11TH INTERNATIONAL CONFERENCE ON HAND-ARM VIBRATION

A PRELIMINARY STUDY OF CROSS-AXIS COUPLING EFFECTS IN BIODYNAMIC RESPONSE OF THE HAND-ARM SYSTEM

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Abstract

Direct and cross-axes driving-point impedance characteristics of the human hand-arm were measured in the laboratory using a three-axes vibration exciter. The measured data were analyzed to derive the cross-axes components of the impedance and thus the coupling effects in responses of the hand-arm system subject to vibration along different individual axes. The measurements were also performed under simultaneous applications of vibration along all three axes. This preliminary study describes the coupling effects in the biodynamic force measured at the driving-point using the data acquired with three subjects. Results suggest appreciable coupling in forces measured along the x_h and z_h-axis, but relatively small coupling was observed in forces along the x_h and y_h-axes.

1. Introduction

Power tools are known to transmit vibration along all three translational axes, and along the rotational axes in many cases. Owing to its elastic and viscous properties along all the translational and rotational axes, the human hand-arm system responds to such multi-axes vibration in a highly complex manner. The magnitudes of vibration transmitted along the translational axis are generally believed to be more important than the rotational components. Stelling and Dupuis [1] investigated different strain parameters of the hand-arm exposed to single and multi-axes vibration, and concluded that the vector sum of vibration measured along the three axes represents a better measure of the exposure dosage than that based upon the single dominant-axis vibration. The revised exposure assessment standard, ISO-5349-1 [2], also requires consideration of vibration exposure along all the three translational directions.

The human hand-arm responses to vibration, however, have been invariably characterized under vibration along a single axis [3-7]. Such responses, expressed in terms of driving-point mechanical impedance, absorbed power and vibration transmitted to different segments of the hand-arm systems, assume negligible contributions due to dynamic coupling between responses to vibration along different axes. The measured data have been applied for developing mechanical-equivalent models of the hand-arm system [8], which can be considered to characterize uncoupled responses of the hand-arm system to single-axis vibration, while neglecting the cross-axis coupling effects. Owing to the important components of tools vibration along all the translational axes, it would be highly desirable to investigate the physical responses of the hand-arm to multi-axes vibration. The lack of such efforts is in-part attributed to technical complexities associated with developing a multi-axes laboratory-based vibration test system capable of replicating tool vibration spectra, and partly due to complexities associated with characterization of the responses of the hand-arm system.

Advances in control technology have evolved into design of controllers and multi-axes vibration equalizers for realization of a laboratory-based multi-axes vibration exciter. A three-axes vibration exciter has been recently developed for studies on human hand-arm responses to vibration applied simultaneously along the three translational axes [9]. In this study, the three-axes vibration exciter is used for exploring the biodynamic responses of the hand-arm system exposed to simultaneous vibration along the x_h, y_h and z_h-axis. The data attained in the preliminary study are analyzed to determine the cross-axis coupling effects in biodynamic responses.

2. Materials and Methods

2.1 Three-Axes Vibration Test System

Experiments were performed using the recently developed 3-D vibration test system available in the NIOSH laboratory [9]. The test system comprises three electro-dynamic vibration exciters oriented along three translational axes that are coupled to a vibration platform through flexible links, as shown in figure 1. The platform and the links were designed to provide flat frequency response up to frequencies above 500 Hz. The test system is capable of generating random vibration of magnitude up 10 g rms acceleration with peak displacement of 12.7 mm along each axis simultaneously. The test system is driven by an integrated multi-axes vibration controller that provides desired equalization of vibration signal along each axis using the feedback from the three-axis accelerometer signal mounted on the platform. The equalization also incorporates the cross-talk between the different axes. An instrumented handle comprising three-axes force and acceleration sensors is installed on the vibration platform. The handle could be oriented to measure the forces imparted by the fingers, palm or the combination of the two, while the push force imparted by the hand is measured using a force platform.

