

Chapter 2

PHYSICS OF ARTIFICIAL GRAVITY

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This chapter discusses potential technologies for achieving artificial gravity in a space vehicle. We begin with a series of definitions and a general description of the rotational dynamics behind the forces ultimately exerted on the human body during level, gravity gradient, factors considerations with a rotating discussed. Finally, engineering options for designing space vehicles with artificial gravity are presented.

Figure 2-01. Artist's concept of one for a manned space station with inflating 22-m-diameter rotating NASA.

of NASA early (1962) concepts artificial gravity: a self-hexagon. Photo courtesy of

1 ARTIFICIAL IS IT?

GRAVITY: WHAT

1.1 Definition

Artificial gravity is defined in this book as the simulation of gravitational forces aboard a space vehicle in free fall (in orbit) or in transit to another planet. Throughout this book, the term *artificial gravity* is reserved for a spinning spacecraft or a centrifuge within the spacecraft such that a gravity-like force results. One should understand that artificial gravity is not gravity at all. Rather, it is an inertial force that is indistinguishable from normal gravity experience on Earth in terms of its action on any mass. A centrifugal force proportional to the mass that is being accelerated centripetally in a rotating device is experienced rather than a gravitational pull. Although the effect of artificial gravity on a human body differs from that of true gravity, which will be discussed in some detail in subsequent sections, the effects are equivalent for any given mass. Therefore, one can think of artificial gravity as the imposition of accelerations on a body to compensate for the forces that are absent in the microgravity of spaceflight (Figure 2-02).

Figure 2-02. The cardinal axes of the human body are defined as x, y, and z. Rotation about these axes is yaw, pitch, and roll, respectively. The positive directions of the gravito-inertial forces (G) along these axes are chosen to be chest-to-back (+G_x), left-to-right (+G_y), and head-to-foot (+G_z), respectively. [Note that the positive directions of the accelerations along these axes would be back-to-chest, right-to-left, and foot-to-head, respectively].

1.2 How to Generate Artificial Gravity

Artificial gravity can be produced in a number of ways. In the following sections, we discuss several interesting mechanisms that could, in theory, be used to develop artificial gravity. However, the practical limitations imposed on spacecraft mass, power, and cost means that achieving some of these designs must wait until technology catches up (from http://en.wikipedia.org/wiki/Artificial_gravity).

1.2.1 Linear Acceleration

Linear acceleration is one means by which artificial gravity in a spacecraft can be achieved. By accelerating the spacecraft continuously in a straight line, objects inside the spacecraft are forced in the opposite direction of that of the applied acceleration. This phenomenon is experienced by astronauts routinely during orbital adjustments of the Space Shuttle and other orbital spacecrafts when the thrusters are fired (it is also experienced by people in cars as the force pushing them back into their seats when they step on their gas pedal after the traffic light turns green). The result is intermittent impulsive artificial gravity imposed on the astronauts (or car driver) that is equal to the acceleration level achieved by the thrusters. However, the duration of this artificial gravity is too short (a few seconds) to be considered as a potential countermeasure.

If, however, a continuously thrusting rocket could be constructed that would accelerate a spacecraft for the first half of the journey to Mars and decelerate for the second half of the journey, a constant artificial gravity situation would result (see [Figure 1-13](#)). Ideally, the acceleration level would be at 1 g during both phases of the flight so that the explorers would feel “normal” gravity loading throughout their trip and arrive on Mars ready to go to work¹. But most rockets accelerate at a rate several times that of Earth’s gravity. This acceleration can only be maintained for several minutes because of limits on the amount of fuel that can be carried on board the launch vehicle as well as the specific impulse of the fuel. Theoretically a propulsion system employing very high specific impulse fuel and the key characteristic of a high thrust-to-weight ratio could accelerate for long periods of time. The result would be the production of useful levels of artificial gravity over longer periods of time, rather than very high gravity loads for a very short period of time. As an added bonus, such a constantly accelerating vehicle could provide relatively short flight times through the solar system. A spaceship accelerating (then decelerating) at 1 g would reach Mars in 2-5 days, depending on the relative distance². In a number of science fiction plots, acceleration is used to produce artificial gravity for interstellar spacecraft, propelled by as yet theoretical or hypothetical means.

1.2.2 Mass

Mass is the key component in producing gravity. Any mass has an associated gravitational field associated with it, be it ever so small for particles, or so overwhelming as the gravitational field associated with infinitely massive black holes. Hence, yet another way that artificial gravity might be achieved is to install an ultra-high density core into a spacecraft so that it would generate its own gravitational field and pull everything inside towards it. In reality, this is not artificial gravity because it *is* gravity! Many science fiction stories have played on this concept by implying that there are artificial gravity generators that create a gravitational field based on a mass that does not exist. In a practical sense, the story is helped because an Earth-like environment is apparently present on the spaceship. This, of

¹ Except that when they get there, they will only have 0.38 g, and an adaptation period may need to occur – some have proposed a decreasing gravity during the last part of the trip so the astronauts will already be adapted to 0.38 g when they get there.

