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TOLERANCE TO VEHICLE ROTATION OF SUBJECTS USING TURNING AND NODDING MOTION OF THE HEAD WHILE PERFORMING SIMPLE TASKS

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TOLERANCE TO VEHICLE ROTATION OF SUBJECTS USING TURNING AND NODDING MOTION

OF THE HEAD WHILE PERFORMING SIMPLE TASKS

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Introduction

Man has long been concerned with the effects of rotation on his faculties. He has used rotation for his amusement, for therapy, to create forces to simulate flight conditions, and now in the space age possibly to create artificial gravity on long-time space missions such as in a manned orbital research laboratory as depicted in figure 1. In rotation, however, certain undesirable effects result which for long-time missions can be disquieting if not intolerable. These effects in our mundane activities cause sea and air sickness and through visual illusions have caused fatal aircraft accidents. The fundamental physical phenomena involved occur when head or body motions are made while in a rotating environment resulting in crossed-coupled angular accelerations which are sensed by the semicircular canals shown schematically in figure 2. These three canals, although nearly orthogonal one to another are not aligned with the body's axis. They mechanically sense the angular accelerations which through the nervous system and appropriate discrimination are interpreted by the brain as turning, nodding, or rolling motions. The problems of man's tolerance to the cross-coupled acceleration have been studied extensively by Ashton Graybiel, et al. (refs. 1 and 2) and by the present authors (refs. 3 and 4). Graybiel has studied these effects for long periods with his subjects normally oriented with their long-body axis parallel to the axis of rotation and has found tolerance levels of 3 to 4 rpm. When attaining artificial gravity by rotation, however, the astronauts will be oriented with their long-body axis perpendicular to the axis of rotation of the vehicle and this is the orientation examined by the present authors. The experiments of references 3 and 4 have indicated a tolerance to 10 rpm while turning the head from side to side (hereinafter this will be called turning). This is, of course, a rather restricted condition in view of the random motions expected in flight and used in Graybiel's work where lower tolerances were indicated. Studies were initiated at Langley to examine nodding motions and combinations of nodding and turning motions with the subjects oriented with their long-body axis perpendicular to the axis of rotation as done in references 3 and 4. Some initial results of these studies are presented herein.

Symbols

α_{G_θ} cross-coupled angular acceleration (nodding)

α_{G_ψ} cross-coupled angular acceleration (turning)

ω_{G_θ} apparent nodding velocity

ω_{G_ψ} apparent turning velocity

θ_G apparent nodding displacement

ψ_G apparent turning displacement

$\dot{\omega}_{h_\theta}$ nodding angular acceleration

$\dot{\omega}_{h_\psi}$ turning angular acceleration

ω_{h_θ} nodding velocity of head

ω_{h_ψ} turning velocity of head

ω_V vehicle rotational velocity

θ_h nodding displacement

ψ_h turning displacement

t time

Subscripts:

lr and ll right and left lateral canals, respectively

pr and pl right and left posterior canals, respectively

ar and al right and left anterior canals, respectively

Head Motion and Semicircular Canal Stimulation

To the subject visually isolated in a rotating environment, the cross-coupled angular accelerations are only apparent (and are so-called herein) as the visual environment does not have a corresponding rotation. This disparity of sensory cues is the basic cause for visual illusions and nystagmus which can lead to a state of disorientation and possible nausea.

The conditions of cross coupling for turning and nodding are shown in figure 3. For the turning motion, ω_{h_ψ} is perpendicular to ω_V, the angular velocity vector of the vehicle. The cross-coupled acceleration experienced is perpendicular to both of these two vectors and represents basically a nodding motion depending on the head position ψ_h so that

$$\alpha_{G_\theta} = \omega_V \, \omega_{h_\psi}$$

That portion of this acceleration sensed as a nodding motion is

$$\cos \psi_h \alpha_{G_\theta}$$

and as a rolling head motion

$$\sin \psi_h \alpha_{G_\theta}$$

For the nodding motion, ω_{h_G} is perpendicular to ω_V and the cross-coupled acceleration experienced is perpendicular to both of these two vectors and represents basically a turning motion depending on the head position θ_h so that

$$\alpha_{G_\psi} = \omega_V \omega_{h_\theta}$$

That portion of this acceleration sensed as a turning motion is

$$\cos \theta_h \alpha_{G_\psi}$$

and as a rolling head motion

$$\sin \theta_h \alpha_{G_\psi}$$

This discussion has dealt basically with the "apparent" head motions experienced. It is of interest to examine the effects of these cross-coupled accelerations as compared with normal head motions. Consider further the stimulation of each of the semicircular canals. As noted previously, the canals are orthogonal one to another but are tilted back so that the lateral canals are from 15° to 30° up in the front (ref. 5) and the anterior and posterior canals as indicated by their names are turned somewhere from 35° to 65° about a near vertical axis, as shown in figure 2. For convenience some calculations have been made assuming a 20° tilt back and a 45° rotation, respectively, for the factors listed above.

