3D Displacement, Velocity, and Acceleration of Seated Operators in a Whole Body Vibration Environment using Optical Motion Capture Systems

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Abstract-- **Whole body vibration (WBV) is traditionally monitored using accelerometry, but optical motion analysis techniques may provide a means to investigate both vibration exposure and kinmatic joint motions simultaneously. While each method has strengths and weaknesses, the objective of this work is to combine these methods into an efficient and effective methodology to obtain three dimensional motion data for WBV. Optical motion capture systems and accelerometers have been used in this article to collect three dimensional (3D) motion data from three seated heavy machinery subjects under five rides that simulate off-road whole body vibration scenarios using a platform motion simulator. 3D displacement data obtained from markers are smoothed and then double differentiated using a five point central finite difference method to obtain linear acceleration values. A number of filtering and smoothing techniques have been implemented to obtain realistic linear acceleration from the markers data. These methods include low pass digital filtering (LPF), B-spline approximation (BSA), wavelet decomposition and reconstruction (WDR) and singular spectrum analysis (SSA). By using four markers and one accelerometer on each segment, the 3D angular velocity and angular acceleration values have been determined. The process of using markers has been designed to achieve two goals. The first goal was to obtain local coordinate system to guide the accelerometer throughout the trial, and the second, was to help in finding the angular velocity and angular acceleration of the segment. The goal of using accelerometers was to define a guide for subsequent filtering operations. The effectiveness of filtering was compared to the accelerometer data in the frequency domain in terms of 1/3-octave band-pass filtering and power spectrum. The results demonstrate the significance of using optical motion capture markers with a minimal number of accelerometers to obtain realistic 3D motion data in a whole body vibration environment.**

Keywords-component; motion capture; accelerometers; vibration; filtering.

I. INTRODUCTION

Human discomfort and health related issues due to vibration exposure are one of the major problems in many occupational fields. Humans are normally exposed to external forces, motions, and accelerations such as those encountered in aircrafts, ships, automobiles, farming machinery, construction equipments, army's vehicles, and other moving environments. Many recently published articles conclude that there is strong epidemiological evidence for a relationship between occupational exposure to WBV, low back pain (LBP) and back disorders, Hand-arm vibration syndrome, and white finger syndrome [1-3].

In WBV, domestic and international guidelines/standards and European Commission laws dictate exposure limits based on measurement of vibration at the interface between the seat and the operator's buttocks using seat-pad accelerometry [4-7]. This is historically based on the assumption that the only major source of vibration is transmitted through the seat pan. However, vibration may also be imparted to the head and neck via the steering wheel and/or arm-rest controls and a relatively rigid upper body. Therefore, in order to better understand whole body response to vibration, it is important to consider all degrees of freedom of each body segment with a high order of details.

Accelerometers have been proven to be effective in collecting motion data in WBV field. Theoretically, to describe the three-dimensional motion of each body segment, six accelerometers should be used. Yet, due to the non linear relation between the linear and angular kinematics variables, and the influence of the gravity-related terms, multiple accelerometers (9-12) placed in a specific configuration are needed to resolve its complete kinematics [8]. This leads to a very high number of sensors required for monitoring whole body motion analysis and may impact the subject's normal movements. In addition, angular and linear displacement estimated by using double integration of accelerations data are often perturbed by the drift and movement artifact belonging to the acceleration signals and requires knowledge of the initial conditions [8].

An alternative effective and efficient way to collect objective data for motion analysis is to use motion capture systems. Motion capture systems today have many applications in biomechanical studies [9, 11]. Motion capture systems have been shown to be accurate, repeatable, and consistent [12] and as an additional benefit, there is no pain or risk involved in using such systems. In the motion capture process, a number of reflective markers are attached over bony landmarks on the participant's body, such as the elbow, the clavicle, or the vertebral spinous processes. As the participant walks or carries out a given physical task or function, the position history of each marker is captured using an array of infrared cameras.

