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ROTATING SPACE STATION STABILIZATION CRITERIA FOR ARTIFICIAL GRAVITY

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16. ABSTRACT

An understanding of man's dependency on a gravity field is an area where research has yielded limited results, thereby, prompting space station designers to include provisions for providing an artificial gravity field capability. A rotogravic environment, though satisfying certain of man's physiological requirements, can introduce other complicated requirements. Therefore, this investigation was devoted to obtaining, for space station designers, insight into how man's physiological tolerances and range of adaptability can be used to define operational and configurational design criteria.

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Symbol	Definition
x, y, z	principal axes attached and rotating with the system
$\underline{i}$, $\underline{j}$, $\underline{k}$	unit vectors oriented along the x, y, z axes respectively
p, q, r	angular velocity components about the x, y, z axes respectively
g	gravity
t	time in seconds
α	angular acceleration magnitude
A, B, C	principal moments-of-inertia about the x, y, z axes respectively
R	radius of rotation
ω	space station spin rate
γ	spin axis deviation angle

$$K = (k_1 k_2)^{1/2}/r_o$$

$$k_1 = \left(\frac{C-B}{A}\right) r_o$$

$$k_2 = \left(\frac{C-A}{B}\right) r_o$$

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

An underline of a parameter indicates a vector quantity.

A subscript o indicates an initial condition.

ROTATING SPACE STATION STABILIZATION CRITERIA FOR ARTIFICIAL GRAVITY

SUMMARY

A man in an artificial gravity field created through space-station rotation may have his vestibular system stimulated in two ways: (1) by normal head movements in the execution of tasks or (2) by disturbed motion of the space-station which causes it to rotate simultaneously about two or more of its axes. In the first situation, only adaption of the man to the environment can overcome the effects of stimulation. The stimulation produced by the second situation, however, is very dependent on space-station configurational and operational criteria.

Limitations in man's ability to function effectively in an artificial gravity field result from the induced rotational effects to which he is not accustomed. Earth and artificial gravity envrioments are first discussed to establish an understanding of their differences. Then, types of earth-based simulation techniques are presented, and the physiological tolerances and range of adaptability experimentally derived on these techniques are discussed and those applicable to this investigation are selected.

Since, disturbances to the rotation plane of a space-station rotating in a passive state cause it to induce fluctuations in the artificial gravity field, the equations of motion are derived in terms of configurational, operational, and rotation plane stability parameters. Next, a parametric analysis of the field is presented, and man's physiological tolerances and range of adaptability in a rotating environment are used to define acceptable disturbance limits to the field in terms of these parameters.

INTRODUCTION

How dependent is man on the force of gravity for his life and health? The planning of long-duration missions — both in near space and to distant planets — requires a reliable answer to this question. Because gravity is such a common force, very little is known about the biological effect of its removal. An adequate study of these effects can now be performed only in an orbital environment; the present United States space program reflects this fact.

On a space mission, after high acceleration-levels from earth-launch and orbital-injection, astronauts enter the zero-gravity condition. In this condition, their total, subjective feeling of weight and orientation (position) is removed. The human body has great adaptability to new environments — the body will attempt to make compensatory adjustments. Adjustments to the stress of zero-gravity will not likely reduce performance while in that environment. During re-entry, however, the stress of high re-entry acceleration and returning earth gravity will be a major concern. Some of the physiological-adjustment problems have been identified by using the data obtained from short orbital flights and from earth based studies using bed-rest and water immersion testing [1, 2]. Two of the problems revealed by test data obtained from the flights of American astronauts [3, 4] and the Russian cosmonauts [5, 6] were: (1) reduced tolerance to acceleration stress (strong effect on the cardiovascular system) and (2) muscular atrophy.

These effects have spurred the study of practical methods [7] to counteract such undesirable adaption trends and thereby avoid compromise of future designs of manned spacecraft. An example was the effort in the Gemini program, with tourniquet techniques operated from an air source. These were intended to counteract the effects on the cardiovascular system. However, compromises in spacecraft-design may be inescapable, depending on the volume, weight, and power requirements necessary to support the specific counteraction. This implies that it may also be necessary to seek a different solution to the problem such as that offered by a rotogravic (gravity created through rotation) environment. The latter Gemini program flights were used to investigate this technique.

Artificial gravity, per se, is a counteraction technique not totally without limitations. A man in a rotogravic environment may have his vestibular system stimulated in two different ways: (1) by normal head-movements in the execution of tasks, or (2) by disturbed motion of the space station,

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which causes it to rotate simultaneously about two or more of its axes. In the first situation, assuming a stable plane of rotation, only adaption of man to the environment can overcome the effects of stimulation. Except for rotation radius and rate, such effects are not dependent on space-station configurational or operational criteria. The stimulation produced by the second situation, however, is very much dependent on space-station configurational and/or operational criteria. This type of stimulation can greatly limit the capability of man to adapt to the rotogravic environment, or even to remain adapted. For example, if the stimulation exceeds man's threshold for sensing angular acceleration, he cannot avoid stimulation — even without head movements. Further, the level of stimulation created by disturbed motion of the space station will be added to that produced by normal head movements, thereby imposing a higher stimulation level on the vestibular system than a man can tolerate and still function efficiently .

Numerous experimental studies have been concerned with man's vestibular system stimulation in a rotogravic environment, but only a few have focused on evolving design criteria for space stations. All have assumed a stable plane of rotation. Observation of the real world recognizes that this mode of rotation characterized an idealized case. Then one must ask: "Just how stable must the rotation plane be?" and "What are the major, influencing factors that must be identified and considered?" Man's physiological tolerances and range of adaptability in a rotogravic environment are the keys to the answers and must be utilized to derive rotating space-station recommended configurational and operational criteria through empirical and theoretical methods.

Purpose

The purpose of this investigation is to use available experimental data on man's physiological tolerances and range of adaptability in a rotating environment and theoretically derived effects expected in an artificial gravity field as a result of disturbances to the plane of rotation to accomplish the following objectives:

1. establish criteria for the selection of moment-of-inertia relationships for a rotating space station

2. establish disturbance limits on a space-station rotation plane for either normal or spin-up/de-spin operations

MAN'S PHYSIOLOGICAL TOLERANCES
AND RANGE OF ADAPTABILITY

Limitations in man's ability to function effectively in an artificial gravity field results from the induced rotational effects to which he is not accustomed. To establish an understanding of their differences, a qualitative discussion of man's functioning in both an earth and artificial gravity environment follows. Also, the types of simulation techniques presently utilized for studying man's functioning in a rotating environment are presented. The physiological tolerances and range of adaptability experimentally derived from these techniques and other influencing parameters are discussed comparatively and those applicable to this investigation are selected.

Functioning Of Man In An Earth Environment

A man on earth is subjected to a force-field environment of approximately 32 ft/sec^2. He recognizes the presence of this field through the use of three major sets of psycho-sensory cues [8]. These are:

1. ordinary visual cues

2. mechanoreceptor cues

   (a) localized skin pressure from supports

   (b) muscle tension from posture-maintenance effort

   (c) connective-tissue tensions from sagging or soft tissues

3. otolithic cues

The acceleration force from gravity acts as a stimulus to the otoliths. The impulses from the stimulus go to the brain, where they are integrated with impulses from the eyes and mechanoreceptors to give a man spatial orientation and balance. In the earth-surface environment, a man can easily maintain his orientation and balance because the impulses that his otoliths send to his brain are in consonance with what the man sees and feels.

In addition to his ability to sense linear accelerations, man also has receptors for sensing angular accelerations in three mutually perpendicular planes. These receptors are called the semicircular canals [8]. Actually,

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the otoliths and semicircular canals are contained in one integrated and complex structure called the vestibular system or labyrinth [9]. This labyrinth or inner ear is embedded in the temporal bone of the skull at the level of each ear as shown in Figure 1. The canals are stimulated by angular accelerations in their respective planes by head motion or by induced, total, body/head-angular motions. The induced, total, body/head-angular motions in a rotating space station are paramount in this investigation.
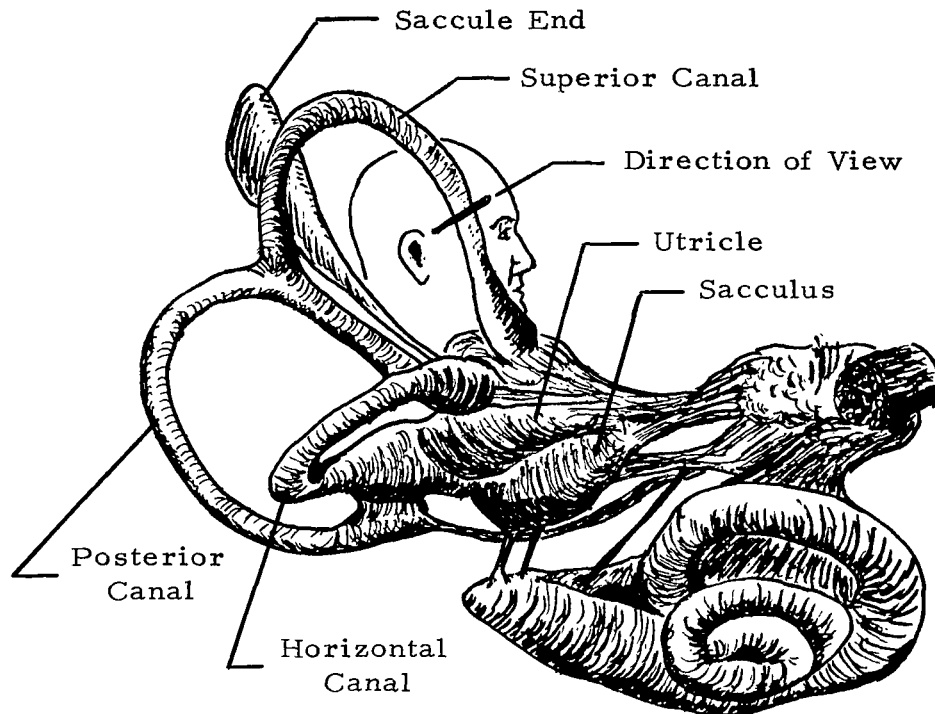
FIGURE 1. VESTIBULAR SYSTEM

Functioning Of Man In An Artificial Gravity Environment

A practical method of producing an artificial gravity field in a space station is by rotating the station to create a centrifugal force. This centrifugal force generates an apparent radial-gravity vector of sufficient

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magnitude to permit satisfactory human functioning: both motor and physiological. The otoliths of a man, which sense gravity or any other inertial acceleration, provide proper stimulus to the brain when exposed to this environment. The semicircular canals, however, will have superimposed on their stimulus (as a result of head motion) the rotation rate of the space station. This compounded stimulus can be quite detrimental to a man's sense of well being.

Rotogravic-simulation studies in recent years have shown that some of the physiological effects that may occur are disorientation, interference with visual-monitoring processes from "nystagmus blurring," and inability to perform operational tasks from incapacitating acceleration or "canal sickness" [10, 11, 12, 13].

Coriolis forces, created either by walking [14] relative to the plane of space-station rotation or from head motions, are the major causes of physiological problems. These forces cause mechanoreceptor stimuli which are not necessarily consonant with visual and otolithic stimuli. Therefore, the man is subjected to a bizarre sensation different from that which he experiences on earth. The coriolis forces acting on the canals are the result of a gyroscopic torque created when two of the canals are subjected to rotational velocity simultaneously [15, 16]. This stimulation can result from head motion superimposed on space-station rotation or from rotation of the space station about two or more of its axes simultaneously. Normally, the torque created is observed as a subjective response commonly called "seeing a Coriolis Illusion." Figure 2 illustrates the mechanics involved in the creation of this phenomenon. A common result of subjecting a man to severe stimulation of this type is malaise and/or nausea.

