EVALUATION OF FULL-SORTIE CLOSED-LOOP SIMULATED AERIAL COMBAT MANEUVERING ON THE HUMAN CENTRIFUGE

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ABSTRACT

The Aerial Combat Environment Simulator (ACES), installed in the human centrifuge at the Naval Air Development Center was evaluated as an approach to creating an acceleration environment that is similar to that encountered in modern tactical aircraft. A pilot in the human centrifuge flew an aircraft simulation to chase a target aircraft through aerial combat maneuvers. The pilot was in complete control of the centrifuge through the simulation, and if the target tracking was accomplished successfully, the centrifuge produced an acceleration profile that matched the target aircraft. ACES used an enhanced aircraft simulation with the a +Gz performance envelope that exceeded the characteristics observed in aerial combat exercises on instrumented ranges. The centrifuge was equipped with the flight controls necessary to fly the simulation in an air combat scenario. Displays included a high-resolution wide field-of-view computer graphics system that was used to present a real-world gaming area, an aerial target aircraft, and a high-fidelity head-up display. Seven volunteer subjects were trained to fly the centrifuge and were able to generate +Gz acceleration profiles that replicated the recorded aerial combat exercises. In using this new experimental method, the +Gz acceleration stresses imposed on the subjects were very different than encountered during typical open-loop programs and produced a wide spectrum of physiologic and psychologic +Gz stress related symptoms.

INTRODUCTION

The Naval Air Development Center completed a series of experiments that integrated high performance flight simulation capabilities into the human centrifuge to investigate the physiologic effects of modern aerial combat.

Acceleration research on the human centrifuge historically used only a limited number of open loop +Gz acceleration profiles. Among them were, the Gradual Onset Rate ramp profile (onset rate less than or equal to 0.1 Gz/second) and the Rapid Onset Rate to plateau profile (onset rate greater than or equal to 1.0 Gz/second). In an effort to expose human subjects to +Gz accelerations similar to that of tactical aircraft, the Simulated Aerial Combat Maneuver (SACM) was often included in centrifuge experiments. The typical SACM consisted of alternating moderate and high +Gz plateaus. These open loop centrifuge profiles were very different from the +Gz time history of acceleration encountered during an actual aerial combat exercise (Figure 1). The human centrifuge could be programmed to reproduce the +Gz time history of an actual combat exercise, but the centrifuge experiment would still have lacked an element of realism since the subject would be a passive passenger and not in control of his own accelerations.

The centrifuge subject in a typical experiment was asked to perform two tasks. The main concern was the effective execution of an anti-G straining maneuver (L1/M1) with a secondary task of monitoring the degradation of peripheral vision. In comparison, the dual task

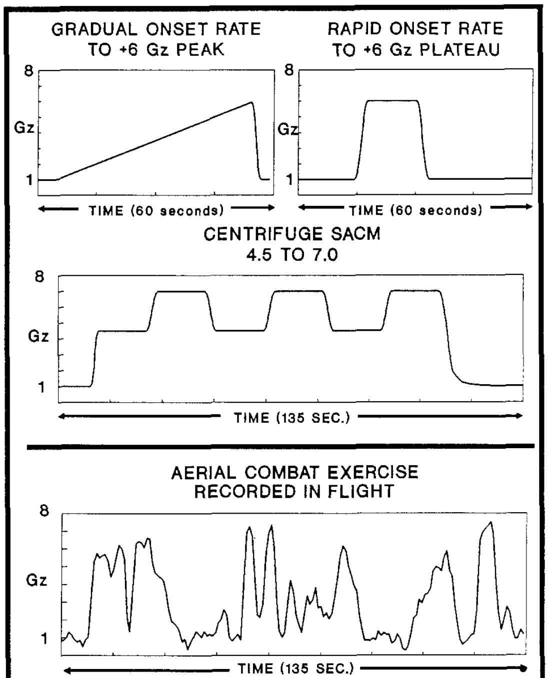

Figure 1 -- Centrifuge vs. Real World Acceleration

responsibility of the centrifuge subject did not resemble the workload of a pilot in the cockpit of a modern high-performance fighter aircraft. This was an important factor when the preparatory aspects of a pilot in control of the aircraft's flight path were considered. While the centrifuge subject concentrated most of his resources on the anti-G straining maneuver, the tactical pilot could not afford this luxury. However, since the pilot was in control of the aircraft, he could prepare for a maximal effort straining maneuver based on anticipated aerial tactics.