With these assumptions the following components of acceleration exist at each of the six canals when the subject normally turns his head.

$$\dot{\omega}_{lr} = 0.9397\dot{\omega}_{h_\psi}$$

$$\dot{\omega}_{ll} = 0.9397\dot{\omega}_{h_\psi}$$

$$\dot{\omega}_{pr} = -0.2418\dot{\omega}_{h_\psi}$$

$$\dot{\omega}_{pl} = -0.2418\dot{\omega}_{h_\psi}$$

$$\dot{\omega}_{ar} = 0.2418\dot{\omega}_{h_\psi}$$

$$\dot{\omega}_{al} = 0.2418\dot{\omega}_{h_\psi}$$

normally nods his head

$$\dot{\omega}_{lr} = 0$$

$$\dot{\omega}_{ll} = 0$$

$$\dot{\omega}_{pr} = 0.7071\dot{\omega}_{h_\theta}$$

$$\dot{\omega}_{pl} = -0.7071\dot{\omega}_{h_\theta}$$

$$\dot{\omega}_{ar} = 0.7071\dot{\omega}_{h_\theta}$$

$$\dot{\omega}_{al} = -0.7071\dot{\omega}_{h_\theta}$$

and normally rolls his head

$$\dot{\omega}_{lr} = 0.3420\dot{\omega}_{h_\phi}$$

$$\dot{\omega}_{ll} = 0.3420\dot{\omega}_{h_\phi}$$

$$\dot{\omega}_{pr} = 0.6645\dot{\omega}_{h_\phi}$$

$$\dot{\omega}_{pl} = 0.6645\dot{\omega}_{h_\phi}$$

$$\dot{\omega}_{ar} = -0.6645\dot{\omega}_{h_\phi}$$

$$\dot{\omega}_{al} = -0.6645\dot{\omega}_{h_\phi}$$

Figures 4, 5, and 6 show schematically the anterior and posterior canals as if viewed from above. The small arrows or vectors indicate the direction of that component of the angular acceleration which is perpendicular to each canal and which therefore it experiences and presumably would sense. According to Löwenstein and Sand (ref. 6), however, nervous responses to acceleration are transmitted from only some canals during any given motion while others are not affected or are inhibited. It is not fully evident what would cause such inhibition, for under the conditions of rolling and turning the anterior and posterior canals are stimulated in a like manner. Reference 6 notes, however, that for these conditions different canals or their signals are inhibited. The only difference that exists between these conditions of stimulation is that the lateral canals have a greater stimulation than the vertical ones in the turning case and a lesser stimulation in the rolling case. This difference could be a signal or trigger for the inhibition.

In comparison to the simple results of individual head motions just discussed, consider the same head motions but in a rotating environment. For these cases the subject is assumed to be oriented as in figure 3 and the motions are considered as acting separately. The components of acceleration at each of the six canals for head turning are

$$\dot{\omega}_{lr} = -0.3420 \sin \psi_h \omega_V \omega_{h_\psi} + 0.9397\dot{\omega}_{h_\psi}$$

$$\dot{\omega}_{ll} = -0.3420 \sin \psi_h \omega_V \omega_{h_\psi} + 0.9397 \dot{\omega}_{h_\psi}$$

$$\dot{\omega}_{pr} = \left(-0.6645 \sin \psi_h - 0.7071 \cos \psi_h\right) \omega_V \omega_{h_\psi} - 0.2418 \dot{\omega}_{h_\psi}$$

$$\dot{\omega}_{pl} = \left(-0.6645 \sin \psi_h + 0.7071 \cos \psi_h\right) \omega_V \omega_{h_\psi} - 0.2418 \dot{\omega}_{h_\psi}$$

$$\dot{\omega}_{ar} = \left(0.6645 \sin \psi_h - 0.7071 \cos \psi_h\right) \omega_V \omega_{h_\psi} + 0.2418 \dot{\omega}_{h_\psi}$$

$$\dot{\omega}_{al} = \left(0.6645 \sin \psi_h + 0.7071 \cos \psi_h\right) \omega_V \omega_{h_\psi} + 0.2418 \dot{\omega}_{h_\psi}$$

for head nodding are

$$\dot{\omega}_{lr} = \left(0.3420 \cos \theta_h - 0.9397 \sin \theta_h\right) \omega_V \omega_{h_\theta}$$

$$\dot{\omega}_{ll} = \left(0.3420 \cos \theta_h - 0.9397 \sin \theta_h\right) \omega_V \omega_{h_\theta}$$

$$\dot{\omega}_{pr} = \left(0.6645 \cos \theta_h + 0.2418 \sin \theta_h\right) \omega_V \omega_{h_\theta} + 0.7071 \dot{\omega}_{h_\theta}$$

$$\dot{\omega}_{pl} = \left(0.6645 \cos \theta_h + 0.2418 \sin \theta_h\right) \omega_V \omega_{h_\theta} - 0.7071 \dot{\omega}_{h_\theta}$$

$$\dot{\omega}_{ar} = -\left(0.6645 \cos \theta_h + 0.2418 \sin \theta_h\right) \omega_V \omega_{h_\theta} + 0.7071 \dot{\omega}_{h_\theta}$$

$$\dot{\omega}_{al} = -\left(0.6645 \cos \theta_h + 0.2418 \sin \theta_h\right) \omega_V \omega_{h_\theta} - 0.7071 \dot{\omega}_{h_\theta}$$

and for head rolling about an axis parallel to the axis of the vehicle no cross coupling exists and results are the same as for normal head motions.

By comparison it is evident that the stimulation in a rotating environment is much more complex than in simple normal conditions. In head turning as has been noted before a stimulation (for $\psi = 0$) that is sensed as nodding exists. In head nodding the lateral canals are stimulated whereas they are unaffected in normal nodding, thus a turning sensation is experienced when nodding.

