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MEASUREMENT OF HEAD VIBRATION AND ITS ERROR ANALYSIS

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ABSTRACT

This paper addresses issues encountered in measuring the general, 6-degree-of-freedom motion of a human head. This measurement requires the usage of multiple accelerometers, such as the well-known "bite-bar" which consists of three measurement blocks positioned differently and separated by a fixed gap. Six accelerometers are chosen to measure the 6-degree-of-freedom motion at a position of the head. This paper proposes a way of estimating the three angular velocity components of the head from five accelerometers. The use of the estimated angular velocity components is shown to give a complete description of the head vibration. Its theoretic formulations are presented in this paper. Experimental results are also illustrated to examine what amount of measurement uncertainty the proposed method can improve.

1 - INTRODUCTION

The transmission of seat vibration to the head has been widely studied by numerous researchers [1-3] for longer than 50 years. The measured transmissibility gives useful information about the biodynamic responses of the whole-body to the various vibration environments and their effects on the loss of comfort, activity interference, and potential injury. To examine those human effects of whole-body vibration, early studies had considered single-axis vertical seat and head vibration. Unlike the early studies only on vertical seat-and-head vibration, even the single-axis vertical or horizontal seat vibration generates not only the vertical head vibration but also other multi-axis head vibration components, e.g. fore-and-aft motion, lateral motion and rotational motions (i.e., roll, pitch, and yaw) [4,5]. Hence, it is of value to measure and evaluate the multi-axis global motion of the head for the assessment of whole-body vibration.

For this purpose, it has been attempted to examine the multi-axis global motion of the head using a limited number of locally measured accelerations [6,7]. Even though the measurement method of nine linear accelerations [7] had been proposed to evaluate the global motions of the head, six linear accelerometers, referred to as "six-axis bite-bar" [6], are more often used to do it. The reason comes from the fact that the former measurement device using nine accelerometers requires the three sets of tri-axial accelerometers support rods assembled perpendicularly while the latter uses only two right-angled support rods fixed on the horizontal plane. Thus, the latter has a simpler structure to use. But, an approximate evaluation of the global head motion suggested by the latter case has been used. Its measurement uncertainty due to such approximation has rarely been reported. The objective of this paper is to suggest a complete form for the calculation of the head motion using the six linear accelerometers. Detailed descriptions are presented not only to evaluate more accurately the head motion but also to analyze its measurement uncertainty. To demonstrate their effectiveness, experimental results are illustrated.

2 - HEAD VIBRATION MEASUREMENT DEVICE

The six-axis bite-bar, shown in Fig. 1, was used in this work. It is a modified model developed by the human factors research group in ISVR. It consists of 6 linear accelerometers with the very low frequency response up to DC (Entran EGA-125(F)*-10D) installed in the differently positioned three blocks. A single accelerometer in block 1 (front right side) is oriented in the z-axis. Three accelerometers in block 2 (front left side) are perpendicularly set up in the x, y, and z-axis directions and two accelerometers in block 3 (back left side) are oriented in the y and z-axis directions. The distance between front block 1 and 2 was chosen to be $\mathrm{d_y} = 200$ mm such that the pared z-axis accelerometers at block 1 and 2 were used to evaluate the angular velocity and acceleration of the x-axis (roll motion component). Similarly, the gap between block 2 and 3 was chosen to be $\mathrm{d_x} = 150$ mm such that the paired y and z-axis accelerometers were used to estimate the angular velocities and accelerations of the z-axis and y-axis, i.e. yaw and pitch motion components, respectively. A T-shaped aluminum rod on which a dental mould was mounted was attached to the center of the lateral rod joining block 1 and 2. In this configuration, the lateral rod was located 35 mm anterior to the subject's front teeth. The subject under test was asked to bite the dental mold so that the bite-bar is almost rigidly attached to the subject's head.

