Study on Uncertainty Factors of Head Vibration Measurements#

머리 진동 측정치의 불확도 인자들에 관한 연구

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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 model. Those conventional bite-bar models are shown to present insufficient information to evaluate a generalized motion of head vibration. In order to overcome such limit, a new theoretical measurement model that consists of four 3-axis linear accelerometers is suggested. It is shown to enable the measurement of three angular acceleration components and six second-order angular velocity-dependent terms. Those nine angular motion-related ones, in addition to the three linear acceleration terms at the origin, are found to make it possible to evaluate the generalized 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 from the developed 12-axis bite-bar are demonstrated in this paper. They illustrate that the popular 6-axis bite-bar model yield about 4.0 % relative measurement uncertainty for the pitch component of head vibration, 14 % and 10 % relative measurement uncertainty for the roll and yaw components of head vibration, respectively. Furthermore, this paper proposes other uncertainty factors to be considered in the future.

요 약

이 논문에서는 기존의 6-축 혹은 9-축 머리진동 측정장치(bite-bar)를 이용한 머리진동 측정에서 직면하는 불확도 인자들에 대한 문제점을 우선 소개한다. 이들 불확도 인자들은 머리의 6-자유도 운동 성분의 추정에 필요한 모든 측정 요소들을 측정하지 않았다는 한계점에서 유발함을 보인다. 이러한 문제점을 극복하기 위하여 4개의 3축 가속도 센서로 구성된 새로운 머리진동 측정장치(12-axis bite-bar)의 모델을 제안한다. 본 모델은 측정 기준점에서의 선형 3축 가속도 뿐 아니라 3축 각 가속도와 함께 6 종의 2차 각속도 성분들의 추정 또한 가능하게 한다. 이러한 12 성분의 추정 모델로부터 비로소 머리의 임의 점에서 6-자유도 운동 성분의 계산이 가능함을 이론적으로 규명한다. 이러한 이론적 배경에 기반을 두고 설계 제작된 12-축 머리진동 장치(12-axis bite-bar)를 소개한다. 본 장치를 이용하여 얻어진 실험 결과 소개 뿐 아니라 기존의 측정 장치의 측정 결과와 비교 분석 내용을 소개한다.

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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 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,[9] referred to the "12-axis bite-bar". Its detailed descriptions are presented in Section 2. 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 3. Finally, the main results of this paper are summarized 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 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.[7~9]

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

$$a_{x,0} = a_{x,R} + \alpha_y \cdot z_{S,0} - \alpha_z \cdot y_{S,0} + \omega_x\omega_y \cdot y_{S,0} + \omega_x\omega_z \cdot z_{S,0} - (\omega_y^2 + \omega_z^2) \cdot x_{S,0}$$
$$a_{y,0} = a_{y,R} + \alpha_z \cdot x_{S,0} - \alpha_x \cdot z_{S,0} + \omega_y\omega_z \cdot z_{S,0} + \omega_y\omega_x \cdot x_{S,0} - (\omega_z^2 + \omega_x^2) \cdot y_{S,0}$$
$$a_{z,0} = a_{z,R} + \alpha_x \cdot y_{S,0} - \alpha_y \cdot x_{S,0} + \omega_z\omega_x \cdot x_{S,0} + \omega_z\omega_y \cdot y_{S,0} - (\omega_x^2 + \omega_y^2) \cdot z_{S,0} \qquad (1)$$

In equation (1), (a_x, a_y, a_z) and $(\omega_x, \omega_y, \omega_z)$ denote the angular acceleration and velocity components of Block 0. Equation (1) means that

