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James W. Useller, and Joseph S. Algranti

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The advantage of having a functional human being on board a space vehicle designed either as a satellite or a space probe is so great that one of the immediate objectives of space research is to explore the adaptability of the human body to the unique conditions that may be encountered in space. The physical and psychological limitations of the human subject present large areas of unknown factors for study.

One important problem is the reaction of the human subject to high-speed rotation. It is important to know the range of conditions in which he can be relied upon to exercise judgment and to maintain coordination of his faculties sufficiently to perform complex functions.

Ten active airplane pilots, all of whom had extensive flight training and experience, have been subjected to rotation in the NASA Multi-Axis Test Facility. The pilots were assigned the task of determining and applying corrective torques required to counteract induced rotations. The induced rotations were at rates up to 70 rpm about a resultant axis. The subject's ability to determine the direction in which to apply the counter thrust from his instrument display, as well as, his agility in timing the thrust application was recorded. His susceptibility to motion sickness was qualitatively determined. Vestibular nystagmus, a disturbance of vision, was encountered during rotational acceleration and deceleration of the subjects.

APPARATUS AND PROCEDURE

Test facility and subject's accommodation:—The Multi-Axis Test Facility (Fig. 1) consists of three concentric, gimbal mounted, support structures that are capable of rotation about the three orthogonal axes. Rotation is produced by a jet-reaction system that utilizes the ejection of high-pressure nitrogen through small nozzles on the periphery of each of the supporting cages. Three sets of jet nozzles actuated by the test subject are located on the innermost cage (pilot's compartment) to permit him to counteract the induced rotation.

The test subject was seated at the center of the innermost cage in a specially molded plastic couch to reduce body shifting during rotation. He was restrained by leg and thigh straps and a chest harness. The head was protected by a padded flight helmet that was held in a fixed position. The upper part of the subject's body was enclosed in a light-proof compartment to eliminate visual orientation.

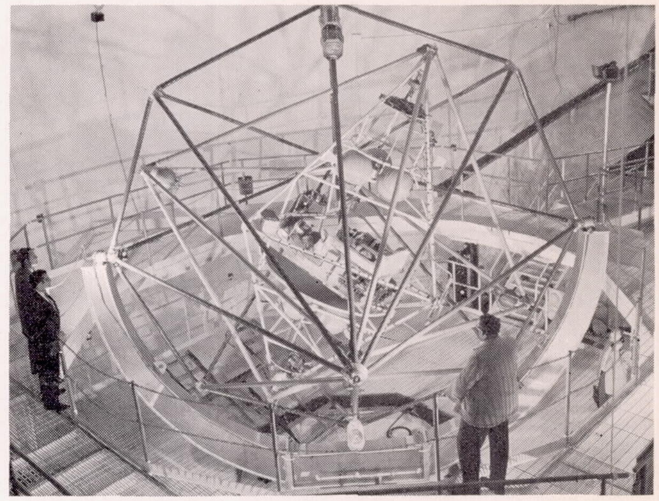

Fig. 1. Multi-axis test facility with subject in support couch.

Rotation was induced at rates up to 70 rpm about a resultant axis. The pitch, roll and yaw components of this rotation are defined from the subject's seated position. Rotation about the vertical axis through the length of his body is denoted as yaw motion. Pitch and roll motion are about the axes perpendicular to the vertical axis as normally defined for aircraft operation.

Procedure and subject's function:—In each test of the subject's ability to control the rotation of his vehicle from an initial condition of rotation about a resultant axis, the procedure was as follows. The desired rate of rotation of each of the three gimbal systems was first established by the engineer at the outside control panel near the facility. The subject was signaled that the problem had been established by means of a light flashed on his instrument panel. He would then begin to counteract the rotation induced by his instruments by using his hand controller to actuate the jet nozzles mounted on the inner cage. The rates of rotation about each of the component axes (roll, pitch and yaw) were displayed on individual instruments. In addition, three pairs of lights were provided near the appropriate gages to indicate the direction the hand controller should be moved to counteract the induced rotation. An additional instrument was later added to the center of the panel that also displayed the rotational rates on a single indicator.

The hand controller actuated three pairs of on-off type valves and jet nozzles that would apply the desired thrust. The subject's task was to determine from his instruments the direction of the required corrective torque and then to initiate it by means of the hand controller. Moving the hand controller forward and back controlled pitch; while a twisting action controlled the yaw motion. Operation of the hand controller to the

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right or left controlled roll motion. The relative position and rate of rotation of each cage as well as the operation of the hand controller was recorded on an oscillograph. From a study of these traces an evaluation of the subject's performance could be made.

RESULTS

When the pilot was subjected to a known resultant rotational vector (rate and direction) and asked to stop his rotation by means of the counter thrust system, his errors usually took two forms. He applied the counter thrust in the wrong direction or he improperly timed the application and cessation of the thrust. A more detailed discussion of his task and operation is contained elsewhere.[1]

The pilot's performance loss or error was determined as a percentage of the total time that he made an incorrect torque input to the system. That is, he was penalized for incorrect inputs, but not for errors of omission. Of course, if he applied no thrust he would make no errors, but would require as much as 10 minutes to coast to a stop as opposed to a minute or so when the thrust system was used. The pilots were not aware that their performance would be evaluated but made every effort to stop rotation as quickly as possible.