Rotational Simulation Techniques

During the past few years, numerous researchers have performed experiments on the functioning of man in a rotogravic environment, employing several rotational techniques. These techniques are compared with the actual orbital situation in Figure 3. One of the basic differences among these simulation techniques is the pattern of vestibular stimulation. This difference is important when an attempt is made to apply canal-stimulation-threshold data derived from one of these techniques. Selected basic observations relative to these experimental techniques are noted below.

Space Station
Rotation Rate

Resulting Visual Field
Motion (Coriolis Illusion)

Input Disturbance
(Head Rotation Rate)
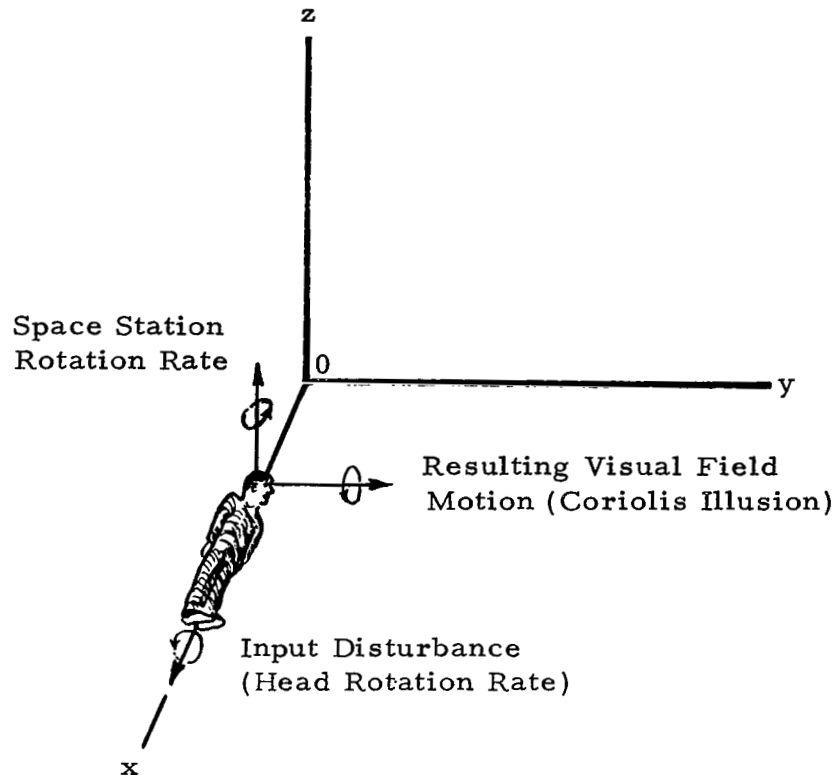
FIGURE 2. GYROSCOPIC TORQUE EFFECT ON SEMICIRCULAR CANALS

(a) Slow Rotating Room
    -Subject Standing

(c) Slow Rotating Room
    -Subject Reclining

(b) Centrifuge
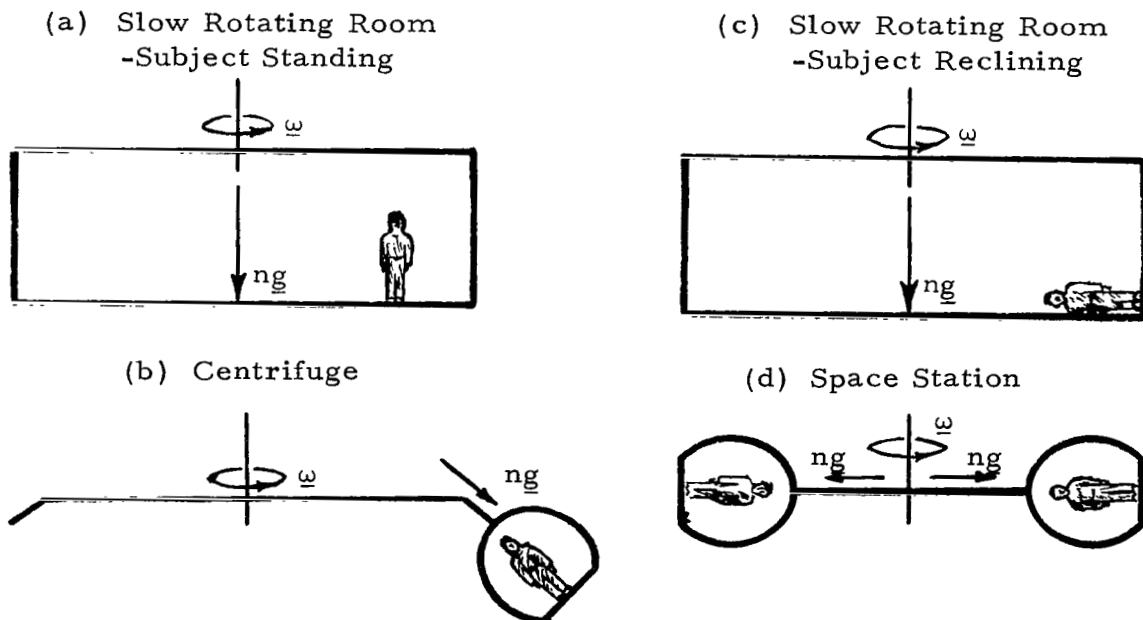
(d) Space Station

FIGURE 3. SCHEMATIC REPRESENTATION OF SEVERAL
ROTATING ENVIRONMENTS

In (d) of Figure 3, the rotating space-station situation, the gravity vector is oriented radially, head to feet, and is in the plane of rotation. None of the simulation techniques fully reproduces this relationship. Therefore, the pattern of canal stimulation obtained in the various simulation methods does not fully reproduce the stimulation pattern expected in the orbital condition. It has been pointed out in the literature [17] that the vestibular stimulation encountered in space-stations will have certain similarities and certain differences to that encountered in rotating rooms on earth. For a man in an upright position in each gravity field, most head movements will produce Coriolis Illusions of the same magnitude. On a centrifuge, head motion in relation to the gravity vector will be at an angle with respect to the plane of spin; but, if head motions are controlled during the experiment, the results will be very similar to those for the upright position. The technique in (c) theoretically produces canal-stimulation patterns identical to those in (d), but experimentation has shown that in the (c) condition, gravity will supplement or decrease the rotational sensation obtained about the radial axis [18]. This latter condition does not occur in (a). Further, the technique (b) results in greater than 1-g magnitude of stimulation. This magnitude not only exceeds the expected magnitude for space operations, but recent experiments indicate that a force of this magnitude may modify experimental results in canal stimulation such as vestibular nystagmus [19].

Canal Stimulation Thresholds

To select thresholds that indicate stimulation of the semicircular canals, an understanding of the vestibulo-ocular-system relationship is necessary. Canal stimulation can be detected by quantitative measurement of eye movement or by subjective response of visual field changes [15, 16, 20, 21]. For the determination of canal stimulation, with an onset of angular acceleration — usually in one plane — experimenters most frequently use the two most popular indicators for the perception of motion: appearance of detectable nystagmus, and the oculogyral illusion. In nystagmus, the eyes drift slowly in one direction, then jerk rapidly back to an approximately central position, and slow drift commences again. The direction of eye drift is related directly to the plane of rotational-acceleration stimulus. The oculogyral illusion is a subjective response indicating detection of apparent movement of a faint light. For the detection of more complex canal-stimulation patterns caused by angular velocity, such as stimulation in two or more planes simultaneously, the Coriolis Illusion is used as an indicator.

Research at the USN Air Development Center, Johnsville, Pennsylvania, using a centrifuge, has yielded several studies in establishment of canal-stimulation thresholds based on subjective detection of the Coriolis Illusion. One of the studies, by Clark [22], has established the threshold as 0.06 rad^2/sec^2 for free head movements on a centrifuge with a 50-foot radius rotating at 1 rad/sec. In another study, utilizing forced full-body tilt [16], the threshold was found to be two to three times greater in magnitude. This latter threshold was established partially under a higher rotation rate. Thus, a higher g level may account for some of the difference in results between those two studies. For this investigation, the lower threshold of 0.06 rad^2/sec^2 was selected. This lower limit is considered most applicable, because with each new orientation of the body, a man on a space station will be subjected to a different canal-stimulation pattern so that other-than-normal stimulation inputs because of head motion must always be minimized.

Subjective detection of the oculogyral illusion has also been verified as a sensitive indicator of onset of angular acceleration. Several investigators [23, 24, 25] have conducted research to establish the time interval between onset of angular acceleration and the subject's signal of onset of apparent rotation (response latency). As a result of the research conducted by Guedry and Richmond [24], the response latency defined by the following equation was chosen for this investigation:

$$0.39 = \alpha(1 - e^{-0.1t}) \tag{1}$$

where

α = magnitude of the applied angular acceleration

t = time to detect the acceleration

0.39 = experimentally derived value for cupula deviation

The research at NASA Langley Research Center, Virginia [26] employs a small centrifuge to position the subjects along the radial axis. This research revealed a relationship between tolerable head-turning rates and vehicle-rotation rates, and defined the region of adaptation for men subjected to various rotation rates. Figure 4 summarizes the results of that research. This identification of a tolerable region is significant for the determination of the time needed to damp a large disturbance.
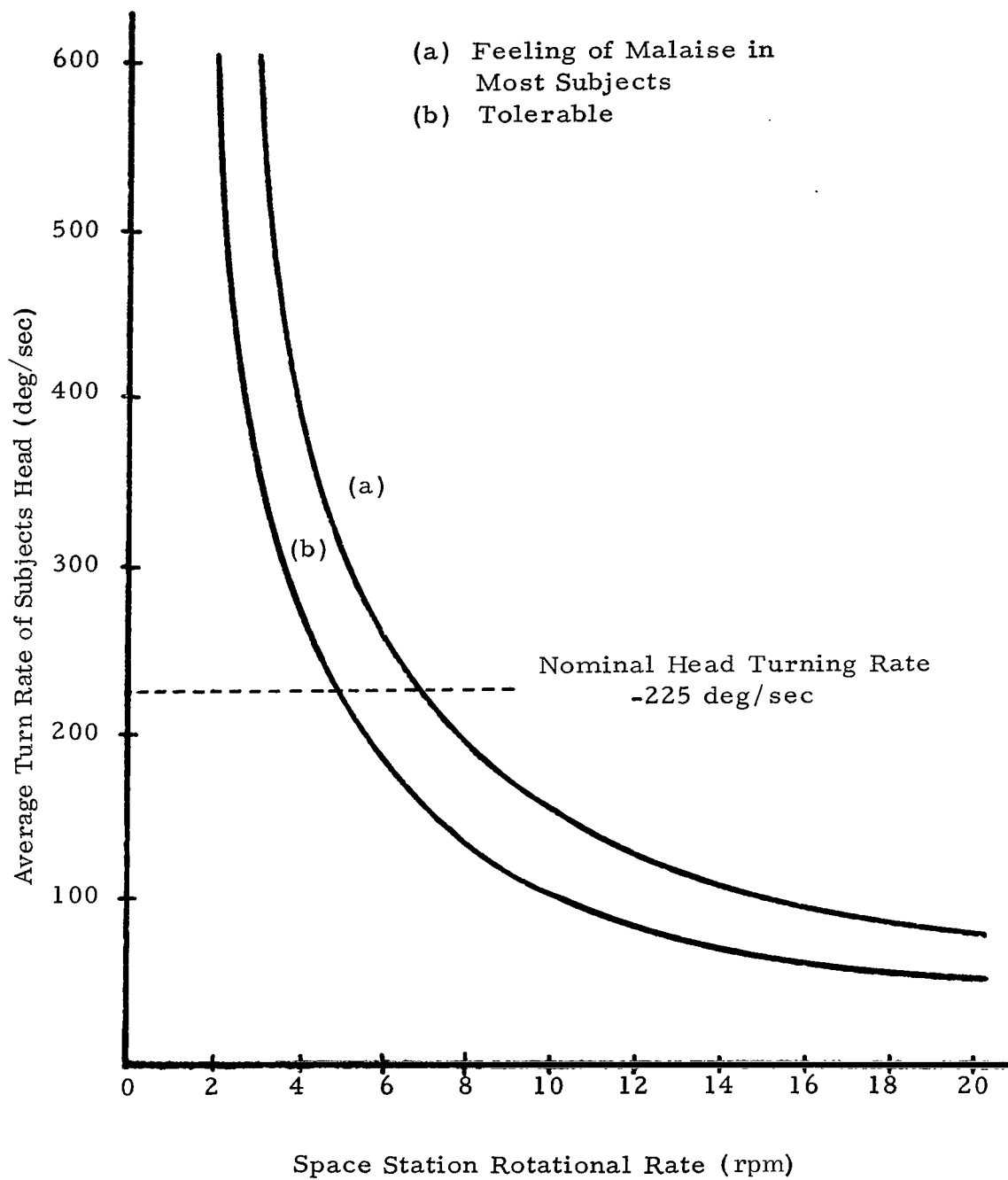
FIGURE 4. RESULTANT GYROSCOPIC TORQUE LIMITS ON
SEMICIRCULAR CANALS

Oscillatory motion (vibratory effect) in man's down direction as defined by the centrifugal-force vector must also be considered. There is no record of research below 1 cps with respect to effects on a man. Figure 5 summarizes most of the existing information in this field [27] and was used as a guide in this investigation.