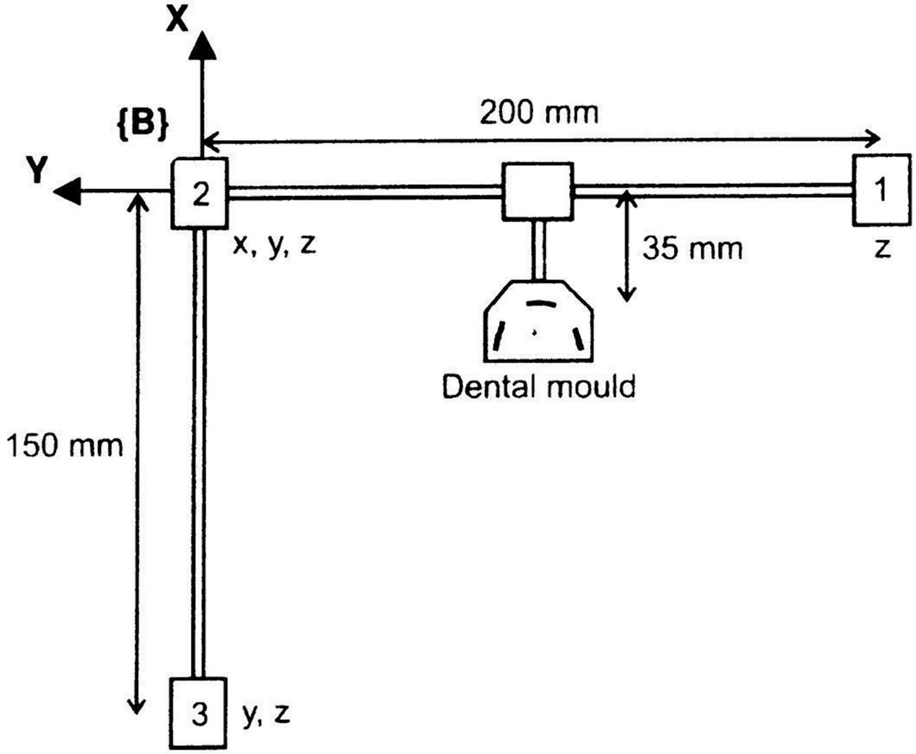

Figure 1: A bite-bar with six translational accelerometers for measuring vibration in the three translational and three rotational axes of the head on the moving reference frame B.

3 - COMPLETE FORM FOR CALCULATION OF HEAD VIBRATION

In rigid body kinematics [8], a general description of acceleration at the position of interest is defined as the sum of three terms: the translation acceleration at the reference position, the product of the angular acceleration with the relative position vector, and the centrifugal acceleration (squared angular dependent acceleration). This understanding leads the derivation of a complete form of calculating the general head vibration using the six linear accelerometers shown in Fig. 1. The measured accelerations at block 1 and 3 enable the estimation of the three-axis angular accelerations as

$$\alpha_\mathrm{x}= (\mathrm{a_{2z}} - \mathrm{a_{1z}}) \div \mathrm{d_y} + \omega_\mathrm{y}\omega_\mathrm{z},\ \alpha_y = (a_{3z} - a_{2z}) \div d_x + \omega_z\omega_x,\ \alpha_\mathrm{z}= (\mathrm{a_{2y}} - \mathrm{a_{3y}})\ \div \mathrm{d_x} + \omega_\mathrm{x}\omega_\mathrm{y} \qquad (1)$$

In equation (1), a denotes the linear acceleration measured, ω and α the angular velocity and acceleration, and d the distance from the reference position (block 2). The subscript implies the block index and measurement axis. Similarly, the translational acceleration at a position (denoted by x,y,z) is also readily calculated by using the following equations

$$\begin{aligned} \alpha_x &= a_{2x} + [(a_{3z} - a_{2z})\, z \div d_x - (\mathrm{a_{2yz}} - \mathrm{a_{3y}})\,\mathrm{y} \div \mathrm{d_x}] + \left\{- \left(\omega_y^2 + \omega_\mathrm{z}^2\right) x + 2\omega_\mathrm{x}\,\omega_\mathrm{y}\mathrm{y} + 2\omega_\mathrm{x}\omega_\mathrm{z}\mathrm{z}\right\} \\ \alpha_y &= a_{2y} + [(a_{2y} - a_{3y})\, x \div d_x - (\mathrm{a_{2z}} - \mathrm{a_{1z}})\,\mathrm{z} \div \mathrm{d_y}] + \left\{- \left(\omega_z^2 + \omega_\mathrm{x}^2\right) y + 2\omega_\mathrm{y}\omega_\mathrm{z}\mathrm{z}\right\} \\ \alpha_z &= a_{2z} + [(a_{2z} - a_{1z})\, y \div d_y - (\mathrm{a_{3z}} - \mathrm{a_{2z}})\,\mathrm{x} \div \mathrm{d_x}] + \left\{- \left(\omega_x^2 + \omega_\mathrm{y}^2\right) z\right\} \end{aligned} \qquad (2)$$

In comparison to the above results for the calculation of the general head vibration using the six-axis bite bar (shown in Fig. 1), the previous work [6] is an approximate form of neglecting all angular velocity dependent terms in equations (1) and 2.