A laboratory testing environment that filled the gap between actual aerial combat and open loop centrifuge tests was the Aerial Combat Environment Simulator (ACES) through its use of closed-loop pilot control of the human centrifuge [1]. The simulation was designed to reproduce the +Gz environment with high fidelity while providing cues to the pilot that suggested accelerations in the +/-Gx and +/-Gy directions.

THE ACES SIMULATION

ACES combined a tactical aircraft flight simulator with the human centrifuge and had a +Gz performance envelope greater than that currently utilized by fighter/attack aircraft in peacetime aerial combat exercises. The simulation was also an extremely stable platform that allowed non-pilot subjects to quickly acquire the skills needed to control the aircraft during aerial combat simulations while providing the degree of fidelity that satisfied even discriminating aviators. The subject flying ACES had the task of maintaining a six o'clock trail position on a target aircraft at a range of 3000 feet. The target aircraft followed a pre-programmed flight path that was obtained from aerial combat range telemetry data or a flight recorded using the ACES flight simulator. The centrifuge, driven through the simulation computer, produced accelerations based on the state of the aircraft model [2]. If the air-to-air tracking task was accomplished successfully, then the subject experienced +Gz accelerations that closely matched those of the target aircraft. The human subject had complete control of the accelerations, had anticipatory cues based of observed target motion, and had a workload level that was higher than typically demanded of centrifuge subjects. These conditions allowed a more accurate replication of the aerial combat environment than an open-loop centrifuge experiment.

The ACES crew station was designed to minimize the total weight of the installation in order to maximize centrifuge performance. The controls for flight included a side arm mounted force control stick (from the General Dynamics F-16A), spring loaded rudder pedals, a single lever throttle, and various switches mounted on an up front control, the force control stick, and the throttle. The installation included a wide field-of-view (FOV) real-world scene generator (Figure 2) with an integrated head-up display (HUD), and a head down multi-function display. The cockpit also had the equipment necessary to support anti-G valves, positive pressure breathing gear, and numerous biomedical instrumentation devices.

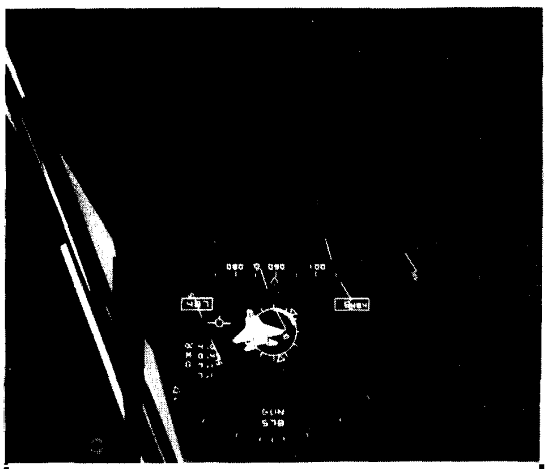

Figure 2 - Center display sceen with integrated HUD

ACES OPERATION

The simulation started with the aircraft trimmed in level flight at a given altitude and airspeed. Since the ACES was designed to be used for a study involving +Gz-Induced Loss of Consciousness (G-LOC) and recovery, the subject first disengaged a simulated auto-pilot. The first step was to extinguish a Master Caution light to measure the total incapacitation time [3]. To investigate the recovery of higher cognitive functions the subject then entered a sequential code on the up front control panel. The throttle controls were then trimmed by minimizing an error signal that was presented on the head down display (HDD).

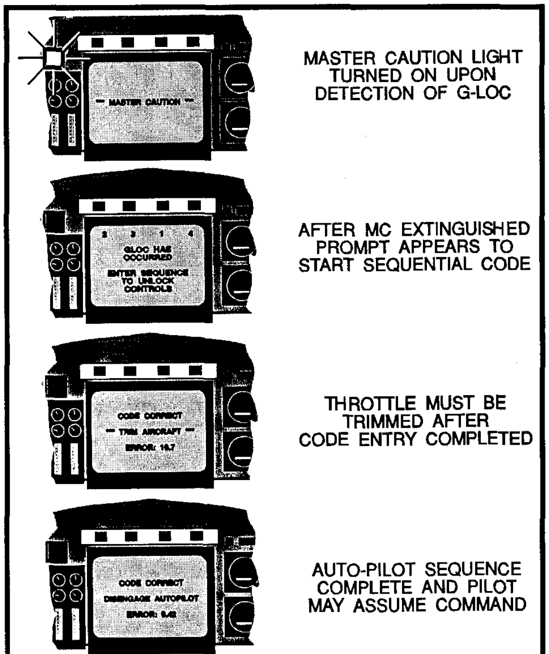

Figure 3 - Auto-pilot disengage sequence

When proper trim was achieved, the subject took command by activating a paddle switch on the control stick (Figure 3).

