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Study on Uncertainty Factors of Head Vibration Measurements

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ABSTRACT

This paper addresses uncertainty issues encountered recently in measuring head vibration using the conventional 6-axis or 9-axis bite-bar. Those conventional bite-bars are shown to present insufficient information to measure a complete 6 degree-of-freedom motion of head vibration. In order to overcome such limit, a theoretical measurement model that consists of four 3-axis linear accelerometers is suggested (Theoretical backgrounds presented in this paper shall have been addressed in the international congress of ICA 2004 in this April). It is shown to enable the direct measurement of three angular acceleration components and six angular velocity-dependent nonlinear terms. In addition to the three linear acceleration terms, those nine angular motion-dependent ones are found to make it possible to evaluate the general head vibration for a given position. To examine the feasibility of the proposed method, a newly designed 12-axis bite-bar was developed. Detailed experimental results obtained using the developed 12-axis bite-bar are illustrated in the presentation of this paper, which illustrates what amount of measurement accuracy provides. But, this paper provides more detailed experimental data and extended uncertainty factors.

1. Introduction

The measurement of head vibration has played important roles in investigating the biodynamic responses of various environmental whole-body vibrations to head and their effects [1,2]. Unlike the early studies on the single-axis head vibration [2], even a 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, lateral and other rotational motions (i.e., roll, pitch, and yaw) [3-5]. Therefore, it is of value to measure and evaluate the multi-axis global motion of the head for the assessment of whole-body vibration. Measurement methods using the nine linear accelerometers [6] and the six linear ones [3-5,7] have been proposed to evaluate the global motions of the head. The latter has a simpler structure to use but its evaluated global head motion cannot avoid measurement uncertainty due to the three approximated angular accelerations [5,7,8].

A complete form of calculating the generalised head motion is considered and is shown to present the theoretical understanding about measurement uncertainty factors encountered in previous studies. Such understanding has enabled the development of a new device of measuring the general head vibration, referred to the "12-axis bite-bar". Its detailed descriptions are presented in Section 3. The 12-axis bite-bar enables not only to measure more accurately the head motion but also to improve its measurement by considering uncertainty factors missed in previous work. To examine their effects in real applications, experimental results are illustrated in Section 4.

2. Complete form of calculating head motion

On the onset of this work, it became apparent that the position of each accelerometer of any three-axis accelerometer was offset in a finite length, not in the one position of the block center. The offset length was found to be about 5 ~ 12 mm by measuring 6 different 3-axis models used in KRISS (supplied from four different manufacturers). This offset length is readily seen not only to cause the estimation error of angular accelerations but also to add much difficulty in fitting all the 'equally offset' accelerometers installed in the multiple blocks of the bite-bar. This point will be further discussed in Chapter 3.

Figure 1 in the next page shows a schematic model that consists of four 3-axis linear accelerometers. Let the offset length of the reference block (Block 0 in Figure 1) of the bite-bar be (x_0, y_0, z_0) from the origin (i.e. the center of the reference block) and the acceleration at the origin be $\mathbf{A}_0 = (a_{x,0}, a_{y,0}, a_{z,0})$. The measured 3-axis acceleration $\mathbf{A}_R = (a_{x,R}, a_{y,R}, a_{z,R})$ at the reference block is given as

$$\begin{aligned} a_{x,R} &= a_{x,0} + \alpha_y \cdot z_0 - \alpha_z \cdot y_0 + \omega_x \omega_y \cdot y_0 \\ &\quad + \omega_x \omega_z \cdot z_0 - (\omega_y^2 + \omega_z^2) \cdot x_0 \qquad (1) \\ a_{y,R} &= a_{y,0} + \alpha_z \cdot x_0 - \alpha_x \cdot z_0 + \omega_y \omega_z \cdot z_0 \\ &\quad + \omega_y \omega_x \cdot x_0 - (\omega_z^2 + \omega_x^2) \cdot y_0 \end{aligned}$$

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$$a_{z,R} = a_{z,0} + \alpha_x \cdot y_0 - \alpha_y \cdot x_0 + \omega_z \omega_x \cdot x_0$$
$$+\omega_z \omega_y \cdot y_0 - (\omega_x^2 + \omega_y^2) \cdot z_0$$

In equation (1), (α_x, α_y, α_z) and (ω_x, ω_y, ω_z) denote the angular acceleration and velocity components of the reference block. Equation (1) means that the acceleration A_O at the origin is not equal to the measured 3-axis acceleration A_R from the reference block and that it can be estimated only when the offset length (x_0,y_0,z_0) and the angular velocity and acceleration (α_x, α_y, α_z) and (ω_x, ω_y, ω_z) are available at hand. But, this point has been neglected in previous work by considering the zero offset length (x_0, y_0, z_0) = (0, 0, 0) without experimental examination. It is the first measurement uncertainty factor pointed out in this work.

