 / A_5 + M_4) j\omega + (F_3 / A_6 + M_3) j\omega \tag{3}$$

where F_4 is the dynamic force on c_4 and k_4, F_3 is the dynamic force on c_3 and k_3, and A_6 is the acceleration of M_6.

Alternatively, the accurate response at the fingers can be calculated from

$$\begin{aligned} Z_{Fingers} &= (F_5 / A_5 - M_{5\_Uncoupled}) j\omega = [(M_5 A_5 + M_4 A_5 + F_4) / A_5 - M_{5\_Uncoupled}] j\omega \\ &= [M_5 + (M_4 + F_4 / A_5) - M_{5\_Uncoupled}] j\omega = (F_4 / A_5 + M_4) j\omega \end{aligned} \tag{4}$$

where $M_{5\text{-}uncoupled}$ is measured in an uncoupled handle test (with no hand coupled to the handle).

In the method proposed by Dong et al. [3, 10], F_5 is directly measured using a force sensor sandwiched between the measuring cap and the handle base, and A_5 is measured using the accelerometer fixed on the measuring cap, as shown in figure 1. Although the acceleration and force acting on M_5 may vary with and without hand coupling, the cap mass value can be considered constant if it is sufficiently rigid in the frequency range of concern. Therefore, the measuring cap method can be considered accurate, as demonstrated in equation 4.

Similarly, when the palm is positioned on the measuring cap, the accurate response at the palm can be calculated from

$$Z_{Palm} = (F_5 / A_5 - M_{5\_Uncoupled}) j\omega = (F_3 / A_5 + M_3) j\omega \tag{5}$$

The only difference between the calculation of Z_{Palm} in equation 3 and that in equation 5 is that while A_6 is used in equation 3, A_5 is used in equation 5. The difference between A_5 and A_6 depends on the handle system parameters. With the parameters listed in table 1, their difference is less than 5% at frequencies below 100 Hz. At higher frequencies, the response at the fingers is practically independent to that of the palm [10] and F_3/A_6 can be considered to be equal to F_3/A_5. This is because the variation of F_3 can be considered to be proportional to A_6 in the linear hand-arm system model if the response at the fingers is independent of that at the palm. Therefore, the summation of the response at the fingers expressed in equation 5 and the response at the palm expressed in equation 6 is equivalent to that expressed in equation 3. This is the theoretical foundation of the method proposed by Dong et al [3, 10].

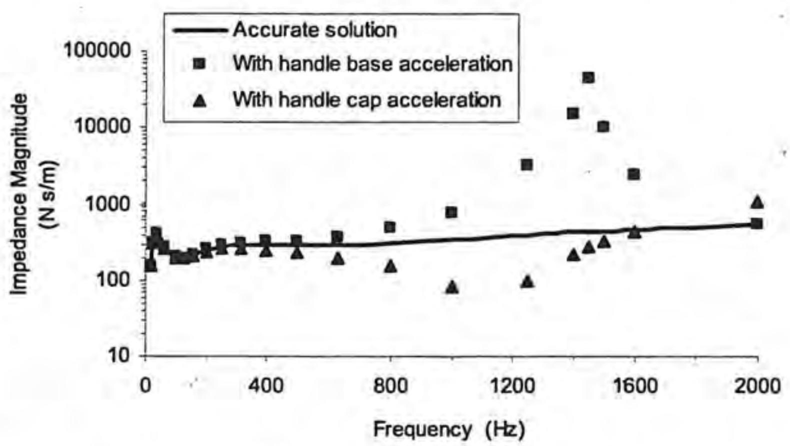


Figure 6 - Comparisons of the hand impedance functions that could be obtained with three different measurement methods

3.2 Simulations of the total response measurement methods

In the majority of the reported studies [e.g., 8, 9], the response of the entire hand-arm system was directly measured using the force measured at the location of c_6 and k_6, and the motion at M_6 or M_5. As shown in figure 6, when the handle base acceleration (A_6) and the dynamic force (F_6) are used to evaluate the response, the impedance magnitude is generally greater than that of the accurate solution. When F_6 and A_5 are used, the measured response is generally less than that of the accurate solution. In both cases, the errors are less than 5% at frequencies below 250 Hz. However, at higher frequencies, the errors become unacceptable.

4. Discussion and Conclusions

The modelling results indicate that as long as the measured vibration is truly representative of the vibration input to the hand-arm system, and the measured dynamic force directly tracks the measured vibration, the measured BR will be theoretically accurate. Hence, these conditions can be used as criteria to evaluate any driving-point biodynamic measurement system.

In many reported studies, the accelerometer was installed on the handle base or one part of the split handle. In principle, the data measured with such a method always exhibit some errors because the vibration at one part of the handle could be greatly different from that at the other part when the frequency increases to a certain point. These errors may be negligible up to a certain frequency, which depends on the stiffness of the handle cap-base connection. The BR evaluation method developed by Dong et al. [3,10] avoids this issue by directly using the cap acceleration and the dynamic force measured at the cap-base connection point (c_5 and k_5) that tracks the measured cap vibration. The results of this study suggest that this is a theoretically valid method. The results also suggest that such a method is applicable even at the fundamental resonant frequency of the handle; this is consistent with the previously reported experimental results [3]. This method is limited by potential bending of the measuring cap. The model used in the present study is based on the assumption that the vibration is sufficiently uniformly distributed on the cap. This assumption may not hold true at very high frequencies (e.g., >1,500 Hz) [3]. Therefore, increasing the bending stiffness of the handle can further increase the applicable frequency range. For a general application, it is suggested to examine the vibration distribution on the cap and base before applying this method for measuring the BR at very high frequencies.

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