Mechanics of Coriolis stimulus and inducing factors of motion sickness

Naoki Isu, Tadaaki Shimizu and Kazuhiro Sugata

Department of Information and Knowledge Engineering, Faculty of Engineering, Tottori University, 4-101 Koyama-minami, Tottori, Tottori, 680-0945, Japan

Abstract To specify inducing factors of motion sickness comprised in Coriolis stimulus, or cross-coupled rotation, the sensation of rotation derived from the semicircular canal system during and after Coriolis stimulus under a variety of stimulus conditions, was estimated by an approach from mechanics with giving minimal hypotheses and simplifications on the semicircular canal system and the sensory nervous system. By solving an equation of motion of the endolymph during Coriolis stimulus, rotating angle of the endolymph was obtained, and the sensation of rotation derived from each semicircular canal was estimated. Then the sensation derived from the whole semicircular canal system was particularly considered in two cases of a single Coriolis stimulus and cyclic Coriolis stimuli. The magnitude and the direction of sensation of rotation were shown to depend on an angular velocity of body rotation and a rotating angle of head movement (amplitude of head oscillation when cyclic Coriolis stimuli) irrespective of initial angle (center angle) of the head relative to the vertical axis. The present mechanical analysis of Coriolis stimulus led a suggestion that the severity of nausea evoked by Coriolis stimulus is proportional to the effective value of the sensation of rotation caused by the Coriolis stimulus.

Introduction

Moving the head during body rotation makes you uncomfortable as you feel when you get a motion sickness. This movement of the head and body is termed Coriolis stimulus, or cross-coupled rotation, since it consists of a combination of two rotations of the head. Coriolis stimulus is so effective to induce motion sickness that it is frequently used in experimental studies. Although it has been shown that nauseogenic effect of Coriolis stimulus is proportional to gyroscopic angular acceleration acting on the head (Isu et al., 1994, 1996), it is still little known what factors, i.e. physical quantities comprised in Coriolis stimulus, cause motion sickness.

To specify inducing factors of motion sickness, we performed an experiment (Isu, 1991). A subject was blindfolded and seated at the center of rotation on a turntable. He/she was rotated horizontally upon the earth-vertical axis at a constant angular velocity $\dot{\psi}_0$ ranging from $\pi/5$ to π rad/s. While being rotated, the subject was oscillated nose-up and down around an axis passing through the ears of both sides. Angle of inclination of the head, $\theta(t)$, varied sinusoidally in accordance with $\theta(t) = \theta_A \cos 2\pi f t$, where θ_A is an amplitude of oscillation ranging from $\pi/60$ to $\pi/12$ rad, and f is a frequency ranging from 0.1 to 0.4 Hz. The subject was given cyclic Coriolis stimuli with 21 combinations of the three parameters in a random order. Duration of every stimulus was 2 min. The severity of

nausea induced by cyclic Coriolis stimuli was measured by the magnitude estimation methods using numerical nausea scores. The results showed that the severity of nausea is proportional to the product of the angular velocity of horizontal body rotation $\dot{\psi}_0$ and the amplitude of head oscillation θ_A , irrespective of the frequency of head oscillation f . Thus it was suggested that the product of $\dot{\psi}_0$ and θ_A determines the severity, in the other words, the product is an inducing factor of motion sickness.

Here, why is the severity proportional to the product? What does the product represent? To solve these questions, it is required to analyze motion of the endolymph in the semicircular canals and estimate the sensation of rotation elicited from them during and after Coriolis stimuli. Although the sensation after Coriolis stimulus has been analyzed and estimated under given conditions in previous studies (Groen, 1961; Peters, 1969; Melvill Jones, 1970; Guedry and Benson 1978), the estimations are applicable only to specific cases that a single Coriolis stimulus of a short period is provided under the given conditions. They can not be applied to estimate the sensation caused by repetitive Coriolis stimuli. In this paper, motion of the endolymph will be obtained by an approach from the mechanics and the sensation produced by the semicircular canal system will be estimated under the minimum restrictions.