Test Equipment and Technique

In order to examine the effects of kinds of stimulation just discussed, a simple rotating-vehicle simulator was used at the Langley Research Center (fig. 7). Subjects were lying on their backs enclosed in a small cabin with their feet 15 feet from the center of rotation. The centrifugal force was felt on the soles of their feet as it would in a rotating space station.

The internal features of the rotating simulator are shown in figure 8. The subject's task was to observe either the light on his left or over his head which were controlled by the experimenter located externally from the simulator. The color of the lights was varied by the experimenter, and the subject, upon observing a light of certain color, was required to turn his head to the right or nod his head forward depending on the light observed and place a probe in an appropriate hole to extinguish the light. The head position and head rate were measured by head-position indicators which were attached to a harness on the subject's head and to the moving head rest. The moving head rest supported the head by negator springs and allowed nodding motions without the need to hold up the head in the supine position. The time from light activation to light cutoff was also measured.

The results presented herein were for experiments made with nodding motions alone and with combination nodding and turning motions. Nine subjects were used in the nodding experiments and ten were used in the combined motions. The subjects who participated in the nodding experiments did not participate in any of the previous experiments. However, three subjects who participated in the experiments of references 3 and 4 also participated in the combined motion experiment. The nodding experiment lasted 1 hour and rates of rotation of 0, 2, 4, 6, 8, and 10 rpm were used. The combined nodding and turning experiments were run at 10 rpm and lasted 3 hours. Figure 9 shows typical initial segments of the time history of light activation for both the nodding-alone experiments and the combined nodding and turning experiments. Each line indicates an activation of the light. For the nodding experiments alone the light was activated about 32 times for each vehicle rotational rate. The light was activated 160 times during the 1 hour of the nodding-alone experiment. During the combined nodding and turning motions 500 light activations were made. These were randomly distributed between the nodding and turning motions as shown in figure 9. Some motion pictures of eye motions were made to determine qualitatively the motion of the eyes under the conditions of the experiments.

Results and Discussion

For the purpose of correlation with the current nodding and combined nodding and turning motions, figures 10 and 11 for turning motions alone are reproduced from reference 4. Figure 10 shows a typical turning-head motion and the apparent cross-coupled nodding motion that is sensed when the turning motion is made when rotating at 10 rpm. It should be noted that the apparent acceleration on the right α_{G_θ} is about 250 deg/sec^2 maximum and occurs in separate increments in contrast to the normal head motion shown on the left, wherein each motion consists of an acceleration followed immediately with one in the opposite direction.

Figure 11 shows a tolerance boundary obtained in reference 4 for head turning while rotating. These results show that a cross-coupled acceleration of from 4 to 6 radians/sec^2 (230 to 345 deg/sec^2) is tolerable at least for 3 hours. These values are appreciably larger than other experimenters have reported.

As noted before, our purpose in this paper is to examine nodding motions and combinations of nodding and turning motions to determine if a similar tolerance exists. Figure 12 shows a typical nodding motion. Nodding accelerations are about the same as those for turning, maximum values of 1600 deg/sec^2 were measured while the head was moved a total of 80°. On the right side of figure 12 is the apparent turning motion that exists when nodding in a vehicle rotating at 10 rpm. In this motion the subject experiences cross-coupled angular accelerations of about 300 deg/sec^2 maximum, which when integrated gives rise to an apparent angular velocity of 80 deg/sec maximum, and an apparent turning displacement of 140°.

The results for the 1-hour experiments performed with head-nodding motions alone are shown on figures 13, 14, and 15. These data, as well as all data presented herein, are numerical averages of the data from all the subjects participating in the experiment. For these tests the subject, as noted previously, was requested to look over his head at a light, the color of which varied; when he saw the light he nodded his head forward about 80° and placed a probe in the appropriate hole to extinguish the light. The subject's head position, rate of motion, and response time (the time from when the light was turned on until extinguished) were recorded. These tests were performed, as previously noted, with vehicle rotations of 0, 2, 4, 6, 8, and 10 rpm with 9 subjects.

The average amplitude of head nodding motions for the subjects at each vehicle rate of rotation is shown by the circles in figure 14. The periods of time at each rotational rate are noted by the stepped line. The amplitude of motion ranges from 80° to 90° without a consistent variation with vehicle rate of rotation. As is noted on the figure near the end of the run, one subject dropped out, two others became nauseous and two dizzy - these all at 10 rpm.

The average rate of head nodding motion by the nine subjects is shown in figure 14. The results are shown by circles and the stepped line indicates the time at each rotational rate as in reference 4. The rates varied between 120 and 140 deg/sec with the lower rates occurring at the higher rpm. This is apparently a subjective attempt to reduce the cross-coupling effects at the higher speeds. The response times are shown in figure 15. There is a decrease in this time occurring at the changeover to 6 rpm, the time dropping from 2 to 1.6 seconds. The faster response in spite of the reduced head rates just discussed can be explained only by a learning process in directing the probe to extinguish the lights or that this task became easier.

In these nodding experiments, contrary to the turning ones reported in references 3 and 4, the subjects reported no fuzziness of vision and motion pictures of the eyes showed that no nystagmus existed. Nystagmus was shown to exist in the turning motions of references 3 and 4 and is confirmed by motion pictures. Also in these nodding experiments the subjects reported aftereffects causing some discomfort following the experiment. Two subjects who reported nausea during the tests were affected for several hours afterwards.