The air-to-air target was initially acquired by executing the Lost Target Procedure. The sequence, started by pressing the "LOST TARGET" button on the up-front control panel, froze the target and showed its altitude, airspeed, and heading on the HDD (Figure 4). The subject then maneuvered his own aircraft to match those parameters. If done correctly, the target appeared at the 12 o'clock level position. With the aircraft in sight, the subject again activated the paddle switch on the stick to "release" the target. The subject used the HDD to re-acquire a target that had left the field of view. At the end of the target file a new target was displayed, and the subject re-aquired this target and continued. If a subject lost consciousness during any engagement, the simulation was placed back into level flight and the subject had to disengage the auto-pilot starting with the Master Caution light. Following completion of the last target profile, the subject navigated back to home base using the available TACAN stations. The tasks involved tuning the radio receiver to the correct frequencies to navigate to one of ten preassigned air stations, tracking the radio beacon, and joining the pattern at the correct altitude, airspeed and runway alignment. The performance tasks for this experiment were chosen to exercise increasingly higher levels of cognitive function after a G-LOC episode.

GROUND STATION TRAINING

Ten volunteer human subjects started training in a ground-based simulator that duplicated the installation on the human centrifuge. Non-pilots, as well as aircrew, were members of the subject panel. Training began with the basic flight control tasks of achieving and maintaining a specified altitude, airspeed, and course. These skills were sharpened by trying to match the parameters to the target aircraft when performing the "Lost Target" procedure. The next step in the training was to learn some basic aerobatic maneuvers to practice controlling the aircraft while in unusual attitudes. As the students' flying skills developed, they were next introduced to the task of the tail chase.

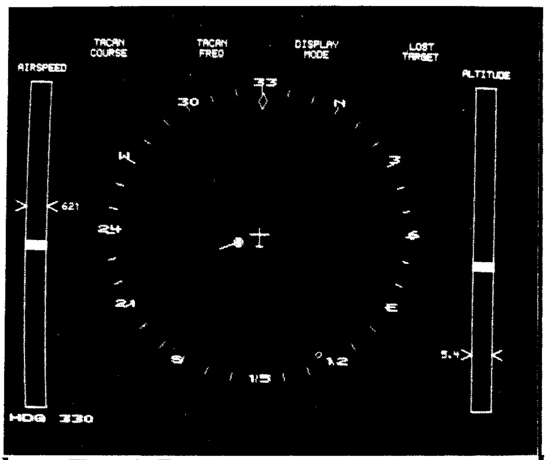

Figure 4 - Target parameters displayed on HDD

Tracking the air-to-air target required the pilot to maintain the target in the 12 o'clock position at a range of 3000 feet. To assist the pilot, enhancements were made to the HUD symbology. Along with a range indicator on the gun aiming reticle, command cues were displayed as doghouse shaped arrows above or below the airspeed and altitude boxes. The airspeed arrow showed the difference between own ship and target airspeed. An up arrow was a command to increase airspeed to match the target. The elevation gap was indicated by an arrow attached to the altitude box. These cues were only active when the target was within 2.5 nautical miles. If the target was beyond this range, then a warning began flashing in the HUD to prompt the pilot to execute a "Lost Target" procedure to re-acquire the target.

The tracking task was made more difficult because the real world field of view was not unlimited. Although the computer generated imagery encompassed a 110 degree horizontal by 45 degree vertical FOV, the target aircraft could easily slip out of view when executing high performance maneuvers. The 3000 foot trail range was empirically determined to be optimum because following closer meant that the target was off the screen more often, while falling farther back meant that high-G maneuvers were not required to keep the target in view. While tracking the target, the HDD presented a god's eye view centered on the pilot's own aircraft, along with a compass rose and a display of own ship and target altitude and airspeed. When the target was not in the forward field of view, the pilot had to integrate the information presented on the HDD to correctly maneuver to intercept the target in the trail position.

