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THE EFFECTS OF THE PLANE OF VESTIBULAR STIMULATION

ON TASK PERFORMANCE AND INVOLUNTARY EYE MOTION

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INTRODUCTION

An analytical examination (ref. 1) indicates that the orientation of the astronaut within a rotating space vehicle has considerable influence on the stimulation of his vestibular system. This postulation of different stimulations for different orientations was also experimentally indicated in reference 2. The analysis of reference 1 further indicates that while a subject is erect with his long-body axis parallel to the axis of rotation, as in the slow rotating room at Pensacola (ref. 3), the position in which he faces has no effect on the stimulation of the vestibular system. In contrast, however, with the subject's long axis perpendicular to the axis of rotation as it would be in a rotating space vehicle, the stimulation of the vestibular system is affected by the manner in which the subject faces while standing. Facing tangentially causes different stimulation than does facing axially. All experimental studies performed at the Langley Research Center have been performed with the subject facing axially; that is, with his neutral or face-forward position being axial (refs. 1, 4, and 5). When performing head motions in these references the subjects moved their heads about $\pm 45^{\circ}$ from the axial position. Because of the previously mentioned effect of orientation

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experiments are now being performed with subject facing tangentially. This paper presents the results obtained thus far with this subject orientation.

SYMBOLS

α_{G_θ}	cross-coupled nodding acceleration
α_{G_ψ}	cross-coupled turning acceleration
α_{G_ϕ}	cross-coupled rolling acceleration

$$\omega_{G_\theta} = \int \alpha_{G_\theta}\, dt$$

$$\omega_{G_\psi} = \int \alpha_{G_\psi}\, dt$$

$$\omega_{G_\phi} \quad \int \alpha_{G_\phi}\, dt$$

ω_{h_θ}	nodding velocity - a fore and aft motion of the head at the neck or from the whole body	These are angular head motions and may be from motions at the neck and shoulders or from body bending, etc.
ω_{h_ψ}	turning velocity - a motion about the neck or long-body axis	
ω_{h_ϕ}	rolling velocity - a sideways motion of the head or from the body	

ω_V	vehicle rotational velocity
ω_{h_x}	total angular velocity of head about rolling axis
ω_{h_y}	total angular velocity of head about nodding axis
ω_{h_z}	total angular velocity of head about turning axis
t	time

$$\theta_G = \iint \alpha_{G_\theta} \, dt^2$$

$$\psi_G = \iint \alpha_{G_\psi} \, dt^2$$

$$\phi_G = \iint \alpha_{G_\phi} \, dt^2$$

θ_n nodding displacement

ψ_n turning displacement

ϕ_n rolling displacement

θ_e, ψ_e, ϕ_e Euler angular displacement using the order of rotation shown in figure 2 of reference 1

θ_{sc} backward tilt of semicircular canals from X_bY_b plane

ψ_{sc} rotation of semicircular canals from X_bY_b plane

X,Y,Z inertial space axes

X_b, Y_b, Z_b body axes

Subscripts:

lr, ll right and left lateral canals, respectively

pr, pl right and left posterior canals, respectively

ar, al right and left anterior canals, respectively

A dot over a symbol indicates its first derivative with respect to time.

ANALYSIS

An analytical development of the angular accelerations which stimulate the semicircular canals is presented in reference 1. The results of this development are the three angular accelerations of the head as functions of head position and vehicle angular velocity. These are:

$$
\left.
\begin{aligned}
\dot{\omega}_{h_x} &= \dot{\omega}_{h_\phi} - \omega_V\left(\omega_{h_\theta} \sin \theta_e + \omega_{h_\psi} \cos \theta_e \sin \psi_e\right) \\
\dot{\omega}_{h_y} &= \dot{\omega}_{h_\theta} - \omega_V\left(\omega_{h_\psi} \cos \theta_e \cos \psi_e - \omega_{h_\phi} \sin \theta_e\right) \\
\dot{\omega}_{h_z} &= \dot{\omega}_{h_\psi} + \omega_V\left(\omega_{h_\theta} \cos \theta_e \cos \psi_e + \omega_{h_\phi} \cos \theta_e \sin \psi_e\right)
\end{aligned}
\right\} \qquad (1)
$$

The two extremes of orientation possible for an upright subject standing on the floor of a rotating space vehicle, as has been noted previously, are facing axially as on the right of figure 1, and facing tangentially as on the left of figure 1. When facing axially ψ_e is zero or 180°; while facing tangentially ψ_e is 90° or 270°. Generally θ_e, a measure of the nodding position of the head, is near zero except when nodding the head, or when bent over, or when lying on the floor or parallel to the floor. The experiments considered in this paper are with $\theta_e = 0°$ and with $\psi_e = 0°$ or 270°, with the head being turned about these values of ψ_e, as neutral positions. The equations for these two specific situations by appropriate substitution in equations (1) above are:

$$
\left.
\begin{aligned}
\dot{\omega}_{h_x} &= -\omega_V \omega_{h_\psi} \sin \psi_e = \alpha_{G_\phi} \\
\dot{\omega}_{h_y} &= -\omega_V \omega_{h_\psi} \cos \psi_e = \alpha_{G_\theta} \\
\dot{\omega}_{h_z} &= \dot{\omega}_{h_\psi}
\end{aligned}
\right\} \qquad (2)
$$

The significance of the difference between facing axially or tangentially lies in the value of ψ_e as noted previously. Table I lists the physical stimulation that occurs because of these different orientations. The accelerations listed are for each of the three canals of the right ear. Also shown is the effect of canal orientation within the head, indicating the effects of the range of variations of canal orientation for the ranges noted in reference 6. Essentially what is indicated by equations (2) and table I is that when turning the head while facing axially the cross-coupled angular acceleration is in the nodding sense, whereas when turning the head while facing tangentially the cross-coupled angular acceleration is in the rolling sense. These cross-coupled angular accelerations are, of course, the unnatural accelerations encountered in a rotating environment and those which cause visual illusions, nausea, and nystagmus.