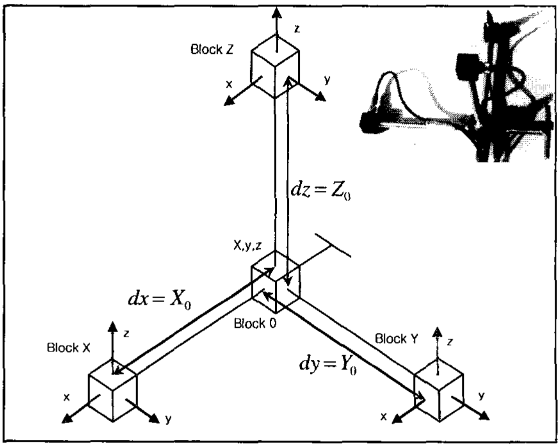


Fig. 1 12-axis bite-bar model with four orthogonal measurement blocks

the acceleration $\mathbf{A}_R$ at the origin is not equal to the measured 3-axis acceleration $\mathbf{A}_0$ from Block 0 and that it can be estimated only when the offset length $(x_{S,0}, y_{S,0}, z_{S,0})$ and the angular velocity and acceleration $(\alpha_x, \alpha_y, \alpha_z)$ and $(\omega_x, \omega_y, \omega_z)$ are available at hand. But, this point has been neglected in the previous work[1~6] by considering the zero offset length $(x_{S,0}, y_{S,0}, z_{S,0}) = (0, 0, 0)$. It is the first measurement uncertainty factor pointed out in this work. It is obvious from Eq. (1) that the determination of the reference acceleration $\mathbf{A}_R$ at the origin can be made only after the estimation of the angular acceleration $(\alpha_x, \alpha_y, \alpha_z)$ and the second order angular velocity terms $(\omega_x \cdot \omega_y, \omega_y \cdot \omega_z, \omega_z \cdot \omega_x, \omega_x^2, \omega_y^2, \omega_z^2)$. In addition, the knowledge of the offset length $(x_{S,0}, y_{S,0}, z_{S,0})$ of a selected three-axis accelerometer is also required to determine the acceleration $\mathbf{A}_R$ at the origin. It is also seen from Eq. (1) that the quantitative analysis of the measurement uncertainty encountered from the zero offset model in the previous work[1~6] can be made by examining the difference between the measured 3-axis acceleration $\mathbf{A}_0$ at Block 0 and the reference acceleration $\mathbf{A}_R$, i.e. $(\mathbf{A}_0 - \mathbf{A}_R)$.

The 12-axis bite-bar designed for this work consists of four orthogonal measurement blocks, as shown in Fig. 1. Each three-axis accelerometer has three linear accelerometers with the identical offset length such that its shape is a cube. Four cube-shaped three-axis accelerometers are arranged in the same orientation for all the three-axis sensing elements. This configuration of the 12-axis bite bar was specifically designed to avoid the mathematical complexity of modeling unequal offset-length three-axis accelerometers. In this work, the offset length of all the three-axis accelerometers was chosen to be equal, i.e. $\{x_{S,k} = y_{S,k} = z_{S,k} = L_S : k = 0, X, Y, Z\}$ (L_S=5.0 mm). The position of the sensing elements of Block X, Y and Z is defined as $(L_S + X_0, L_S, L_S)$ for Block X, $(L_S, L_S + Y_0, L_S)$ for Block Y, and $(L_S, L_S, L_S + Z_0)$ for block Z, respectively. Note that X_0, Y_0 and Z_0 are the span between the centre of Block X, Y, Z and that of the reference Block 0, as shown in Fig. 1. By substituting the offset position $(x_{S,0}, y_{S,0}, z_{S,0})$ of equation (1) for $(L_S + X_0, L_S, L_S)$ for Block X, $(L_S, L_S + Y_0, L_S)$ for Block Y, and $(L_S, L_S, L_S + Z_0)$ for Block Z, it is straightforward to derive all the 3-axis acceleration components for the three X, Y and Z blocks of the bite-bar.

