Human Centrifuges in Research and Training

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The use of centrifuges for human research has been reported for almost 200 years. Centrifuges have been used for research, medical treatment, and training of flight crew. These centrifuges have been designed and built in a variety of configurations with arms as short as 1.5 m and as long as 15 m. Acceleration on a centrifuge is usually measured in Gs which is the acceleration divided by the standard acceleration of gravity. The forces encountered in a centrifuge are the simple application of Newton's Three Laws of Motion. Axes have been defined for G vectors in relation to the human body. These are designated Z (aligned with the spine), Y (left to right), and X (front to back). Most research and training is in G_z and there are two methods of maintaining alignment with that axis. The USAF is examining the possibility of building a large radius centrifuge (200 m or larger) on a track to avoid the inertia of such a long arm. This type of machine could have advantages over the conventional centrifuge.

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HUMAN CENTRIFUGES IN RESEARCH AND TRAINING

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The use of centrifuges in human research is not a new idea. The first recorded instance was reported by Erasmus Darwin, grand-father of Charles, in 1795. This "centrifuge" was a stone wheel, used to mill corn, on which a man was rotated to induce sleep (5). Centrifuge use became rather common in the 1800s, used both in research and as a treatment for mental illness. A 2 m radius centrifuge was built in 1898 by Dr. F. R. von Wenusch for research; in 1903 Sir Hiram Maxim built a machine capable of over 7 G (1). The first large centrifuge designed solely for human research was built in Germany in 1933. It had a radius of 2.7 m and was capable of 15 G. The first human centrifuge in the United States was built at Wright Field, Ohio in 1938.

The potential problems caused by high acceleration were recognized as early as World War I when G was implicated in several aircraft accidents. During World War II, as aircraft performance increased, the need became apparent for more research and development of technology to protect the pilot in high G maneuvers. During this period a number of new G protection devices were developed including the anti-G suit and the anti-G valve. By the end of the war six allied countries had human centrifuges in operation. During the next fifteen years the advancement of jet aircraft continued to fuel the need for G research. Several more human centrifuge facilities came into operation including the giant machine at the Naval Air Development Center (NADC) in Warminster, Pennsylvania and the centrifuge at the Armstrong Laboratory, Brooks AFB, Texas.

While research has remained the primary use of human centrifuges, training of air crew in a high acceleration environment is becoming common. Many of the research centrifuges are being used for training part time, and several new facilities have been built exclusively for training purposes. NASA built a large centrifuge at the Johnson Spacecraft Center in Houston, Texas in 1965 for astronaut training. The USAF has trained pilots on centrifuges at the Armstrong Laboratory, the Dynamic Environment Simulator (DES) at Wright Patterson AFB, and on centrifuges in The Netherlands, and Korea. In 1988 the USAF built a new centrifuge at Holloman AFB specifically for training pilots. The U. S. Navy has trained pilots at NADC and has contracted for a new training centrifuge to be built at Lemoore NAS, California.

Human centrifuges have been designed in almost every conceivable configuration. Centrifuge arms have been as short as 1.5 m in the centrifuge at Miami University, Ohio (2) and as long as 15.25 m in the machine at NADC (4). Drive systems have been hydraulic, electric, or even, as in the case of the French centrifuge, pneumatic. Most of the old centrifuges were originally manually controlled, that is the G level and onset rate were set manually in variable resistors and the machine was activated by a series of switches. All of the newer machines and most of the older ones now have computerized control systems. All of the centrifuge facilities now use Closed Circuit Television (CCTV) to monitor the subject during runs. In early machines an individual was seated at the center of the arm and visually monitored the subject from this somewhat "dizzying" vantage point. The British still use this system today in addition to a CCTV system.

The housing for the subject, usually called a "gondola" has also taken a number of forms. The miniature centrifuge at Miami University uses a flat circular plate for an "arm" and the subject is held to this plate by any number of seat or restraint devices. Most machines have some sort of enclosure, or gondola, at one end of the arm with a counterweight at the other. This is not always the case, however, as the British machine has two opposite and identical arms with a gondola at each end.

The terms "G" and "onset rate" used in this article may require a brief explanation. Acceleration, as encountered in a centrifuge or maneuvering vehicle is conventionally measured in "G's". A "G" is the acceleration applied to the body, divided by the standard acceleration of gravity. For example a body being accelerated at 88.2 m/sec^2. would be at: 88.2 / 9.8 or 9 G. "G" must not be confused with "g" which is used to designate the standard acceleration of gravity. "Onset rate" is used to designate a change in G with respect to time. Onset rate can be either positive or negative; negative onset rate is sometimes called "offset rate".

It is intuitive that the forces created on a body by G are vector quantities, that is they have a direction as well as a magnitude. Cartesian axes have been defined for the human body so that the forces produced by G can be specified. Acceleration along or parallel to the spine is designated G_z, with + being in the head to foot direction. Fore and aft acceleration, colorfully referred to by the astronauts as "eyeballs in" or "eyeballs out" is designated G_x with + being front to back. Acceleration from side to side is designated G_y with + being toward the left. In pilots seated upright in an aircraft, the forces produced by sharp changes in direction result in $+ G_z$ which prevents oxygenated blood from reaching the eyes and brain, producing "blackout" or loss of consciousness. For this reason the area of most interest for research conducted in centrifuges is $+ G_z$.