Actually, the value of ψ_e is variable when the head is being turned. Figure 2 is a graphical indication of the cross-coupled angular acceleration that would occur while turning the head about 45° from the left to 45° to the right of the neutral positions of $\psi_e = 0^\circ$ and 270°. The head motion shown in figure 2 is an actual motion from which the head position was measured. The apparent motions were computed for the axially and tangentially facing conditions based on equations (2). There is, as implied previously, a considerable difference in the stimulation. Generally one would expect an illusion of the spacecraft pitching relative to the subject when facing axially, and an illusion of the spacecraft rolling relative to the subject when facing tangentially. When facing axially one also expects that a vertical nystagmus will occur because of the real pitching or nodding stimulation; this is experimentally verified in reference 2. When facing tangentially where the cross-coupled angular stimulation is in the rolling sense, one may expect that some eye counterrolling will be incurred.

TEST EQUIPMENT AND TECHNIQUE

The experiments performed to evaluate the influence of the differences in stimulation discussed previously were performed on the Langley Research Center's rotating space vehicle simulator shown in figure 3. This device consists basically of two concentric rotating cylindrical walls, one with a 20-foot diameter and the other with a 40-foot diameter. These cylindrical walls simulate the floor of a rotating vehicle upon which subjects, as described in reference 1, can walk and otherwise perform as they would in a rotating space vehicle. The tests performed for the purposes of this report, however, did not use the simulator in the sense just described. For the current results a small cabin was installed on the short-diameter cylinder similar to that described in reference 1. Thus the radius for these experiments was 10 feet. For the purposes of the current results the subjects lay in this cabin on their sides facing tangentially with their long-body axis oriented radially (perpendicular to the axis of rotation) with their feet outward. On previous experiments, using another simulator, the subjects were lying on their back facing axially and with their feet 15 feet from the center of rotation. The system, measuring devices, and testing techniques are the same as used in previous experiments at Langley and are described in reference 1. A sketch showing the internal features of this simulator is shown in figure 4. Briefly the subjects are required to turn their heads to the left and observe three lights of different colors. When a specific light was lit, the subject was required to turn his head to his right and turn off the light by placing a probe in an appropriate hole to extinguish the light. The head position and rate of head motion and the time required to extinguish the light were measured. For the results presented herein 12 subjects were used, all facing in the tangential direction. Each head-turning experiment lasted 1 hour and rates of rotation of 0, 9, 12, 14, and 16 rpm were used. The lights were activated in a random fashion with time periods between tasks of from 20 to 35 seconds. This is as essentially described in reference 1. Some motion pictures of the eyes were made to determine the motion of the eyes under the conditions of the experiment.

RESULTS AND DISCUSSION

In order to determine the effect of the subject orientation and the resulting differences in cross-coupled angular accelerations on task performance, the results of reference 4 are compared with the present results in figures 5, 6, and 7. It should be pointed out that the present results were obtained on the rotating simulator shown in figure 3 with the subject's feet 10 feet from the center of rotation while those of reference 4 were obtained on another simulator with the subject's feet located 15 feet from the center of rotation. However, it can be assumed that the radius of rotation would have an insignificant effect on the results based on the data of reference 1. The results of reference 1 indicated that there was little or no effect of radius on the performance and tolerance for nodding head motions where the results for 3 radii, 10, 15, and 20 feet were compared. It is felt that the effects of 10- and 15-foot radius for the comparisons presented here will not be significant. The data presented on figures 5, 6, and 7 are the numerical averages from all the subjects participating. There were 29 subjects oriented facing axially in the tests of reference 4 and 12 subjects oriented facing tangentially for the present tests.

The average amplitude of head motion plotted against vehicle rpm is shown in figure 5 with the axial and tangential orientation of the subjects represented by the circles and squares, respectively. The amplitude of head motion used by the subjects oriented axially is generally about 12° less than that used by the subjects when oriented tangentially. This may be due to small differences in the location of the lights and switches and in the way the subjects used their eyes. For both orientations there was a small decrease in head motion amplitude with increase in vehicle rpm. This is also true for the head rate variation with rpm shown in figure 6. This is probably caused by the subjects attempting to limit the magnitude of the stimulus and the resulting disquieting effects. The subjects of reference 4 first found motion intolerable at a head rate of about 220°/sec at a vehicle rate of 10 rpm. Although one of the subjects of the present test used head rates considerably lower than this, even at 9 rpm, in order to avoid malaise, he completed the entire experiment. As can be seen from figure 6 the subjects of the present tests averaged head rates 100°/sec higher than those of reference 4. This indicates that, in general, the subjects could tolerate greater cross-coupled accelerations while oriented facing tangentially than when oriented facing axially. It should be pointed out that only 2 subjects participated in both sets of tests.

The variation of response time with vehicle rpm is shown in figure 7 for both subject orientations. There is essentially only a small effect of vehicle rate or orientation on the response time (time from light activation to time light was extinguished). The response time for the tangential orientation is about 0.2 to 0.4 second less than that for the axial orientation. However, this decrease is not as great as would be expected on the basis of the greatly increased head rate used in the tangential orientation. One of the factors which may have affected this result is that different arm movements were used in the different orientations. For the tangential orientation the subject's arm had to be raised vertically to extinguish the light and this evidently is not as easy as moving the arm laterally as was required in the axial orientation.