Let $\{\mathbf{A}_X, \mathbf{A}_Y, \mathbf{A}_Z\}$ be the measured three-axis acceleration vectors for Block X, Y, and Z. Their relative accelerations with respect to the reference block (Block 0), $\{\Delta\mathbf{A}_X = \mathbf{A}_X - \mathbf{A}_R, \Delta\mathbf{A}_Y = \mathbf{A}_Y - \mathbf{A}_R, \Delta\mathbf{A}_Z = \mathbf{A}_Z - \mathbf{A}_R\}$, are used to estimate the angular acceleration and velocity components. Let the relative three-axis acceleration components be $\{\Delta a_{x,k}, \Delta a_{y,k}$ and $\Delta a_{z,k} : k = X, Y, Z\}$. Those nine relative acceleration components are used to determine the angular acceleration and angular velocity-related components in Eq. (2), i.e. the nine unknowns $\{\alpha_x, \alpha_y, \alpha_z, \omega_x\omega_y, \omega_y\omega_z, \omega_z\omega_x, \omega_x^2, \omega_y^2, \omega_z^2\}$.

$$\begin{bmatrix} \Delta a_{x,X} \\ \Delta a_{y,X} \\ \Delta a_{z,X} \\ \Delta a_{x,Y} \\ \Delta a_{y,Y} \\ \Delta a_{z,Y} \\ \Delta a_{x,Z} \\ \Delta a_{y,Z} \\ \Delta a_{z,Z} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & -X_0 & 0 \\ 0 & 0 & X_0 & X_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -X_0 & 0 & 0 & 0 & X_0 & 0 & 0 & 0 \\ 0 & 0 & -Y_0 & Y_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -Y_0 \\ Y_0 & 0 & 0 & 0 & Y_0 & 0 & 0 & 0 & 0 \\ 0 & Z_0 & 0 & 0 & 0 & Z_0 & 0 & 0 & 0 \\ -Z_0 & 0 & 0 & 0 & Z_0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -Z_0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \\ \omega_x\omega_y \\ \omega_y\omega_z \\ \omega_z\omega_x \\ \omega_x^2+\omega_y^2 \\ \omega_y^2+\omega_z^2 \\ \omega_z^2+\omega_x^2 \end{bmatrix} \quad (2)$$

The nine unknowns in Eq. (2) are uniquely determined from the nine relative acceleration components. Some algebraic manipulation of Eq. (2) enables the derivation of a simple form of calculating the nine unknowns as follows:

$$\alpha_x = \frac{1}{2}\left(\frac{\Delta a_{z,Y}}{Y_0} - \frac{\Delta a_{y,Z}}{Z_0}\right), \quad \alpha_y = \frac{1}{2}\left(\frac{\Delta a_{x,Z}}{Z_0} - \frac{\Delta a_{z,X}}{X_0}\right),$$

$$\alpha_z = \frac{1}{2}\left(\frac{\Delta a_{y,X}}{X_0} - \frac{\Delta a_{x,Y}}{Y_0}\right),$$

$$\omega_x\omega_y = \frac{1}{2}(\frac{\Delta a_{y,X}}{X_0} + \frac{\Delta a_{x,Y}}{Y_0}),\ \ \omega_y\omega_z = \frac{1}{2}(\frac{\Delta a_{z,Y}}{Y_0} + \frac{\Delta a_{y,Z}}{Z_0}),$$

$$\omega_z\omega_x = \frac{1}{2}(\frac{\Delta a_{x,Z}}{Z_0} + \frac{\Delta a_{z,X}}{X_0}),$$

$$\omega_x^2 = \frac{1}{2}(\frac{\Delta a_{x,X}}{X_0} - \frac{\Delta a_{y,Y}}{Y_0} - \frac{\Delta a_{z,Z}}{Z_0}),$$

$$\omega_y^2 = \frac{1}{2}(-\frac{\Delta a_{x,X}}{X_0} + \frac{\Delta a_{y,Y}}{Y_0} - \frac{\Delta a_{z,Z}}{Z_0}),$$

$$\omega_z^2 = \frac{1}{2}(-\frac{\Delta a_{x,X}}{X_0} - \frac{\Delta a_{y,Y}}{Y_0} + \frac{\Delta a_{z,Z}}{Z_0}) \tag{3}$$