Coordinate systems and transform of coordinates

In order to simplify expressions in mechanical analysis, let us define several coordinate systems. First one is the inertial space-fixed coordinate system $O_0(x, y, z)$. Strictly speaking, it must be placed at the center of gravity in the solar system, but we may place it on the surface of the earth, i.e., in a laboratory, with a negligible error. Second coordinate system $O_1(x', Y, z)$ is fixed on a turntable which rotates upon the z axis. Third one $O_2(X, Y, Z)$ is fixed on

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Address for correspondence: Naoki Isu

Department of Information and knowledge Engineering,

Faculty of Engineering, Tottori University

E-mail: isu@ike.tottori-u.ac.jp

Fig. 1 Spatial relations between the coordinates. (a). $O_0(x, y, z)$, $O_1(x', Y, z)$ and $O_2(X, Y, Z)$. (b). $O_2(X, Y, Z)$ and $O_*(\xi, \eta, \zeta)$.

the head of a subject who is oscillated around the Y axis. Furthermore, we define 6 coordinate systems that are fixed on the individual semicircular canals in both sides. Figure 1 shows spatial relations between the coordinate systems. Since our subject of inquiry in this paper is limited at rotation, we do not need consider parallel transition of coordinate systems. At time t , the turntable has rotated by $\psi(t)$ on the z axis, and the head of a subject has been inclined at $\theta(t)$ nose-down. Rotate the inertial space-fixed coordinates $O_0(x, y, z)$ by $\psi(t)$ around the z axis, and you get the turntable-fixed coordinates $O_1(x', Y, z)$. Further rotate it by $\theta(t)$ around the Y axis, and you get the head-fixed coordinates $O_2(X, Y, Z)$. Furthermore, rotate the head-fixed coordinates $O_2(X, Y, Z)$ by angle β around the Y axis, and then rotate by angle α around the X axis, and you get an semicircular canal-fixed coordinates $O_*(\xi, \eta, \zeta)$, where subscript $*$ specifies semicircular canals. Here, $\psi(t)$ and $\theta(t)$ are time variables while α and β are constants.

Let us define R_1 , R_2 , and R_* as the operators of transform of coordinate systems from the inertial space-fixed to the turntable-fixed, from the turntable-fixed to the head-fixed,

Table 1 Angles α_* and β_* in transform matrices R_* (deg)

	LH	LA	LP	RH	RA	RP
α_*	-9.2	-49.1	34.3	-170.8	-130.9	145.7
β_*	-21.9	-88.5	-112.9	-21.9	-88.5	-112.9

and the head-fixed to the individual semicircular canal-fixed coordinate system. Then, the operators are given by these matrices:

$$R_1 = \begin{bmatrix} \cos \psi(t) & \sin \psi(t) & 0 \\ -\sin \psi(t) & \cos \psi(t) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} \cos \theta(t) & 0 & -\sin \theta(t) \\ 0 & 1 & 0 \\ \sin \theta(t) & 0 & \cos \theta(t) \end{bmatrix}$$

$$R_* = \begin{bmatrix} \cos \beta_* & 0 & -\sin \beta_* \\ \sin \alpha_* \sin \beta_* & \cos \alpha_* & \sin \alpha_* \cos \beta_* \\ \cos \alpha_* \sin \beta_* & -\sin \alpha_* & \cos \alpha_* \cos \beta_* \end{bmatrix}.$$

Angles of α and β for the individual semicircular canals are shown in Table 1. They are recalculated from the data measured by Blanks *et al.* (1975).