Since it is felt that the level of distress experienced by the subjects during rotation depends on the magnitude of cross-coupled accelerations, tolerance to rotation can be assumed to be determined by tolerance to cross-coupled accelerations. Thus constant values of this acceleration, which is the product of head rate and vehicle rate, form boundaries above which motion can become intolerable.

Figure 8 presents a comparison of the tolerance boundaries for the axial and tangential orientations together with some test points from both experiments. The figure is a plot of head rate versus vehicle rate of rotation. The curves shown are hyperbolas and are loci of constant cross-coupled accelerations. The tolerance boundary from reference 4, shown by the solid curve, was prepared on the basis of 10 rpm where the subjects of reference 4 first found motion intolerable. This curve represents a cross-coupled acceleration of 4.0 radians/sec^2. The circles at 14 and 17 rpm represent, respectively, the conditions tolerated by 80 percent and 50 percent of the subjects of reference 4. For comparison purposes the boundary for the tangential orientation of the present tests was also prepared based on the results obtained at 10 rpm and is shown by the dashed curve. This curve represents a constant cross-coupled acceleration of 5.85 radians/sec^2. However, as shown by the data points for the tangential orientation the subjects generally tolerated cross-coupled accelerations considerably higher than this value. In contrast to the previous experiment where only about 50 percent of the subjects completed the entire experiment, all of the subjects completed the present tests. These results tend to indicate that the tangentially oriented subjects apparently can tolerate cross-coupled accelerations of considerably greater magnitude than that tolerated by the subjects oriented axially. As mentioned earlier the cross-coupled acceleration for the tangentially facing subjects is in the rolling sense while that for the axially facing subjects is in the nodding sense.

CONCLUDING REMARKS

Consideration of the results of this paper indicates that, for a turning head motion, the stimulation experienced by the tangentially oriented subjects is considerably different than that experienced by the axially oriented subjects, the stimulation being a cross-coupled acceleration in the nodding sense when tangentially oriented and in the rolling sense when axially oriented. The data of both experiments generally indicate a tolerance to 10 rpm for most subjects. The data also indicate that the subjects could tolerate greater cross-coupled accelerations when facing tangentially than they could while facing axially. The results presented are for a limited number of subjects performing a relatively simple task for short periods and should be confirmed by other subjects and experiments.

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TABLE I.- CANAL STIMULATION FOR VARIOUS ORIENTATIONS

ON THE CANALS IN THE HEAD (HEAD TURNING)

[Assume that the head moves steadily through the noted values of ψ_e, ϕ_e, and θ_e for consideration of this table]

Canal acceleration	$\theta_{sc} = 15^\circ$		$\theta_{sc} = 30^\circ$	
	ψ_{sc}		ψ_{sc}	
	35°	65°	35°	65°
Axial orientation, $\psi_e = \phi_e = \theta_e = 0$				
$\dot{\omega}_{sc_{lr}}$	0	0	0	0
$\dot{\omega}_{sc_{ar}}$	$-0.8192\omega_V\omega_{h_\psi}$	$-0.4226\omega_V\omega_{h_\psi}$	$-0.8192\omega_V\omega_{h_\psi}$	$-0.4226\omega_V\omega_{h_\psi}$
$\dot{\omega}_{sc_{pr}}$	$-0.5736\omega_V\omega_{h_\psi}$	$-0.9063\omega_V\omega_{h_\psi}$	$-0.5736\omega_V\omega_{h_\psi}$	$-0.9063\omega_V\omega_{h_\psi}$
Tangential orientation, $\psi_e = 270$, $\phi_e = \theta_e = 0$				
$\dot{\omega}_{sc_{lr}}$	$0.2588\omega_V\omega_{h_\psi}$	$0.2588\omega_V\omega_{h_\psi}$	$0.5000\omega_V\omega_{h_\psi}$	$0.5000\omega_V\omega_{h_\psi}$
$\dot{\omega}_{sc_{ar}}$	$-0.5540\omega_V\omega_{h_\psi}$	$-0.8754\omega_V\omega_{h_\psi}$	$-0.4967\omega_V\omega_{h_\psi}$	$-0.7894\omega_V\omega_{h_\psi}$
$\dot{\omega}_{sc_{pr}}$	$0.7193\omega_V\omega_{h_\psi}$	$0.4082\omega_V\omega_{h_\psi}$	$0.7094\omega_V\omega_{h_\psi}$	$0.3660\omega_V\omega_{h_\psi}$