This estimation model can be readily implemented in real-time even for the sampled time series. It is the reason that this work uses the 12-axis bite-bar shown in Fig. 1. By substituting the estimated angular motion related terms $\{\alpha_x, \alpha_y, \alpha_z, \omega_x\omega_y, \omega_y\omega_z, \omega_z\omega_x, \omega_x^2, \omega_y^2, \omega_z^2\}$ and the offset position $(x_{S,0}, y_{S,0}, z_{S,0})$ $(x_{S,0} = y_{S,0} = z_{S,0} = L_S)$ of Block 0 into Eq. (1), the reference acceleration $\mathbf{A}_R$ at the origin is shown to be determined since the measured 3-axis acceleration $\mathbf{A}_0$ from Block 0 is available. It should be noted that the reference acceleration at the origin is determined from the knowledge of the angular motion related terms in Eq. (3) and the offset length of the selected accelerometer with respect to the origin. The use of the measured 3-axis acceleration from Block 0, instead of the estimated reference one at the origin, cannot avoid any measurement uncertainty commented previously. A main aim of estimating the nine angular motion related components in Eq. (3) is to estimate the generalized motion of head at the position of interest.[1~5] Let (x, y, z) be the position to be estimated. By substituting the offset position $(x_{S,0}, y_{S,0}, z_{S,0})$ in Eq. (1) for (x, y, z), the three-axis acceleration components are readily calculated from the knowledge of the estimated reference acceleration $\mathbf{A}_R$ and the estimated angular motion related terms given in Eq. (3).

It is interesting to note that the 12-axis bite-bar enables the systematic error analysis for previous measurement methods. Table 1 illustrates what kinds of measured acceleration components are selected for the estimation of angular motion related components.

The 6-axis bite-bar model[1,3~5] was designed to obtain only the three-axis angular acceleration components $\{\alpha_x, \alpha_y, \alpha_z\}$. This model assumes that all of the offset length for six accelerometers is equal to zero, i.e. $\{x_{S,0} = y_{S,0} = z_{S,0} = y_{S,X} = z_{S,X} = z_{S,Y} = 0\}$. Such assumption enables the approximate estimation model for the three-axis angular acceleration given in Eq. (4).

$$\alpha_x = \frac{a_{z,Y} - a_{z,0}}{Y_0} - \omega_y \cdot \omega_z,\ \ \alpha_y = -\frac{(a_{z,X} - a_{z,0})}{X_0} + \omega_x \cdot \omega_z,$$

$$\alpha_z = \frac{a_{y,X} - a_{y,0}}{X_0} - \omega_x \cdot \omega_y \tag{4}$$

The 6-axis bite-bar model regarded the second order angular velocity terms as a negligible one, i.e. $\omega_x\omega_y \cong \omega_y\omega_z \cong 0$ and $\omega_z\omega_x \cong 0$. As a result, the estimated three-axis angular acceleration components are approximate since the neglected terms cannot be estimated from the six acceleration measurements. Of course, the neglected second order angular velocity terms in Eq. (4) are found to be the uncertainty factors for the estimated three angular acceleration components. The analysis of those uncertainty factors shall be made in Section 3. The 9-axis bite

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

	6-axis bite-bar[1,3~5]		9-axis bite-bar[illegible]	12-axis bite-bar[illegible]
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

bar model(6) is easily realised by deleting the x-axis element for Block X, the y-axis one for Block Y, the z-axis one for Block Z. This accelerometer layout is seen to obtain the six angular motion terms $\{\alpha_x, \alpha_y, \alpha_z, \omega_x\omega_y, \omega_y\omega_z, \omega_z\omega_x\}$ except the three centrifugal force related terms $\{\omega_x^2, \omega_y^2, \omega_z^2\}$. It means that the 9-axis model enables the estimation of the angular acceleration components and the angular velocity cross-product terms but cannot obtain the squared angular velocity terms. Because of such insufficient information, it is not possible to obtain the generalized motion of head at the position of interest.