² In the late 1950s, an experiment was conducted in the centrifuge at the Aviation Medical Acceleration Laboratory (AMAL) in Johnsville, Pennsylvania (see [Figure 11-06](#)) to investigate if humans could tolerate 2 g (+Gz) for 24 hours. The single subject (Dr. C. Clark) was medically monitored. At the end of the run, he was still able to talk and move, but he reported extremely fatigues. If accomplished in a straight line, a constant acceleration would take a space vehicle to approach near Mars. The total travel time, however, would take about 30 hours because of deceleration time (Chambers and Chambers 2005).

course, makes bringing a story to the big screen or television much more cost effective because it is significantly less expensive to produce a video in 1 g than it is to produce the special effects needed to simulate weightlessness.

An extremely large amount of mass is required to produce even a tiny gravitational field. For example, fairly large asteroid produces only several thousandths of a g^3 . One could imagine that by attaching a propulsion system of some kind to this asteroid, it might loosely qualify as a space ship. The downside is that gravity at such a low level is not likely to have any practical value. In addition, the mass would obviously need to move with the spacecraft. Any significant acceleration required for such a craft would come with the penalty of hugely increased fuel consumption. The only pragmatic way to implement artificial gravity based on the principle of mass is to find as of yet undiscovered materials with very high densities such that significant mass is present in a low volume of space. However, one still needs to grapple with getting so much mass into orbit in the first place.

1.2.3 Magnetism

If we again look to science fiction, we often see spacecraft in which artificial gravity (or the cancellation of gravity) is clearly present, yet the spacecraft is neither rotating nor accelerating. Current magnetic technologies have not yet developed to the point that such an artificial gravity system can be created in this way. Similar effects can certainly be created through the mechanism of diamagnetism. However, for this to work, it would involve avoiding any non-diamagnetic materials in or near the strong magnetic field that would be required for diamagnetism effects to be evident. Magnets of incredible strength would also be required for the implementation of such an artificial gravity system. Right now we can manage to levitate a frog using such devices, implying that up to 1 g can be produced. But this is accomplished using a magnet system that weighs thousands of kilograms and must be super cooled using very expensive cryogenics to keep it superconductive. This is hardly a practical device for implementation on a spacecraft.

1.2.4 Gravity Generator

No verified technique currently exists to produce gravity, apart from mass itself, even though there have been many claims over the years that such a device has been developed and exists. Eugene Podkletnov, a Russian engineer, has claimed since the early 1990s to have built such a device consisting of a spinning superconductor producing a powerful gravitomagnetic field. However, no verification has been provided and third parties have even purported negative results. In 2006 a research group from ESA claimed to have created a similar device that demonstrated positive results for the production of gravitomagnetism. The device produced only 100 millionths of a g, hardly a usable level of gravity in any application.

1.2.5 Centrifugal Force

Centrifugal force results from the centripetal acceleration generated by circular motion (rotation). Examples of circular motion include artificial satellites in geosynchronous orbit, a racecar going through a curve on a racetrack, an aircraft executing a coordinated turn, or an object tied to the end of a rope and twirled about in circles. Most of us have experienced it as the force that pushes us to the left (right) as we make right (left) hand turns in our cars. Spinning motion or rotational motion is a special case of circular motion that occurs when an object rotates or spins about its own center of mass. An example of this kind of motion is a record spinning on a turntable, or indeed, the turntable itself. The spinning produces centripetal acceleration in a radial direction away from the center.

Centripetal force is the product of the centripetal acceleration times the mass of an object. Artificial gravity could therefore be generated in the following ways:

- a. By a spacecraft spinning about its axis (Figure 2-01).

³ To achieve 1 g would require the mass of the Earth!

- b. By the rotation of two spacecraft connected by a tether (Figure 2-03, left).
- c. By a short-radius centrifuge on board a spacecraft (Figure 2-03, right).

Figure 2-03. Left: In this NASA photograph, astronauts Charles Conrad (center) and Richard F. Gordon (right) use models of Gemini-11 spacecraft and the Agena Target Docking Vehicle to demonstrate tether procedures and maneuvers. Right: Schematic of an on-board short-radius centrifuge.

In the case of a spinning spacecraft (a and b), anything inside would be forced toward the outside radius of spin by centripetal acceleration, which is the source of the artificial gravity. In the case of an internal short-radius centrifuge (c), only the subject and the objects on the centrifuge will be exposed to artificial gravity.

2 ARTIFICIAL GRAVITY GENERATED BY ROTATION

As previously stated, throughout this book the term *artificial gravity* is used to describe the centrifugal force generated by a spinning spacecraft or by a centrifuge within the spacecraft. In a rotating system there are forces present other than the centrifugal force that influence how objects move in the rotating environment and, consequently, how humans feel in such a rotating frame. The parameters involved in centrifugation are now reviewed. Keep in mind that for the information presented in the following subsections, we are assuming that any movement by an astronaut or particle in a rotating coordinate frame is at a constant velocity. Furthermore, we will not consider accelerations in an inertial frame, but only in the rotating coordinate frame associated with the rotating centrifuge or spacecraft. This significantly simplifies things. For a full analysis of moving particles in a rotating coordinate frame in inertial space, see Greenwood (1965).