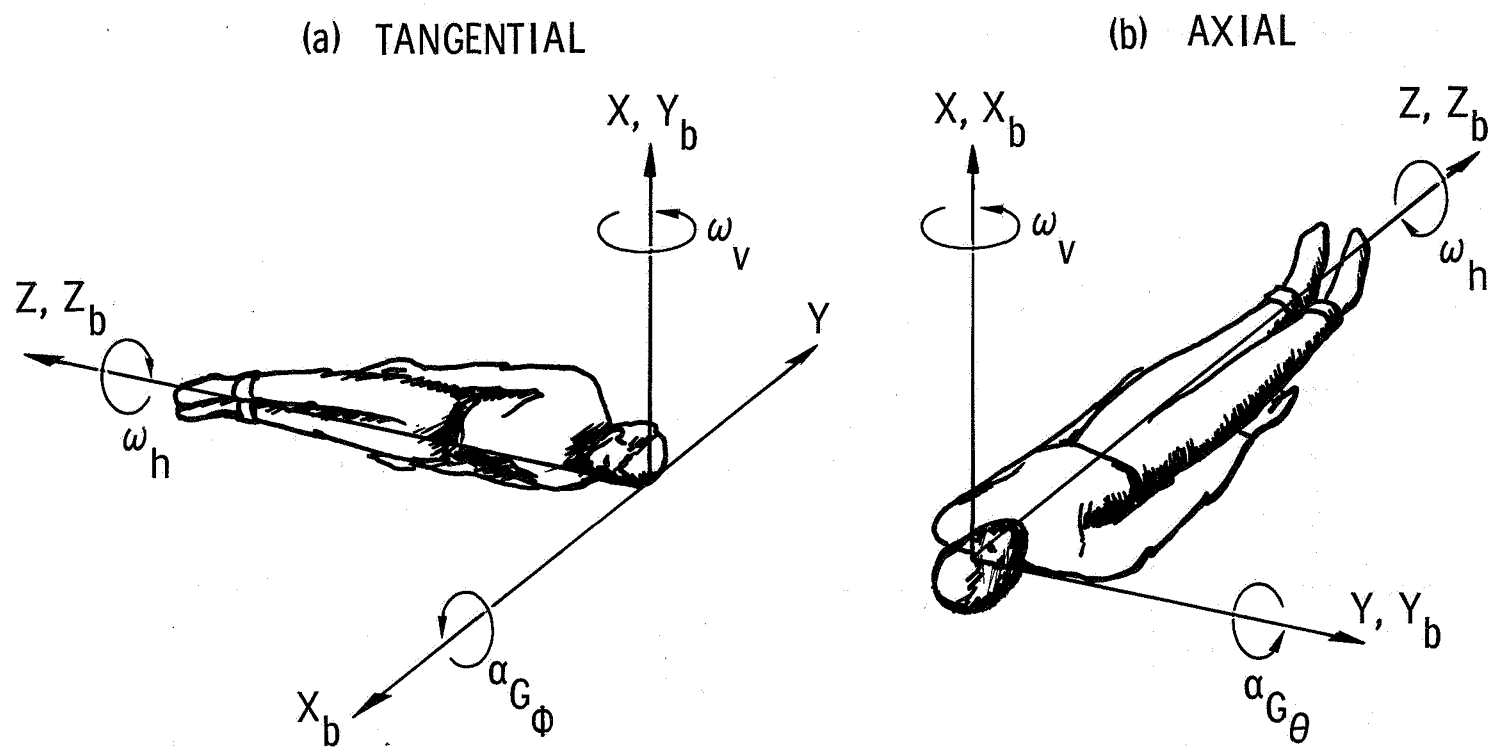

Figure 1.- Sketch showing axial and tangential orientation of subjects.