The physics describing the forces produced in a centrifuge are the simple application of Newton's three laws of motion. When the centrifuge is revolving at a constant angular velocity the subject in the gondola is prevented from traveling in a straight path (as Newton's First Law would predict) by the centrifuge arm which applies a centripetal (or center seeking) acceleration and constrains the motion of the gondola in a curved path. Since the gondola velocity is a vector, this change in direction with respect to time produces an acceleration along the centrifuge arm according to Newton's Second Law. The product of the equal and oppositely directed acceleration (Newton's Third Law) and the mass is the centrifugal force experienced in a centrifuge (1). However this is not quite the whole story. The subject in the gondola is also being acted upon by the ever present acceleration of gravity (g). The total force acting on the subject is, then, the vector sum of the radial acceleration and gravity times the mass or $(G_r + g) X m$. At this point the careful reader might cry foul and point out that we are adding the vectors of two totally different physical phenomenon ie. centripetal acceleration and the acceleration of gravity. We are saved from this embarrassment by no less an authority than Albert Einstein who stated in his Principle of Equivalence that forces produced by these two accelerations, although different in nature, are totally equivalent.

Maintaining the alignment of G_z and the subject in a centrifuge gondola is a problem that has been solved in a number of different ways. The simplest and most common way to achieve this objective is to mount the gondola in bearings along its transverse axis allowing it to rotate. With the center of gravity kept below the center of rotation, the force produced by G_z acting on the center of gravity will assure proper alignment. This is often referred to as "passive control". Passive control is fine as long as the centrifuge is turning at a constant angular velocity. When the centrifuge is speeded up or slowed down (onset or offset) some small error in alignment will occur using this method because the necessary damping of the gondola rotation will cause it to lag slightly behind the G_z vector. A second method of gondola control, called "Active", is to mount the gondola in a powered gimbal and maintain alignment with the G_z vector using a computer. Another problem with passive control also occurs during onset or offset. An increase or decrease in angular velocity of the centrifuge causes a positive or negative tangential linear acceleration of the gondola which is perceived by the subject in the gondola as G_x. Since this perceived force does not ordinarily occur in an aircraft "pulling Gs", it is an artifact. The simultaneous change in both G_x and G_z also causes vestibular disturbances which can produce nystagmus and in extreme cases nausea. These vestibular disturbances can be alleviated to some extent by using a powered gimbal in the pitch axis (rotation about the lateral axis of the gondola) and computer control. In this case during onset the powered gimbal pitches the gondola down slightly so that G_x is at least partially resolved into G_z and is not perceived by the subject. The reverse is used during offset. Active control greatly increases the cost and complexity of a centrifuge and is used in only the most sophisticated machines.

The turn radius of even the largest centrifuges is much shorter than the turn radius of aircraft. The short turn radius of centrifuges produces Coriolis forces that cause vestibular disturbances in the subject. For instance turning the head rapidly for even a few degrees in a centrifuge causes a severe tumbling sensation and perhaps nausea. In order to reduce this Coriolis effect to a level approaching that experienced in an aircraft, the radius must be increased to over 60 m. To build a conventional centrifuge with an arm of this length is nearly impossible because of the motor torque required to turn it. The torque needed to accelerate a centrifuge is directly related to the inertia of the arm, gondola, counterweight, drive shaft and the armature of the motor itself, in other words everything that turns. Unfortunately for the designer of a large centrifuge the inertia varies with the square of the radius. An arm of 60 m or longer would require a motor of enormous proportions.

To build a centrifuge with low Coriolis forces the USAF is examining the possibility of building a "centrifuge" that runs on a circular track instead of being turned by an arm. Called the Combined Accelerator Flight Simulator (CAFS), this device would travel on a special track built against a reinforced circular wall and would be propelled and suspended by an electro-magnetic (EM) system. Since the device would be suspended and powered by this track, no arm would be required and the inertia problem would be solved. As demonstrated by the high speed train which has been built in Japan, magnetic forces are generated between the vehicle and the track and suspend the vehicle on a magnetic "cushion." By designing the gondola in a spherical enclosure, free to turn in all three axes, it could be rapidly positioned by computer to control G vector direction. The proposed EM drive would be capable of very high linear acceleration rates and by properly aligning the gondola during onset or offset, G_x could be translated into G_z. As the velocity of the vehicle around the track increased, radial G (G_r) would also increase and the subject would be rolled toward head inward until the desired terminal G_z was reached and linear acceleration would be reduced to zero. Extremely high onset rates could be attained in this way making it possible to simulate devices such as high performance ejection seats (3). A facility such as the CAFS would be very expensive to build and would present many technical and engineering challenges.

Today there are at least 30 centrifuges in operation around the world and more are being built every year. The French are building a new centrifuge for aircrew training and Brazil is also installing a new human centrifuge.

The extreme performance of fighter aircraft such as the F15, the F16, and the Advanced Tactical Fighter prototypes demand that research keep pace by developing equipment to protect flight crew at G levels as high as 9 G and onset rates as high as 10 G/sec. Pilots flying future aircraft will require even more protection with the potential for 15 G operations and loading in the G_y axis as well as G_z. If acceleration research is to stay abreast of tomorrow's high technology aircraft and spacecraft, more new human centrifuges will be needed and perhaps even such a complex machine as the CAFS will become a reality.