More specifically, the above formulae indicate that the estimation of both angular and translational accelerations involves that of the angular velocity on the head. The three-axis angular velocity of the head are obtained from the linear velocity at the three block as

$$\omega_x = (v_{2z} - v_{1z}) \div d_y, \qquad \omega_{\mathrm{y}} = (\mathrm{v}_{3\mathrm{z}} - \mathrm{v}_{2\mathrm{z}}) \div \mathrm{d}_{\mathrm{x}}, \qquad \omega_{\mathrm{z}} = (\mathrm{v}_{2\mathrm{y}} - \mathrm{v}_{3\mathrm{y}}) \div \mathrm{d}_{\mathrm{x}} \qquad (3)$$

In this work, the linear velocity at each block is estimated by the "spectrally equivalent integration" method using the Fourier transforms of measured acceleration signals. The method first makes the estimation of Fourier coefficients for the frequency range of interest from the time series of measured acceleration signals, second integrates the continuous time domain model constructed by the estimated Fourier coefficients, and finally calculates the linear velocity from the integrated time domain model at each sampling interval. The calculated velocity signals at the three blocks are used to estimate the angular velocity according to equation (3).

4 - EXPERIMENTAL RESULTS AND DISCUSSIONS

An experiment for analysis of the head vibration due to vertical seat vibration was conducted in ISVR using an electro-hydraulic vibrator with the maximum stroke of 1 m. A Korean male subject (height = 1.83 m, weight = 73 kg) was sited on the rigid flat seat in the normal (subject's back erected without backrest) and 'slouched' postures. Input stimuli were chosen to be bandpass filtered Gaussian random vertical motions with the equal acceleration power spectral density in the frequency range of 0.5 to 30 Hz. Three vibration amplitudes were chosen to be 0.5, 1.0 and 2.0 m/s^2(r.m.s.), each with the duration of 60 seconds. For each experimental condition, the six accelerations at the three measuring blocks on the bite-bar were simultaneously measured for analysis of the head motion.

As shown in equation (1), the complete form of the angular acceleration on the head is determined from the paired linear accelerations and other two-axis angular velocity components. Table 1 shows the estimated angular acceleration only from the paired linear acceleration, denoted by $\alpha_{A,i}$ (i = x,y,z), and the relative ratio of the angular velocity dependent terms $\alpha_{R,i}/\ \alpha_{A,i}$. As the seat vibration level increases, angular acceleration on the head is observed to become higher. Even in case of seat vibration level 2.0 m/s^2 (r.m.s), the maximum angular velocity dependent terms are seen to be about 3 % in comparison to the z-axis angular acceleration $\alpha_{A,z}$. But, its relative significance for other x and y axes is quite small, that is less than 1 %. It is shown in Table 1 that when the angular acceleration is estimated only from the paired linear accelerometers without considering any angular velocity the estimated z-axis angular acceleration can have more measurement error than other axes.

Axis	Normal Posture			Slouched Posture		
	0.5 m/s^2	1.0 m/s^2	2.0 m/s^2	0.5 m/s^2	1.0 m/s^2	2.0 m/s^2
Roll, $\alpha_{A,x}$ (rad/s^2)	0.81	1.52	2.40	0.99	1.75	2.67
Pitch, $\alpha_{A,y}$ (rad/s^2)	2.55	3.97	6.03	2.91	5.70	9.59
Yaw, $\alpha_{A,z}$ (rad/s^2)	0.56	1.09	1.39	0.69	1.04	1.52
$\alpha_{R,x}/\alpha_{A,x}$	0.17 %	0.29 %	0.43 %	0.52 %	0.46 %	0.90 %
$\alpha_{R,y}/\alpha_{A,y}$	0.02 %	0.05 %	0.07 %	0.09 %	0.05 %	0.10 %
$\alpha_{R,z}/\alpha_{A,z}$	0.43 %	0.77 %	1.79 %	0.56 %	1.48 %	3.26 %

Table 1: Angular acceleration levels $\alpha_{A,i}$ and percentage ratios of angular velocity dependent terms $\alpha_{R,i}/\ \alpha_{A,i}$ (i = x,y,z) for different postures and seat acceleration levels.