Biofunctional Design Envelope

A number of studies reported in the literature were concerned with the evolution of a design envelope in which a man can function optimally in a rotating environment [28, 29, 30]. These studies dealt with enhancing the operational capability of the man. They assumed that the man will adapt to the environment and that disturbances to the field do not exist. The significant results are defined as limits on space-station radii and rotation rates. These are the parameters of interest in this investigation. The biofunctional design envelope evolved by Loret [28] is reproduced in Figure 6 for reference.

DERIVATION OF DISTURBANCE EFFECTS TO ARTIFICIAL GRAVITY FIELD

Disturbances to the rotation plane of a space station rotating in a passive state causes it to rotate simultaneously about two or more of its axes. The resulting fluctuations induced into the artificial gravity field change it from a constant magnitude-and-direction field sensed by a man to one which exhibits complex, magnitude-and-frequency characteristics. The equations of motion describing these characteristics are derived below in terms of space-station configurational, operational, and rotation plane stability parameters.

Orientation Of Man

The orientation selected for the man in this analysis is shown in Figure 7. He is positioned so that his superior canal is aligned with the xy plane, his posterior canal with the xz·plane, and his horizontal canal with the yz plane. The +x direction represents his down-direction and the +y axis, his face looking forward. This positions the man rotating, face-forward in the +ω (rotation rate) direction.
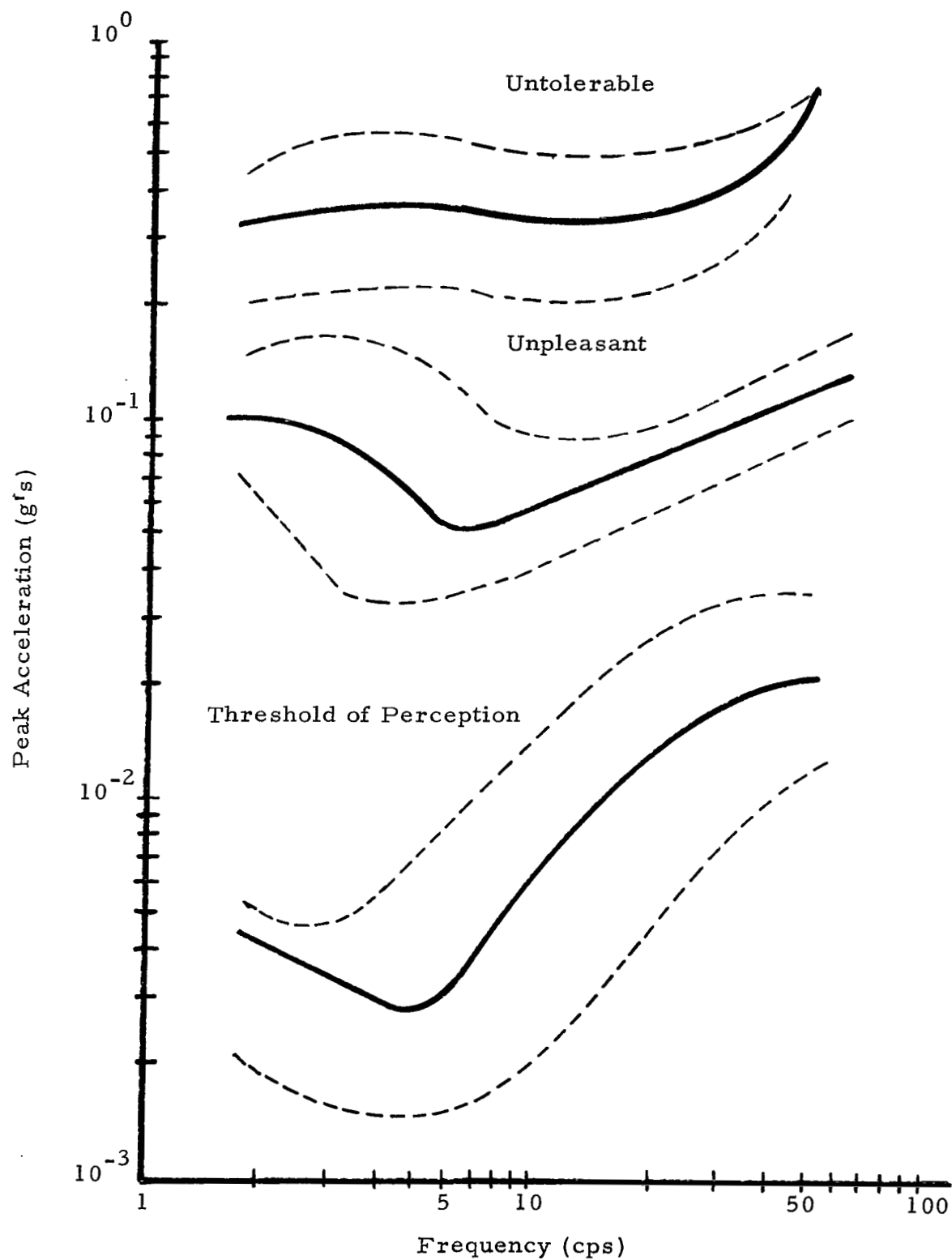
FIGURE 5. SUBJECTIVE RESPONSES TO VIBRATION

12
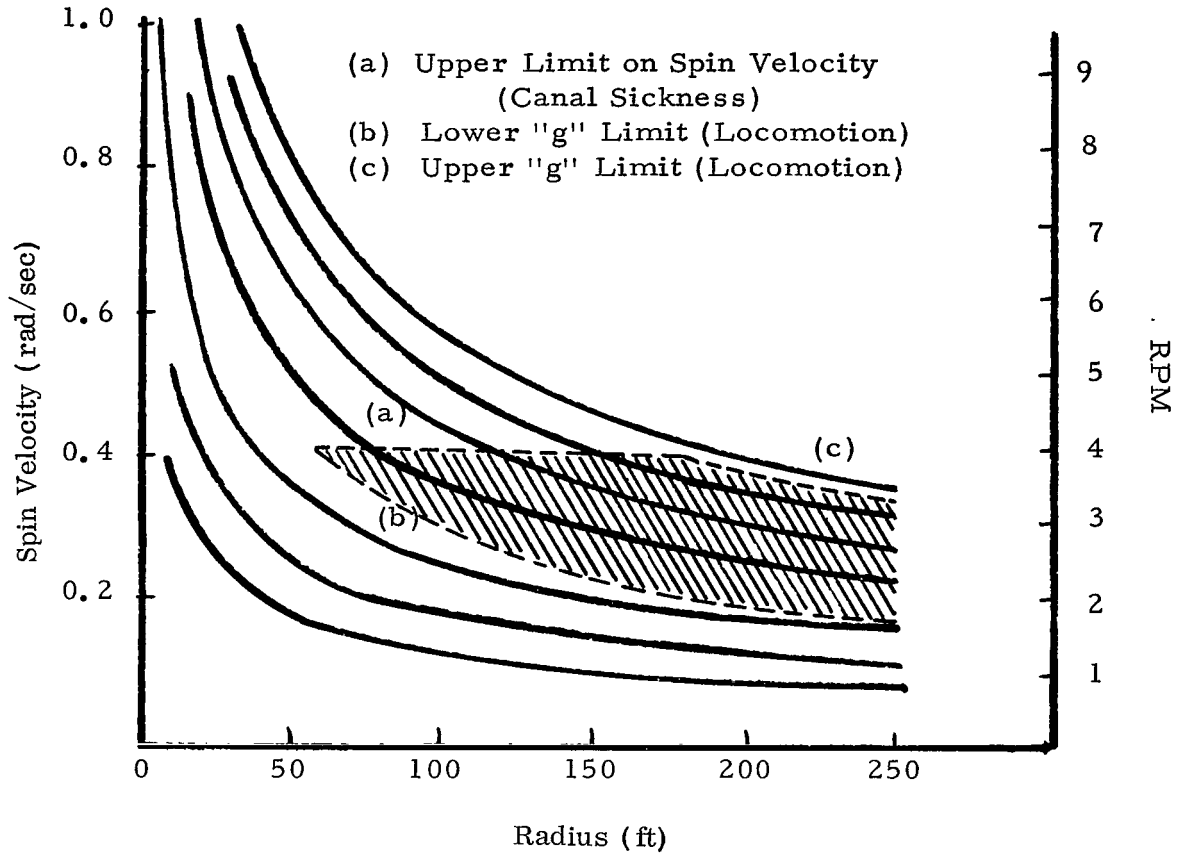
FIGURE 6. BIOFUNCTIONAL DESIGN ENVELOPE

Field Equation Derivation

This investigation will consider only the rotation of a rigid-body space-station configuration in a passive state. For a rotating configuration, the accelerations acting at any point P_o when referred to axes aligned and moving with the body's principal axes [31] can be written in equation form as

$$\underline{\partial} = \underline{\ddot{p}} + \underline{\dot{\omega}} \; x\underline{r} + \underline{\omega}x(\underline{\omega}x\underline{r}) + 2\underline{\omega} \; x\underline{N} + \underline{f} \qquad . \tag{2}$$

This shows that the acceleration at point P_o is composed of five terms. The first, $\underline{\ddot{p}}$, represents the acceleration of the origin of the axes, the