There are many advantages to using optical motion capture systems to collect motion data in WBV environments. First, the markers are passive sensors, meaning that they are only reflective surfaces and they can be attached easily to any area on the body of the subject without the need for wires to connect them to a data collection system. Second, theoretically only three markers are required to define the three-dimensional velocity and acceleration of each body segment; however, four markers were used in this work to provide for the most accurate results [13]. In the WBV environment, however, markers can not be used alone to obtain velocity and acceleration data due to the level of noise presented at various frequencies. Therefore, a guide such as an accelerometer is needed for subsequent filtering and smoothing operations.

A potential problem with passive markers, though, is *occlusion*, where the markers do not appear in enough of the camera shots due to blockage of the line of sight between the marker and the cameras by objects in the scene or by other parts of the subject's body. The research team, however, has obtained experience in dealing with problems such as occlusion. In this regard, the research team used redundant markers (more than the minimum required in the standard protocol) to compensate for occluded markers. With redundant markers, methodologies are available to fill in the motion data from occluded markers with information from the redundant markers. Further, there are numerous post-processing options available to digitally filter and differentiate the motion data. Particularly in a vibration and shock environment, it has not previously been shown which methodology is most appropriate.

The objective of the present work was to use optical motion capture data to determine 3D linear and angular velocity and acceleration components of various body segments in whole body vibration environment. While data collection for such an environment is very sensitive to frequency and noise, at least one accelerometer was needed for each segment to be used as a reference for any subsequent filtering or smoothing operations. The head segment was considered in this work, as an example, to demonstrate the effectiveness of the proposed approach.

I. METHODS

A six-degree of freedom man rated shaker table was used to simulate rides from five heavy construction machines conducting tasks in real sites. Three subjects [5%, 50%, and 95 percentile in height] were used in the testing after signing informed consent documents, as dictated by the approval of the project by the Human Subjects Office at The University of Iowa. Two types of seats with their damping unit assembly were borrowed from real machines and were used in this study. With each seat, three types of controls were used which include: seat mounted armrest control, steering wheel, and floor mounted armrest control. In all tests, the operators were instructed to put their feet on the pedals and their hands on the controls. Sixty passive reflective markers were attached over bony landmarks on the operator upper extremity, head, torso, and lower extremity. Time history of the location of these markers was collected at rate of 200 frames per second. Additional markers were also used to define the location of the platform, seat, and steering wheel.

A. Data Smoothing

Smoothing and differentiation techniques to 3D motion data have been widely implemented in the literature in different forms and in various practical fields [14]. In this study, four methods were used to smooth markers position data before obtaining velocity and acceleration data. The smoothing methods include low pass digital filtering (LPF, 18 Hz cut-off), B-spline approximation (BSA), wavelet decomposition and reconstruction (WDR) and singular spectrum analysis (SSA). The goal of using these methods was to study the behavior of each method throughout the tested range of frequencies (up to 40 Hz in the current experiments). For all smoothing techniques, programs were written in a Matlab environment except for the SSA where the Matlab embedded functions were used [15].

B. Velocity and Acceleration

Fig. 1 shows the markers location for one trial. At least four markers were attached to each body segment. One tri-axial accelerometer was attached to a marker on the head of the subject, one tri-axial accelerometer was attached to the seat pan, and one vertical uni-axial accelerometer was attached to a marker on the seat base, rigidly fixed to the motion platform.

The three-dimensional velocity and acceleration components of any point on a rigid segment can be obtained by knowing the linear velocity and acceleration of one point on the segment and the angular velocity and angular acceleration of the segment. The linear velocity and acceleration of any point can be obtained by differentiating the time history of a marker's position at that location. In WBV, the displacement data is normally very noisy and it is very hard to filter out the noise without prior knowledge of the frequency spectrum and the noise level. Therefore, for the head segment, as an example, a tri-axial accelerometer was attached to a marker on the head and was used as a guide for noise detection and smoothing operations. Nevertheless, there is a potential difficulty associated with the measurement of the acceleration components in three-dimensional motion due to the influence of the gravity component. One way to resolve this problem is to determine the time history of the local coordinate system of the accelerometer with respect to the global coordinate system; in this case, it becomes possible to remove the gravity component from the system. In this study, three markers were used to define a local coordinate system for the segment with respect to the global coordinate system