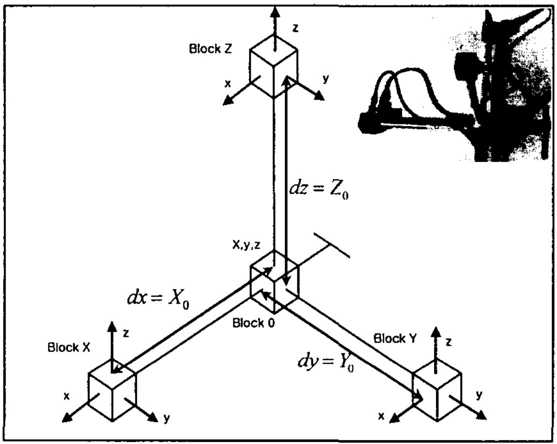

Fig. 1 12-axis bite-bar model with three orthogonal measurement blocks

The 12-axis bite-bar designed in this work consists of three orthogonal measurement blocks. Each block has three linear accelerometers. It is straightforward to derive all the 3-axis acceleration components for the three other blocks of the bite-bar by substituting the offset position (x_0, y_0, z_0) in equation (1)for (x_X+X_0, y_X, z_X) for block X, (x_Y, y_Y+Y_0, z_X) for block Y, and (x_Z, y_Z, z_Z+Z_0) for block Z. Note that {(x_k,y_k,z_k): k = X, Y, Z}denotes the offset length of each block and {X_0, Y_0, Z_0} does the span between the centre of block X, Y, Z and reference block 0.

$$\begin{bmatrix} \Delta a_{Xy} \\ \Delta a_{Xz} \\ \Delta a_{Yx} \\ \Delta a_{Yz} \\ \Delta a_{Zx} \\ \Delta a_{Zx} \end{bmatrix} = \begin{bmatrix} 0 & 0 & X_0 & X_0 & 0 & 0 \\ 0 & -X_0 & 0 & 0 & 0 & X_0 \\ 0 & 0 & -Y_0 & Y_0 & 0 & 0 \\ Y_0 & 0 & 0 & 0 & Y_0 & 0 \\ 0 & Z_0 & 0 & 0 & 0 & Z_0 \\ -Z_0 & 0 & 0 & 0 & Z_0 & 0 \end{bmatrix} \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \\ \omega_y \omega_z \\ \omega_z \omega_x \\ \omega_x \omega_y \end{bmatrix} \quad (2)$$

$$\Delta a_{Xx} = -\left(\omega_y^2 + \omega_z^2\right) \cdot X_0, \qquad \Delta a_{Yy} = -\left(\omega_z^2 + \omega_z^2\right) \cdot Y_0$$
$$\Delta a_{Zz} = -\left(\omega_x^2 + \omega_y^2\right) \cdot Z_0$$

Let {A_X, A_Y, A_Z} be the acceleration vector for block X, Y, and Z. Their relative accelerations with respect to the reference block (block 0), {$\Delta A_X = A_X - A_R$, $\Delta A_Y = A_Y - A_R$, $\Delta A_Z = A_Z - A_R$}, are used to estimate the angular acceleration and velocity components. The nine number of those relative acceleration components are used to determine the angular acceleration and velocity-related components, i.e. the nine unknowns {α_x, α_y, α_z, $\omega_x\omega_y$, $\omega_y\omega_z$, $\omega_z\omega_x$, ω_x^2, ω_y^2, ω_z^2}. As shown in equation (2), the nine unknowns are uniquely determined from the nine relative acceleration components. It is the reason that this work uses the 12-axis bite-bar shown in Figure 1.

It is interesting to note that the 12-axis bite-bar enables the systematic error analysis for previous measurement methods. Table 1 illustrates the comparison between the previous methods. The 6-axis bite-bar [1,3-5] model gives the three approximated angular acceleration components {α_x, α_y, α_z}, which neglects all the angular velocity dependent terms. When this method is used to estimate the acceleration of head vibration, it is seen to involve all the measurement error factors related to the angular velocity dependent terms, as shown in (1). The 9-axis bite bar [6] enables the estimation of six terms {α_x, α_y, α_z, $\omega_x\omega_y$, $\omega_y\omega_z$, $\omega_z\omega_x$} but does not give any information of determining {ω_x^2, ω_y^2, ω_z^2}. This method is seen to yield the measurement error of head vibration related to the squared angular velocity dependent terms.