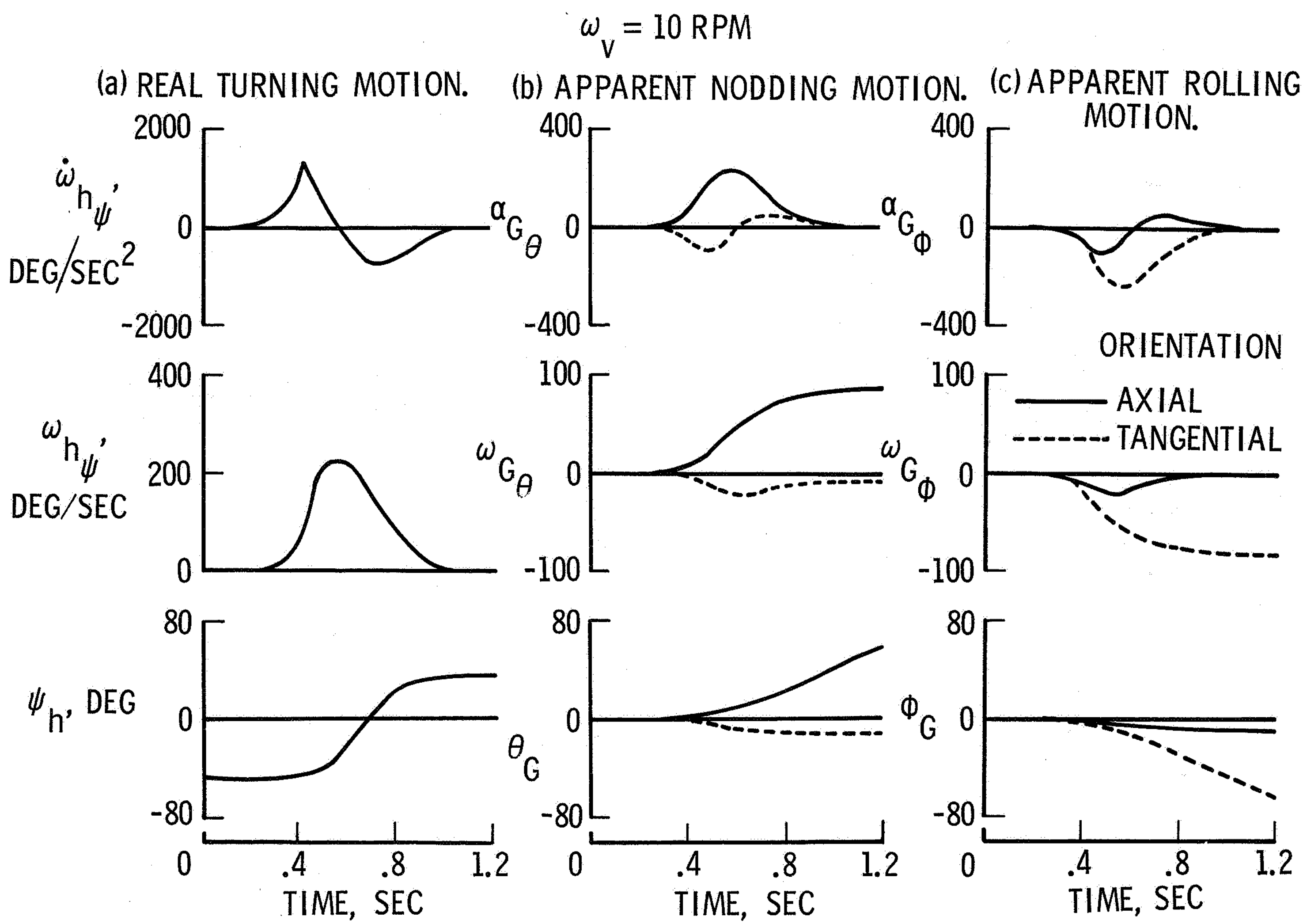

Figure 2.- Typical head motion and resulting apparent motions while turning the head in a vehicle rotating at 10 rpm. Subjects are oriented facing axially and tangentially.

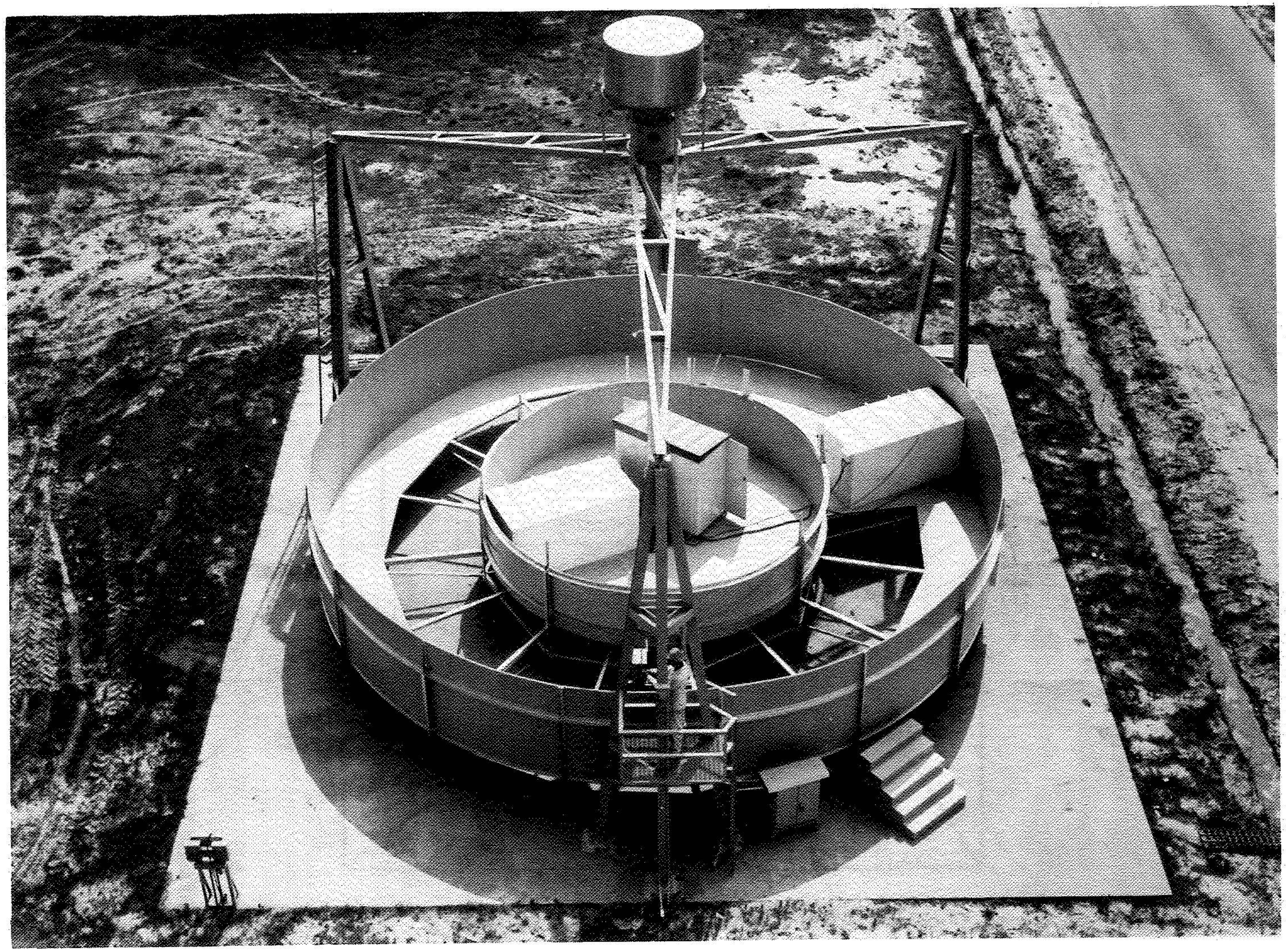

Figure 3.- The Langley rotating-vehicle simulator.