(T_{MG}), and the sensor axes were used to define the local coordinate system for the accelerometer (T_{AG}), as shown in Fig.2. Since the two local coordinate systems are rigidly fixed to each other, they share the same rotation matrix (R).

$$T_{MG}^{j} = R \times T_{MG}^{i} \qquad (3)$$

$$T_{AG}^{j} = R \times T_{AG}^{i} \qquad (4)$$

where i and j represents two static tilting positions. Mathematically, if more than three distinct static tilting positions are measured, (4) becomes an over-determined system, which can be solved using optimization techniques. Once T_{AG} is obtained, the time history of the acceleration orientation in gravity field can be readily determined. The time history of the 3D motion data of four markers on any body segment forming six relative position vector equations can be used to obtain the angular velocity and angular acceleration of the segment [12]. From the four markers on the segment, it is possible to determine the velocity and acceleration of any point on the segment,

$$\mathbf{v}_n = \mathbf{v}_m + \boldsymbol{\omega} \times \mathbf{r}_{n/m} \qquad (1)$$

$$\mathbf{a}_n = \mathbf{a}_m + \boldsymbol{\alpha} \times \mathbf{r}_{n/m} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}_{n/m} \qquad (2)$$

where $\mathbf{v}_n$ is the velocity of a point (n) on the head segment, $\mathbf{v}_m$ is the velocity of another point (m) on the head segment, ω is the angular velocity of the head segment, and $\mathbf{r}_{n/m}$ is the relative position vector between point m and n, $\mathbf{a}_n$ is the acceleration of point n, $\mathbf{a}_m$ is the acceleration of point m, and $\boldsymbol{\alpha}$ is the angular acceleration of the of the segment.

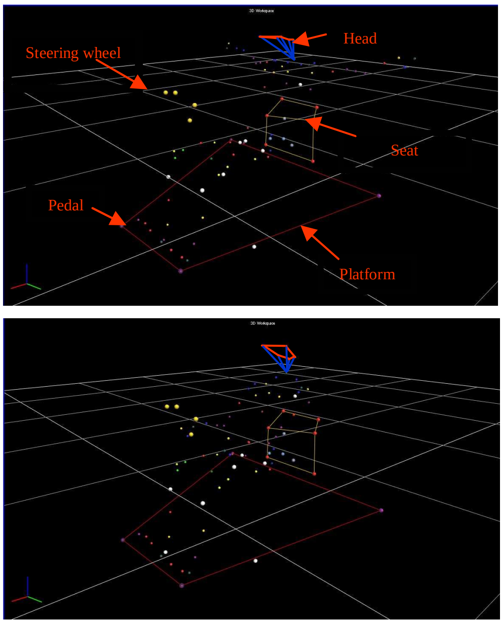

Fig.1: Marker locations on various parts of the body's segments, seat, steering wheel, and platform. The above figure shows the starting position in each trial, and the lower figure depicts an intermediate frame in the trail

The three dimensional angular acceleration and velocity of the head segment can be obtained by writing (1) and (2) for any relative position vectors that may be formed between the four markers [13]. The over-determined system can then be solved using the least square method.

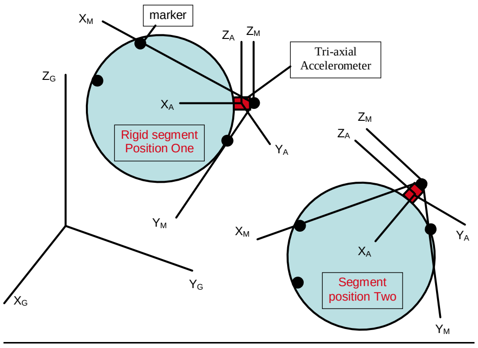

Fig. 2, Global and local coordinate systems for the accelerometer and the marker set