In that most of the subjects tolerated the experience at 10 rpm and because similar experience with turning head motions showed tolerance and adaptation to 10 rpm (refs. 3 and 4) an experiment with combined turning and nodding motions was performed at 10 rpm. These tests were run for 3 hours and consisted of random head motion in turning and nodding in response to lights in both planes. The amplitudes of head motion, the rates of head motion, and the response times were recorded. Ten subjects were used in this experiment. As noted before, none of these subjects were the same as those who participated in the nodding experiments just discussed. The results are presented in figures 16, 17, and 18. The data on these figures are for a constant vehicle rate of rotation and are plotted as a continuous curve based on the average head motions and response of all subjects at the time of each light activation.

On figure 16 is shown the amplitude of head position showing variations in the amplitude of motion used for both nodding and turning. There was a decrease in turning amplitude during the first hour and an increase thereafter. An increase in nodding amplitude was used during the first 3/4 hour and a decrease thereafter. Five of the 10 subjects, however, dropped out of the experiment within the first 15 minutes because of nausea. The other subjects completed the entire experiment without any ill effects. Some aftereffects of dizziness during head motions were experienced by each subject for a short duration following the completion of the 3-hour run.

The rates of turning and nodding motions during these combined motion experiments are shown in figure 17. There is an increase in the turning rate throughout the experiment which is consistent with the increase shown in reference 4 for turning motions alone although the rates for the current experiment are normally slower than those used in the previous experiments with turning motions alone. The rates of nodding motion remained rather constant after the first half hour and were not greatly different than the rates for nodding motions alone previously discussed.

The response times required to extinguish the lights for the combined experiments are shown in figure 18. There are decreases in the response to both nodding or turning stimulations. The response times are, however, somewhat larger than those for turning alone in reference 4 and for nodding alone just discussed. It appears that although the turning and nodding motions occur separately, that is, one is completed before another is started, the subjects required more time to perform the tasks indicating again a more stressful condition or at least psychologically a more complex situation requiring more deliberation and time. The responses are not exceptionally long however and are certainly adequate for normal operations.

The general results of these experiments are summed up in figure 19, which is a tolerance boundary plot, with head rates of rotation plotted versus vehicle rates of rotation. These boundaries are based on the concept that tolerance or intolerance to such motions is dependent on the cross-coupled angular accelerations and not specifically the rates of rotation that exist. Shown on this figure are boundaries for the separate and the combined motions that represent curves of constant cross-coupled angular acceleration based on the maximum average acceleration that was experienced and tolerated during the experiments. It appears generally that man can tolerate and adapt to larger cross-coupled angular accelerations when performing turning motions than when performing nodding motions. Further it appears that even in the combined exposure to nodding and turning an adaptation to higher cross-coupled acceleration exists, as shown by the somewhat higher values for the 3-hour run than for the 1-hour runs. Also shown on this figure are two data points representing the average conditions that existed for the five dropouts in the combined experiment. These data points are plotted at the vehicle rate of 10 rpm and at an average turning head rate of 180 deg/sec and at an average nodding head rate of 110 deg/sec, which are the average rates of the subjects at the time they dropped out of the experiments. Tolerable conditions for these subjects are probably at head rates much lower than for the data points shown. These data are somewhat smaller cross-coupled accelerations than exist for the subjects who tolerated the entire experiment. It appears that certain subjects have a marked intolerance to the combined situations, whereas others adapt rather readily.

It should be remembered that these cross-coupled accelerations are in a nodding sense when turning the head and in a turning sense when nodding the head. There is evidence therefore of a greater sensitivity to cross coupling that affects the lateral semicircular canals than to cross coupling that affects the vertical (anterior and posterior) canals. This is evidenced by the dropouts, the aftereffects, and the somewhat slower head rates used in these cases. The lack of nystagmus when the cross coupling is in the lateral plane and its presence when in the nodding direction however is not fully understood. In normal examinations of disorientation, as elicited on a Barany chair, nystagmus is readily obtained by appropriate stimulation of the lateral semicircular canals. The nausea and dizziness so obtained is, however, like that obtained in the present experiments.

It would appear that experiments of the kind reported herein and like those of references 3 and 4 may well be used as a selection test of persons who may not be prone to motion sickness and who may tolerate rotation in space vehicles. The data also indicate that, if one is careful not to elicit cross coupling in the lateral semicircular canals, adaptation to rotation may be obtained more readily and by more people.

Concluding Remarks

The effects of rotation as may be used in space vehicles to obtain artificial gravity, may be quite varied among persons having normal semicircular canal systems. Some subjects were tolerant of rates of rotation of 10 rpm and would probably adapt for long time periods; others, however, were very intolerant of these conditions when combined motions of the head were used. The results of the experiments reported herein indicate a greater sensitivity to cross-coupled angular accelerations when they occur so as to be sensed by the lateral semicircular canals. Adaptation to rotation would be more readily obtained therefore if the head could be moved so as not to stimulate the lateral canals by cross-coupled accelerations. Further study and collaboration of these phenomena should be obtained however. The kinds of experiments reported herein may be useful as a selecting test of persons who may not be prone to motion sickness.