Angular velocity of head rotation

Let us obtain an angular velocity of head rotation when Coriolis stimulus is given. Let $\dot{\psi}(t)$ be an angular velocity of turntable rotation, and $\dot{\theta}(t)$ be an angular velocity of head movement relative to the turntable. Then, the angular velocity of head rotation is given by

$$\boldsymbol{\omega}_t(t) = R_1 \begin{bmatrix} 0 \\ \dot{\theta}(t) \\ 0 \end{bmatrix} + R_1 \begin{bmatrix} 0 \\ 0 \\ \dot{\psi}(t) \end{bmatrix} = \begin{bmatrix} -\dot{\psi}(t) \sin \theta(t) \\ \dot{\theta}(t) \\ \dot{\psi}(t) \cos \theta(t) \end{bmatrix}$$

as an expression in the head-fixed coordinate system. Transform it by R_* , and you get its expression in the semicircular canal-fixed coordinate system as

$$\boldsymbol{\omega}_*(t) = R_* \boldsymbol{\omega}_t(t)$$

$$= \begin{bmatrix} -\dot{\psi}(t)(\sin \theta(t) \cos \beta_* + \cos \theta(t) \sin \beta_*) \\ \dot{\psi}(t)(-\sin \theta(t) \sin \alpha_* \sin \beta_* + \cos \theta(t) \sin \alpha_* \cos \beta_*) + \dot{\theta}(t) \cos \alpha_* \\ \dot{\psi}(t)(-\sin \theta(t) \cos \alpha_* \sin \beta_* + \cos \theta(t) \cos \alpha_* \cos \beta_*) - \dot{\theta}(t) \sin \alpha_* \end{bmatrix}$$

Here, since the semicircular canals are fixed in the head, the angular velocity of semicircular canal rotation, and of course, the angular velocity of rotation of the coordinate systems fixed on them are identical to the angular velocity of head rotation.

Hypotheses on the semicircular canals

Prior to estimating the sensation evoked by Coriolis stimulus, we must analyze motion of the endolymph caused

in the semicircular canals by head rotation. For that purpose, we build up the minimum hypotheses on the semicircular canals. First, the endolymph in the semicircular canals can be treated as a rigid body. Secondly, the principal axes of inertia of the endolymph coincide with the axes of coordinates fixed on the individual semicircular canals. Thirdly, the endolymph rotates only around the ζ axis. Fourthly, the semicircular canals can be regarded as uniform circular tubes. Although this hypothesis is obviously against the anatomical fact, we need to build it up to give the propriety to the above 3 and the next hypotheses. Lastly, moment of force, i.e., torque, around the ζ axis is attributable to the viscosity of the endolymph and the elasticity of the cupula.

Equation of motion of the endolymph

Base on the hypotheses, let us set up an equation of motion of the endolymph. Let $\psi(t)$ be an angle of rotation of the endolymph relative to the semicircular canal, $\dot{\varphi}(t)$ be an angular velocity of it, I_ζ , I_η and I_ξ be principal moments of inertia of the endolymph, $\omega = [\omega_\zeta, \omega_\eta, \omega_\xi]$ be a vector of angular velocity of head rotation, and $M = [M_\zeta, M_\eta, M_\xi]$ be a moment of force acting on the endolymph. Then, the angular momentum of the endolymph is given by

$$\mathbf{H} = \begin{bmatrix} I_\xi \omega_\xi \\ I_\eta \omega_\eta \\ I_\zeta (\omega_\zeta + \dot{\varphi}) \end{bmatrix}$$

since the angular velocity of the endolymph around the ζ axis is a sum of ω_ζ and $\dot{\varphi}(t)$. Equation of motion is formulated as

$$\frac{d'}{dt} \mathbf{H} + \omega \times \mathbf{H} = \mathbf{M}.$$

Since we hypothesize that the endolymph rotates only around the ζ axis, it is enough to consider only the equation of motion around the ζ axis, that is given by

$$I_\zeta \frac{d}{dt} (\omega_\zeta + \dot{\varphi}) - (I_\xi - I_\eta) \omega_\xi \omega_\eta = M_\zeta.$$