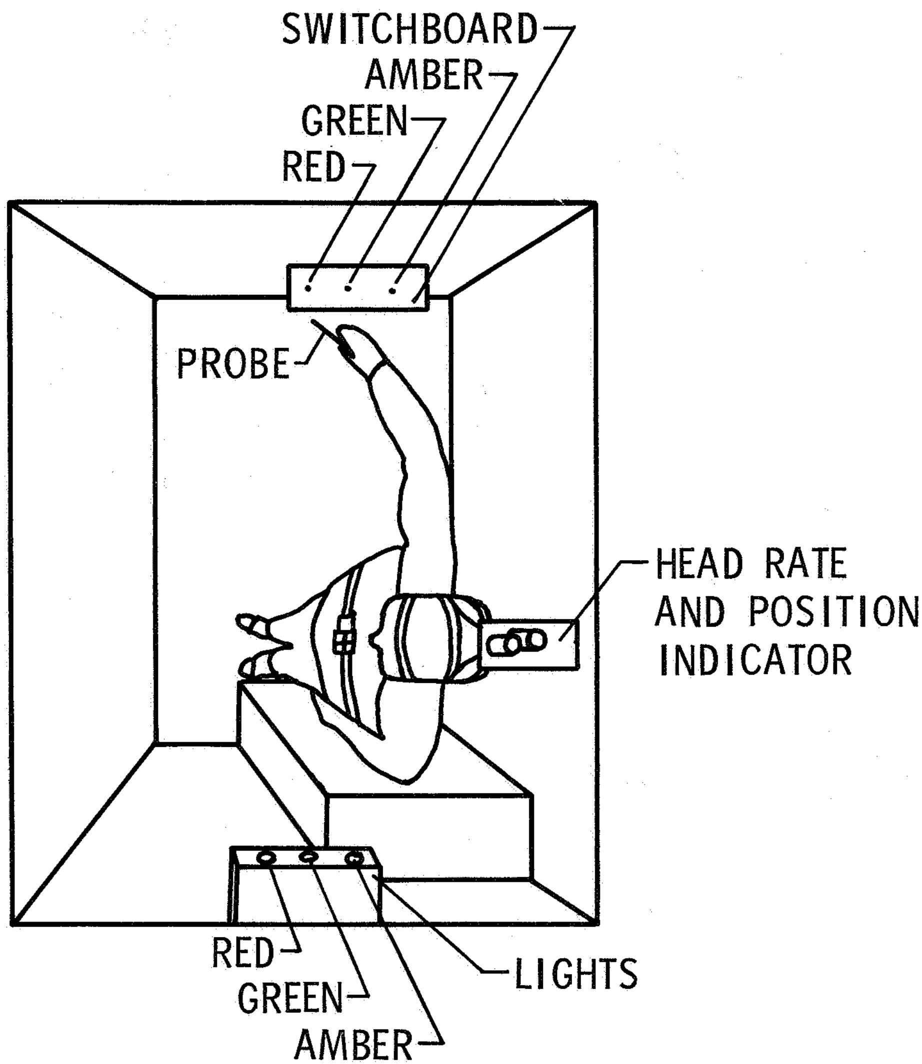

Figure 4.- Internal features of simulator.

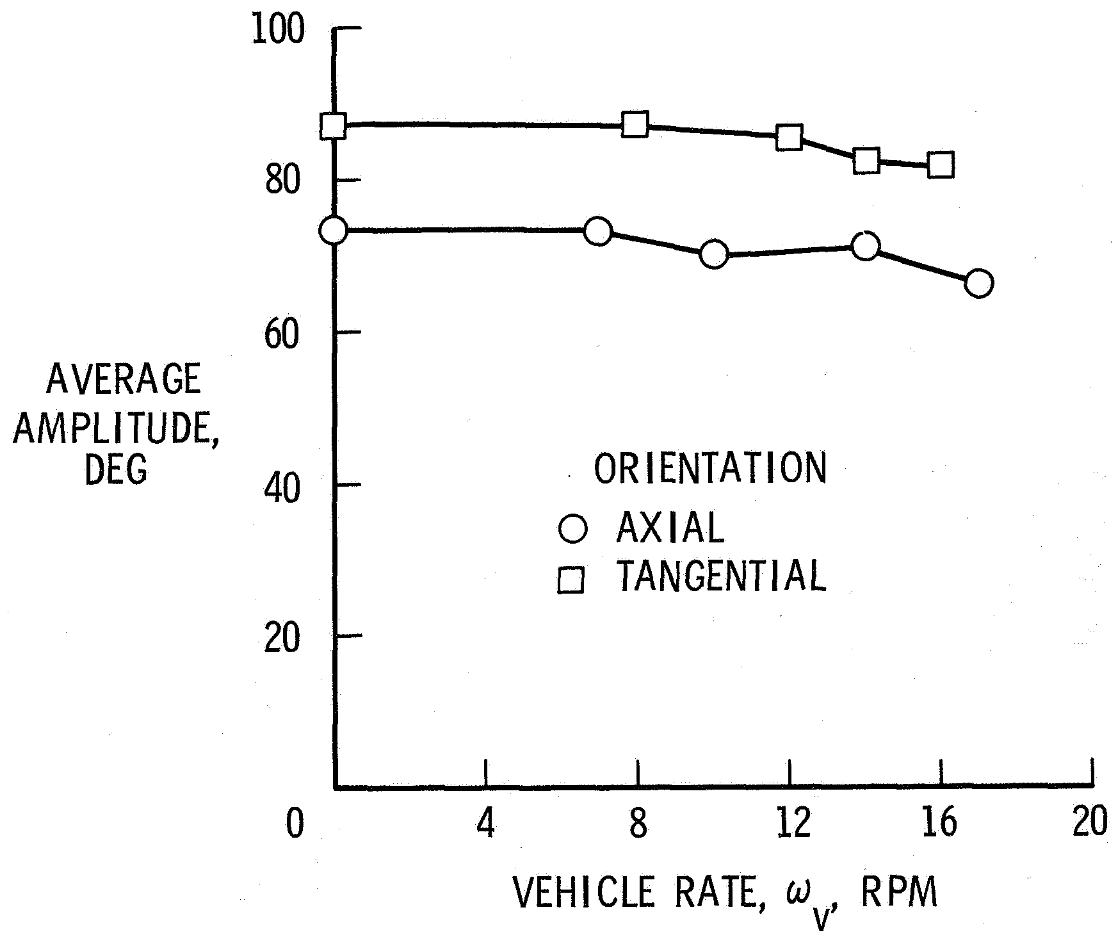

Figure 5.- Amplitude of head turning motion at various rates of simulator rotation for subject facing axially and tangentially.