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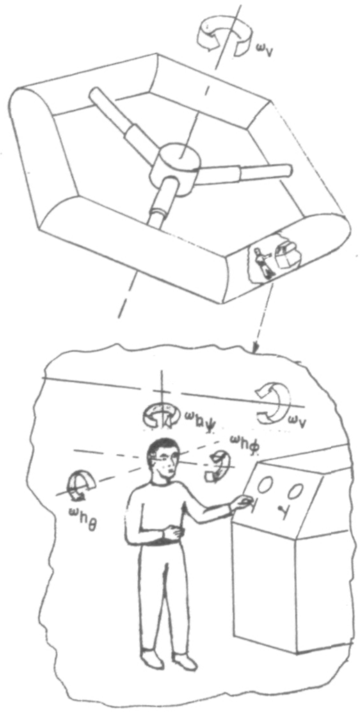


Figure 1.- Rotational environment of man in a space station.

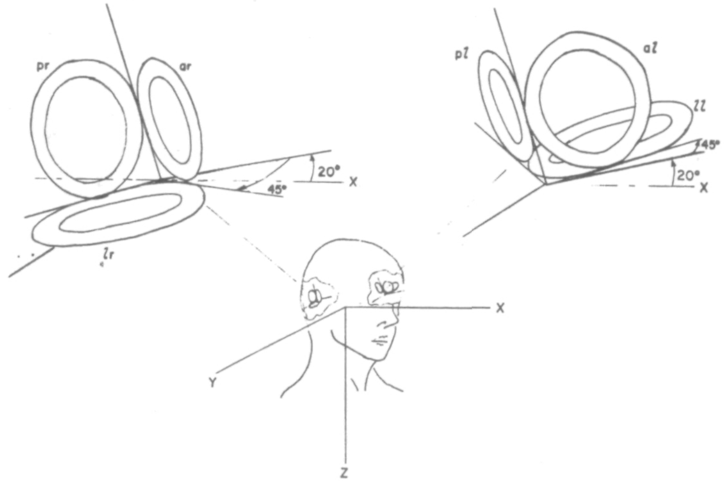
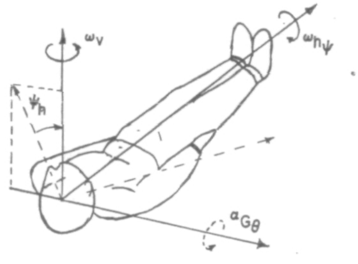
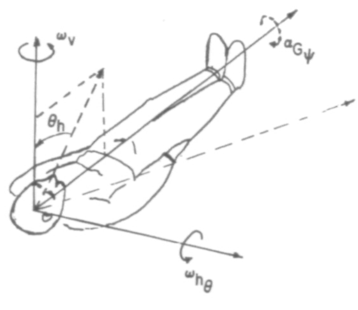


Figure 2.- The semicircular canal system.



(a) Turning.

Figure 3.- Motion definitions.



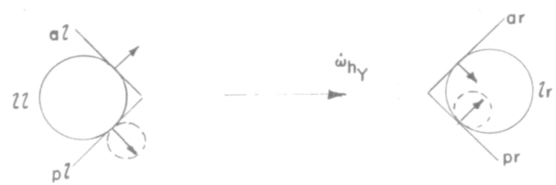
(b) Nodding.

Figure 3.- Concluded.

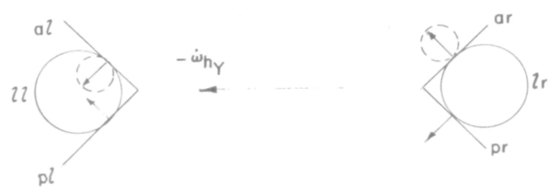
(a) Right.

(b) Left.

Figure 4.- Vectorial representation of the stimulation of the semicircular canal system with head rolling. Vectors are perpendicular to plane of canels. Circled vectors indicate responsive canals according to Löwenstein and Sand (ref. 6).



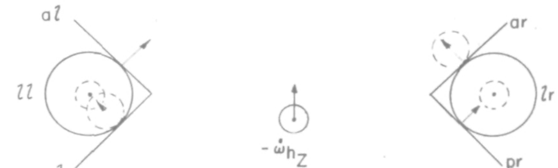
(a) Backward.



(b) Forward.

Figure 5.- Vectorial representation of the stimulation of the semicircular canal system with head nodding. Vectors are perpendicular to plane of canals. Circled vectors indicate responsive canals according to Löwenstein and Sand (ref. 6).

(a) Clockwise.



(b) Counterclockwise.

Figure 6.- Vectorial representation of the stimulation of the semicircular canal system with head turning. Vectors are perpendicular to plane of canals. Circled vectors indicate responsive canals according to Löwenstein and Sand (ref. 6).