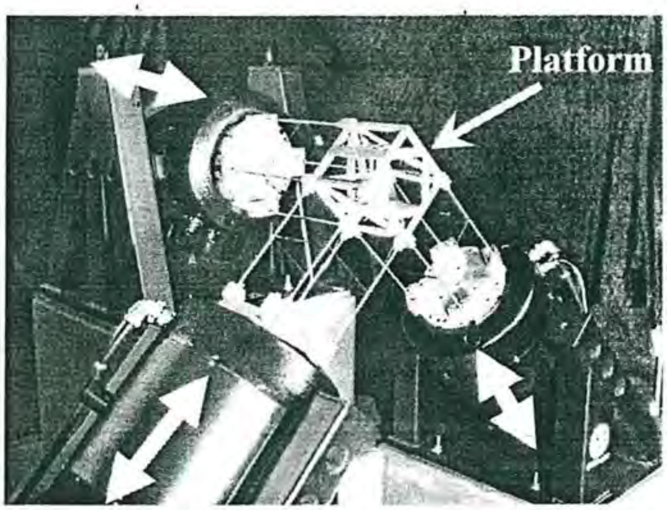

Figure 1 - A pictorial view of the test system

2.2 Measurements and Data Analysis

In this preliminary study, two series of experiments were undertaken using three adult male subjects, while the handle was configured to measure the biodynamic forces due to palm alone. Owing to relatively small contributions of the fingers to the overall biodynamic force developed at the hand-handle interface at frequencies less than 100 Hz, the measured data are considered to adequately provide the coupling effects in the biodynamic responses of the hand-arm system in this frequency range and the responses of the palm-wrist-arm system at higher frequencies. The first series involved measurements of mechanical impedance responses of the hand-arm system exposed to broad-band random vibration (magnitude: 2.5 m/s^2; frequency range: 10-500 Hz) along each individual axis, while the vibration along the non-vibration axes was limited to only 5% to ensure stable operation of the equalizer and controller. Figure 2, as an example illustrates the spectra of rms accelerations measured at the platform, when the vibration is applied along the z_h-axis.

The measured force and acceleration data during each trial were acquired in a multi-channel signal analyzer. Each trial was repeated 3 times and the mean responses were used to study the cross-axes coupling effects of multi-axes vibration. The data acquired under single-axis vibration were analyzed to derive the direct and cross-axis components of the driving-point mechanical impedance (DPMI). The inertia corrected direct- and cross-axis DPMI components could be applied to formulate the (3x3) impedance matrix relating the biodynamic force vector to the vibration velocity vector, such that:

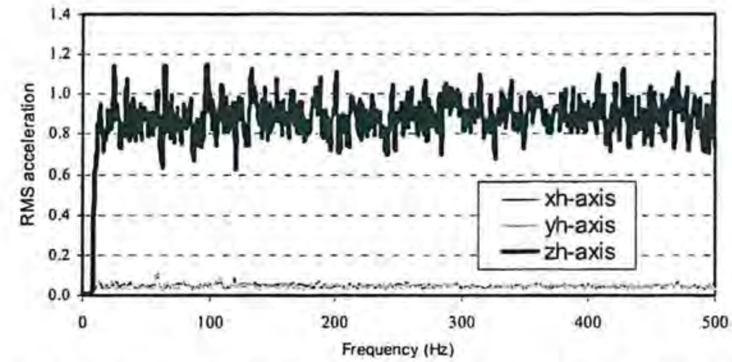

Figure 2 - Rms spectra of acceleration measured along 3-axes under z_h-axis excitation

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} & Z_{xz} \\ Z_{yx} & Z_{yy} & Z_{yz} \\ Z_{zx} & Z_{zy} & Z_{zz} \end{bmatrix} \begin{Bmatrix} \dot{x}_h \\ \dot{y}_h \\ \dot{z}_h \end{Bmatrix} \tag{1}$$

In the above equation, element Z_{ij} refers to impedance or ratio of cross-spectral density of biodynamic force measured along axis i (F_i) and velocity $\dot{x}_j$ due to vibration along axis j to the auto-spectral density of velocity $\dot{x}_j$. The element Z_{ij} is referred to as cross-axis impedance, when $i \neq j$, and represents the coupling effects. The diagonal terms Z_{ij} ($i=j$) are the direct DPMI components corresponding to each axis of vibration, which have been generally reported in the literature.

The above equation suggests that the total biodynamic force developed along a particular axis at the driving-point is the sum of forces caused by the direct and cross-axis DPMI impedance components. The second series of experiments involved measurements under simultaneous applications of vibration of identical magnitude along all the three-axes. The data acquired during the second series of experiments could be analyzed to derive the total biodynamic force developed under three-axis vibration. The results attained from the first series of experiment alone, however, are presented in the following section to illustrate the cross-axes impedance responses and thus the coupling effects.

3. Results and Discussion

Figure 3 illustrates the mean magnitudes of measured direct as well as cross axis impedance components of the hand-arm system. The figure shows the magnitudes of impedance components, described in equation 1, measured under broad-band vibration along x_h, y_h and z_h-axis, respectively. The results clearly suggest appreciable magnitudes of some of the cross-axes components. Stronger coupling between responses along the x_h and z_h, and y_h and z_h directions could be clearly seen under each axis of vibration. Under x_h-axis vibration, the mean magnitude of direct component of impedance Z_{xx} peaks near 40 and 140 Hz. The magnitude of cross-axis component, Z_{xz}, also exhibits peaks near the same frequencies, while its magnitude is comparable to that of Z_{xx} around the primary peak near 40 Hz. While the primary peak in Z_{xy} occurs at a higher frequency near 57 Hz, its magnitude is considerably smaller compared to that of Z_{xx} in the entire frequency range, suggesting weaker coupling between responses along y_h and x_h directions. The results suggest stronger coupling between the responses along the x_h and z_h directions at lower frequencies, where predominant motions of the hand-arm structure occur. This coupling weakens considerably at higher frequencies, as the vibration becomes more localized within the hand. This is also evident from the rms spectra of mean measured force components under x_h-axis vibration, as illustrated in figure 4(a).