Table 1 Comparison of head vibration measurement methods used in previous studies.

Block	6-axis bite-bar [1,3,4]		9-axis bite - bar [5]	12-axis bite-bar[8]
Block 0	a_x, a_y, a_z			
Block X	a_x or a_y	a_z	a_y, a_z	a_x, a_y, a_z
Block Y		a_z	a_x, a_z	a_x, a_y, a_z
Block Z	Not used		a_x, a_y	a_x, a_y, a_z

In order to determine the nine angular acceleration and velocity dependent terms {α_x, α_y, α_z, $\omega_x\omega_y$, $\omega_y\omega_z$, $\omega_z\omega_x$, ω_x^2, ω_y^2, ω_z^2}, this work uses the nine relative acceleration components measured from the three blocks shown in Figure 1. They enable the estimation of the acceleration at the origin, $\mathbf{A}_0$ = ($a_{x,0}$, $a_{y,0}$, $a_{z,0}$). Given a position $\mathbf{x}$ = (x, y, z) of interest, the acceleration at the position is calculated by substituting the offset position (x_0,y_0,z_0) *for the desired one* (*x*, *y*, *z*).

3. Experimental setup and results

The uncertainty factors, which depend on the head vibration measurement methods and their devices, have been raised in Section 2. Experimental attempts to examine their effects on the measurement uncertainty of head vibration are introduced. In this work, four 3-axis accelerometers of a cube-shaped model (Endevco Model 63B-100) were chosen. Each sensing part of the 3-axis accelerometer is assembled in the same offset length from the center, whose structure enables fitting all the equal offset length of each block (i.e. $x_k = y_k = z_k \cong 5$ mm; k = X,Y,Z) to that of the reference block. The equal span between the center of the three blocks and that of the reference one was chosen to be 100 mm ($X_0 = Y_0 = Y_0 = 100$ mm). Figure 2 illustrates the developed 12-axis bite-bar.

To examine the uncertainty characteristics of different bite-bars for measuring head vibration, this work carried out the subject test as shown in Figure 2. The subject was asked to sit as the normal posture. Three different vertical vibration levels {0.5, 1.0, 2.0 m/s^2 r.m.s.} whose spectra are equally distributed over the frequency range of 1 ~ 50 Hz were chosen.

Fig. 2 Picture of the head vibration measurement using the 12-axis bite-bar

The outputs of a 12-channel signal conditioner that amplify the voltage outputs of the four 3-axis accelerometers were recorded into the digital recorder (Sony DAT PCCX32A). The digitally recorded 12-channel signals were read into the personal computer using the interface hardware and the software (Sony PCIF-5 and PCScan II) and stored in the binary format. MATLAB software was used to carry out all the signal processing procedures to obtain the time series of 12-axix vibration signals using equation (2) and their spectral density functions.

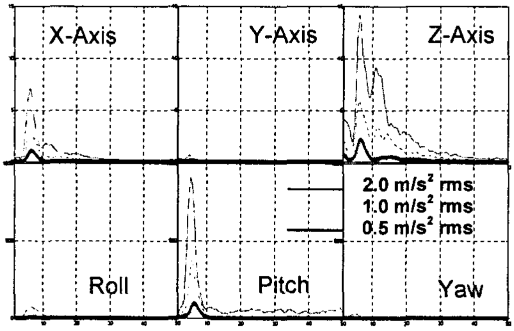

Fig. 3 Measured power spectra of head vibration for three different vibration levels {0.5, 1.0, 2.0 m/s^2 r.m.s.}.

It is interesting to see a single-axis vertical seat vibration to cause what kind of head vibration of the subject. Figure 3 shows the vibration spectra evaluated at the reference block according to equation (1) and (2). The single-axis vertical vibration is seen to generate not only the vertical head vibration but also other multi-axis head vibration components, e.g. the x-axis (fore-and-aft) and y-axis (lateral) vibration and other rotational motions (i.e., roll, pitch, and yaw), as in the precious work [3-5]. Although the vertical vibration component is dominant, the fore-and-after (x-axis) one is also significant. Among the rotational vibration components, the pitch vibration is most noticeable but roll and yaw components are not so observable.