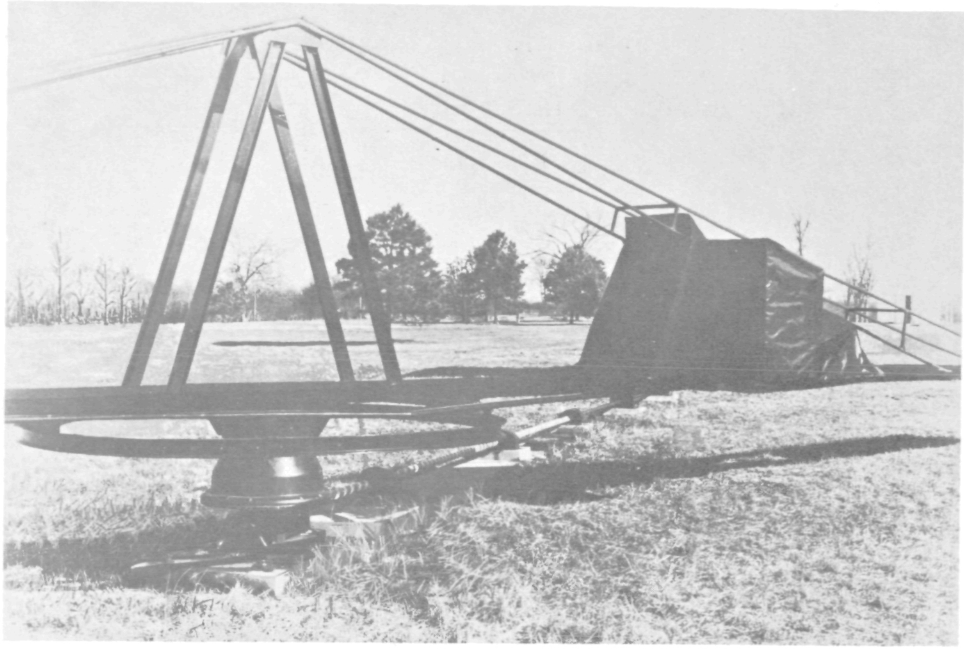


Figure 7.- External view of rotating vehicle simulator.

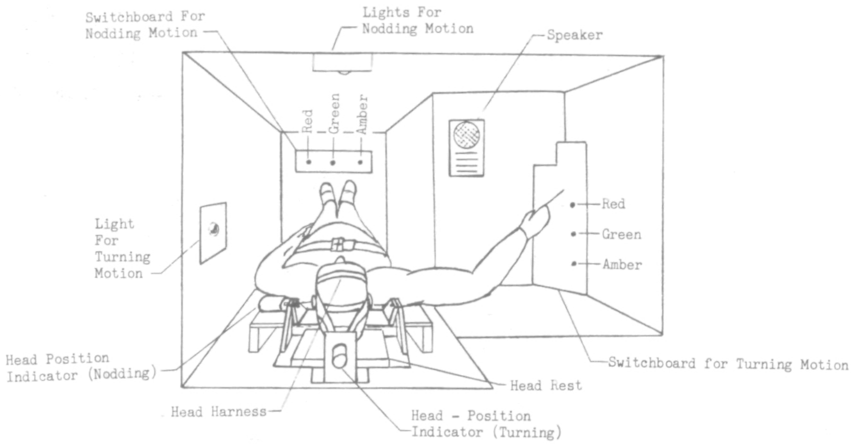


Figure 8.- Internal features of simulator.

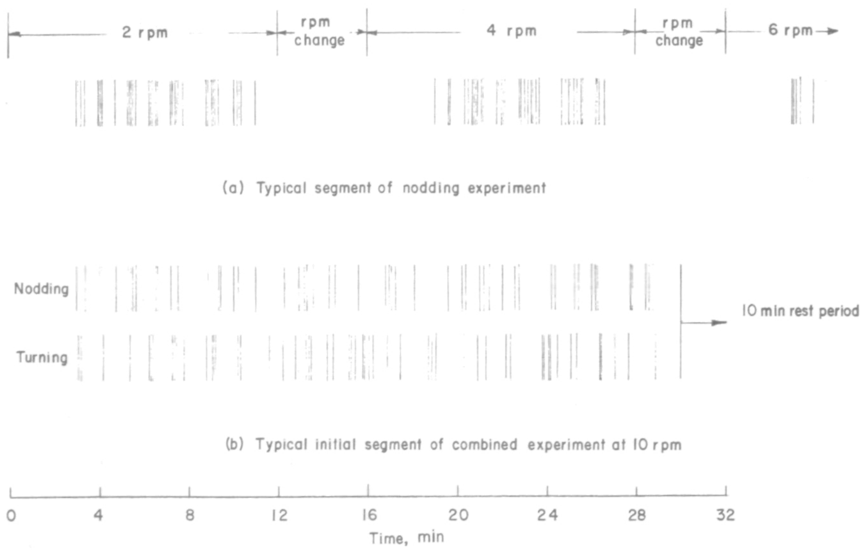
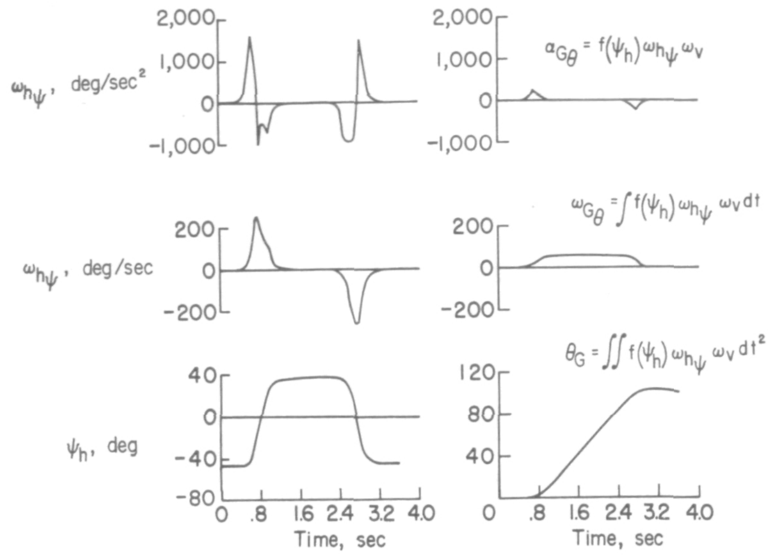


Figure 9.- Time histories of light activations. Each line indicates activation of light.