Since the semicircular canal is hypothesized to be a uniform circular tube, the principal moment of inertia around the ξ axis is equal to that around the η axis, i.e., $I_\xi = I_\eta$. Moment of force is given by the viscosity of the endolymph proportional to the angular velocity $\dot{\varphi}(t)$ and the elasticity of the cupula proportional to the angle $\varphi(t)$, i.e., $M = -B\dot{\varphi} - K\varphi$. Substituting these into the above equation, we get

$$I_\zeta \frac{d}{dt} (\omega_\zeta + \dot{\varphi}) = -B\dot{\varphi} - K\varphi.$$

Thus the equation of motion is written as a second order differential equation, i.e.,

$$\frac{d^2 \varphi}{dt^2} + \frac{B}{I_\zeta} \frac{d\varphi}{dt} + \frac{K}{I_\zeta} \varphi = -\frac{d\omega_\zeta}{dt}.$$

Angle of rotation of the endolymph

Let us solve the equation. Initial values are given by $\varphi(0) = \varphi_0$ and $\dot{\varphi}(0) = \dot{\varphi}_0$. The solution of the equation, i.e., the angle of rotation of the endolymph is obtained as

$$\varphi(t) = \frac{\tau_1 \tau_2}{\tau_2 - \tau_1} \left\{ \left(-\int_0^t \frac{d\omega_\zeta}{du} e^{\frac{u}{\tau_2}} du + \frac{\varphi_0}{\tau_1} + \dot{\varphi}_0 \right) e^{-\frac{t}{\tau_2}} - \left(-\int_0^t \frac{d\omega_\zeta}{du} e^{\frac{u}{\tau_1}} du + \frac{\varphi_0}{\tau_2} + \dot{\varphi}_0 \right) e^{-\frac{t}{\tau_1}} \right\}$$

where the constant values B , K and I_ζ are replaced by τ_1 and τ_2 in accordance with $\tau_1 + \tau_2 = B/K$ and $\tau_1 \tau_2 = I_\zeta/K$. Here, time constant τ_1 is much smaller than τ_2 ; it is known that τ_1 is nearly 3 ms, and τ_2 is nearly 10 s in human (Wilson and Melvill Jones, 1979). Now, let us consider cases that Coriolis stimuli are provided during or just after long time rotation of turntable at a constant angular velocity. Then, initial values of φ_0 and $\dot{\varphi}_0$ can be set to 0, since the endolymph is stationary in the semicircular canal. Under this condition, $\varphi(t)$ is simply written as

$$\varphi(t) = -\tau_1 \int_0^t \frac{d\omega_\zeta}{du} \left(e^{\frac{u-t}{\tau_2}} - e^{\frac{u-t}{\tau_1}} \right) du.$$

In a case that a single Coriolis stimulus is provided, i.e., duration of stimulus T is enough shorter than τ_2 , $\varphi(t)$ is given by

$$\varphi(t) = -\tau_1 \int_0^t \frac{d\omega_\zeta}{du} du = -\tau_1 (\omega_\zeta(t) - \omega_\zeta(0))$$

during the stimulus. That is, it is proportional to the angular velocity change from time 0 to t . After the stimulus, $\varphi(t)$ is damped exponentially with a time constant τ_2 , i.e.,

$$\varphi(t) = \varphi(T) e^{-\frac{t}{\tau_2}} = -\tau_1 (\omega_\zeta(T) - \omega_\zeta(0)) e^{-\frac{t}{\tau_2}}.$$

On the other hand, in a case that Coriolis stimuli are repetitively provided, i.e., duration of stimulus is enough longer than τ_2 , $\varphi(t)$ is given by

$$\varphi(t) = -\tau_1 \int_0^t \frac{d\omega_\zeta}{du} e^{\frac{u-t}{\tau_2}} du = -\tau_1 (\omega_\zeta(t) - \bar{\omega}_\zeta).$$