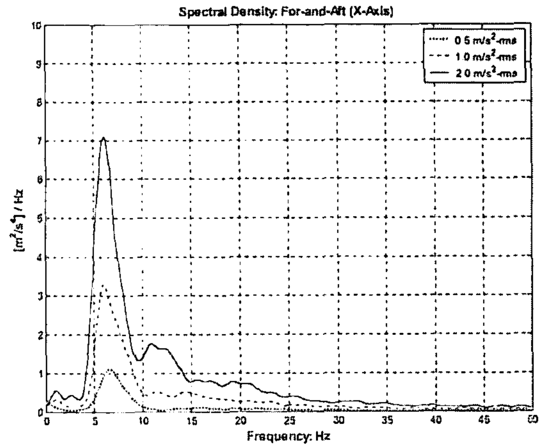
3. Experimental Setup and Results

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 had been made 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. $x_{S,k} = y_{S,k} = z_{S,k} = 5$ mm ; k=0, X, Y, Z). The equal span between the center of the three blocks and that of the reference one was chosen to be 100 mm ($X_0 = Y_0 = z_0 = 100$ mm).

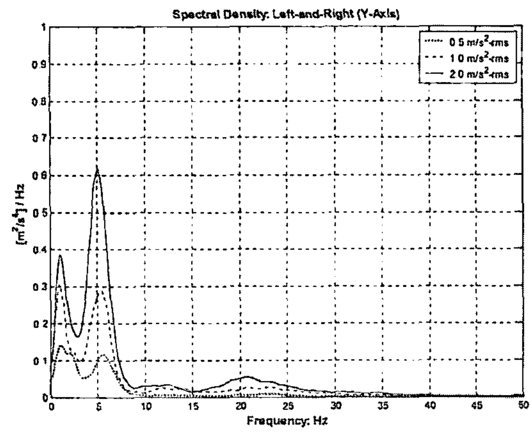
Fig. 2 Picture of the head vibration measurement using the 12-axis bite-bar

To examine the uncertainty characteristics of different bite-bars for the measurement of head vibration, this work carried out the subject test as shown in Fig. 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.} on the seat whose spectra are equally distributed over the frequency range of 1~50 Hz were considered in this work. The hydraulic exciter with the 250 mm maximum vertical stroke capacity (TEAM model 80) was used to generate the vertical vibration whose excitation level was controlled by the single-axis vibration test software (LMS CADA-X Vibration Control).

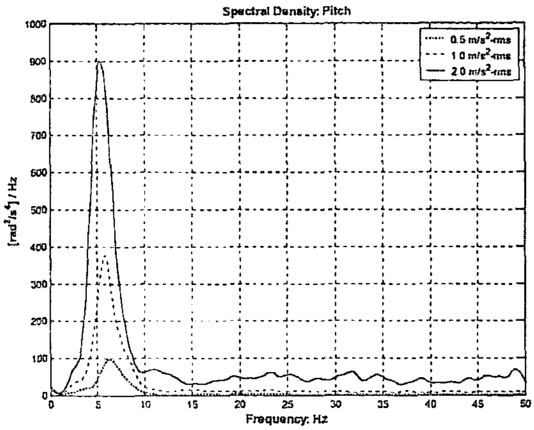
The outputs of a 12-channel signal conditioner that amplify the voltage outputs of the four 3-axis accelerometers were recorded into the 16-bit 32-channel digital recorder (Sony DAT PCCX32A). The digitally recorded 12-channel signals were read into the personal computer using the interface hardware and the software (Sony PCIF-5 and PC Scan II) and stored in the binary format. MATLAB software was used to carry out all the digital signal processing procedures to obtain the time series of 12-axis vibration acceleration signals using Eq. (3). Fig. 3 (a), (b) and (c) show the spectral density functions of the three-axis linear acceleration signals ($a_{x,R}, a_{y,R}, a_{z,R}$) estimated at the origin of Block 0. Fig. 3 (d), (e) and (f) illustrate the spectral density functions of the estimated three-axis rotational acceleration signals ($\alpha_x, \alpha_y, \alpha_z$). As shown in the legend of Fig. 3, the solid line indicates the vibration spectral density function for the vertical vibration excitation level of 2.0 m/s^2−r.m.s., the thin-dotted line does that for the vibration excitation level of 1.0 m/s^2−r.m.s., and the thick-dotted line does that for the vibration excitation level of 0.5 m/s^2−r.m.s.