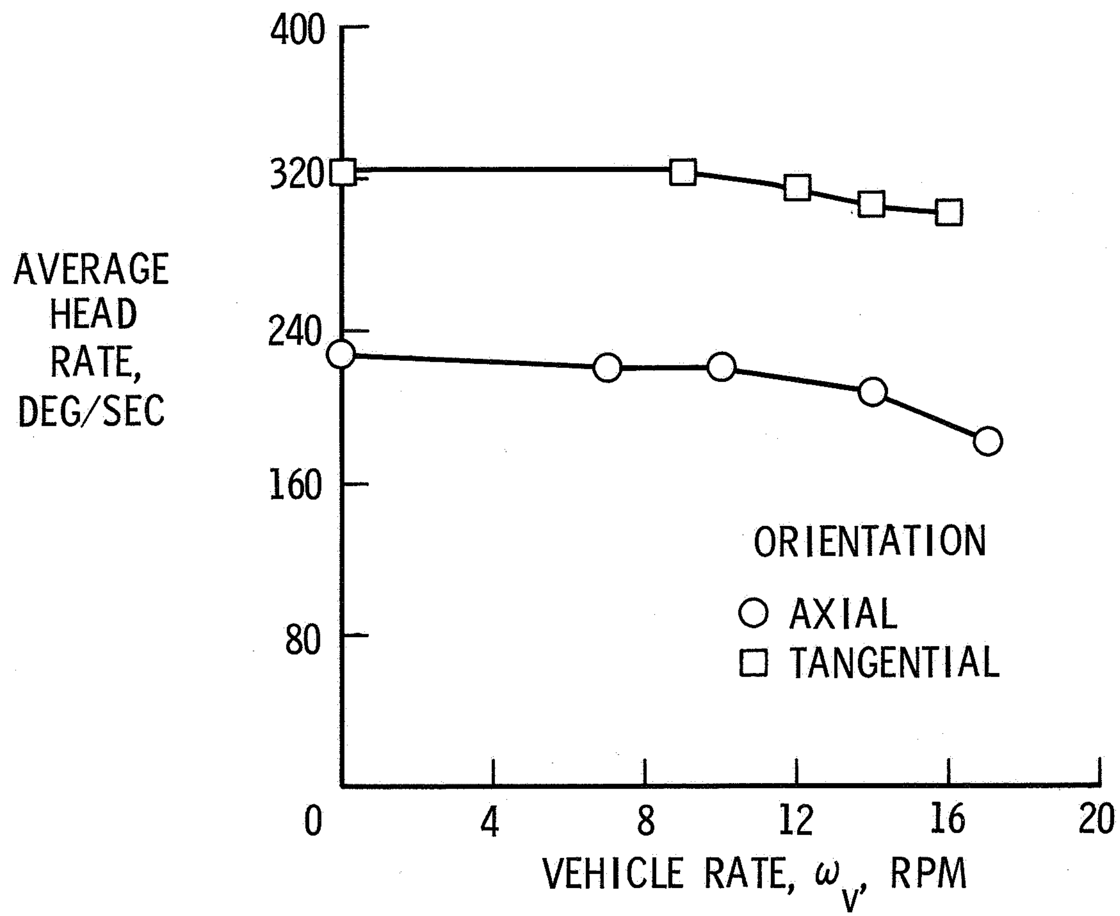

Figure 6.- Rates of head turning at various rates of simulator rotation for subjects facing axially and tangentially.