It is proportional to a difference of angular velocity at time t from its temporal average which is given by

$$\bar{\omega}_\zeta = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T \omega_\zeta(t) dt = \frac{1}{\tau_2} \int_0^t \omega_\zeta(u) e^{\frac{u-t}{\tau_2}} du.$$

Hypotheses on the sensory system

In order to estimate the sensation of rotation produced by the semicircular canal system, we need to build up additional hypotheses on the sensory system. First, rotation of the endolymph causes deflection of the cupula, which inclines cilia of hair cells. Then membrane potential in the hair cells varies depending on angles of inclination of the

cia, and it changes firing rate of primary vestibular afferents. As a result, the change in firing rate of primary vestibular afferents is proportional to the angle of rotation of the endolymph. This hypothesis is approximately consistent with physiological observations (Goldberg and Fernandez, 1971; Fernandez and Goldberg, 1971). Secondly, sensory output from a single semicircular canal is proportional to the change in firing rate of primary vestibular afferents. Thirdly, each semicircular canal contributes by half to the sensation of rotation with one degree of freedom. Lastly, the sensory nervous system is organized so that the transform matrix from stimulus to sensation is given by a unit matrix. The last hypothesis means that the sensory system perceives a rotational stimulus as it acts on the head. This hypothesis comprehends the above 3 hypotheses as a consequence.

Sensation produced by the semicircular canal system

Now, let us estimate sensory output from a semicircular canal. Let $\Delta\omega_\zeta(t)$ be an angular velocity change around the ζ axis of a semicircular canal for both cases of a single Coriolis stimulus and repetitive Coriolis stimuli, that is,

$$\Delta\omega_\zeta(t) = \omega_\zeta(t) - \omega_\zeta(0) \text{ (for a single Coriolis stimulus)}$$

$$\Delta\omega_\zeta(t) = \omega_\zeta(t) - \bar{\omega}_\zeta \text{ (for repetitive Coriolis stimuli) .}$$

Then the angle of rotation of the endolymph is simply written as

$$\varphi(t) = -\tau_i \Delta\omega_\zeta(t).$$

Based on the above-mentioned hypotheses, sensory output is proportional to the angle of rotation of the endolymph, then is proportional to the angular velocity change. Hence, sensory output is written as a half of the angular velocity change, i.e.,

$$\tilde{\omega}(t) = \frac{1}{2} \Delta\omega_\zeta(t).$$

Let $\Delta\omega_\zeta(t)$ be a vector of angular velocity change of head rotation expressed in the head-fixed coordinate system. Transform it to the semicircular canal-fixed coordinates, and take its ζ component. Then, sensory output from a single semicircular canal is estimated by

$$\Delta\omega_{\zeta_s}(t) = [0 \ 0 \ 1] R_s \Delta\omega_\zeta(t).$$

If the sensory nervous system was organized so that sensory output from each semicircular canal caused the sensation of rotation on its own plane, and it was summed together evenly to create the sensation of rotation, the sensation of rotation produced by the semicircular canal system would be given by a sum of sensory outputs from the 6 individual semicircular canals, that is,

$$\tilde{\omega}_s(t) = \sum_s R_s^{-1} \begin{bmatrix} 0 \\ 0 \\ \tilde{\omega}_s(t) \end{bmatrix} = \sum_s R_s^{-1} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1/2 \end{bmatrix} R_s \Delta\omega_\zeta(t).$$

$$= \begin{bmatrix} 1.143 & 0 & -0.105 \\ 0 & 0.916 & 0 \\ -0.105 & 0 & 0.942 \end{bmatrix} \Delta\omega_\zeta(t).$$

It does not coincide with a given stimulus. This is resulted from an anatomical fact that the semicircular canals are not arranged at right angles with each other (Blanks et al., 1975; Curthoys et al., 1977).