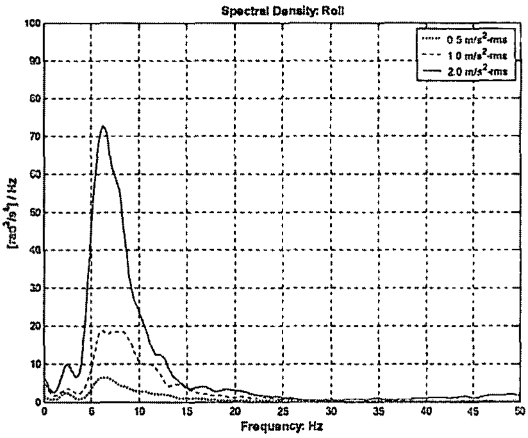
(a) Fore-and-aft (X-axis)



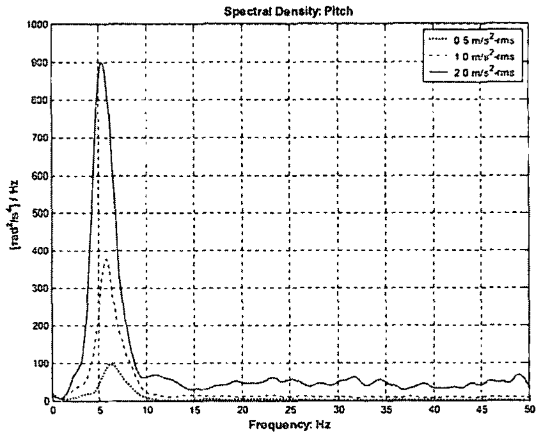
(b) Left-and-right (Y-axis)



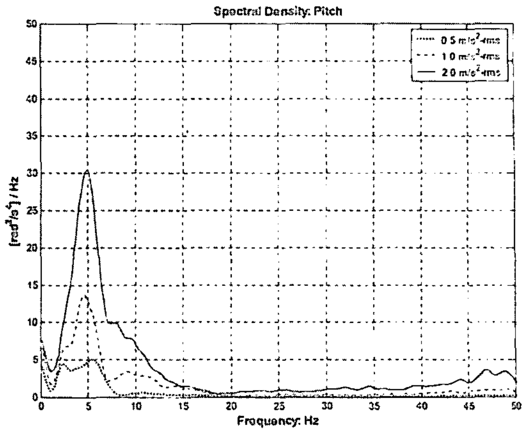
(c) Up-and-down (Z-axis)



(d) Roll (X-axis rotation)



(e) Pitch (Y-axis rotation)



(f) Yaw (Z-axis rotation)

Fig. 3 Measured power spectral density functions 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. As shown in Fig. 3, 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 (left-and-right or lateral) vibration and other rotational motions (i.e., roll, pitch, and yaw), as discussed in the previous work.[1, 3~5, 7~8] Although the vertical vibration component is dominant, the fore-and-aft (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 significant.

The vibration spectra shown in Fig. 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. The 6-axis bite-bar model has been most widely used in the research area of human response to vibration. Figure 4 illustrates two pitch spectra obtained by the 6-axis bite-bar model and the 12-axis bite-bar respectively.

The spectral level of the 6-axis model (depicted as the dotted line) is seen to be lower than that of the 12-axis model (depicted as the solid line)

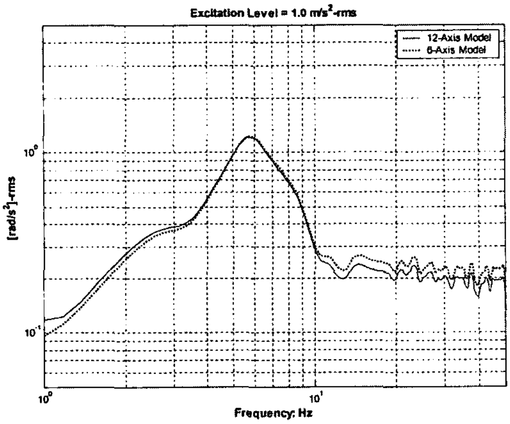


Fig. 4 Comparison between two pitch spectra evaluated using the 6-axis and 12-axis bite-bars for the vertical vibration level of 1.0 m/s^2 r.m.s.