The calculation of the translational acceleration on the head, as shown in equation (2), also involves the angular velocity dependent terms that was neglected in the previous work. To examine their effects on the translational acceleration, the acceleration distribution on the three reference planes (mid-coronal plane, mid-sagittal plane, horizontal plane shown in Fig. 2) was carried out.

Fig. 3 shows the percentage ratios of the linear acceleration-dependent terms (first two terms in the right hand-side of equation (2)) to the angular velocity-dependent terms (last terms braced in the right hand-side of equation (2)). The peak percentage sorted out for each axis on the three reference planes

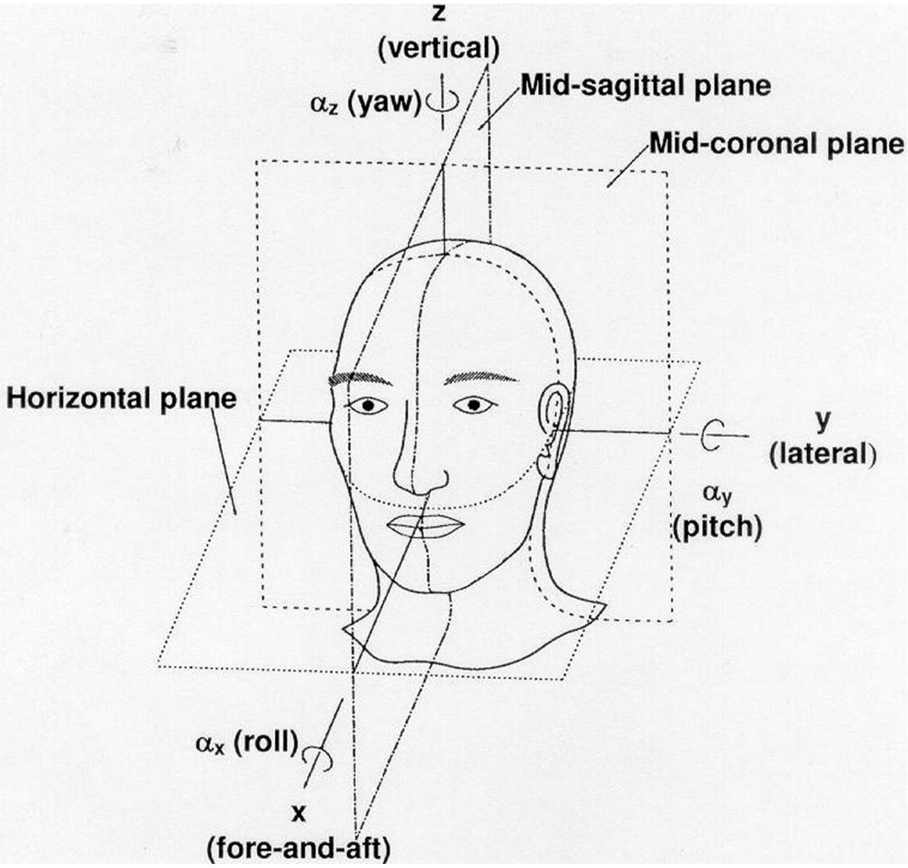

Figure 2: Biodynamic axes and biodynamic planes for the human head defined in ISO 8717 (by Paddan and Griffin [6]).

are listed in Table 2. The angular velocity dependent terms are shown to contribute more than 5 % on the x-axis of the mid-sagittal and horizontal planes in addition to the linear acceleration-dependent terms. They are observed to contribute 2 % ∼ 3 % to systematic measurement uncertainty on the other axes.

Axis	Mid-coronal plane		Mid-sagittal plane		Horizontal plane	
	Normal	Slouched	Normal	Slouched	Normal	Slouched
$a_{R,z}$ / $a_{A,z}$	1.4 %	2.9 %	2.5 %	5.1 %	2.7 %	5.4 %
$a_{R,z}$ / $a_{A,z}$	1.0 %	1.7 %	0.9 %	1.5 %	0.9 %	1.3 %
$a_{R,z}$ / $a_{A,z}$	0.8 %	2.1 %	0.8 %	2.2 %	0.3 %	0.7 %

Table 2: The peak percentage ratios observed in the translational acceleration components on the three biodynamic planes for seat acceleration amplitude 2.0 m/s^2 (r.m.s) planes.