Accordingly, we build up the above-mentioned hypothesis, that is, the sensory nervous system adjusts the summation of sensory outputs so as to produce the sensation coincident with a stimulus. The sensory nervous system is thought to adopt a different matrix R_*^{-1} , instead of R_s^{-1} , to transform sensory outputs to the sensation. The sensation of rotation produced by the semicircular canal system is given by

$$\tilde{\omega}_s(t) = \sum_s R_*^{-1} \begin{bmatrix} 0 \\ 0 \\ \tilde{\omega}_s(t) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \Delta\omega_\zeta(t) = \Delta\omega_\zeta(t).$$

Angles α' and β' for R_*' corresponding to α and β for R_s are shown in Table 2.

Sensation of rotation caused by Coriolis stimuli

Single Coriolis stimulus

Let us consider the sensation of rotation caused by Coriolis stimulus. First, consider a case that a single Coriolis stimulus is provided. Let $\dot{\psi}(t)$ be an angular velocity of turntable rotation, and $\dot{\theta}(t)$ be an angular velocity of head movement relative to the turntable. Angular velocity of head rotation is given by

$$\omega_2(t) = \begin{bmatrix} -\dot{\psi}(t) \sin \theta(t) \\ \dot{\theta}(t) \\ \dot{\psi}(t) \cos \theta(t) \end{bmatrix}$$

as an expression in the head-fixed coordinate system. If a duration of Coriolis stimulus is much shorter than τ_s , i.e., 10 seconds, the angular velocity change is given by

$$\Delta\omega_2(t) = \omega_2(t) - \omega_2(0).$$

Then the sensation of rotation becomes

$$\tilde{\omega}_2(t) = R_s^{-1} \tilde{\omega}_2(t) = R_s^{-1} \Delta\omega_2(t) = \begin{bmatrix} -\dot{\psi}(0) \sin(\theta(t) - \theta(0)) \\ \dot{\theta}(t) - \dot{\theta}(0) \\ \dot{\psi}(t) - \dot{\psi}(0) \cos(\theta(t) - \theta(0)) \end{bmatrix}$$

when expressed in the turntable-fixed coordinate system.

Table 2 Angles α'_s and β'_s in transform matrices R_*' (deg)

	LH	LA	LP	RH	RA	RP
α'_s	-3.8	-59.8	34.3	-176.2	-120.2	145.7
β'_s	-15.0	-109.8	-112.9	-15.0	-109.8	-112.9

Fig. 2. Sensation of rotation $\tilde{\omega}_1(t)$ caused by a single Coriolis stimulus. It varies along the indicated curve irrespective of the initial angle of inclination $\theta(0)$.

Further let us impose an additional condition that Coriolis stimulus is provided during horizontal body rotation at a constant angular velocity; that is, $\dot{\psi}(t)$ is a constant $\dot{\psi}_0$. Before starting the Coriolis stimulus, the angular velocity of head movement $\dot{\theta}(0)$ is 0. Substitute them into the last formula, and we get the sensation of rotation as

$$\begin{aligned} \tilde{\omega}_1(t) &= \begin{bmatrix} -\dot{\psi}_0 \sin(\theta(t) - \theta(0)) \\ \dot{\theta}(t) \\ \dot{\psi}_0 \{1 - \cos(\theta(t) - \theta(0))\} \end{bmatrix} \\ &= 2\dot{\psi}_0 \sin\left(\frac{\theta(t) - \theta(0)}{2}\right) \begin{bmatrix} -\cos\left(\frac{\theta(t) - \theta(0)}{2}\right) \\ 0 \\ \sin\left(\frac{\theta(t) - \theta(0)}{2}\right) \end{bmatrix} + \dot{\theta}(t) \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}. \end{aligned}$$

It varies in magnitude and direction as indicated by the locus shown in Fig. 2.