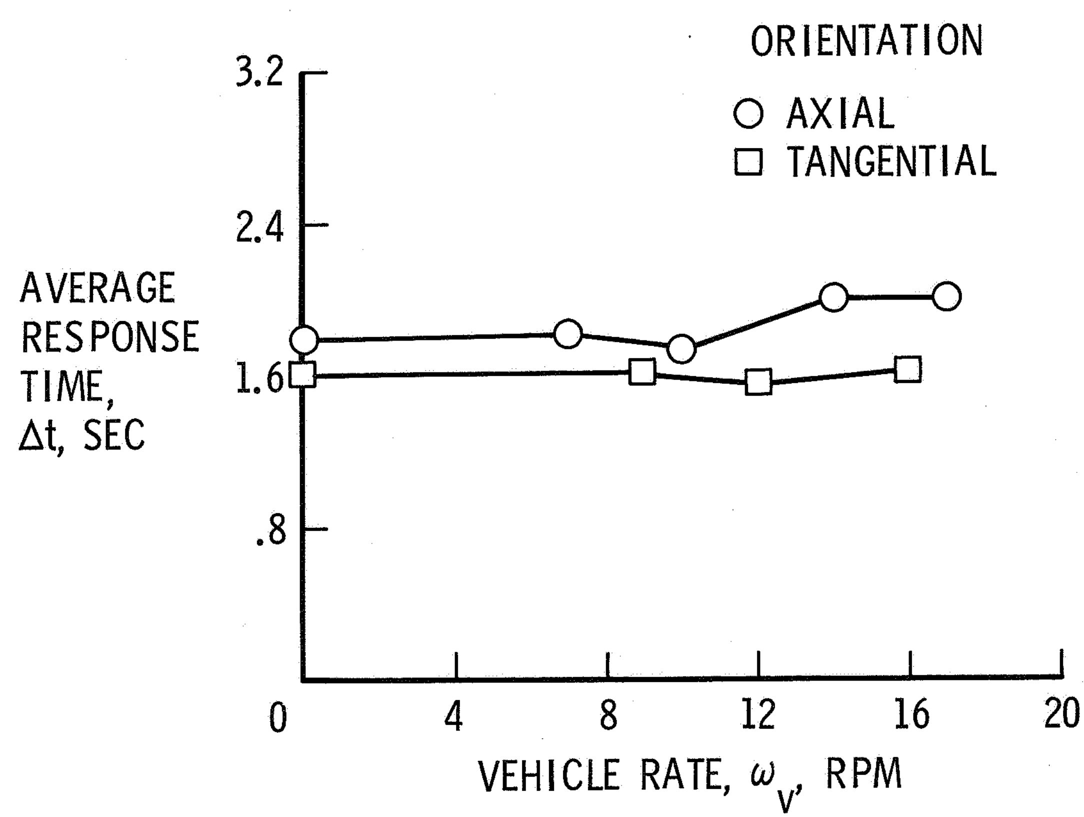

Figure 7.- Response time while turning head at various rates of simulator rotation for subjects facing axially and tangentially.

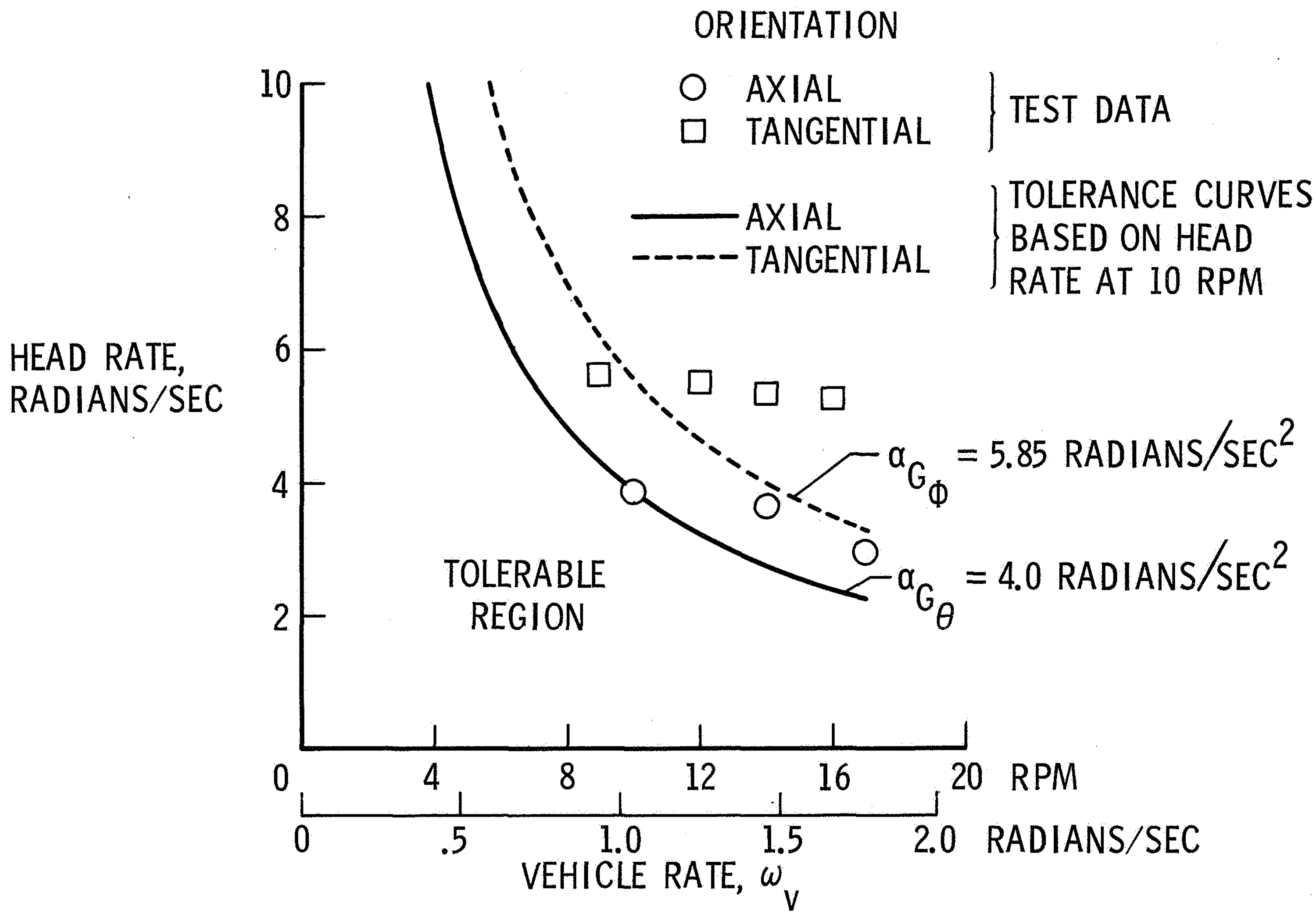

Figure 8.- Tolerance to cross-coupled angular accelerations while head turning for subjects facing axially and tangentially.

NASA-Langley, 1967