CENTRIFUGE TRAINING

When the subjects demonstrated a proficiency in tracking the air-to-air target by smoothly controlling their own aircraft, they began the transition to the dynamic environment of the human centrifuge. The simulation of aerial combat on the centrifuge presented several unique problems. The main goal of the simulation was to replicate the +Gz time history of actual aerial combat. Since the centrifuge, a three degree of freedom motion platform, was trying to simulate actual flight, which has six degrees of freedom, there were some compromises which had to be made. In preserving the linear acceleration (+Gz) of the aircraft, the fidelity of the simulation of angular accelerations was sacrificed. By reproducing the +Gz profile of the aircraft, the centrifuge introduced angular accelerations that were not normally encountered in flight. Replication of flight at less than 1.0Gz was also not possible since the centrifuge was anchored to the ground. This flight regime was simulated by introducing the centrifuge bias function [2]. With the bias function in place, flying the aircraft at 1.0Gz caused the centrifuge to produce a 1.49Gz acceleration. After a few moments, the pilot accommodated to this level and it "felt" like 1.0Gz. This allowed for the sensation of a relative unloading when maneuvering below 1.0Gz. The bias function varied the centrifuge acceleration to between 1.49Gz at 1.0Gz on the aircraft, and 1.3Gz at 0.0Gz on the aircraft (Figure 5).

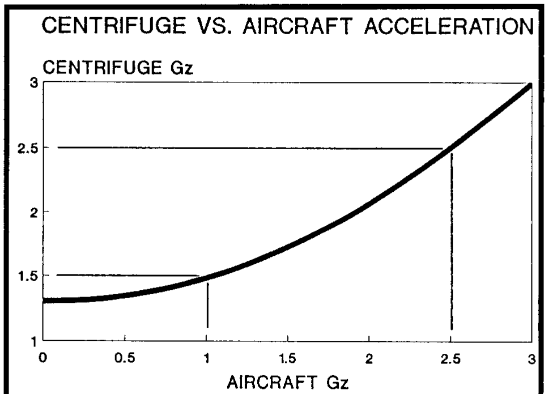

Figure 5 - Centrifuge Bias Function

The subjects were exposed to gradually increasing limits of centrifuge performance in order to develop proficiency in tracking the air-to-air target in the high onset to high sustained +Gz aerial combat environment. The peak acceleration level was limited to +3.0Gz for the first time that the subject took control of the centrifuge. However, the limiter was not a simple clipping process. Simple clipping would have limited the centrifuge acceleration to 3.0 Gz regardless of the simulation's commanded level. When limiting was tried by clipping centrifuge acceleration, the subjects would fly the simulation to an acceleration level above 3.0Gz and then freely maneuver without causing any additional motion in the centrifuge thereby producing a comfortable ride. This procedure did not encourage smooth and deliberate control of the aircraft throughout the centrifuge exposure. The process that provided an appropriate training environment was scaling the centrifuge bias function. For the initial training run, scaling required the aircraft to be flown to +12 Gz to reach the centrifuge limit of +3 Gz (Figure 6). This training method provided an extremely smooth first flight while still allowing the feeling of control throughout the operating envelope. The centrifuge peak +Gz limits were increased by one G on successive training sessions until the project limits were reached. Gradual increases in the acceleration limits were required to acclimate the subject to the artificial angular accelerations.

DISCUSSION

Seven of the ten original subjects, including four non-pilots, were successfully trained to fly ACES to its designed limits. The maximum acceleration was 12.0Gz sustained for a maximum of three seconds (The model was capable of sustaining 10.0Gz indefinitely). The onset rate of acceleration was important for the investigation into sudden +Gz induced incapacitation [4]. The measured +Gz onset rates exceeded the performance of a typical modern fighter aircraft (Figure 7). The centrifuge pilots followed the targets throughout most of the engagements thus recreating the +Gz time history of the target's real-world combat exercise (Figure 8).

After the initial training period, there was no disorientation induced by the simulation. Even though the centrifuge was attached to the earth and spinning counter-clockwise, the subjects were able to fly the simulation through left and right hand turns, climbs, descents, power changes, inverted flight, aerobatic maneuvers and air-to-air tracking

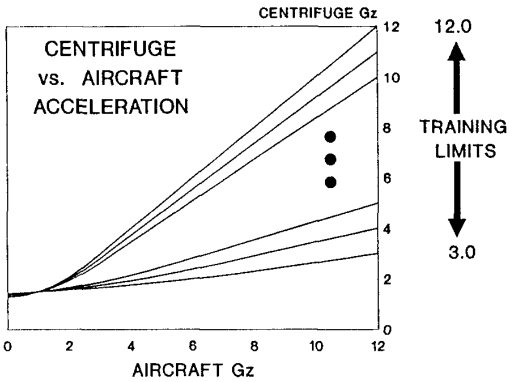

Figure 6 - Centrifuge training progression

while maintaining an unimpaired situational awareness. Though the centrifuge gondola was well lighted, the computer scene generator's 110 degree horizontal field of view greatly stimulated the peripheral visual field to provide the illusions necessary to simulate normal flight.