13
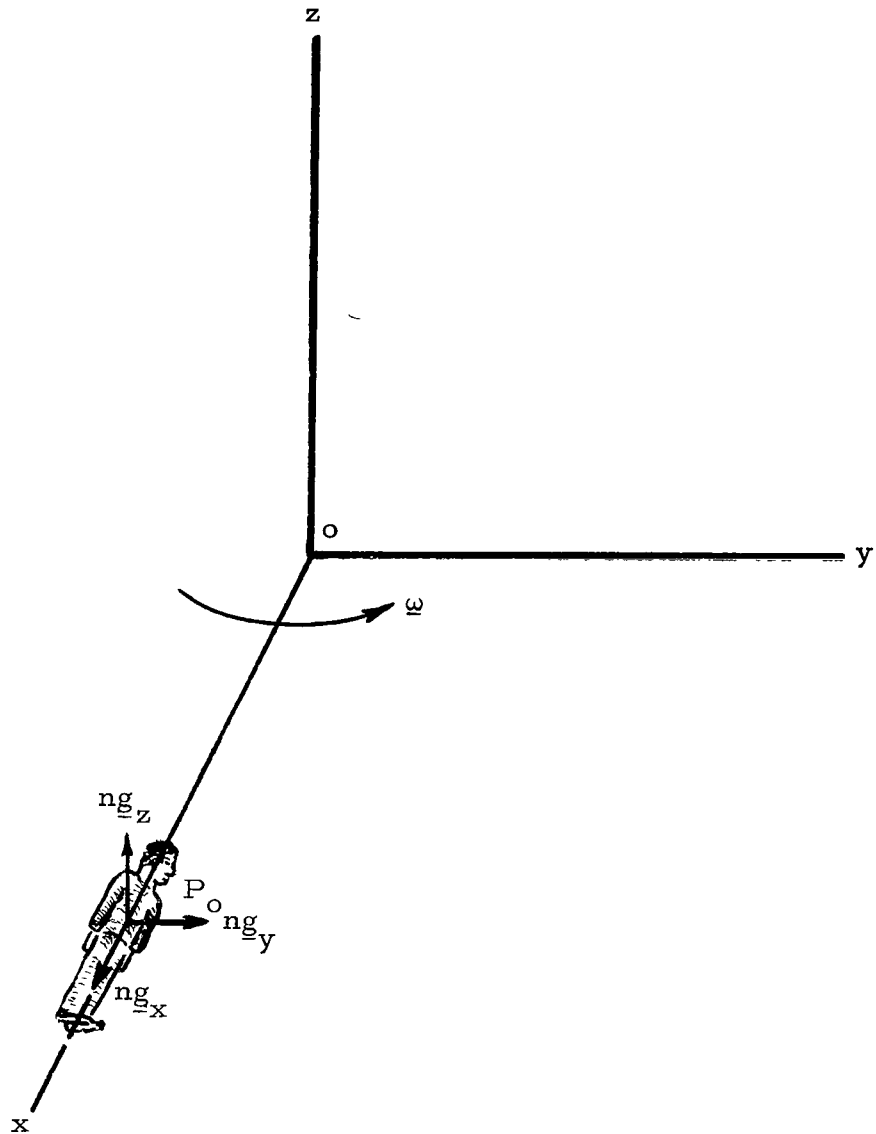
FIGURE 7. SELECTED ORIENTATION OF MAN IN A ROTATING
SPACE STATION

second is the linear acceleration due to the angular acceleration $\dot{\omega}$ of the moving axes, the third is the centripetal acceleration due to the constant rotation of the moving axes, the fourth is the so-called Coriolis acceleration due to moving P_o at the velocity N, and the fifth is the apparent acceleration of P_o to the moving axes. If the point P_o is rigidly fixed to the moving axes, the terms f and N vanish. Further, assuming the axes are moving in space at a constant velocity allows elimination of the $\dot{p}$ term. Since the man senses

reaction forces, the negative of the remaining acceleration terms gives the gravity field sensed by the man. For a man positioned on the x axis, the gravity field in vectorial form can be reduced to

$$n\underline{g} = -\underline{\dot{\omega}} \times \underline{r} - \underline{\omega} \times (\underline{\omega} \times \underline{r}) = x \, [\underline{i} \, (q^2 + r^2) - \underline{j} \, (pq + \dot{r}) - \underline{k}(pr - \dot{q})] \quad . \tag{3}$$

Equation (3) assumes that energy dissipation $(-\dot{\omega})$ can exist in the absence of external torques to a configuration rotating in a passive state; so the only stable condition for a rotating system is rotation about the axis of maximum moment-of-inertia [31]. The disturbed motion of this type of configuration (which can be described generally as having its principal moments-of-inertia related by C>B>A) is not readily described, because the equations of motion (Euler's dynamic equations [31, 32, 33, 34]) are not directly integrable. An analytic solution can be obtained for these equations, however, through utilization of elliptic integrals. The artificial gravity field equation in terms of these functions is derived in the Appendix. Because of the complexity in applying this derivation to this investigation, the approach taken is to: first, analyze the resulting motion by the technique developed by Poinsot [32, 33, 34] to give insight into the complex interaction of the parameters involved; and then, to perform an analog computer solution of the parameter interactions of interest.

The polhode cone and its trace on the inertia ellipsoid, which Poinsot developed to describe the motion, is now examined in more detail. This polhode cone and its trace in the xz plane are shown in Figure 8. Note that the major factor causing the distortion of the trace in the xz plane is the change in spin velocity r. This change in r results from the energy coupled to the z axis from about the other axes. To analyze the change, the equation of the polhode trace in this plane is examined. It is given by

$$A(A-B) p^2 + C(C-B) r^2 = L^2 \quad . \tag{4}$$

From Figure 6, p can be expressed as a function of the spin velocity r by

$$p = r \tan \gamma \quad . \tag{5}$$

Then, equation (4) can be rewritten as

$$A(A-B) r^2 \tan^2 \gamma + C(C-B) \, r^2 = L^2 \tag{6}$$

or

$$r = L \, \left[C(C-B) - A(B-A) \tan^2 \gamma \right]^{-1/2} \quad . \tag{7}$$

z

ee' and ff' are planes separating
polhode traces about the axis of
maximum moment of inertia from those
about the axis of minimum moment
of inertia.

e' Polhode Trace

f'

P

ω

r

Inertia Ellipsoid

γ

f   O   e

x
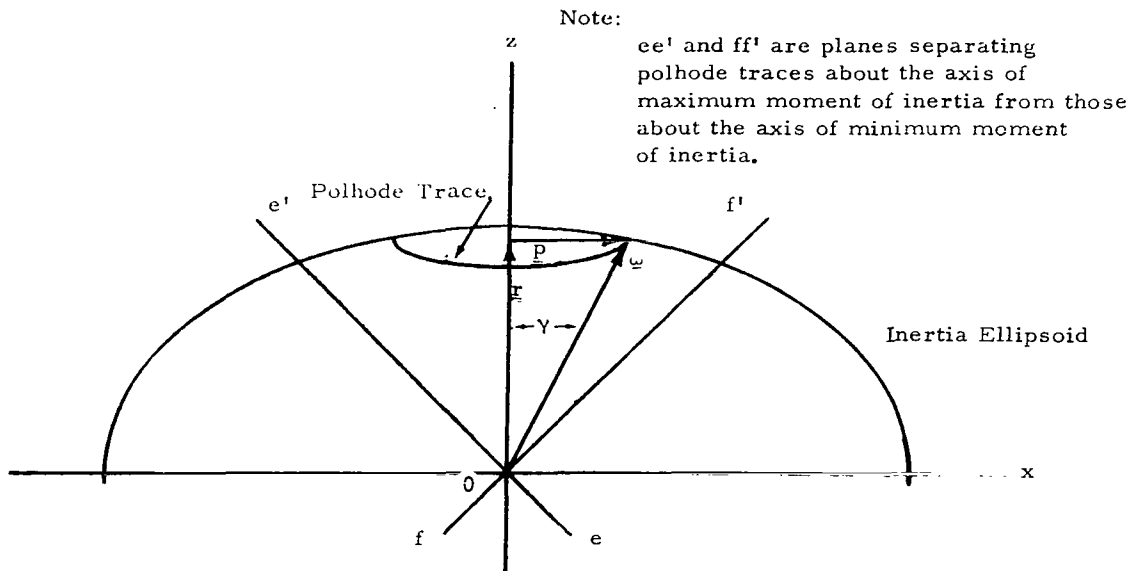
FIGURE 8. POLHODE TRACE IN THE xz PLANE

Referring to Figure 8 again, in the motion of the ω vector about the z axis,
the maximum angle, γ, is normally swept out in the xz plane for B>A (the
angle is equal in both the xz and yz planes when A = B); hence, this angle is
related directly to the maximum size of the polhode cones about the z axis.
Using this relationship, the variation in r can be calculated with respect to
the mean value of r during a rotation of ω by the following expression:

where $\qquad r\% = \left[(r - r_o)/(r + r_o) \right] \, 100$ $\qquad\qquad\qquad\qquad$ (8)

where $\qquad r \;\; =$ spin velocity at γ_{max}

$\qquad\qquad r_o \;\; =$ spin velocity at $\gamma = 0$.

For several representative types of configurations, a plot of percent-variation
of r with γ is determined and presented in Figure 9. In cases of small
disturbances ($\gamma \leq 7$ deg), there is less than 1 percent variation in the spin
velocity r. It can be concluded that for small disturbances, Euler's equations
of motion for moving axes aligned with the bodies principal axes for the
C>B>A configuration can be written, generally, as

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$$A\dot{p} + (C - B)\, qr = 0$$

$$B\dot{q} + (A - C)\, pr = 0$$

$$r = r_o \qquad \qquad (9)$$

The solutions of equation (9) become

$$p = p_o \cos Kr_o t - (k_1/Kr_o)q_o \sin Kr_o t$$

$$q = q_o \cos Kr_o t + (k_2/Kr_o)p_o \sin Kr_o t$$

$$r = r_o \qquad . \qquad (10)$$

Substituting the values for p, q, and r as derived in equation (10) into equation (3) gives

$$
ng = x \left\{ \underline{i} \left[q_o^2 \cos^2 Kr_o t + 1/2\,(k_2/k_1)^{1/2} p_o q_o \sin 2Kr_o t \right. \right.
$$

$$
\left. + (k_2/k_1)\, p_o^2 \sin^2 Kr_o t + r_o^2 \right] - \underline{j} \left[-1/2\,(k_1/k_2)^{1/2} q_o^2 \sin 2Kr_o t \right.
$$

$$
\left. + p_o q_o (\cos^2 Kr_o t - \sin^2 Kr_o t) + 1/2(k_2/k_1)^{1/2} p_o^2 \sin 2Kr_o t \right]
$$

$$
- \underline{k} \left[(1 - k_2/r_o)\, p_o r_o \cos Kr_o t \right.
$$

$$
\left. \left. - (k_1/k_2)^{1/2} (1 - k_2/r_o)\, q_o r_o \sin Kr_o t \right] \right\} \qquad . \qquad (11)
$$
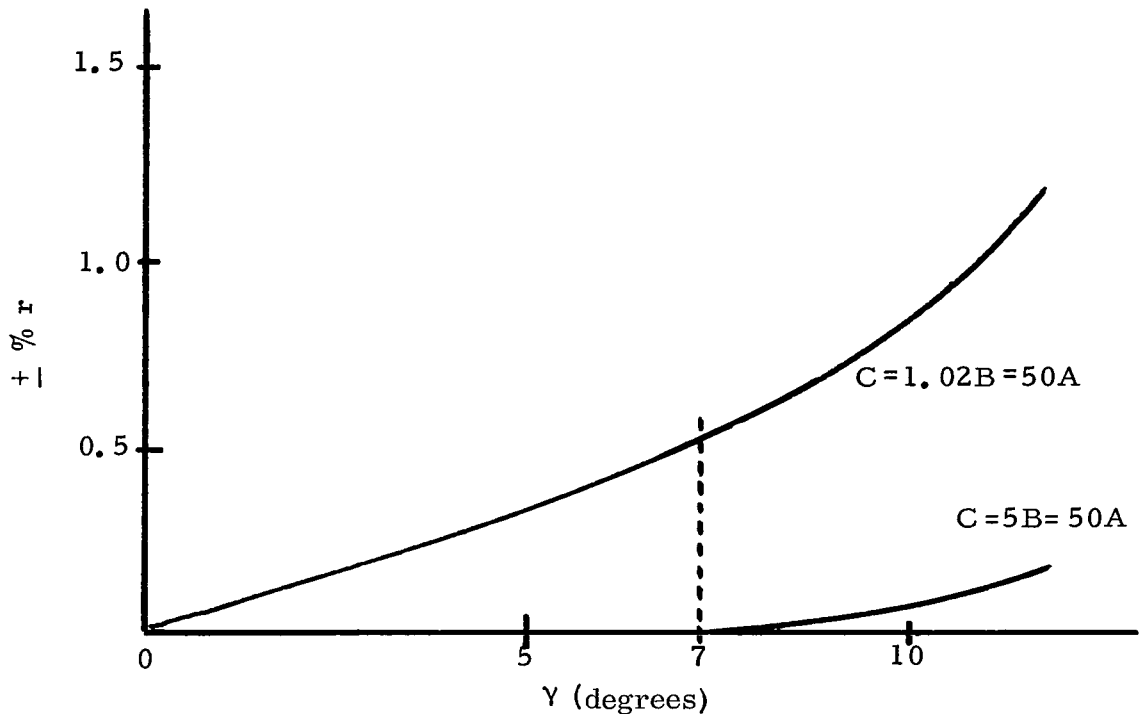
FIGURE 9. SPIN VELOCITY VARIANCE VERSUS γ

Observations Concerning The Field

An analysis shows that the force-field environment defined by equation (11) for directions along each of the body principal axes is oscillatory in direction and in magnitude. Along the x axis, man's down-direction, the resulting acceleration is composed of oscillatory components superimposed on the constant term xr_o^2. This constant term is the centrifugal force generated by rotation about the z axis. The acceleration terms perpendicular to the x axis given by the j and k terms disclose an interesting result [35] when plotted (see Fig. 10). This figure shows that the gravity vector in the yz plane will vary in a "figure eight" with respect to the man's down-direction when he's positioned on the x axis. From this discussion, it follows that the constant-magnitude-and-direction, centrifugal force-field (normally associated with constant rotation about an axis) transforms into a field of complex, oscillatory magnitude-and-frequency-characteristics when a space station

exhibits disturbed rotational motion. This illustrates the need for either passive or active methods to maintain control of space-station rotational plane variations to within man's physiological tolerance limits.