2.1 Gravity Level

Circular motion is characterized by a radius r and an angular velocity ω (in rad/s). The radius is measured from the center of gravity of the spinning object to its edge, which will henceforth be assumed to be circular with the center of mass exactly in the middle. The angular velocity is simply how fast the spacecraft or object is spinning. Most people are familiar with angular rate being expressed in revolution per minute, or rpm. However, the units of radians per second are often used to express angular velocity because they simplify the mathematics⁴. The magnitude of the resulting centrifugal force is the product of the mass m of the object moving in a circle times the centripetal acceleration. The centripetal acceleration is a vector quantity that can be derived by vector multiplication (the cross product of the tangential velocity and the angular velocity. The magnitude of the tangential velocity is $r \omega$ and it is oriented in the direction of the rotation of the rim of the spacecraft or object. The magnitude of the centripetal acceleration is simply the product of the magnitudes of the tangential and angular velocities, and is always directed radially outward from the center of the rotating body. Therefore, the magnitude of the centripetal force is:

$$F = m \omega^2 r \quad [1]$$

In a reference frame that is fixed to the rotating body or centrifuge, that is, rotating along with the centrifuge, it appears as an external force pulling the subject toward the outer rim of the centrifuge. The centrifugal force is exerted on all objects in the rotating frame and is always directed away from the axis of rotation towards the rim. Every stationary object within the centrifuge is forced away from the axis of the object and the magnitude of this force is a function of its mass, distance from the center of rotation, and the square of the angular velocity of the device (Figure 2-04). In this book, the centripetal acceleration will be referred to as *the gravity level*. Accordingly, if an astronaut is standing on the rotating

⁴ 1 rpm is approximately equal to 10 rad/s.

floor of a spinning vehicle, or is lying on an internal short-radius centrifuge with his feet outward, the artificial gravity level at his foot, A , is:

$$A = \omega^2 r \quad [2]$$

Figure 2-04. Gravity level generated during centrifugation as a function of angular velocity and distance from the center of rotation (radius) for four given rotation rates of the centrifuge. This graphs illustrates one of the problems with artificial gravity created by centrifugation: for a given rotation rate, the gravity level varies along the radius. It turns out (no pun intended!) that in order to generate a 1-g artificial gravity, the radius needs to be very large with a slow rotation rate (e.g., 35 m for 5 rpm), or very small with a fast rotation rate (e.g., 4 m for 15 rpm).

2.2 Gravity Gradient

Because the gravity level varies along the radius of the centrifuge, an astronaut lying in a centrifuge along a radius with her feet positioned at the rim will have her head closer to the axis of rotation than her feet. The head will have a smaller radius of rotation (see Figure 2-03, left). Consequently, the gravity level at the head will have a smaller magnitude than the gravity level at the feet. The difference in artificial gravity level with distance from the center of rotation is referred to as the *gravity gradient*.

For an astronaut of height h , lying in a centrifuge along a radius with his feet positioned at the rim and his head pointing towards the center of rotation, his head has a radius of rotation equal to $r - h$. The ratio of head acceleration to foot acceleration can be simply expressed as

$$A_{\text{head}}/A_{\text{foot}} = \omega^2 (r - h) / \omega^2 r = (r - h) / r \quad [3]$$

By way of example, for an astronaut of height $h = 2$ m in a rotating environment with a radius of 100 m, this ratio is 98%, corresponding to a gravity gradient of 2%. This 2% difference would presumably not be perceived by the individual. However, for radii of rotation less than 10 m, the gravity gradient ranges from 20 to 100% (Figure 2-05), which may be perceived as a bent posture.

Figure 2-05. Gravity gradient as a function of radius of rotation for an astronaut's height of 2 m standing on the floor of a spinning vehicle or lying on an internal centrifuge with his feet outward.

Let us now consider the effects of a person moving inside a rotating vehicle. If an astronaut jogs around the rim of a spinning vehicle in the same direction of rotation, as Frank Poole in the movie *2001: A Space Odyssey* (see Figure 3-10), then his instantaneous linear velocity adds to the tangential velocity of the vehicle and the gravity level at his feet would increase as a result. (Recall that the centripetal acceleration is the cross product of the angular and tangential velocity.) On the other hand, if an astronaut runs in the opposite direction to the rotation of the vehicle, then his instantaneous linear velocity would oppose the tangential velocity, thus decreasing the effective magnitude of the tangential velocity of the astronaut, and the apparent gravity level would be decreased. If the rim speed of the centrifuge were small enough, it would be therefore theoretically possible for the astronaut to cancel out the artificial gravity by running in the opposite direction of rotation. Another force is playing a considerable role in this particular situation. The Coriolis force that results from the astronaut's velocity in the rotating frame as he runs along the rim is directed radially and either add to or subtract from the radial centrifugal force depending on the direction of movement. This Coriolis acceleration is described in the following section.

2.3 Coriolis Force

Although subjects at rest in a rotating system feel only the sensation of weight (i.e., the gravity level) generated by the centrifugal force, when they move, another force, called *Coriolis force*, is felt. The Coriolis acceleration is a direct result of any linear movement within the rotating reference frame and is 2

times the cross product of the angular velocity ω and the linear velocity vector v of the moving object, person, or body part. The direction of the Coriolis acceleration is perpendicular to the plane formed by ω and v in a right-hand-rule sense in accordance with vector calculus. Of course, the resulting force is obtained by multiplying the mass of the moving object or person by the acceleration, so the magnitude of the Coriolis force (Figure 2-06) is as shown in Equation [4]:

$$F = 2m \omega v \quad [4]$$

Figure 2-06. People trying to walk radially outward on a spinning carousel will feel a surprising force pushing them sideways, parallel to the circumference. This Coriolis force depends upon both the speed of motion, its direction relative to the axis of rotation, and the angular speed of rotation.