The mean magnitude of direct impedance component (Z_{yy}) under y_h-axis vibration also exhibits primary peak near 57 Hz, as seen in figure 3(b). The cross-axis component Z_{yz} response exhibits similar variations with frequency in the entire frequency range, although its magnitude is relatively lower. This suggests stronger coupling between the responses along y_h and z_h directions under vibration along y_h-axis, particularly at frequencies below 100 Hz, where predominant motions of the hand-arm structure occur. This is also evident from the spectra of measured forces shown in figure 4(b). This coupling weakens considerably at higher frequencies, as the vibration becomes more localized within the hand.

The mean magnitude of Z_{zz} obtained under z_h-axis vibration exhibits peaks near 40 and 180 Hz, as shown in figure 3(c), which are consistent with those reported in many published studies. The magnitude of Z_{zy}, however, peaks near 57 Hz, as observed for the direct impedance component of Z_{yy} in figure 3(b). The magnitudes of both cross axis impedance components (Z_{zx} and Z_{zy}) under this axis of vibration are appreciable, although considerably small compared to that of Z_{zz}. The rms spectra of mean measured forces shown in figure 4(c) also reveal considerably smaller magnitudes of components along the directions.

4. Conclusions

Experiments were performed to characterize cross-axis components of the driving-point mechanical impedance response of the hand-arm system exposed to vibration along the x_h, y_h and z_h-axes. The results attained from this preliminary study suggest strong couplings between responses along the x_h and z_h, and y_h and z_h directions, while relatively weaker coupling between responses along x_h and y_h directions were observed. Stronger coupling between the measured forces was clearly evident only at lower frequencies associated with predominant motions of the hand-arm structure. This coupling weakens considerably at higher frequencies, as the hand decouples from the hand-arm structure. The coupling effects appear to be asymmetric ($Z_{xz} \neq Z_{zx}$; and $Z_{yz} \neq Z_{zy}$), which suggests the likely nonlinear biodynamic responses of the hand-arm system under multi-axes vibration.