below the frequency of 6 Hz. However, such trend is seen to reverse above the frequency of 6 Hz. These are seen to come from the 'incomplete' model of the 6-axis bite-bar pointed out in Section 2. To examine these effects quantitatively, two relative difference indicators are considered.

$$I_{rel,power} = \frac{\sum_{f=1.0}^{50} \left|P_{rms,12-Axis}(f)\right|^2 - \sum_{f=1.0}^{50} \left|P_{rms,6-Axis}(f)\right|^2}{\sum_{f=1.0}^{50} \left|P_{rms,12-Axis}(f)\right|^2},$$

$$I_{rel,rms} = \sqrt{I_{rel,power}} \qquad (5)$$

Note that $P_{rms,6-Axis}$ and $P_{rms,12-Axis}$ denote the r.m.s-level power spectra obtained from the 6-axis and 12-axis bite-bars and that $I_{rel,power}$ and $I_{rel,rms}$ do the power-level and r.m.s-level indicators. Table 2 shows the relative difference for the three-axis (roll, pitch and yaw) angular acceleration components evaluated over the frequency range of 1 Hz to 50 Hz. The power-level based relative difference indicators of the roll and yaw components are higher than 10 % and that of the pitch is close to 10 %. The r.m.s-level based relative difference indicator for the pitch is seen to be less that 5 %. But those for the roll and yaw components are higher than or close to 10 %. As pointed out in Section 2, the incomplete angular acceleration estimation model for the 6-axis bite bar is seen to yield those estimation errors, i.e. an approximate model that neglects each angular velocity cross-product term in Eq. (4). It should be noted that those estimation errors for the

Table 2 Relative difference indicators for three angular acceleration components

Vibration level	Relative difference indicator					
	Power-level ($I_{rel,power}$)			r.m.s.-level($I_{rel,rms}$)		
	Roll	Pitch	Yaw	Roll	Pitch	Yaw
0.5 m/s^2 r.m.s.	31 %	8 %	13 %	14 %	4.0 %	6.3 %
1.0 m/s^2 r.m.s.	31 %	9 %	20 %	14 %	4.4 %	9.5 %
2.0 m/s^2 r.m.s.	33 %	7 %	29 %	15 %	3.4 %	14 %

6-axis bite bar model were obtained by considering six accelerometers with zero offset length. Those estimation errors are expected to increase by considering the effect of each finite offset length for six accelerometers. The above experimental results were very extraordinary in the research field of human vibration, as observed from the presentation of the preliminary work[9] in ICA 2004. They were unexpected results, which was consistently obtained even for several repeated tests.

In order to improve the estimation errors not commented in this paper, there are several technical 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 model. Those conventional bite-bar models are shown to present insufficient information to evaluate a generalized motion of head vibration. The reason comes from the fact that their incomplete measurement systems fail to enable the evaluation of second-order angular velocity terms required to describe a generalized motion of head vibration. In order to determine the generalized motion of head vibration without any missing term, a new theoretical measurement model that consists of four 3-axis linear accelerometers is suggested. It is shown to enable the measurement of three angular acceleration components and six second-order angular velocity-dependent terms. Those nine angular motion-dependent ones, in addition to the three linear acceleration terms, 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 this paper. To analyze quantitatively measurement uncertainty caused by the precious 6-axis bite-bar model, this work suggests two relative difference indicators, the power-level and r.m.s.-level based indicators. The r.m.s-level based relative difference indicator for the pitch component of head vibration is shown to be about 4 %. But those for the roll and yaw components of head vibration are about 14 % and 10 %, respectively. Such large measurement uncertainty seems to be a big challenge to the 'accurate and reliable' measurement of head vibration. In order to improve further measurement uncertainty of evaluating the generalized motion of head vibration, three technical issues are proposed as follows: (1) modeling of the rigid body motion for all angular motion components of head vibration, (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.

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