To repeat, the Coriolis acceleration is derived by vector multiplication (cross-product of ω and v). In non-vector terms, at a given angular velocity of the observer, the magnitude of the Coriolis force of the subject will be proportional to the velocity of the subject in the rotating frame and also to the sine of the angle between the direction of movement of the subject and the axis of rotation. It is important to note that the Coriolis force is independent of the radius of centrifugation. That is, its magnitude is the same at all distances from the center of rotation (Figure 2-07).

Figure 2-07. Coriolis force generated during centrifugation as a function of rotation rate of the centrifuge. Note that the Coriolis force is the same regardless of the distance from the center of rotation.

The Coriolis acceleration acts in a direction that is perpendicular both to the direction of the velocity of the moving subject mass and to the axis of rotation. We can therefore make the following statements regarding the characteristics of the Coriolis force or acceleration:

- a. When the velocity v (as always, in the rotating system) is zero, the Coriolis acceleration is zero.
- b. When v is parallel to the rotation axis, the Coriolis acceleration is zero.
- c. When v is directed radially inward (outward) towards (away from) the axis of rotation, the resulting Coriolis acceleration is aligned with (opposed to) the direction of rotation (parallel to the tangential velocity).
- d. If v is aligned with (opposed to) the direction the rotation (parallel to the tangential velocity), the Coriolis acceleration acts radially outward from (toward) the axis of rotation.

Figure 2-08. Coriolis and centrifugal forces exerted on a passenger climbing a ladder up (left) or down (right) in a rotating environment. The Coriolis force has the same amplitude in both conditions, but its direction is reversed. Note that the module of the centrifugal force is larger when the space traveler is at the bottom of the ladder, due to the longer distance from the axis of rotation. Adapted from Stone (1973).

So, if a person standing on the outside rim of a centrifuge or spinning vehicle and she jumps off the “floor” with a velocity directed radially inward towards the axis of rotation, she would not come straight “down”, rather she would land a few centimeters to one side. Referring again to *2001: A Space Odyssey*, in the film we see scenes of the astronauts climbing ladders up and down from the rim of the spacecraft to the center. Because of the movie set they used in the studio (see Chapter 3, Section 1.2), the Coriolis accelerations did not exist during the making of these scenes. However, were those individuals actually on a spacecraft climbing and descending ladders as shown in the movie, they would feel the effects of the Coriolis acceleration in the form of a force that would tend to push them to one side or the other (Figure 2-08). If the spacecraft were rotating in the counter-clockwise direction and the astronaut were climbing a ladder towards the center of the vehicle in the manner shown in the figure, he or she would feel a force pushing to the right. When descending the ladder, the force would seem to be pushing

to the left. As will be discussed in subsequent sections of this book, the Coriolis acceleration plays a significant role causing the onset of motion sickness.

3 HUMAN FACTORS CONSIDERATIONS

Theoretical spacecraft designs using artificial gravity have a great number of variants with intrinsic problems and advantages. The parameters that mostly influence the design options are now discussed.

3.1 Gravity Level

The minimum artificial gravity level, normally measured at the rim of a centrifuge, is the key parameter in the design of an artificial gravity system. Data from the limited animal tests executed in orbit suggest that continuous rotation generating 1 g at the feet of a small rodent is sufficient to maintain normal growth during spaceflight (see [Chapter 3, Section 2.1](#)). However, it remains to be determined whether or not a reduced magnitude gravity level will suffice. Based on centrifuge studies of long-duration on Earth, Russian scientists suggest that the minimum level of effective artificial gravity in humans is about 0.3 g. They further recommend a level of 0.5 g to increase a feeling of well-being and normal performance (Shipov *et al.* 1981). Perception studies have shown that humans can detect artificial gravity of 0.5 g in orbit. Artificial gravity levels of 0.22 g and lower, however, are not perceived by the astronauts (Bukley *et al.* 2006).

As for the maximum artificial gravity level in the +Gz direction (along the long body axis), ground-based studies during bed rest suggest that gravity levels up to 2 g at the feet are probably useful, especially if combined with exercise (see [Chapter 5](#)). Passive hypergravity levels as high as 3-4 g at the feet are tolerable for more than 90 minutes in most subjects (Piemme *et al.* 1966). Active (bicycling) exercise on human powered centrifuges is also well tolerated from a hemodynamic perspective at gravity levels up to 3 g at the feet (Caiozzo *et al.* 2004, see also [Chapter 5](#)). However, peripheral vision starts to decrease (*grey-out*) at 2-3 g at the head level, which would correspond to a rotation rate of 60 rpm at a radius of 0.5 m, i.e., conditions that would never be reached in an artificial gravity setting. However, it is well known that on Earth the tolerance to acceleration varies from day to day and is modified by body build, muscular tone, gender, and experience. It can be increased by continued exposure and education. On the other hand, it is decreased by poor health, physical deconditioning, and fatigue (see Burton and Whinnery 2002 for review). Tolerance to acceleration is reduced after bed rest, but little is known about tolerance to acceleration after spaceflight. Also, most of the ground-based studies on the physiological effects of gravity levels have been performed with long-radius centrifuges, and the effects of gravity gradient, for example, have not been investigated. Consequently, tolerance to acceleration during short-radius centrifugation needs to be further investigated.