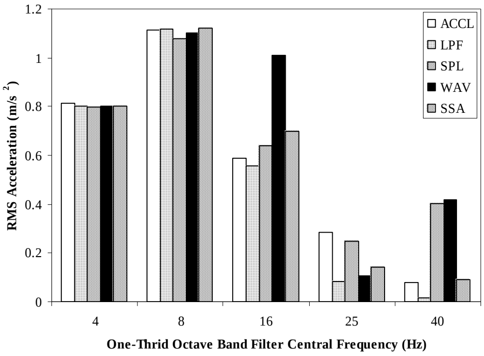

Fig. 3: The resulting Arms with frequency bands for various filtering techniques

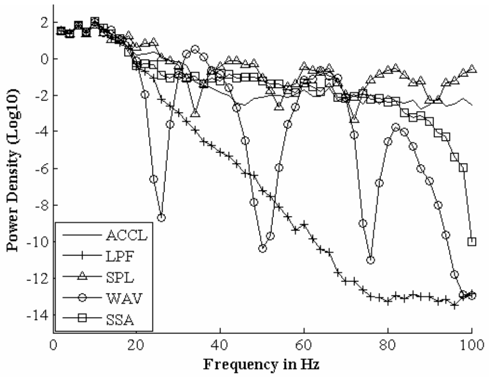

Fig. 4: Power spectrum analysis showing the distribution of power density with frequency for the accelerometer and various smoothing techniques

II. RESULTS AND DISCUSSION

The measured acceleration from accelerometers and calculated acceleration from markers were compared in terms of frequency distribution and banded RMS acceleration (Fig.3). As can be seen from the figure, all filtering techniques perform similarly and efficiently in the frequency range up to 8Hz; however, they start performing differently above that range. The wavelet filtering technique produced the least similar acceleration time history profile, whereas the other three techniques produced qualitatively similar results, and this was consistent with the power spectrum analysis shown in Fig. 4.

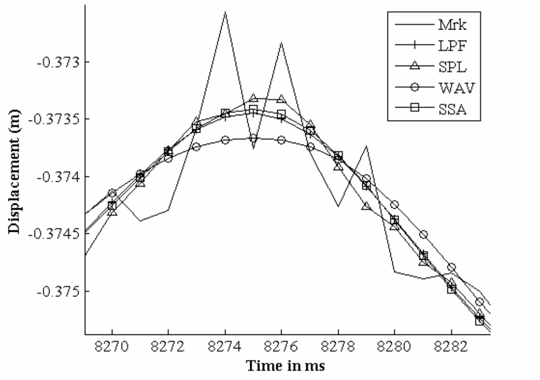

Fig. 5: Original and smoothed marker displacement data

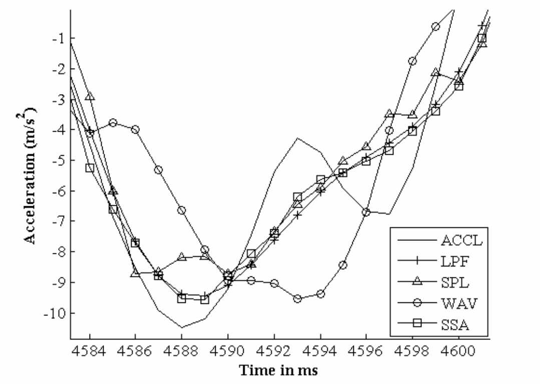

Fig. 6: The time history of acceleration obtained from accelerometers and that obtained from markers using various smoothing techniques

Fig. 5 shows the performance of the various smoothing techniques in time domain. All the methods have shown realistic behavior. However, and after the smoothed displacement have been double differentiated to obtain acceleration values (Fig. 6), each method behaved in relatively similar manner except for the wavelet method. The low pass filter behaved nicely in the beginning and then turned down after reaching the cutoff frequency of 16 Hz.

This study has demonstrated the advantage of adding accelerometers to the marker set in WBV environment to obtain more accurate velocity and acceleration components, and the methodology to extract realistic information from the accelerometer and use it as a guide for subsequent filtering operations.

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