The subjects easily integrated the information presented on the HDD and found targets that had flown out of the forward display. A larger vertical field of view would make tracking the target much easier. In using the tail chase, the expectation was that the trailing aircraft followed the flight path of the target. The geometry of coincident fight paths during high sustained maneuvering dictated that the target aircraft would be visible in the upper part of the front windscreen. Maneuvering that placed the target in the HUD resulted in an intercept and would not replicate the targets flight path. When the target aircraft exited the forward FOV, smooth control inputs to re-acquire the target were very difficult. A greater vertical field of view would keep the target visible in the main display area during the high sustained Gz maneuvers and would minimize the time that the pilot had to transition to the head down display to re-acquire the target.

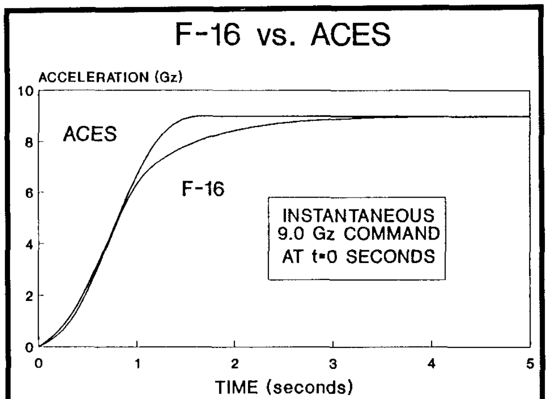

Figure 7 - +Gz onset rate comparison

The run times in the centrifuge ranged from 20 minutes to just over one hour. The subjects actively tracked air-to-air targets most of that time. This type of acceleration exposure was in sharp contrast to both then typical "open loop" experiments where the subjects were given rest periods measured in minutes between acceleration trials that were measured in seconds, and real world aerial combat sorties where a few engagements lasting several minutes happened between the prolonged flights to and from the exercise area. This new type of acceleration exposure produced numerous +Gz related symptoms that were not previously reproducible on the centrifuge using open-loop techniques. These symptoms were manifested when the exposure termination limits were increased to include G-LOC.

The G-LOC study that utilized ACES included exposures that did not have to terminated when 60 degrees of peripheral light loss was present. Therefore, when following target aircraft through numerous high Gz excursions, the subjects reported significant episodes of total central light loss (blackout). G-LOC had been previously classified as Type I or Type II depending upon the degree of incapacitation and signature of the recovery of consciousness [5]. By utilizing the more dynamic environment of ACES, a continuous spectrum of +Gz-induced incapacitation was revealed. Some findings were confusion without G-LOC, loss of motor control without G-LOC, and periods of indifference. During these periods of indifference the subject would provide no active control inputs for an extended time, with some periods ending with the exclamation "I'm back!".

CONCLUSIONS

These findings indicate the utility of using ACES to investigate the environment that exists in the tactical fighter cockpit. By having the subject actively controlling his aircraft thus producing an infinitely variable G-time history, the physiologic stress due to acceleration, and to some extent pilot workload, is closer to the stress encountered during aerial combat. The ability to reproduce the acceleration environment of tactical fighters also has an important application in the transition of new G-protective systems from the laboratory to the flight line. If these new systems are designed to take pilots beyond current tolerance limits, how can they be adequately tested?

A high-fidelity acceleration laboratory can serve as a test bed for personal protective equipment being considered for incorporation into fighter aircraft. Using aircraft to evaluate equipment designed to take a pilot beyond current tolerance limits would be risky. Flight tests of new systems typically involve a safety pilot wearing standard gear. Flight maneuvers that test the new protective systems could incapacitate the safety pilot thus compromising the test program. ACES could be used to test these systems, and additionally provide a more flexible environment in which system modifications could be easily incorporated at a greater cost and time savings. Some proposals for acceleration protection involve complex, high-technology systems. In order to adequately evaluate these new systems, acceleration researchers need a firm foundation on which to base recommendations. This foundation will come from conducting studies using acceleration and workload conditions that approach the tactical aircraft environment. Experiments conducted under higher fidelity conditions ensure a greater confidence in the transfer of systems from the laboratory to the cockpit.