Repetitive Coriolis stimuli

Next, let us consider another case that Coriolis stimuli are provided repetitively during horizontal body rotation at a constant angular velocity $\dot{\psi}_0$. The head is oscillated sinusoidally with an amplitude of θ_A and a center angle of oscillation of θ_0 at a frequency of f , that is, $\theta(t) = \theta_0 + \theta_A \cos 2\pi f t$. Then, the temporal average of angular velocity of head rotation is approximately given by

$$\bar{\omega}_1 = \begin{bmatrix} -\dot{\psi}_0 \sin \theta_0 \cos\left(\frac{\theta_A}{\sqrt{2}}\right) \\ 0 \\ \dot{\psi}_0 \cos \theta_0 \cos\left(\frac{\theta_A}{\sqrt{2}}\right) \end{bmatrix}$$

when θ_A is smaller than 1 rad. Then the sensation of rotation is given by

Fig. 3. Sensation of rotation $\tilde{\omega}_1(t)$ caused by repetitive Coriolis stimuli. It varies along the indicated curve irrespective of the center angle of oscillation θ_0 .

$$\begin{aligned} \tilde{\omega}_1(t) &= R_2^{-1} \tilde{\omega}_1(t) = R_2^{-1} (\omega_1(t) - \bar{\omega}_1) \\ &= \begin{bmatrix} -\dot{\psi}_0 \cos\left(\frac{\theta_A}{\sqrt{2}}\right) \sin(\theta_0 \cos 2\pi f t) \\ \dot{\theta}(t) \\ \dot{\psi}_0 \left\{1 - \cos\left(\frac{\theta_A}{\sqrt{2}}\right) \cos(\theta_0 \cos 2\pi f t)\right\} \end{bmatrix} \end{aligned}$$

when expressed in the turntable-fixed coordinate system. The sensation of rotation varies so that the tip of its vector draws the locus shown in Fig. 3, irrespective of the center angle of oscillation θ_0 .

Mean square of the sensation of rotation is given by

$$\|\tilde{\omega}_1\|^2 = \dot{\psi}_0^2 \sin^2\left(\frac{\theta_A}{\sqrt{2}}\right) + (\sqrt{2}\pi f \theta_A)^2.$$

If the angular velocity of horizontal body rotation is enough higher than $2\pi f$, the effective value of the sensation is given by

$$\|\tilde{\omega}_1\|_{\text{eff}} = |\dot{\psi}_0| \sin\left(\frac{\theta_A}{\sqrt{2}}\right) \approx |\dot{\psi}_0| \frac{\theta_A}{\sqrt{2}}.$$

Thus, it is proportional to a product of the angular velocity of horizontal body rotation $\dot{\psi}_0$ and the amplitude of head oscillation θ_A .

Discussion

Sensations caused by Coriolis stimuli were analyzed and estimated with focusing on those elicited from the semicircular canal system in this paper. This aimed to give an interpretation of the meaning to our experimental observation that the severity of nausea was proportional to a product of the angular velocity of horizontal body rotation $\dot{\psi}_0$ and the amplitude of head oscillation θ_A (Isu, 1991). The present mechanical analysis of Coriolis stimulus led a suggestion that the severity of nausea evoked by Coriolis stimulus is proportional to the effective value of the sensation of rotation caused by the Coriolis stimulus.

On the other hand, it is well known that Coriolis

stimulus scarcely induce motion sickness under weightlessness (Graybiel, 1980). Motion sickness was induced by repetitive Coriolis stimuli in preflight and postflight, but scarcely induced in mission days, that is, under micro gravity. Woodman et al. (1997) reported a difference in nausea enhanced by Coriolis stimulus between directions of head movement. Head movement from a nose-up posture to the upright enhanced nausea more frequently than that of the reversed direction. These results indicate that the gravity, therefore the otolithic organs and the somatic sensation, also play important roles in inducing motion sickness. It would be important to consider an interaction, or sensory conflict, between the sensation of rotation produced by the semicircular canal system and that by the otolithic system and the somatic sensory system in order to elucidate the causes of Coriolis motion sickness.

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