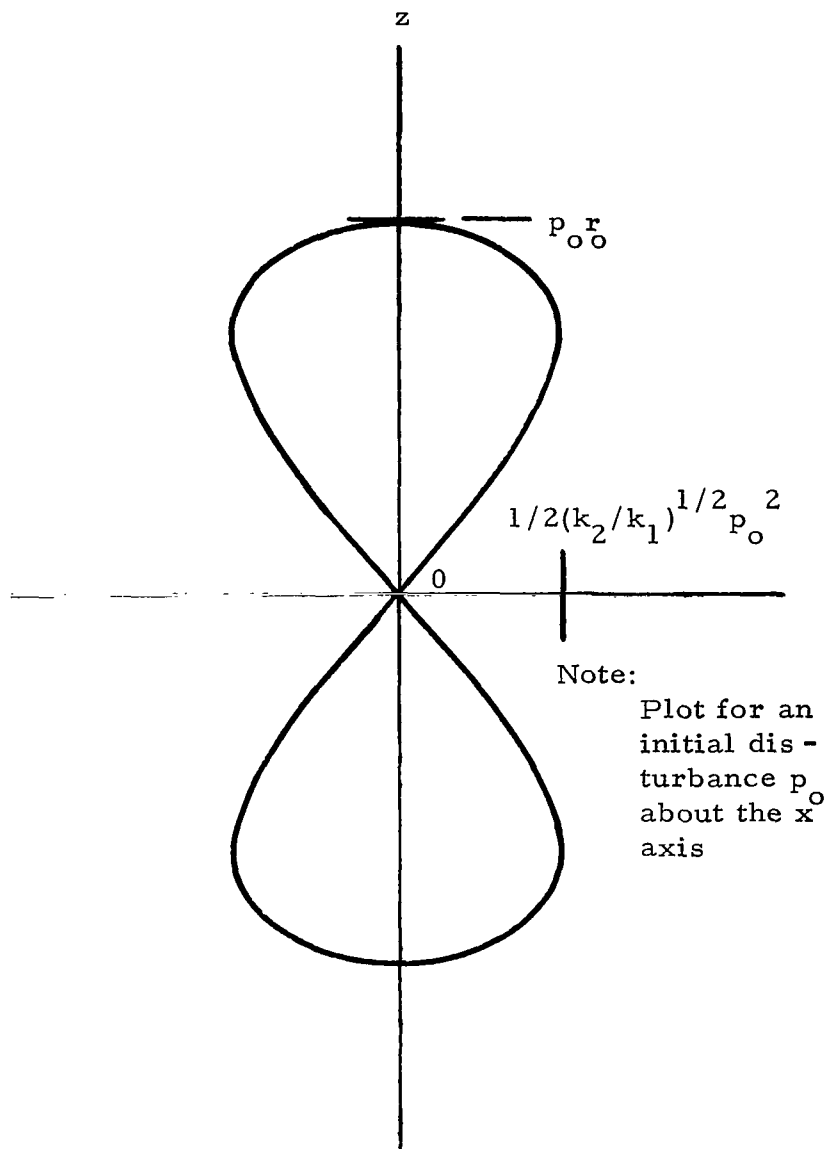FIGURE 10. GRAVITY VECTOR PLOT IN yz PLANE

ANALYSIS OF PARAMETERS INFLUENCING
ARTIFICIAL GRAVITY FIELD

The equation derived for the artificial gravity field showed that various space-station configurational, operational, and rotation plane stability parameters influence the magnitude and frequencies of the oscillatory components. Below, an analysis of these parametric effects on the field is presented. Man's physiological tolerances and range of adaptability in a rotating environment are used to define acceptable disturbance limits to the field in terms of these parameters.

Moment Of Inertia Relationships

For space-station design it would be usful to be able to define configurational parameters, such as moment-of-inertia and radius-of-rotation, in terms of the degree of influence to the artificial gravity field during disturbed rotational motion. In equation (11) it is noted that the characteristics of the terms of oscillatory acceleration are related directly, in magnitude and frequency, to initial–disturbance magnitudes for p_o and q_o and to the moment-of-inertia relationship for the rotating space station. The radius of rotation is directly dependent on the x value chosen. First, some general conclusions can be reached. Beginning with component–acceleration magnitudes, the ratios k_2/k_1 and k_1/k_2 play an important role. The ratio k_2/k_1 is plotted in Figure 11 versus the moment-of-inertia ratio C/B for various C/A moment-of-inertia ratios.

From this figure, for a given C/A value, the k_2/k_1 ratio equals one for two different values of C/B; i.e., a so–called "dumbbell" configuration C>(B>>A) and a "wheel" or "torus" configuration C>(B = A). Between these C/B values, the ratio drops to a minimum. An initial response to this result may be to select the minimum k_2/k_1 value for a selected C/A curve as defining a best configuration. But, note that the ratio k_1/k_2 is an inverse function that will tend to magnify the magnitudes of the terms it affects with a possible result of a greater fluctuation in the field than with $k_2/k_1 = 1$.

In regard to the frequency of the oscillatory components, in equation (11), the factor K multiplied by the spin rate and time is the major consideration. Figure 12 presents a plot of K versus C/B for C/A ratios. Note that the period of oscillation is longer for a dumbbell than for a wheel
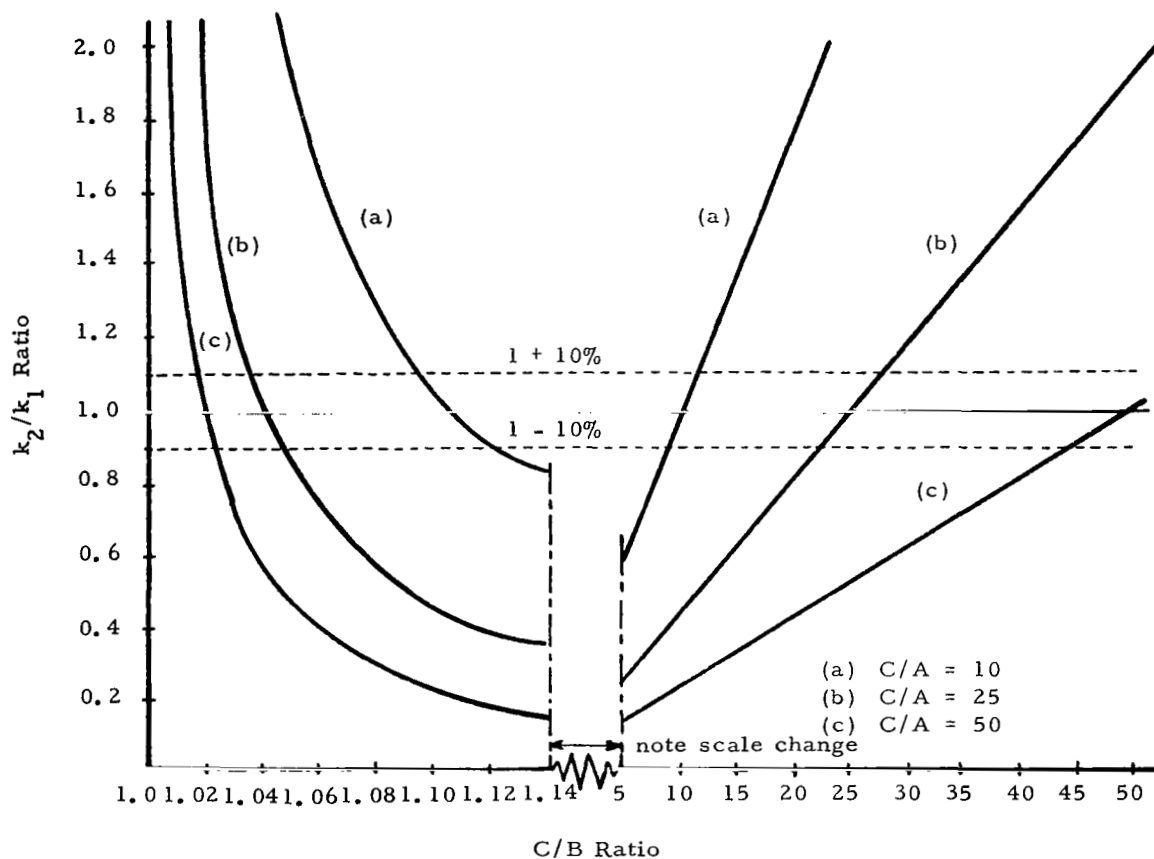
FIGURE 11. k_2/k_1 VERSUS C/B FOR VARIOUS C/A VALUES

configuration. Further, as the configurations grow larger in size (as indicated by the C/A ratio), the K factor grows larger too. The K factor is also most sensitive to change in the range C/B = 1 to 5.

In an analysis of a special case, Euler's dynamic equations were programmed on an analog computer for small disturbance inputs, which was equivalent to obtaining results defined by equation (11). Table I shows the radii of rotation, initial disturbance magnitudes, and moment-of-inertia relationships considered. Table II summarizes the resulting acceleration magnitudes and frequencies that would be sensed at the x (radii of rotation) dimension selected. One case that is representative of the results obtained will be discussed here.