ACES effectively fills the gap between open-loop centrifuge testing and live flight tests to simulate the +Gz operational environment. Although the cost in subject training is higher than standard centrifuge programs, the payoff in terms of the increased insight into the effects of aerial combat on human physiology makes it a valuable investment.

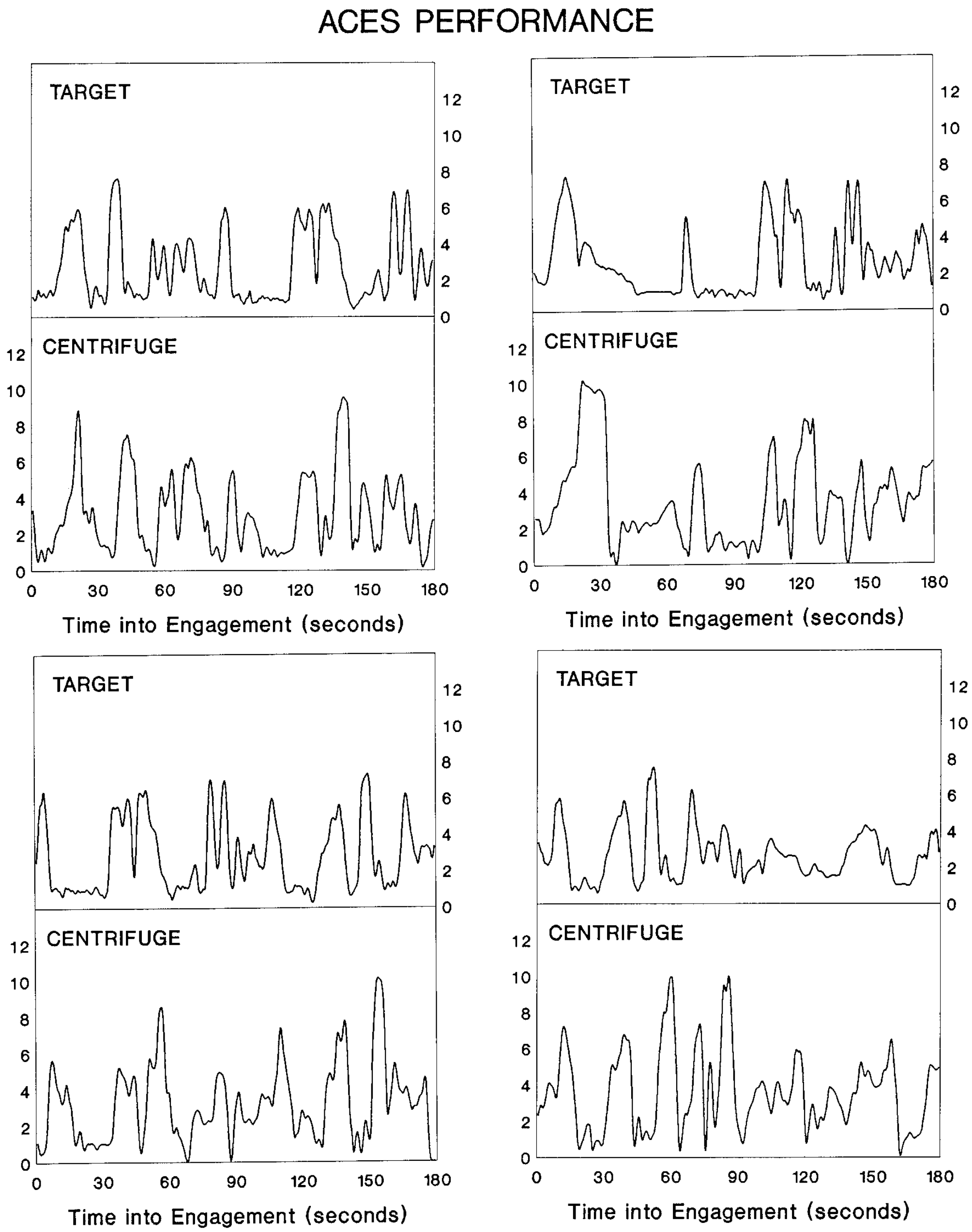

Figure 8 - ACES vs. Target +Gz Acceleration Time History in Manned Closed-Loop Operations

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