In addition, it is not yet known if exposure to high gravity levels for short periods of time is as beneficial to health as continuous exposure to normal gravity. It is also not known how effective gravity levels below 1 g would be to counteracting the health effects of weightlessness. An artificial gravity level of 0.1 g can be achieved by a reasonably low rotation rate (5 rpm) at radius as low as 4 m (see [Figure 2-04](#)). Likewise at a radius of 4 m, about 15 rpm would be required to produce Earth gravity at the feet (although gravity would be 50% less at the head), or 21 rpm to produce 2 g. If brief exposure to high gravity could negate the health effects of weightlessness, then a small centrifuge could be used intermittently on board the space vehicle, as is the case now with muscle exercise devices, but with a multiple physiological systems efficacy.

3.2 Rotation Rate

The maximum rotation rate of a centrifuge or spinning spacecraft is limited by the Coriolis force encountered when walking or when moving objects in the rotating environment. Coriolis forces are the result of real inertial accelerations that occur when moving within a rotating framework. Any movement in a straight line with respect to the rotating frame, except for movements parallel to the axis of rotation,

is in fact a curved motion in inertial space (see Figure 4-08). The curve reflects the effects of the Coriolis acceleration in the sideways direction and entails a sideways inertial reaction force.

At body motions or centrifuge rotation rates that are small in magnitude, the effects of the Coriolis force are negligible, as on Earth. However, in a centrifuge rotating at several rpm, there can be disconcerting effects. Simple movements become complex and eye-head movements can be altered: turning the head can make stationary objects appear to rotate and continue to move once the head has stopped. This is because Coriolis forces also create cross-coupled angular accelerations in the semicircular canals of the inner ear (see Figure 4-01) when the head is turned out of the plane of rotation. Consequently, motion sickness can result even at low rotation rates (<3 rpm), although people can eventually adapt to higher rates after incremented, prolonged exposure (see Chapter 3, Section 3.1).

Previous studies had suggested that the Coriolis force should be kept to less than some fraction of the artificial gravity level. Stone (1973) suggests that this be no higher than 25%. However, in the light of recent ground-based data showing a rapid adaptation to the vestibular conflict generated by Coriolis force (Young *et al.* 2001), this limit seems overly conservative. Also, during an experiment performed on board Skylab, it was observed that head movements made during rotation after 6 days in microgravity failed to elicit motion sickness or desorientation (Graybiel *et al.* 1977). **Parabolic flight experiments also indicate that the severity of side effects from Coriolis forces during head movements is gravitational force-dependent, raising the possibility that an artificial gravity level less than 1 g would reduce the motion sickness associated with a given rotation rate** (Lackner and DiZio 2000). Finally, restraining head movement during centrifugation can also mitigate the nausea-inducing effects of Coriolis forces.

Finally, as mentioned above, the artificial gravity is constantly being distorted as the astronaut moves about within the spacecraft (except along an axis that is parallel to the axis of rotation). To reduce this effect, the rim speed needs to be much faster than the astronaut could walk or run. The minimum rim velocity is limited only by the need to maintain enough friction for locomotion when walking against the direction of spin. The normal velocity during walking is about 1 m/s so that the estimated minimum rim velocity should be 6 m/s.

3.3 Gravity Gradient

Because most studies on artificial gravity employed long-radius centrifuges in which the gravity gradient is limited, there are no data available on the effects of gravity gradient on subject's comfort and well-being or on their physiological responses.

For a 2-m astronaut, the radius would need to be at least 4 m for a 50% maximum gravity gradient. For continuous rotation at smaller radii, comparable to the astronaut's height, the gravity gradient may become more of a problem. In particular, this situation might make movement and changing body positions awkward, which can affect both physiological function and the ease of handling materials in space. For example,...

ADD COMMENT ON the material handling issues (maybe in the context of weight lifting) associated with becoming lighter as one "lifts" them toward the center of rotation. It may also be illustrative to mention that one gets heavier when squatting down and lighter when on tip.

3.4 Comfort Zone

With the beginning of manned spaceflight in the 1960s, there was a concerted effort to determine the comfort criteria for rotating habitats. In the USA, much of this research took place in centrifuges, rotating rooms and rotating space station simulators at the Naval Aviation Medical Acceleration Laboratory in Johnsville, Pennsylvania, the Naval Aerospace Medical Research Laboratory in Pensacola, Florida, and the NASA Langley Research Center in Hampton, Virginia (Chambers and Chambers 2005).

Over the past four decades, several authors have published guidelines for comfort in artificial gravity (see Hall 1997 for review), including graphs of the hypothetical *comfort zone* bounded by values of gravity level, head-to-foot gravity gradient, rotation rate, and tangential velocity (Figure 2-09).

The outputs of these studies are often discordant. For example, Clark and Hardy (1960) performed centrifuge studies and concluded that a space station rotation rate should not exceed about 0.1 rpm to stay completely below the threshold of vestibular illusions and nausea due to cross-coupling accelerations when moving the head. At 0.1 rpm, a 1-g spinning station would need a radius of about 90,000 meters! Later, Stone (1973) assumed acceptable cross-coupling for up to three times the nausea threshold predicted by Clark and Hardy, giving a maximum station rotation rate of 6 rpm. This is 60 times the maximum rotation rate proposed by Clark and Hardy and brings the radius of a 1-g station down to only 25 meters. However, this solution could still only be achieved by a large spinning station or by a tether cable connecting two sections of a spaceship, possibly a habitat module and a counterweight consisting of every other part of the spacecraft.