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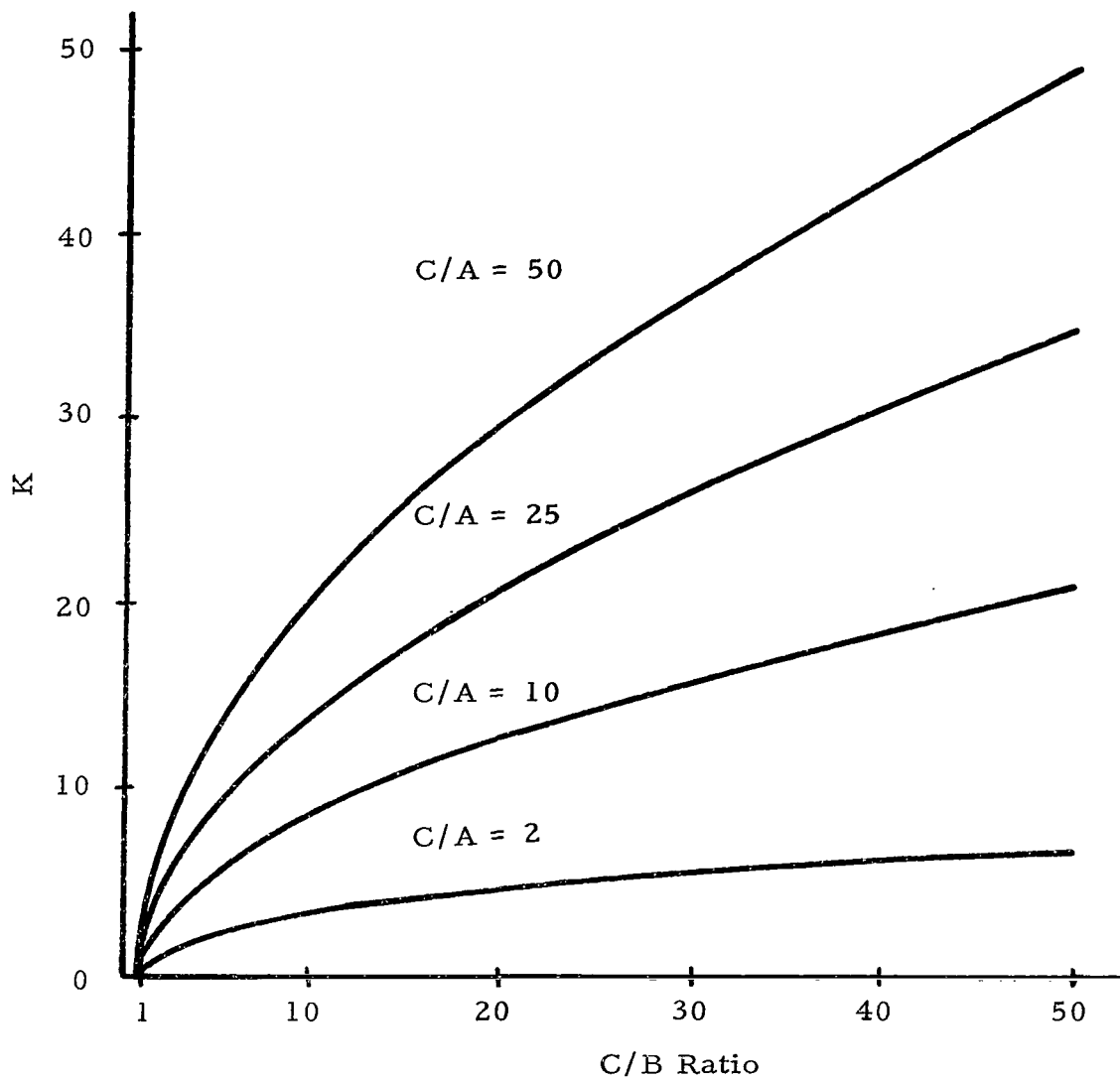
FIGURE 12. K VERSUS C/B FOR VARIOUS C/A VALUES

The conditions for this case are

r_o = 0.418 rad/sec (4 rpm)

p_o = 0.0105 rad/sec (small disturbance about x axis)

C/A = 10

R   = 75 and 100 ft   .

The results for this case are given in Table II (Trials 1 through 12).
Included are the acceleration magnitude and frequency changes which were
calculated for each C/B change.

Note that, as the configuration is changed from a dumbbell to a wheel
configuration, both the magnitude and the frequency of the oscillatory compon-
ents increase. Radius increase tends to decrease the magnitude, but not the
frequency, of the resulting acceleration components. Also, the down-accelera-
tion components (x axis) does not vary significantly with respect to the other
components until a wheel configuration is attained. Significantly, these
resulting disturbance-acceleration magnitudes are, of course, very small,
but they are related directly to the initial-disturbance magnitude. This re-
lationship of resulting acceleration magnitude to initial-disturbance magnitude
is, however, not linear. That is, a growth in initial disturbance will magnify
the results. (See trial 2, Table II.) These results are representative of the
relative relationships between the acceleration magnitudes and C/B changes
that can be expected to influence the field.

Movement off-axis in the y and z direction was also considered for the
dumbbell configuration and a slight variation of it, i.e., $k_2/k_1 = 1.11$ and 1.12.
These results are presented in Table II (trials 3, 4, 7, and 8). The movement
considered was 10 feet in either the +y or +z direction, but not in both simultane-
ously. The results show that for the dumbbell case ($k_2/k_1 = 1.11$), the
resulting field-component accelerations increase in magnitude compared with
those on the x axis. Also, the movement in the z direction introduces an
oscillation in the down-direction. Referring to Figure 5, the magnitude of this
mode of oscillation is not significant and will probably not introduce serious
control considerations. For $k_2/k_1 = 1.12$, movement off-axis causes oscil-
latory-acceleration components similar to that for a dumbbell. Again, the
magnitudes increase significantly, and the frequencies about the y and z axes
change indicating a change from the figure eight effect. This shows that the
field-acceleration component changes, with respect to position from the
x axis, are significantly increased in complexity with moment-of-inertia change;
i.e., variance from $k_2/k_1 = 1$. The fact that two different radii were used to
obtain these data does not affect this conclusion, which indicates radius does
not affect selection of disturbance limits. Since it is desirable to reduce all
acceleration-component magnitudes simultaneously (to reduce possible adverse
effects to a man), it is considered that $k_2/k_1 = 1 \pm 10\%$ should be the range
chosen initially for the moment-of-inertia relationship for a given configuration.

TABLE I. SPACE STATION MOMENT-OF-INERTIA RELATIONSHIPS
SELECTED FOR ANALYSIS

Trials	C (slug-ft^2)	p_o (rad/sec)	r_o (rad/sec)	x (ft)	y (ft)	z (ft)	C/A	C/B
1	$6.8\text{x}10^4$	0.0105	0.418	75	0	0	10	1.11
2		0.0262			↓	↓		↓
3		0.0105		↓	10			
4					0	10		
5				100		0		
6					↓			1.12
7					10	↓		↓
8					0	10		
9						0		1.15
10								3.0
11								9.0
12	↓	↓	↓	↓	↓	↓	↓	10.0
13	$6.8\text{x}10^4$	0.0105	0.418	75	0	0	25	1.04
14				↓	10	↓		↓
15					0	10		
16				100		0		
17								1.045
18								1.15
19								3.0
20								22.0
21	↓	↓	↓	↓	↓	↓	↓	25.0
1A*	$17\text{x}10^6$	0.0105	0.418	75	0	0	2	1.5
2A				↓		10		
3A				50		↓		
4A				↓		0		
5A				25		↓		
6A	↓	↓	↓	↓	↓	10	↓	↓

*Parameters derived from NAS 9-1665, "Study of a Rotating
Manned Orbital Space Station," March 1964.

TABLE II. ACCELERATION MAGNITUDE AND FREQUENCY RESULTS FOR
THE MOMENT-OF-INERTIA RELATIONSHIPS ANALYZED

Trials	ng_x Mag. (g's)	ng_x Freq. (cps)	ng_y Mag. (g's)	ng_y Freq. (cps)	ng_z Mag. (g's)	ng_z Freq. (cps)
1	0.38	–	3.8×10^{-5}	0.14	–	–
2	0.38	–	1.5×10^{-4}	0.14	–	–
3	0.38	–	5.3×10^{-2}	–	–	–
4	0.38 $\pm 1 \times 10^{-2}$	0.065	2.8×10^{-3}	0.07	–	–
5	0.55	–	2.6×10^{-5}	0.07	–	–
6	0.55	–	2.6×10^{-5}	0.14	5.1×10^{-5}	0.07
7	0.55	–	5.6×10^{-2}	–	5.1×10^{-4}	0.07
8	0.55 $\pm 5.1 \times 10^{-3}$	0.07	2.8×10^{-3}	0.07	5.1×10^{-4}	0.07
9	0.55	–	1.3×10^{-4}	0.14	9.2×10^{-3}	0.07
10	0.55	–	2.6×10^{-4}	0.50	2.6×10^{-4}	0.25
11	0.55 $\pm 2.6 \times 10^{-4}$	1.25	1.5×10^{-4}	1.15	9.7×10^{-2}	0.58
12	0.55 $\pm 3.1 \times 10^{-4}$	1.25	1.8×10^{-4}	1.25	1.1×10^{-1}	0.63
13	0.38	–	–	–	–	–
14	0.38	–	5.4×10^{-2}	–	–	–
15	0.38	–	3.1×10^{-3}	–	–	–
16	0.55	–	–	–	–	–
17	0.55	–	–	–	–	–
18	0.55	–	–	–	1.0×10^{-3}	0.14
19	0.55	–	–	–	2.6×10^{-2}	0.04
20	0.55	–	–	–	2.6×10^{-1}	0.14
21	0.55	–	–	–	3.1×10^{-1}	0.16
1A	0.47	–	–	1.00	2.6×10^{-2}	0.50
2A	0.47	–	2.5×10^{-3}	0.50	1.3×10^{-1}	0.50
3A	0.325	–	2.5×10^{-3}	0.50	1.7×10^{-2}	0.50
4A	0.325	–	–	1.00	1.7×10^{-2}	0.50
5A	0.194	–	–	1.00	8.2×10^{-3}	0.50
6A	0.194	–	2.4×10^{-3}	0.50	8.2×10^{-3}	0.50

– implies zero or insignificant magnitude or frequency

Disturbance Limits On Space Station Rotation Plane

As stated initially in this work, the reason for rotating a manned space station is to generate a simulated gravity field that is habitable by man, i.e., a field whose magnitude and directional changes are kept within human physiological-tolerance limits. It is understood that this objective is attainable only when man adapts to ordinary head movements in a rotating environment. For that reason, the approach herein is to define disturbance limits on a space station rotation plane that will prevent canal stimulation when the man's head is stationary. This approach will allow a man to escape bizarre effects until he can learn to adapt. In addition, this will not require the man to adapt to a higher stimulation level (vehicle movement plus head movement) which can complicate the adaptation requirement.

1. Disturbance Limits During Normal Operation. The canal stimulation thresholds selected were those defined by Coriolis Illusions and nystagmus. Subjective Coriolis Illusion manifestations caused by disturbed space-station motion are considered the most detrimental to man's sense of well being. The threshold selected for this investigation is 0.06 rad^2/sec^2. The discussion on the field-equation showed that the greatest effect to the field resulted from a p_o or q_o disturbance. On this basis, the following relationship can be derived

$$(p^2 + q^2)^{1/2} r_o \leq 0.06 \text{ rad}^2/\text{sec}^2 \quad . \tag{12}$$

Considering the case of an equal initial disturbance about the x and y axes, i.e., $p_o = q_o$,

Then

$$(2p_o^2)^{1/2} r_o \leq 0.06 \text{ rad}^2/\text{sec}^2 \tag{13}$$

or

$$p_o r_o \leq 0.0426 \text{ rad}^2/\text{sec}^2 \quad . \tag{14}$$

As an example, for $r_o = 0.418$ rad/sec, the equation yields $p_o \leq 0.1$ rad/sec. This relationship shows that as the spin-rate of the space station is increased, the requirement for greater control of p_o and q_o to minimize disturbance rates

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about the x and y axes is increased. The requirement on the attitude control to maintain $r_o/p_o \geq 5$ is well within the present state-of-the-art capability.