Figure 2 shows a typical trace of the variation of the

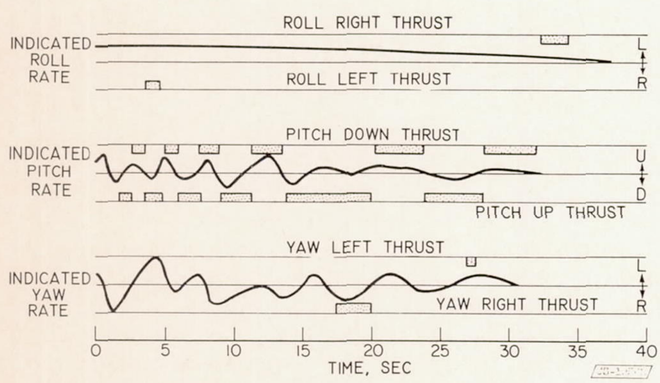


Fig. 2. Typical three-axis rotation case. Induced rotation rates: pitch, 10.0 rpm; roll, 8.9 rpm; yaw, 20.7 rpm. Resultant rotational vector, 24.6 rpm.

rates of rotation about each axis as indicated by the pilot's instrumentation for an induced rotation of 10.0 rpm in pitch, 8.9 rpm in roll, and 20.7 rpm in yaw. In this particular case, the pilot began by counteracting the pitch motion and the majority of his corrections were in the pitch direction. Pitch motion in a vertical plane is the most uncomfortable for the pilot because of the action of the earth's gravitational field on his head each time he pitches over. This, of course, would not be so in a space vehicle outside the influence of gravity. In this example, the pilot did erroneously introduce a left roll between 3.6 and 4.7 seconds. When he pulled the control stick up to counteract pitch, he inadvertently turned it to the left causing a left roll correction to be introduced.

Several examples of failure to change the direction of the counter thrust soon enough may be seen at 10.8 and at 19.0 seconds. Between 15.4 and 18.0 seconds the pilot had an indication of pitch-up and erroneously continued to apply a counter thrust in the pitch-up direction.

The percentage of the total correction time that the subject introduced the wrong correction is shown in Figure 3 as a function of the resultant rotational vector.

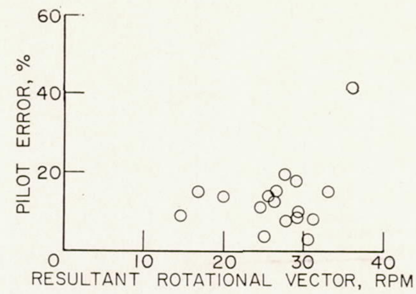


Fig. 3. Pilot error in counteracting random rotation.

As might be expected with any human function, the data have considerable random scatter, but median loss of 11 per cent is shown for this subject.

Figure 4 shows the average pilot error for each of the ten subjects tested. The pilots' aircraft operational experience is also shown in hours. There appears to be no relation between the amount of the subject's experience as an aircraft pilot and his ability to control the vehicle rotation. The range of the pilot error data is not significant other than to demonstrate the general level to be expected from a group of experienced pilots.

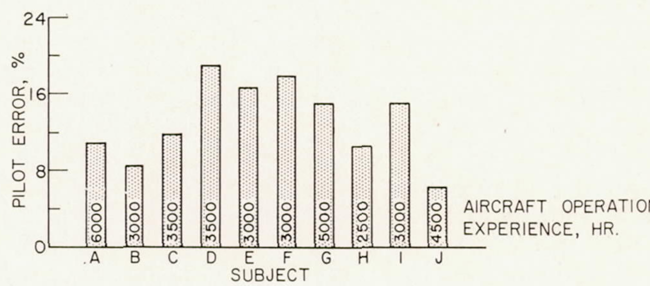
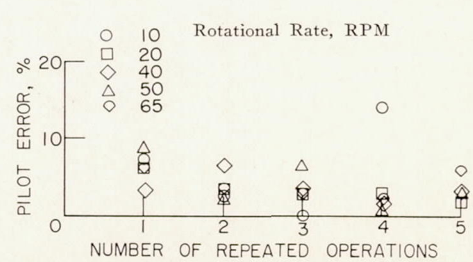


Fig. 4. Average error for ten experienced pilots. Aircraft operational experience shown in hours for each individual.

Following the above tests, subject J was exposed to five rotational tests at resultant rates from 8 to 70 rpm



RESULTANT ROTATIONAL VECTOR, RPM

Fig. 5. Influence of repeated experience on pilot operation error during random rotation.

repeated five times each in succession to determine the effect of experience on his ability to counteract the rotation. The results are shown in Figure 5. Although some random scatter is evident, repeating the test problem reduced the subject's error significantly. Not only was he able to reduce the percentage error, but he became more adept at counteracting rotation about more than one axis simultaneously. That is, he was able to introduce two corrections at one time with considerable effectiveness.