Recent data indicate that these earlier limits in rotation rate for eliciting Coriolis motion sickness are overly conservative. For example, Young *et al.* (2001) have recently shown that subjects can quickly adapt to motion sickness induced by rotation of the head during centrifugation at 23 rpm. Higher rotation rates permit a shorter radius to obtain a specified gravity level. Consequently, this result opens the possibility for a short-radius centrifuge within the space habitat to provide artificial gravity as an alternative to rotating the entire space vehicle.

The upper limit for the gravity level is fixed at 1 g, and the lower limit at 0.3 g. This lower limit was based upon results from Russian animal studies during spaceflight and from human subjects' performance during the hypogravity phase of parabolic flight (Faget and Olling 1968). This limit also came from the results of ground-based studies performed at NASA Langley using a circular platform of 12 m in diameter with a 1.8-m vertical wall at the periphery. During rotation of the platform, subjects were suspended horizontally and allowed to "walk on the wall" (Letko and Spady 1970). Walking in the direction of rotation at simulated gravity level between 0.16 and 0.3 g at the feet (Gz) was found to be the most comfortable. At levels above 0.3 g, the subjects reported "sensations of leg and body heaviness", which became quite disturbing at 0.5 g. Consequently the lower limit of 0.3 g was chosen in most design studies for implementation of artificial gravity.

A minimum radius of 12 m has been specified to limit the gravity gradient to a value of about 15% (see Figure 2-05). This limit is imposed taking into account the human factors consideration of work efficiency. For example, an object will get heavier when it is lowered from head to foot level by a person standing on the rim of a spinning station. Despite the virtual absence of data on the effects of gravity gradient (because most the studies were performed on large-radius centrifuge that minimized the gravity gradient), the 15% upper limit was obviously a conservative value aimed at easing materials handling and reducing the potential risk of musculoskeletal injuries.

It is important to note that the limits for comfort criteria mentioned above address the issues of humans *walking* and *moving objects* in an artificial gravity rotating environment. Indeed, these limits were proposed at a time where large rotating stations were foreseen for space missions (see next section). These limits for comfort obviously need to be re-evaluated for the case of on-board short-radius centrifuges, where body, limb, and head movements will be more restricted.

Figure 2-09. Rotation rate as a function of the radius of rotation for four gravity levels. Previous studies performed in the 1960s referred to as the "comfort zone" the area in gray delimited by a minimum radius of 12 m, maximum and minimum gravity levels of 1 g and 0.3 g, respectively, and a maximum rotation rate of 6 rpm. However, recent data indicate that these limits are overly conservative.

4 DESIGN OPTIONS

The choice of artificial gravity design depends on a basic decision whether the crew is to be transported with continuous artificial gravity, requiring a large-radius spinning vehicle, or exposed to intermittent artificial gravity, in which case a small centrifuge can be employed. In the following subsections, which are based to a significant extent on material contained in the final report of the

International Academy of Astronautics Study Group 2.2 entitled “Artificial Gravity as a Tool in Biology and Medicine” (Paloski 2006), these two design options are reviewed.

4.1 Continuous Artificial Gravity: Spinning the Vehicle

The classical large spinning space station, as proposed by von Braun, was the basis for early designs in the Apollo era (Loret 1963) (Figure 2-10).

Figure 2-10. The three basic rotating space station configuration concepts are the I, the Y, and the “toroidal” configurations, by reference to their basic shape. The Y and the toroidal configurations have a better rotational stability, because the greatest moment of inertia is about the axis of rotation. The I configuration, however, has a large moment of inertia in two axis. Therefore, its stability must be augmented by a stabilizing device such as a momentum wheel. On the other hand, the I configuration is less complicated to transport and deploy in orbit. Adapted from Faget and Olling (1968).

At one time, a large toroid 75 m in diameter and constructed of six rigid modules joined by an inflatable material, was envisioned (Figure 2-11). The large mass and excess volume of such designs forced consideration of the ways of generating centrifugal forces at large radii. The two that emerged are the rigid truss (or boom), and the tether concept, which are detailed below. Another engineering issue was the propulsion system required to spin up (or spin down) the angular momentum (the amount of energy to spin) of the vehicle. Also, if parts of the spaceship are intentionally not spinning, friction and torque will cause the rotation rate to decrease (as well as cause the otherwise-stationary parts to spin). Flywheels and thrusters would be needed to keep the appropriate sections of a spacecraft spinning or not. Angular inertia can also complicate spacecraft propulsion and attitude control.

Figure 2-11. Display of various models of early concepts of space station with artificial gravity by NASA in 1962. This design called for a large modular manned space station, which although essentially rigid in structure, could still be automatically erected in space. The idea was to put together a series of six rigid modules that were connected by inflatable spokes or passageways to a central non-rotating hub. Photo courtesy of NASA.

4.1.1 Rigid Truss

A rigid truss design typically would have the crew quarters and operations module at one end and a large counterweight at the other end. The counterweight might be an expended fuel tank or an active element such as a nuclear power source. In most cases a counter-rotating hub is present at the center of rotation to provide both a non-spinning docking port and to allow for a zero-g workspace for experiments.

A variation on the rigid truss is the extendable or telescoped boom concept, in which the radius of the artificial gravity systems could be varied more easily than with a fixed truss and slider. However, both of these designs imply considerably more mass and power requirements than a tether system.