Next, the effect on the stabilization criteria because of nystagmus will be considered, because disturbances resulting from p_o are oscillatory. Exceeding this threshold can cause nystagmus-blurring or, in a subjective sense, the creation of an oculogyral illusion. This analysis is complicated by its dependence on the factor K, but a representative case for both a dumbbell and a wheel will be discussed to establish a "feel" for this effect. The nystagmus threshold given by equation (1) is

$$0.39 = \alpha(1 - e^{-0.1t}) \tag{15}$$

where

α = angular acceleration in deg/sec^2

t = duration of disturbance-acceleration

Since the angular velocity from the disturbance is oscillatory, its rms magnitude will be used. By selecting a K value for a dumbbell, a wheel from Figure 12 for C/A = 10, and a spin rate of 4 rpm, the values for p_o can be calculated as follows

$$\text{Dumbbell } 1/2\text{-Cycle Period } (t_D) = \frac{\pi}{Kr_o} = \frac{3.14}{(0.96)(0.418)} = 7.8 \text{ sec} \tag{16}$$

$$\text{Wheel } 1/2\text{-Cycle Period } (t_w) = \frac{3.14}{(9.0)(0.418)} = 0.833 \text{ sec} \quad .$$

To solve for p_o (angular velocity), equation (15) must be rewritten as follows

$$0.39 \geq 0.707 \, p_o/7.8(1 - e^{-0.1(7.8)}) \quad \text{dumbbell}$$
$$\tag{17}$$
$$0.39 \geq 0.707 \, p_o/0.83(1 - e^{-0.1(0.83)}) \quad \text{wheel} \quad .$$

The value for p_o under each of these conditions is then calculated as

$$p_o \text{ (dumbbell)} \leq 6.9°/\text{sec} = 0.187 \text{ rad/sec}$$
$$\tag{18}$$
$$p_o \text{ (wheel)} \leq 0.078°/\text{sec} = 0.0021 \text{ rad/sec} \quad .$$

These results show that stabilization of a dumbbell configuration will not likely be a severe control requirement, but that larger wheel configurations (defined by the C/B ratio) are much more sensitive to disturbances. The primary reason for this effect is the increase in frequency represented by the factor K (comparison of a wheel to a dumbbell configuration). The K value for a wheel decreases as the C/B ratio decreases; therefore, for smaller wheel configurations, the r_o/p_o ratio will approach that of a dumbbell. As an example, for a configuration defined by C = 2(B = A), which is a realistic estimate of a small wheel configuration that could be launched by present booster capability, it can be shown that the ratio as defined by the oculogyral illusion is the same value as that defined above for the Coriolis Illusion. Therefore, within the capability of present launch-and-orbital-assembly techniques, the ratio $r_o/p_o \geq 5$ defines a tolerable, disturbed-motion state of space-station rotation for a man with limited head motions. The angle of spin-axis deviation (γ) as defined by this ratio is calculated to be 11 degrees. Present sensing and control capability greatly exceeds this requirement and should be used to minimize the total canal-stimulation level that a man is subjected to (as defined by vehicle motions and head motions combined). Therefore, a spin-axis deviation no greater than 1 degree or $r_o/p_o \geq 50$ should be set as a design goal for normal operational periods. Note that p_o will include both the external or internal, initial perturbation and the flexing or oscillation modes that are set up in the structure. Greater spin-axis deviation-control accuracy may be required also for other mission considerations such as antenna pointing, etc.

2. Disturbance Limits During Spin-Up/De-Spin Operations. During spin-up or de-spin operations, the acceleration-level and time duration at that level will be the key factors affecting the man. Exceeding the nystagmus threshold is a good indication of the presence of these factors. The threshold is given by equation (1) and is rewritten in terms of time as follows

$$t = 10 \ln \left(\frac{\alpha}{\alpha - 0.39} \right) \tag{19}$$

This equation describes a relationship between spin-up/de-spin time and angular acceleration. Figure 13 shows this relationship. This figure shows that the angular acceleration and the time are related indirectly. For example, at the $1°/sec^2$ level, only 4 seconds are available for each spin-up period. If this level is reduced below $1/2°/sec^2$, time is greatly increased — it would probably be acceptable to spin-up or de-spin in one continuous operation.

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Response Latency (t) (secs)

x - Experimental Results
(Guedry and Richmond)

$- t = 10 \ln\left(\dfrac{\alpha}{\alpha - 0.39}\right)$

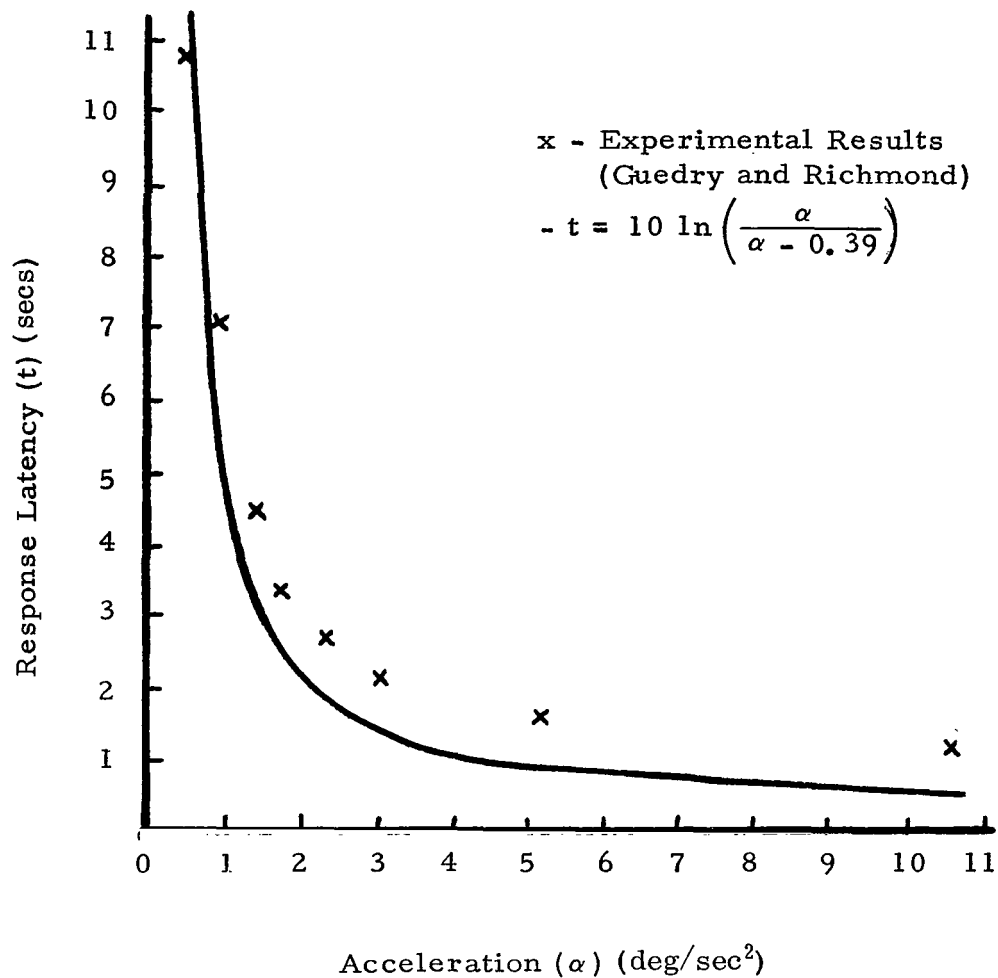Acceleration (α) $(\deg/\sec^2)$

FIGURE 13. RESPONSE LATENCY VERSUS ANGULAR ACCELERATION

Bergstedt [36] has shown experimentally that 0.25 rpm change per hour up to
3 rpm was tolerated well by his subjects. This is assuming that no additional
problems, because of readaptation, are super-imposed on the operation.
During the spin-up/de-spin operation, if the crew are instructed to limit head
movements, attitude-control requirements (stability control) can probably be
relaxed by a factor of 10 to the $r_o/p_o \geq 5$ ratio discussed previously. There-
fore, a small degree of misalignment in the torque-producing thrusters can be
tolerated.

3. <u>Time to Damp a Large Disturbance</u>. A man's exposure time to large perturbating changes in the field, resulting from a large external or internal disturbance to the space-station rotation, has not been studied directly. Studies concerned with rotational system-disturbances have approached the topic only from energy expenditure versus time. Of course, a solution to man's exposure time should not be attempted without considering these disturbances, but the proper, analytic trade-offs are beyond the scope of this investigation. Therefore, only some considerations of man's exposure time are discussed here.

To define reasons for time estimates for damping large disturbances, reexamine Figure 4 for an understanding of the effects influencing the man. From that figure, the upper curve defines the limit beyond which the man is subjected to malaise, while the region between the curves can be interpreted as probably tolerable. Then, the region below the lower curve is that where stimulation to the canals can be termed tolerable after adaptation, so a man does not continue to experience Coriolis and oculogyral illusions.

Assuming a rotation rate of 4 rpm for the space station, observe from the figure that 400 deg/sec defines the upper limit and 275 deg/sec defines the lower limit. Now, if the crew is instructed to maintain a fixed head-position after onset of the disturbance, it can be calculated that the resulting disturbance to the man gives the spin axis an angle of disturbance (γ) greater than 45 degrees in each case. Actually, this would be an unusual case. For smaller disturbances giving 20- to 30-degree excursions of the spin vector, the resulting effect on the adapted crewman with limited head motion would be considered within his tolerable region. Since this total problem is not a function of space-station configuration, but only rate of rotation, the time needed to damp for spin rates 4 rpm and smaller emerges as: the time from an energy and operational trade-off that it is practical to restrict man's head and body motion, i.e., restrict him from performing useful work until station rotational stability is attained. It is recommended that an attempt for a minimum time always be made, because other physiological problems not recognized at this time may be encountered in subjecting a man, who was adapted to head motions in a field of minimum disturbance, to an environment imposing high-level canal stimulation through forced full-body motions.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

As a result of this theoretical investigation the following conclusions are drawn:

1. The constant-magnitude-and-direction centrifugal force-field, normally associated with constant rotation about an axis, transforms into a field of complex, oscillatory magnitude-and-frequency characteristics when a space station exhibits disturbed rotational motion.

2. Man's physiological tolerances and range of adaptability to rotation can be utilized to derive space-station configurational and operational criteria for artificial gravity.

3. The configurational criteria derived from the analysis are:

(a) The moment-of-inertia relationship selected for a given configuration should be defined by $k_2/k_1 = 1 \pm 10\%$.

(b) Radius of rotation increase was found to influence (decrease) the magnitude, but not the frequency, of the resulting acceleration components of the field. This parameter should be selected within the limits defined by the Biofunctional Design Envelope given in Figure 6.

4. The disturbance limits for the space-station rotation plane derived from this analysis are:

(a) During normal operations at a constant rate of rotation, the disturbance defined by p_o should be related to the spin velocity r_o by the ratio $r_o/p_o \geq 50$. Limited operational time periods at the level defined by $r_o/p_o \geq 5$ are also considered acceptable.

(b) During spin-up/de-spin operations, the ratio $r_o/p_o \geq 5$ should be maintained.

(c) The time to damp a large disturbance at spin rates 4 rpm and smaller should be: the time from an energy and operational tradeoff that it is practical to restrict man's head and body motion, i.e., restrict him from performing useful work until rotational station stability is attained. In general, this time should always be minimized.

Recommendations

It is recognized in this investigation that the man's physiological tolerances and range of adaptability to a rotating environment were not derived through simulation that truly represented the disturbed rotational motion of a space station. Some investigators such as Newsom [37] have recognized the lack of research in this area and its possible influence on the biofunctional design envelope for rotating space stations. Therefore, in conclusion it is recommended that:

1. Ground-based simulators be reexamined for the applicability to simulation of disturbed, rotational motion of various space-station configurations.