5 - CONCLUDING REMARKS

This paper presents a complete form of calculating the general motion of head using the bite bar configured by six accelerometers. It is shown to be an generalized description in comparison to the previous work that neglected the angular velocity dependent terms required in calculating both angular and translational accelerations. Even in case of seat vibration level 2.0 m/s^2 (r.m.s), the maximum angular velocity dependent terms are seen to be about 3 % for the z-axis angular acceleration. Their relative significance for other x and y axes is quite small, that is less than 1 %. In estimating the translational acceleration, the angular velocity dependent terms are shown to contribute more than 5 % additionally to the linear acceleration-dependent terms on the x-axis of both mid-sagittal and horizontal planes. They are also observed to contribute 2 % ∼ 3 % to measurement uncertainty on the other axes. Resultantly, the inclusion of angular velocity dependent terms suggested in this paper gives less systematic error in measuring the general vibration on the head.

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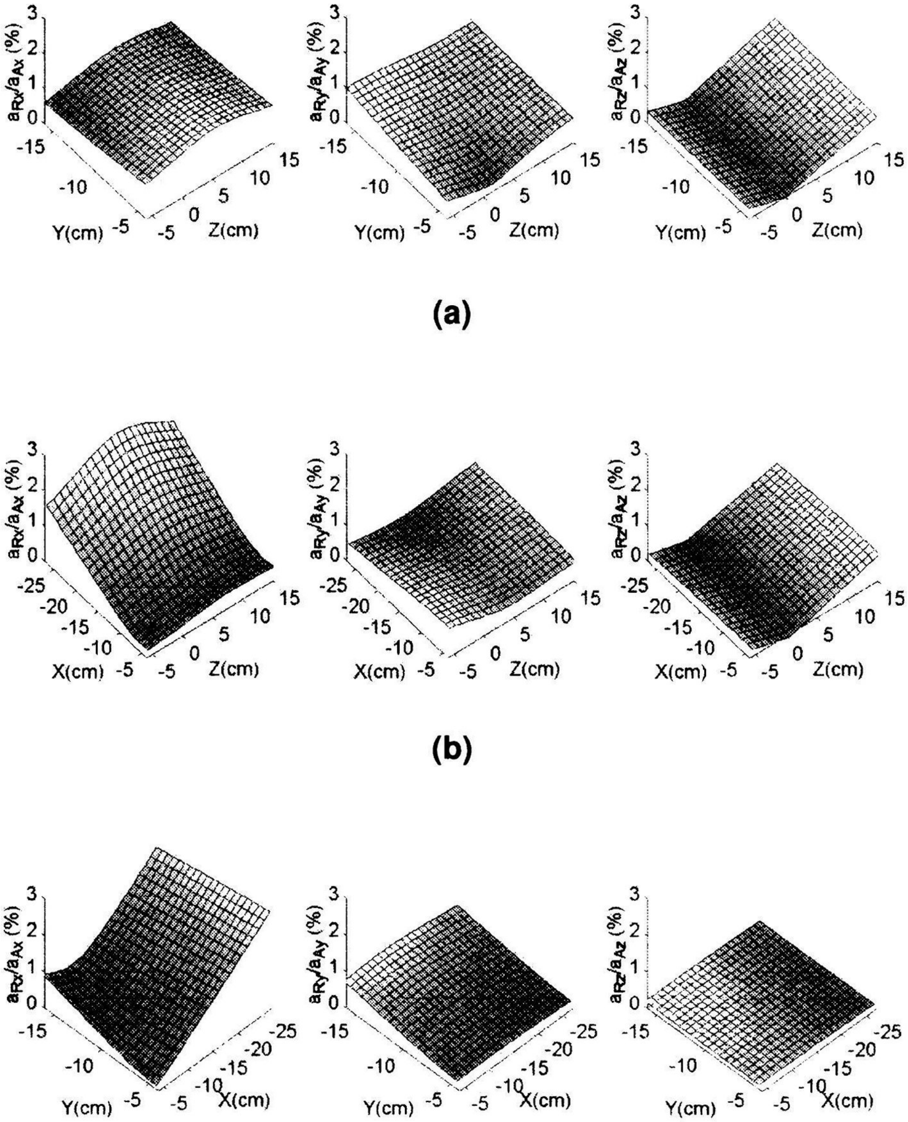

(a)

(b)

(c)

Figure 3: Spatial distributions of the percentage ratios of the angular velocity-dependent terms to the translational velocity dependent terms, i.e. $a_{R,i}/a_{A,i}$ ($i = x,y,z$) for normal posture and seat acceleration level 2 m/s^2 (r.m.s) on three bio-dynamic planes; (a) mid-coronal plane; (b) mid-sagittal plane; (c) horizontal plane.