Joosten (2002) developed a truss-based vehicle design capable of meeting typical Mars mission requirements while providing acceptable artificial gravity parameters. His 50-m radius configuration would generate continuous 1 g at 4 rpm (Figure 2-12). The vehicle mass associated with the mission is consistent with previous design solutions, and steering strategies were identified consistent with mission requirements without excessive propellant expenditure. The vehicle mass penalties associated with artificial gravity were minimal (a few per cent). He noted that providing an artificial gravity environment by crew centrifugation aboard deep-space human exploration vehicles has received surprisingly limited engineering assessment, most likely due to: the lack of definitive design requirements, especially acceptable artificial gravity levels and rotation rates, the perception of high vehicle mass and performance penalties, the incompatibility of resulting vehicle configurations with space propulsion options (i.e., aerocapture), the perception of complications associated with de-spun components such as antennae and photovoltaic arrays, and the expectation of effective crew micro-gravity countermeasures. He concluded that these perceptions and concerns may have been overstated.

Figure 2-12. A recent NASA architecture study to support a manned mission to Mars proposed to use a high-power nuclear electric propulsion (NEP) system based on a high-temperature liquid-metal cooled fission to generate thrust. The architecture includes a reactor power module near the center of rotation, a crew vehicle at the end of a boom (to distance the crew from the reactor's radiations), and radiators at the other end. Rotation of the structure at 4 rpm would generate 1-g artificial gravity in the crew compartment located at a radius of 56 meter from the rotation axis. Photo courtesy of NASA.

4.1.2 Tether

The Gemini-11 mission demonstrated basic tethered spacecraft technology in 1966, when the crew connected their capsule to the Agena booster with a 30-m tether (see Figure 2-03) and put the assembly into a slow rotation to produce a minuscule amount of artificial gravity. A longer tether or faster rotation, or both, would be needed to produce artificial gravity at useful levels. The Gemini-11 tethered vehicle exercise revealed some unexpected tether dynamics that will need to be considered in designing an artificial-gravity space habitat (Wade 2005).

A variable length tether that can be unreeled in orbit and used to connect a spacecraft to a counterweight has emerged as the most acceptable design for a large artificial gravity system. As envisioned for a Mars mission (Schultz *et al.* 1989), it would consist of an 80,000 kg habitat module 225 m from the center of mass, with a 44,000 kg counterweight 400 m beyond. A tether, weighing 2,400 kg, reeled out by a deployment mechanism weighing 1,700 kg, connects the two. All told, the additional weight for accommodating a tethered artificial gravity system for a human Mars mission is about 21,000 kg, or about 5% of the 0-g weight, plus about 1,400 kg of propellant.

One of the obvious concerns about a tethered artificial gravity system is its vulnerability to tether breakage. For the Mars mission design, a tether in the form of a band 0.5 cm x 46 cm x 750 m would provide a dynamic load safety factor of 7, offering a working strength of 630,000 N. That concern has otherwise been addressed by using webbing or braided cable to maintain tether integrity, even in the event of a meteoroid collision. (The probability of tether impact with a micrometeoroid of mass greater than 0.1 gm was calculated as 0.001 for a mission of 420 days.) A second concern about a tethered system lies in its dynamic stability, especially during unreeling and during spin up and spin down. The interaction with orbital maneuvers is complex, whether the spin axis is inertially fixed or tracking the Sun to facilitate the use of solar panels.

4.1.3 Spinning the Vehicle about an Eccentric Axis

In a recent study, Bukley *et al.* (2006) investigated two scenarios wherein artificial gravity levels ranging from 0.2 to 0.5 g could be created on board the Space Shuttle (Figure 2-13). One possible means is by rotating the vehicle about an eccentric roll axis⁵ (in this case, the baseline orbital trajectory of the vehicle) at a constant angular velocity. This roll maneuver would create artificial gravity in the +G_z direction of the vehicle, such as when the vehicle is on Earth. The other means is by rotating the vehicle in pitch about its center of gravity. This pitch maneuver would create artificial gravity in the +G_x direction of the vehicle, so that astronauts could “stand” on the middeck lockers.

A feasibility analysis of the eccentric roll maneuver was executed beginning with the simple dynamics of a point mass in a central gravitational field to ascertain the force levels required to execute the proposed maneuver. Once the force levels were determined, they were then compared to the capability of the Space Shuttle orbital control system, which includes the *Orbital Maneuvering System* (OMS) and the *Reaction Control System* (RCS). The former controls the spacecraft orbital altitude, and the latter its attitude. Assuming that the force levels were within the capability of the orbital control system, they could then be translated from inertial coordinates to vehicle coordinates and ultimately distributed amongst the various thrusters in accordance with an appropriate control law.

⁵ This maneuver was originally proposed by John Charles (NASA) during the NASA/NSBRI Artificial Gravity Workshop held in League City, Texas, in January 1999 (Paloski and Young 1999).

The eccentric roll maneuver analysis was executed assuming that the orbital altitude was 400 km, which is typical for Space Shuttle missions. The Shuttle mass was assumed to be 99,117 kg, which is also the typical vehicle mass near the end of a mission (Joels and Kennedy 1992). Results of the point mass dynamic analysis indicated that the force levels needed to generate an artificial gravity environment in the +Gz direction of the Space Shuttle vehicle exceed the capability of its orbital control system (Table 2-01). While the OMS engines have a thrust capability of 26,700 N, which would appear to be sufficient for the 0.2-g artificial gravity maneuver, there is only enough OMS fuel for about 21 minutes total of operation. Furthermore, to execute the eccentric roll maneuver, a thrust in the –Gz direction in the Space Shuttle coordinate frame must also be generated. The Space Shuttle has no capability to generate a thrust in this direction. However, designers of future space vehicles, e.g., the Crew Exploration Vehicle, may wish to keep the results of this analysis in mind when designing that vehicle in the event that it may be desired to execute such a maneuver. The mass of the Shuttle dictates the required thruster force, therefore a lighter vehicle with a more robust thruster system may have the capability to fly such a trajectory.