(a) Real turning head motion. (b) Apparent nodding motion.

Figure 10.- Typical head turning motion and resulting apparent nodding motion. Simulator rate ω_v = 10 rpm.

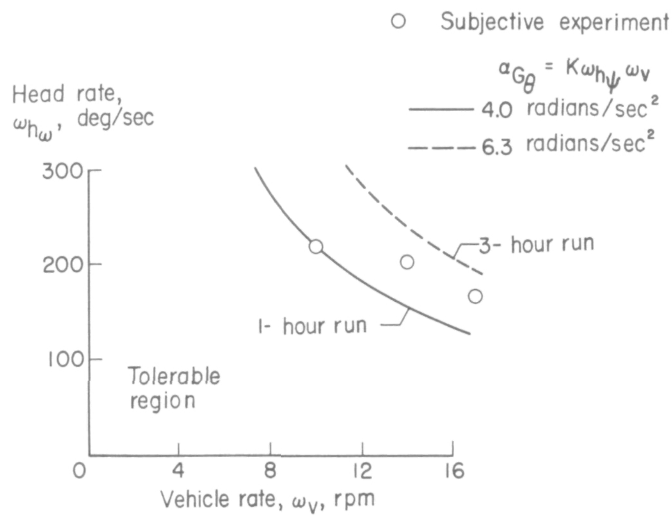
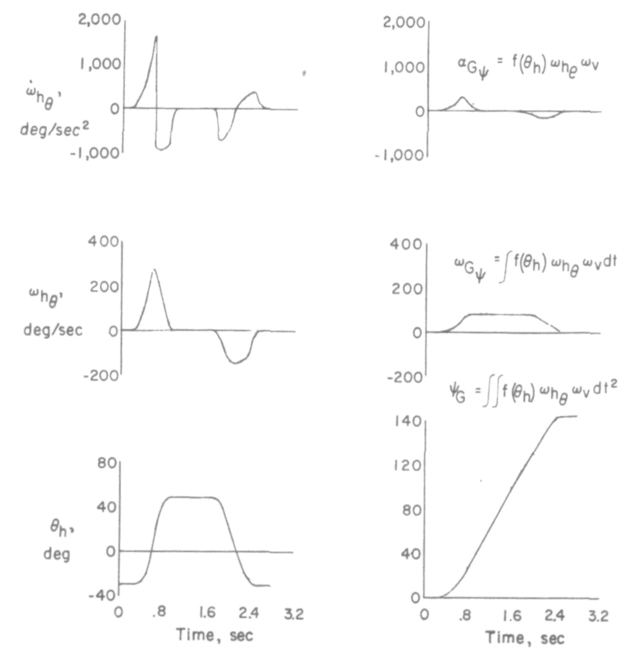


Figure 11.- Tolerance to cross-coupled angular acceleration while turning head.



(a) Real nodding head motion. (b) Apparent turning motion.

Figure 12.- Typical head nodding motion and resulting apparent turning motion. Simulator rate ω_v = 10 rpm.

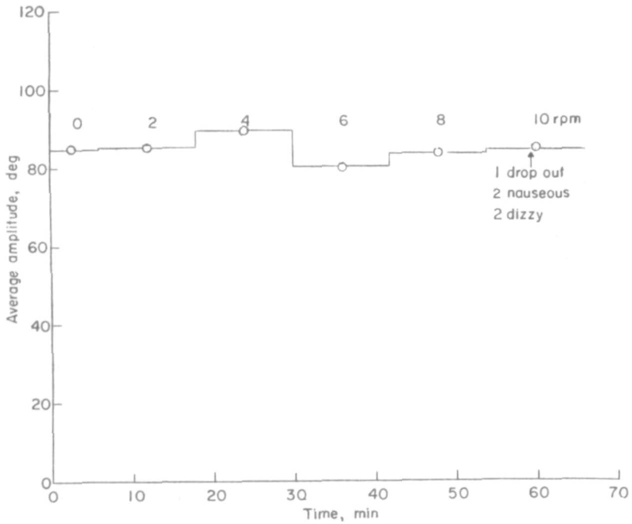


Figure 13.- Amplitude of head nodding at various rates of rotation of the simulator.

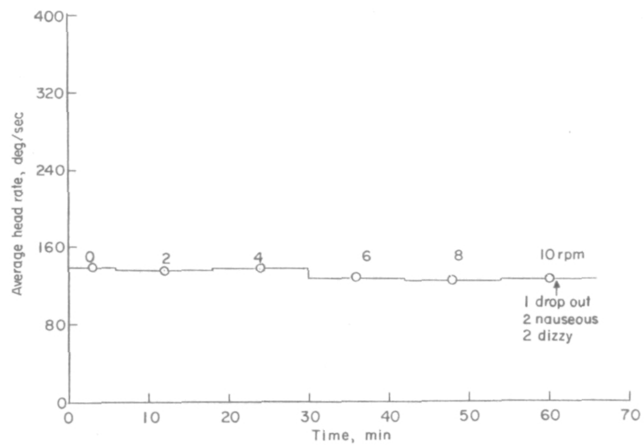


Figure 14.- Rates of head nodding at various rates of rotation of the simulator.