The vibration spectral shown in figure 3 were evaluated using the 12-axis bite-bar model. It is quite interesting to see what difference between the evaluated angular acceleration when other bite-bars are chosen. Figure 4 illustrates two pitch spectra obtained by the 6-axis bite-bar model and the 12-axis bite-bar respectively.

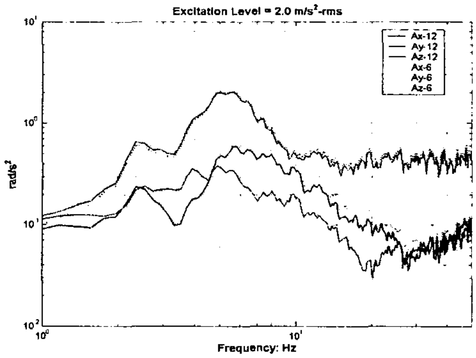

Fig. 4 Comparison between pitch spectra evaluated using the 6-axis and 12-axis bite–bars for the vertical vibration level of 1.0 m/s^2 r.m.s (PSD denotes 'power spectral dendity')

The spectral level of the 6-axis mode is seen to be lower than that of the 12-axis model below the frequency of 6 Hz. However, such trend is seen to reverse above the frequency of 6 Hz. These seem to be caused by the 'incomplete' model of the 6-axis bite-bar. To examine these effects quantitatively, a relative difference indicator I_{rel} is used,

$$I_{rel} = 100 \times \frac{\sum_{f=f_l}^{f_u} \left| P_{12-axis}(f) - P_{6-axis}(f) \right|}{\sum_{f=f_l}^{f_u} P_{12-axis}(f)} \qquad (3)$$

Note that $P_{6\text{-axis}}$ and $P_{12\text{-axis}}$ denote the power spectra obtained using the 6-axis and 12-axis bite–bars and that f_1 and f_2 do the lower and upper frequency limit. Table 2 in the next page shows the relative difference for three angular acceleration components $\{\alpha_x, \alpha_y, \alpha_z\}$ evaluated for $f_1 = 1$ Hz and $f_2 = 50$ Hz. The relative difference indicators of the roll and yaw components are higher than 10 %. That of the pitch is less than but close to 10 %. It should be noted that the difference indicator in equation (3) is the percentage ratio of power spectral level, not the root mean squared (r.m.s.) value.

Table 2 Relative difference indicators for three angular acceleration components

Vibration Level	Relative Difference Indicator (Power Level Difference)		
	Roll	Pitch	Yaw
0.5 m/s^2 r.m.s	31 %	8 %	13 %
1.0 m/s^2 r.m.s	31 %	9 %	20 %
2.0 m/s^2 r.m.s	33 %	7 %	29 %

The above observation was unexpected results, which was consistently obtained even for several repeated tests. There would be several possible issues: (1) modeling of the rigid body motion for all angular motion components for the head, (2) dynamic response of the thin-tubed rod connecting each 3-axis accelerometer, (3) uncertainties generated from the electrical characteristics of all the accelerometers and their corresponding signal conditioners, etc. Of course, those uncertainty-related factors should be carefully considered so as to identify the reason for such large difference indicators observed in this work. These issues do still motivate more future research work.

4. Concluding Remarks

This paper introduces uncertainty issues encountered in measuring head vibration using the conventional 6-axis or 9-axis bite-bar. Those conventional bite-bars are shown to present insufficient information to measure a complete 6 degree-of-freedom motion of head vibration. In order to overcome such limit, a theoretical measurement model that consists of four 3-axis linear accelerometers is suggested. It is shown to enable the direct measurement of three angular acceleration components and six angular velocity-dependent nonlinear terms. In addition to the three linear acceleration terms, those nine angular motion-dependent ones are found to make it possible to evaluate the general head vibration for a given position. To examine the feasibility of the proposed method, a newly designed 12-axis bite-bar was developed. Detailed experimental results obtained using the developed 12-axis bite-bar are illustrated in the presentation of this paper.

This work suggests a relative difference indicator to see what amount of measurement accuracy provides when different bite-bars are used. Most of relative difference indicators are higher than 1.0 %. The relative difference indicator is the percentage ratio of power spectral density functions, not the root mean squared (r.m.s.) values. Such large indicator seems to be a big challenge to the 'accurate and reliable' measurement of head vibration. Several measurement and modeling factors that should be considered in the future work is pointed out in this paper.

Theoretical backgrounds presented in this paper shall have been addressed in the international congress of ICA 2004 in this April. But, this paper provides more detailed experimental data and extended uncertainty fsctors.

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