For the pitch maneuver, the analysis is considerably simpler. Rather than altering the orbital trajectory of the Space Shuttle center of gravity, the vehicle is simply pitched about the center of gravity, nose-over-tail, at a rate sufficient to generate a centrifugal acceleration at the desired gravity level. Figure 2-14 shows the rotation rate required to generate varying levels of artificial gravity at the forward bulkhead of the middeck, which would be now be used as the “floor” by the astronauts. It is interesting to note that the Space Shuttle actually flew this rotational pitch maneuver during the return-to-flight missions STS-114 and STS-121 prior to docking with the ISS. This maneuver allowed the crew on board ISS to capture photographs of the heat shield on the belly of the Shuttle. However, the rotation rate during this 360-degree back-flip maneuver was 0.125 rpm, thus generating artificial gravity in the Space Shuttle crew compartment of 0.0003 g, a level way too low to be perceived as artificial gravity by its passengers.

Figure 2-13. Two possibilities of spinning the Space Shuttle for creating artificial gravity: the eccentric roll (toroidal) maneuver (above) and the pitch maneuver (below). The eccentric roll maneuver, however, is beyond the capabilities of the Space Shuttle orbital control system. Adapted from Bukley et al. (2006).

Gravity Level	Max Force Level
0.2 g	19,440 N
0.3 g	29,150 N
0.4 g	38,900 N
0.5 g	48,600 N

Table 2-01. Maximum thrust force levels required in both the vehicle Gx and Gz axes to execute the eccentric roll maneuver for artificial gravity levels of 0.2, 0.3, 0.4, and 0.5 g. Forces required in the Gy direction are significantly smaller. Adapted from Bukley et al. (2006).

Figure 2-14. Artificial gravity level generated at a distance of 16.8 m from the center of rotation (e.g., corresponding to the middeck forward bulkhead in the Space Shuttle becoming the “floor”) as a function of rotation rate of the vehicle in pitch. Adapted from Bukley et al. (2006).

4.2 Intermittent Artificial Gravity: Internal Centrifuge

The alternative approach to continuous, rotating vehicle artificial gravity is to use a short-radius centrifuge intermittently. In this case, the exposure would not necessarily be limited to 1 g or less, but could be as high as 2 or 3 g to deliver adequate acceleration in exposures of perhaps 1 hour daily or several times per week. Of course, such a short-radius device would need to spin much faster than the 6-rpm limit envisioned for a large continuous system, and would produce significant Coriolis forces and motion sickness stimuli with head movement, at least until adaptation occurs. However, recent work on adaptation shows the likelihood of successful adaptation by most subjects to head movements, even at high angular rates (Young *et al.* 2001). The short-radius centrifuge becomes particularly attractive when

its dimensions shrink to the point that intermittent centrifugation could be carried out within the confines of a spacecraft.

Rather than entailing the rotation of an entire complex, a 2-m-radius artificial gravity device permits subjects to stand upright and even walk within its limited confines. Of course, the head is then close to the center of rotation and a significant gravity gradient is manifested as one goes from head to toe. Many of the ground studies conducted with intermittent short-radius centrifugation have been conducted with rotators of radius from 1.8-2.0 m. As the radius decreases even further to less than 1.5 m, the taller subjects can no longer stand erect but must assume a squatting or crouching posture. For many such designs, the subject would also provide the power to turn the device and perform valuable exercise by bicycling the centrifuge into rotation. Indeed, from the engineering point of view, a shorter radius centrifuge permits less mass and less kinetic energy for any particular centripetal acceleration (artificial gravity). Although the power saving may be trivial, or not even used, the importance of active exercise while exposed to intermittent centrifugation might lie in its protection against syncope, or fainting, as the body is exposed to the unaccustomed footward forces that tend to pool blood in the lower extremities. Also, if the head could be placed far enough off-axis to allow sufficient vestibular otolith stimulation, vestibulo-spinal reflexes might be protected, resulting in increased neuro-motor activation and improved motor tone. The on-board short-radius centrifuge has implications for mass and momentum balance, pressurized volume, and crew scheduling. The intensity and duration of the required therapeutic dose of artificial gravity remains unknown and is a worthy research topic (Clément and Pavy-Le Traon 2004, Hall 2004).

Figure 2-15. In this NASA 1969 space station concept, the station was to rotate on its central axis to produce artificial gravity. It was to be assembled on-orbit from spent Apollo program stages. Photo courtesy of NASA.

Figure 2-16. This NASA drawing for a space station in 1977, designed to use Space Shuttle hardware, is known as the "Spider" concept. A solar array was to be unwound from the exhausted main fuel tank. The structure could then be formed and assembled in one operation. The main engine tank would then be used as a space operations control center, a Shuttle astronaut crew habitat, and a space operations focal point for missions to the Moon and Mars. Photo courtesy of NASA.

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