2. The theoretical conclusions derived in this investigation can be validated through experimental simulation.

APPENDIX
DERIVATION OF ARTIFICIAL GRAVITY EQUATION
UTILIZING ANALYTIC SOLUTION
OF EULER'S DYNAMIC EQUATIONS

Euler's Dynamic equations for unequal moments of inertia are given by

$$A\dot{p} + (C - B) \; qr = 0$$

$$B\dot{q} + (A - C) \; pr = 0 \hspace{4cm} (A-1)$$

$$C\dot{r} + (B - A) \; pq = 0 \hspace{2cm} .$$

Multiply the first equation by p, the second by q, and the third by r, to give

$$q\dot{q} = \left(\frac{A}{B-C}\right) \left(\frac{C-A}{B}\right) \; p\dot{p}$$

$$ \hspace{8cm} (A-2)$$

$$r\dot{r} = \left(\frac{A}{B-C}\right) \left(\frac{A-B}{C}\right) \; p\dot{p} \hspace{2cm} .$$

The initial conditions for the spin rates are specified by

$$p \; (o) = p_o$$

$$q \; (o) = q_o \hspace{5cm} (A-3)$$

$$r \; (o) = r_o \hspace{2cm} .$$

Now integrate equation (A-2) and use the initial condition (A-3) to yield

$$q^2 = \left[\left(\frac{A}{B-C}\right) \left(\frac{C-A}{B}\right)\right] \; \left(p^2 - p_o^2\right) \; + q_o^2$$

$$ \hspace{8cm} (A-4)$$

$$r^2 = \left[\left(\frac{A}{B-C}\right) \left(\frac{A-B}{C}\right)\right] \; \left(p^2 - p_o^2\right) \; + r_o^2 \hspace{1cm} .$$

Next, define the following quantities

$$y = \frac{1}{q_o} \sqrt{\left(p^2 - p_o{}^2\right) \frac{A}{B} \frac{A - C}{B - C}}$$

$$N = r_o \sqrt{\frac{(B - C)(A - C)}{AB}} \tag{A-5}$$

$$k = \frac{q_o}{r_o} \sqrt{\frac{B}{C} \left(\frac{B - A}{A - C}\right)} \quad .$$

Equation (A-4), can be written then as

$$\left(\frac{q}{q_o}\right)^2 = 1 - y^2$$

$$\left(\frac{r}{r_o}\right)^2 = 1 - k^2 y^2 \quad . \tag{A-6}$$

Squaring the first of equation (A-1) and substituting from equation (A-5) and equation (A-6) yields

$$\frac{1}{r_o{}^2 q_o{}^2} \left(\frac{A}{B - C}\right)^2 \dot{p}^2 = \left(1 - y^2\right)\left(1 - k^2 y^2\right) \quad . \tag{A-7}$$

The left side of equation (A-7) is seen to be

$$\frac{A}{B} \left(\frac{A - C}{B - C}\right) \left(\frac{\dot{p}}{q_o}\right)^2 \frac{AB}{r_o{}^2 (B - C)(A - C)} = \left(\frac{dy}{dNt}\right)^2 \tag{A-8}$$

This allows reducing equation (A-7) to the recognizable form

$$\left(\frac{dy}{dNt}\right)^2 = \left(1 - y^2\right)\left(1 - k^2 y^2\right) \quad , \tag{A-9}$$

which can be expressed in terms of the elliptic integral of the first kind

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$$Nt = \int_{0}^{y} \frac{dy}{\sqrt{(1 - y^2)(1 - k^2 y^2)}} \qquad . \qquad (A-10)$$

If $y = \sin \phi$, equation (A-10) becomes

$$Nt = F(\phi, \dot{k}) = \int_{0}^{\phi} \frac{d\phi}{\sqrt{1 - k^2 \sin^2 \phi}} \qquad . \qquad (A-11)$$

Thus, it can be written as

$$y = \sin \phi = Sn(Nt, k) \qquad . \qquad (A-12)$$

Utilizing definitions given by equation (A-5), the solutions for the spin rates can be written as

$$p = \sqrt{q_o^2 Sn^2(Nt, k)\left[\frac{B}{A}\left(\frac{B - C}{A - C}\right)\right] + p_o^2}$$

$$q = q_o Cn(Nt, k) \qquad\qquad\qquad (A-13)$$

$$r = r_o Dn(Nt, k) \qquad\qquad ,$$

where the Cn and Dn functions are related to the Sn function by the equations

$$Cn^2(Nt, k) = 1 - Sn^2(Nt, k)$$
$$\qquad\qquad\qquad\qquad\qquad\qquad (A-14)$$
$$Dn^2(Nt, k) = 1 - y^2 Sn^2(Nt, k) \qquad .$$

From equation (3) in the text, the artificial gravity field for a man standing on the x axis, is given by

$$\underline{ng} = -\underline{\dot{\omega}} \times \underline{r} - \underline{\omega} \times (\underline{\omega} \times \underline{r}) = x\left[\underline{i}(q^2 + r^2) - \underline{j}(pq + \dot{r}) - \underline{k}(pr - \dot{q})\right] . \quad (A-15)$$

Substituting from equations (A-1) and (A-13) into equation (A-15) gives

$$ng = x\left\{ i\left[q_o^2 \, Cn^2 \, (Nt, \, k) + r_o^2 \, Dn^2 \, (Nt, \, k)\right]\right.$$

$$-\underline{j}\left[\left(q_o \, Cn \, (Nt, \, k) \, \sqrt{q_o^2 \, Sn^2 \, (Nt, \, k) \left[\frac{B}{A}\left(\frac{B-C}{A-C}\right)+p_o^2\right]}\right)\left(1+\left(\frac{A-B}{C}\right)\right)\right]$$

$$-\underline{k}\left[\left(r_o \, D_n \, (Nt, \, k) \, \sqrt{q_o^2 \, Sn^2 \, (Nt, \, k) \left[\frac{B}{A}\left(\frac{B-C}{A-C}\right)+p_o^2\right]}\right)\left(1+\left(\frac{A-C}{B}\right)\right)\right]\right\} .$$

$$(A-16)$$

Equation (A-16) gives an analytic solution for the artificial gravity field that would be sensed by a man positioned on the x axis of a rotating space-station configuration.

REFERENCES

1. Lamb, L. E.: Circulatory Aspects of Manned Space Flight. Third International Symposium on Bioastronautics and Exploration of Space, San Antonio, Texas, November, 1964.

2. Crockett, A. T. K., et al.: Hypodynamic Urolithiasis: A Potential Hazard During Prolonged Weightlessness in Space Travel. Review 2-62, School of Aerospace Medicine, USAF Aerospace Medical Center, Brooks AFB, Texas, December, 1961.

3. Berry, C. A., et al.: Aeromedical Analysis. Results of the Third U. S. Manned Orbital Space Flight, October 3, 1962, NASA SP-12, 1962.

4. Catterson, A. D., et al.: Aeromedical Observations. Project Mercury Summary Including Results of the Fourth Orbital Manned Orbital Flight, May, 1963, NASA SP-45, 1963.

5. Gazenko, O. G., et al.: Biological and Physiological Investigations During Flights on Rockets and Artificial Earth Satellites. IAF/IAA Symposium on Basic Environmental Problems of Man in Space, Paris, France, October 29 - November 2, 1962.

6. Yazdovskiy, V. I., et al.: Basic Problems in the Study of Weightlessness. Problems in Space Biology, Vol. III, Moscow, U.S.S.R., 1964.

7. Graveline, D. E.: Maintenance of Cardiovascular Adaptability During Prolonged Weightlessmess. ASD Tech. Rept. 61-707, Wright-Patterson AFB, Ohio, December, 1961.

8. Wenger, F. A.; Jones, F. N.; and Jones, M. H.: Physiological Psychology. Henry Holt and Co., New York, 1956.

9. Gray, R. F.: Relationship Between Semicircular Canal Function and Otolith Organ Function. NADC-MA-5911, Aviation Medical Acceleration Lab., USN Development Center, Johnsville, Pennsylvania, September, 1959.

REFERENCES (Continued)

10. Lisa, J. and Wenzel, C.: Man in a Rotating Space Station. Thirty-Fourth Annual Eastern Region Safety Convention and Exposition, New York, New York, April 9, 1964.

11. Steele, J. E.: Motion Sickness and Spatial Perception: A Theoretical Study. ASD Tech. Rept. 61-530, Wright-Patterson, AFB, Ohio, November, 1961.

12. Johnson, W. H., et al.: Stimulus Required to Produce Motion Sickness. J. Aviation Medicine, 22:365, 1951.

13. Spiegel, E. A., et al.: Experimental Production of Motion Sickness. War. Med., 5:283, 1944.

14. Greening, C.P.: Coriolis Effects on Operator Movements in Rotating Vehicles. Human Factors Unit, Advanced Systems, Autonetics, North American Co.

15. Guedry, F. E. and Montague, E. K.: Quantitative Evaluation of the Vestibular Coriolis Reaction. Aerospace Med., 32:487, 1961.

16. Gray, R. F., et al.: The Presence or Absence of Coriolis Illusions at Various Combined Angular Velocities. NADC-MA-6131, Aviation Medical Acceleration Lab., USN Air Dev. Center, Johnsville, Pennsylvania, June 1961.

17. Guedry, F. E.: Comparison of Vestibular Effects in Several Rotating Environments. Symposium on the Role of the Vestibular Organs in Exploration of Space, USN School of Aviation Medicine, Pensacola, Florida, January, 1965.

18. Lansberg, M. P., et al.: Effect of Changing Resultant Linear Acceleration Relative to the Subject on Nystagmus Generated by Angular Acceleration. Aerospace Med., Vol. 36, No. 5, May, 1965.

19. Guedry, F. E.: Orientation of the Rotation Axis Relative to Gravity: Its Influence on Nystagmus and the Sensation of Rotation. Acta Otolaryng., 60, 1965, pp. 30 - 48.

REFERENCES (Continued)

20. Graybiel, A. and Hupp, D.: The Oculogyral Illusion: A Form of Apparent Motion Which May be Observed Following Stimulation of the Semicircular Canals. J. Aviation Med. 17:3, 1946.

21. Guedry, F. E.: Nystagmus Eye Movements During Interacting Vestibular Stimuli. Report No. 275, U. S. Army Research Lab., Fort Knox, Kentucky, 1957.

22. Clark, C. C. and Hardy, J. D.: Gravity Problems in Manned Space Stations. Symposium on Manned Space Stations, Los Angeles, California, April, 1960.

23. Guedry, F. E. and Richard, G.: Differences in Response Latency with Different Magnitude Angular Accelerations. Report No. 301, U. S. Army Medical Research Lab., Fort Knox, Kentucky, 1957.

24. van Egmond, A. A. J.; Groen, J. J.; and Jongkees, L. B. W.: The Mechanics of the Semicircular Canal. J. Physiol., 110:1-17, 1949.

25. Mayne, R.: The Dynamic Characteristics of the Semicircular Canals. J. Comp. and Physiol. Psychol., 43:309-319, 1950.

26. Stone, R. W., Jr., and Letko, W.: Some Observations on the Stimulation of the Vestibular System of Man in a Rotating Environment. Symposium on the Role of the Vestibular Organs in the Exploration of Space, USN School of Aviation Medicine, Pensacola, Florida, January, 1965.

27. Shock and Vibration Handbook, Vol. 3, Engineering Design and Environmental Conditions, McGraw Hill Book Co., Inc., 1961.

28. Loret, B. J.: Optimization of Manned Orbital Satellite Vehicle Design with Respect to Artificial Gravity. ASD Tech. Rept. 61-688, Wright-Patterson AFB, Ohio, December, 1961.

29. Dole, S. H.: Design Criteria for Rotating Space Vehicles. The Rand Corp., Santa Monica, California, 1960.

REFERENCES (Concluded)

30. Thompson, A. B.: Physiological Design Criteria for Artificial Gravity Environments in Manned Space Systems. Symposium on the Role of the Vestibular Organs in the Exploration of Space., USN School of Aviation Medicine, Pensacola, Florida, January, 1965.

31. Thomson, W. T.: Introduction to Space Dynamics, John Wiley and Sons, Inc., New York, 1961.

32. Page, L.: Introduction to Theoretical Physics. D. Van Nostrand Co., Inc., Princeton, New Jersey, 1935, 2nd Edition.

33. Routh, E. J.: Dynamics of a System of Rigid Bodies. Dover Publications, Inc., New York, New York, 1905, 6th Edition.

34. MacMillan, W. D.: Dynamics of Rigid Bodies. Dover Publications, Inc., New York, New York, 1936.

35. Larson, C. A.: Space Station Design Parameter Effects on Artificial g Field. AIAA Journal, August, 1964, pp. 1454-55.

36. Bergstedt, M.: Stepwise Adaptation to a Velocity of 10 rpm in the Pensacola Slow Rotation Room. Symposium on the Role of the Vestibular Organs in the Exploration of Space, USN School of Aviation Medicine, Pensacola, Florida, January, 1965.

37. Newsom, B. D. and Brady, J. F.: Observations on Subjects Exposed to Prolonged Rotation in a Space Station Simulator. Symposium on the Role of the Vestibular Organs in the Exploration of Space, USN School of Aviation Medicine, Pensacola, Florida, January, 1965.
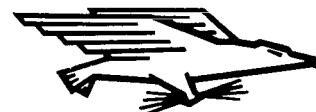
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