DISCUSSION

In general, the pilots tested were able to perform a complex task requiring a coordination of judgment and manual dexterity with a reasonably small error (from 6.5 to 18 per cent depending on the individual concerned.) The rotating environment had no measurable effect on their ability to function and there was no increase in pilot error with the higher rotational speeds. The pilot error was also reduced appreciably by repeated experience with the same problem.

Motion sickness:—Although observing the gyrations of the facility during a high-speed rotation from the stationary platform might give one the impression that motion sickness would be easily induced, none of the subjects tested was seriously indisposed as a result of his experience in the facility. However, some of the subjects did experience the onset of symptoms of motion sickness under certain conditions.

All human beings with the normal body balance mechanism are subject to motion sickness, but the degree of sensitivity varies depending at least in part on experience and training. Our subjects would be expected to have a low susceptibility to motion sickness because of their background and experience as aircraft pilots. Of the ten pilots subjected to rotation at high-speed rates, only one subject (C) experienced the syndrome of motion sickness when subjected to rotation for less than 15 minutes. Rotation during the 15 minutes was not continuous, but for several minutes at a time with breaks of 3 to 4 minutes between tests. Subject C experienced excessive perspiration and the onset of nausea after only two test runs. Testing was discontinued after three runs. Following a period of about 2 hours of relaxation he was completely recovered.

Pilot A, who has accumulated over 60 hours of operation of the test facility while most of the subjects totaled only 4 hours, was normally able to endure more than an hour of high-speed, intermittent operation without discomfort. If the testing was continued for longer periods, he would begin to fatigue and experience the usual symptoms of motion sickness. Recovery was usually rapid, requiring less than an hour of reclining.

Several subjects reported that the repeated pulsing experienced by the head during a pitch maneuver caused by the earth's gravitational field seemed to accelerate the onset of motion sickness. In this investigation the subject's head was restrained by the helmet and not permitted to move about during the rotation. However, it was pointed out by others [2] that if the head is not held rigid during this type of motion, the incidence of motion sickness could increase by as much as seven times. In general, however, for the pilots of this investigation it required prolonged exposures (up to 1 hour) of intermittent rotation at a resultant vector of 50 rpm or greater to induce motion sickness symptoms.

Vestibular nystagmus:—The nystagmic reaction was observed during these tests when the subject was rotated to speeds in excess of 15 rpm. It is known that primary nystagmus is related to the total sensory output, that is, it is a function of the acceleration and the duration of its application.[3] The threshold acceleration for inducement of nystagmus is about 0.3 degree per second. The acceleration rate used in these studies was considerably higher than the threshold value. However, although the same acceleration rate was used to reach both the low angular speeds and those above 15 rpm, only the time required to reach rates above 15 rpm was sufficient (about 10 sec.) to allow development of the nystagmic condition. The latency period of approximately 10 seconds is explained by van Egmond [4] by the fact that periods of time of this order are required for the cupula of the inner ear to experience an angular deviation sufficient to produce a physical stimulation. However, latency periods of approximately 4 seconds have been reported for the acceleration rate of these tests.[5] The period of latency is dependent on several factors in addition to individual differences. Among these are the illumination to which the eye is subjected during angular acceleration, the alertness of the subject at the time, as well as his past history with rotation. Pilots, for example, have been found to have a latency period longer than the average subject because of experience with rotation during aircraft maneuvering.

Although no method is known for eliminating nystagmus during rotational acceleration, the sensitivity of the vestibular reaction is reduced by visual fixation.[6] It was found during these tests that when the subject fixed his gaze on a localized area the severity of the nystagmus was lessened as characterized by a reduction in the amplitude of oscillation of the eye. It was found that if the subject concentrated on a well-illuminated, centrally located instrument during periods of rotational acceleration, the effects of nystagmus were reduced. When he continually shifted his gaze to scan a number of individual instruments, the subject experienced a more distracting effect from the nystagmus.

SUMMARY

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The exposure of a series of pilots to high-speed rotation in the Multi-Axis Test Facility has produced the following conclusions:

During rotation at rates up to 70 rpm about a resultant axis, the pilots were able to perform a complex task requiring judgment and manual dexterity with a performance error that ranged from 6.5 to 18 per cent, depending on the individual evaluated. The rotating environment had no measurable influence on their operation or their performance error.

Repeated operation of a similar type rotational test showed that the pilot was able to reduce his error appreciably. He also was able to improve his technique by introducing several corrections simultaneously.

Although motion sickness would be expected to be

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encountered relatively infrequently with experienced pilots, intermittent rotation at rates of 50 rpm or greater for periods longer than 1 hour could induce motion sickness symptoms.

Vestibular nystagmus was encountered by all the subjects tested when the acceleration was endured for at least ten seconds. However, if the subject concentrated on a centralized area of his instrument panel, the effects were reduced.

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