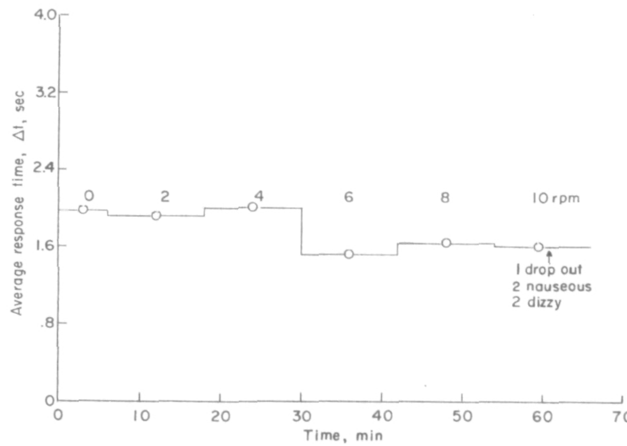


Figure 15.- Response time while nodding head at various rates of rotation of the simulator.

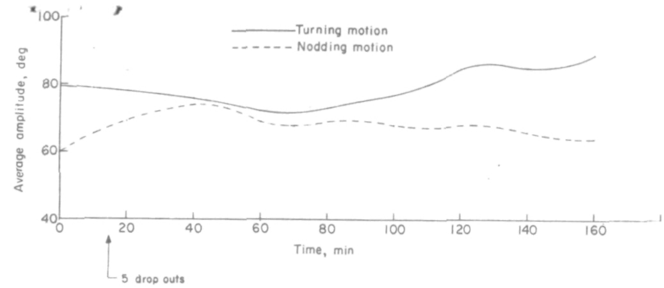


Figure 16.- Amplitude of head motions during combined tests of turning and nodding motion at a rate of rotation of the simulator of 10 rpm.

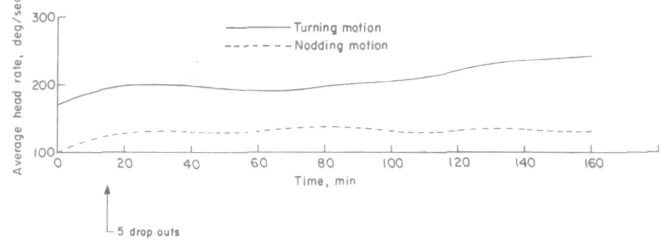


Figure 17.- Rate of head motion during combined tests of turning and nodding motion at a rate of rotation of the simulator of 10 rpm.

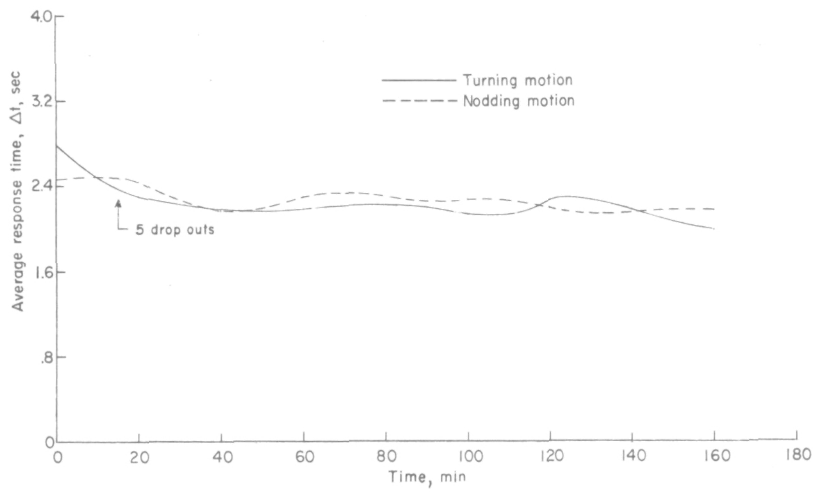


Figure 18.- Response time while turning and nodding head during combined tests of turning and nodding motion at a rate of rotation of the simulator of 10 rpm.

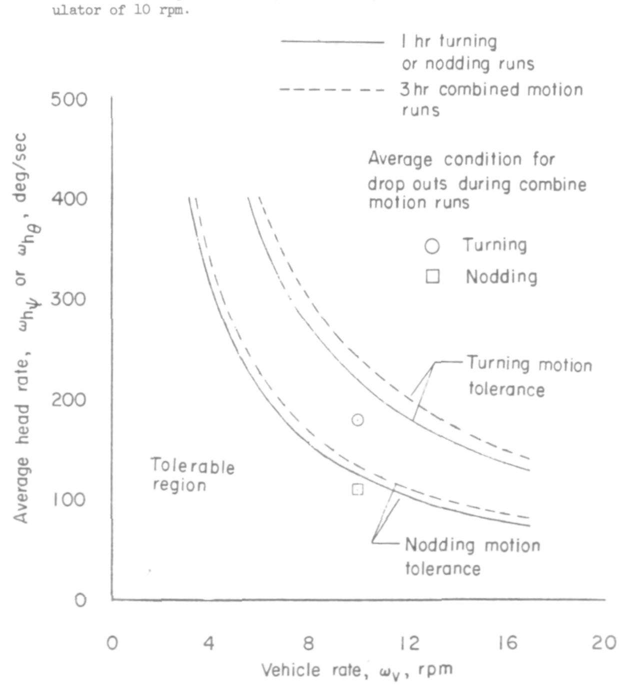


Figure 19.- Tolerance to cross-coupled angular accelerations while turning and nodding head.