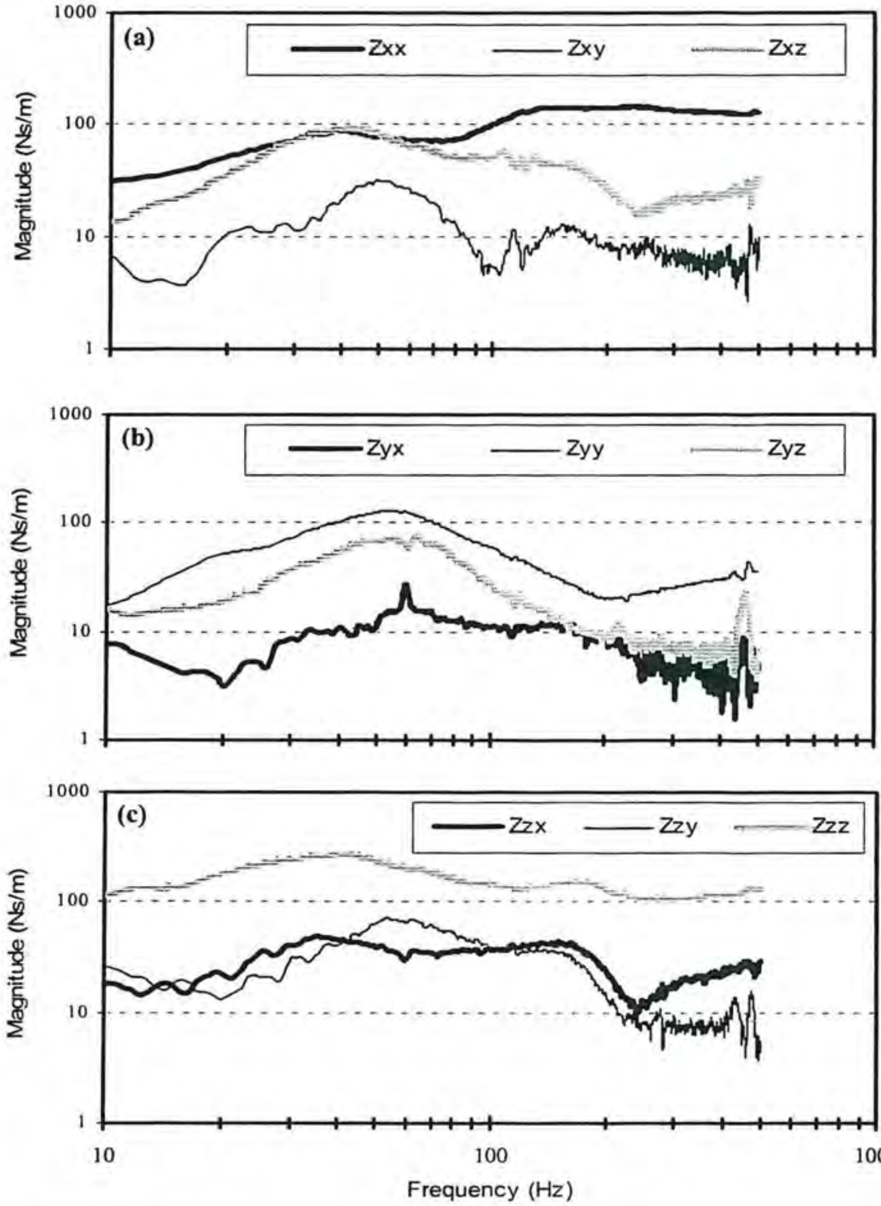

Figure 3 - Mean magnitudes of direct and cross-axis components of driving-point mechanical impedance response to vibration along: (a) x_h-; (b) y_h- and (c) z_h-axis.

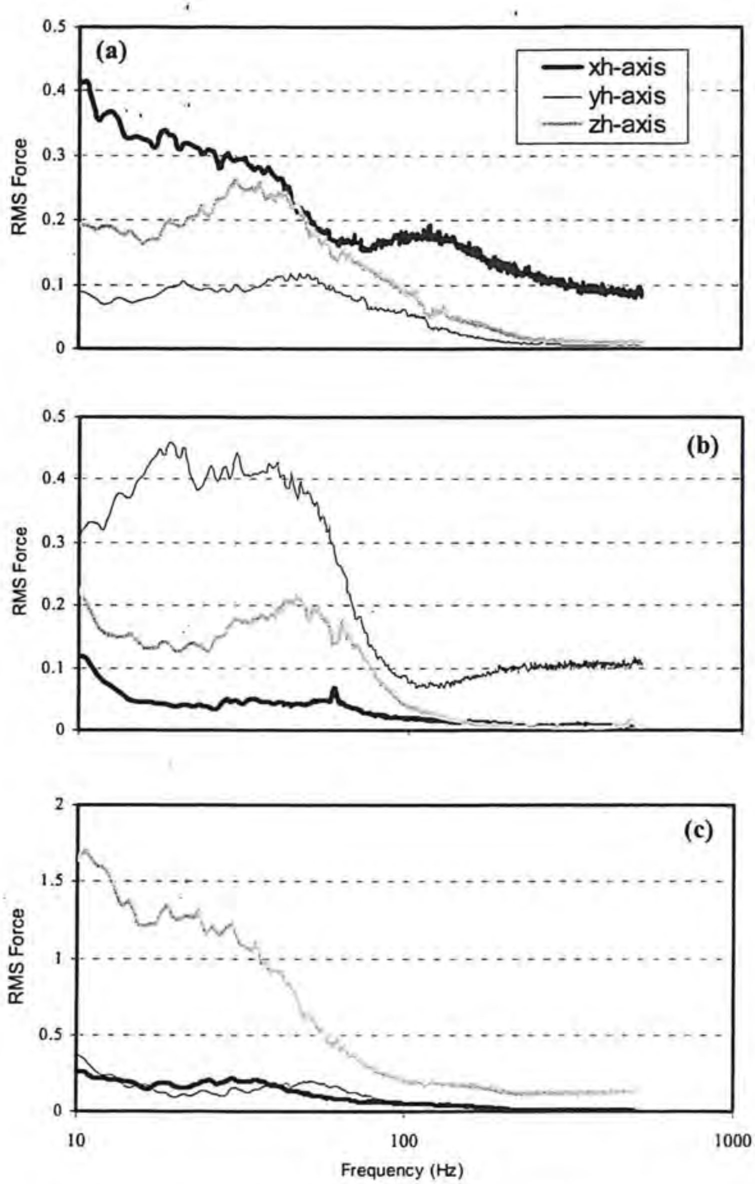

Figure 4 - Rms spectra of mean force components measured along the three-axes under vibration along: (a) x_h-; (b) y_h- and (c) z_h-axis.

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Bologna, Italy
3-7 June 2007

Proceedings edited by

M. Bovenzi, A. Peretti,
P. Nataletti, G. Moschioni