Dynamic Flight Simulation: 45 Years of Research & Development

Kenneth L. Ginader, Michael C. Newman, Richard A. Leland
Environmental Tectonics Company (ETC) Southampton, PA
kginader@etcusa.com, mnewman@etcusa.com, dleland@etcusa.com

ABSTRACT

This paper will present the development of technologies available for the next generation of flight simulation that would provide realistic training, combined with physical and physiological stressors, and recent results on research conducted on their effectiveness. Included will be information highlighting the development of motion for flight simulators, the distinct differences between transient motion cueing and G on Demand motion, the misnomer that motion cueing provides G forces, and that transient motion cueing in hexapod motion-based simulator cannot provide realistic motion sufficient for tactical flight training.

In the early 1980s both the U.S. Navy and Air Force concluded (hexapod) motion-based simulators did not justify their cost and complexity in transfer of training. However, by 2004 both manufacturing and software technology advanced to the point where it was possible to combine high fidelity flight simulator training with acceleration stressors for realistic tactical flight training.

Conventional wisdom has held that Coriolis Cross-Coupling (CCC) artifacts in centrifuge-based systems prevent any useful motion-based tactical training. This paper will present research establishing sufficient management of motion artifacts that allows not only for adaptation but also increased mitigation of CCC induced by cockpit and head movements in a high performance motion system. This research further establishes that real motion for tactical flight simulation is achievable and replicates an experience just like flying an aircraft. Information will additionally be presented on the technology of high performance motion, software technology that can provide realistic G on Demand and sustained G motion, and technology that provides the "real feel" of an aircraft in flight simulation.

Finally, high performance motion in flight simulation has the added benefit for advanced research on the effects of air combat accelerations on pilot training, G tolerance refreshment, and protective modalities that will provide significant cost savings when applied to realistic air combat training.

ABOUT THE AUTHORS

Kenneth L. Ginader is a retired U.S. Navy Captain and a highly qualified Naval Flight Officer. He served in three operational flying tours in the F-14 TOMCAT, including Commanding Officer of Fighter Squadron 21, and two operational staff tours. Captain Ginader also served as an instructor at the Navy Fighter Weapons School, TOPGUN. He completed ten overseas deployments on five different aircraft carriers, accumulating over 3500 flight hours and 900 arrested landings. Upon retirement from active duty, he accepted his current position as Director, Business Development, Tactical Flight Training Systems, Environmental Tectonics Corporation, Southampton, PA.

Michael C. Newman received a B.S. in Mechanical Engineering from Villanova University in 2007 and a M.S. in Aeronautics and Astronautics from MIT in 2009. He is currently the director of research and development for human factors at the National AeroSpace Training and Research (NASTAR) Center in Southampton, PA. His research is focused on modeling and understanding human perception and cognition in extreme environments.

Richard A. Leland is President, National Training and Research (NASTAR) Center. He is responsible for the implementation of NASTAR Center training programs and for the design, production and fielding of ETC's aircrew training systems throughout the world. Mr. Leland is a former USAF pilot with over 3100 hours in high performance jet aircraft and a retired USAF Field Grade officer with 20 years of service.

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INTRODUCTION

As the United States winds down its military efforts in Iraq and Afghanistan many global threats remain. Recent events, such as the destabilization of northern Africa and the encroachment of Russia into the Crimean peninsula highlight the dynamic geopolitical challenges that we continue to face on top of our prolonged engagement in the Global War on Terror. Despite these challenges, a shrinking budget and aging fleet has forced the U.S. Air Force and Naval Aviation to reduce flight hours and shift a larger portion of pilot training to the simulator (Erwin, 2012). These reductions come at a time when the complexity and capability of the aircraft continue to increase at an accelerated rate. This disparity presents a need for a simulator based training platform that can replicate all aspects of the flight environment including motion fidelity, physiological stress and cognitive engagement under physical workload.

BACKGROUND

Legacy Flight Simulation

Traditional simulation technology has been built upon fixed-based or hexapod platforms. These devices are able to provide limited motion response either using visual cues or through transient linear and angular motion that is slowly "washed out" as the simulation progresses. While these platforms remain useful for many applications, including helicopter simulation and procedural training, they lack the ability to provide the sustained G-forces necessary for realistic tactical flight training.

In order to accommodate for this deficiency, many legacy platforms have adopted various techniques to generate G-force or acceleration "cues". These cues are designed to produce a simulated sensation of acceleration force and the physiological effects they tend to induce. For example, inflating seat cushions and mechanically tightened harnesses (Albery, Gun, & Kron, 1978) have been used to simulate the somatosensory perceptions of high-G flight. Likewise, displays of fading brightness and variable transparency helmet visors (Brown et al., 1991) were introduced to mimic the vision loss produced by prolonged +Gz exposure. Although these measures provide some sham verisimilitude to the physiological stressors of air combat, they are inadequate for many aspects of training. G-cueing devices cannot account for changing hemodynamics due to repeated G-exposure or push/push maneuvering (Banks et al., 1994), noted variability of vision loss and ALOC/GLOC tolerance within the pilot population (Gillingham, 1987), or changes in G-tolerance due to fatigue, workload and overall conditioning (Balldin, 1986). These devices do not provide a sufficiently stressful or realistic representation of the true flight environment.

Dynamic Flight Simulation

Dynamic Flight Simulation (DFS) refers to an emerging class of flight simulation technology that attempts to bridge the gap between cognitive engagement and physiological stress in a ground based training system. DFS integrates the essential features of traditional high-fidelity flight simulation (i.e., domed visual displays, aircraft specific switchology, active stick, rudder, and throttle controls and realistic sound) with a high-performance centrifuge motion base. The resulting platform allows a pilot to command and control a simulated aircraft and coincidently experience the expected, authentic, and sustained G-forces that would be felt during actual maneuvering (Leland, Folescu, & Mitchell, 1999). DFS addresses all elements of fidelity including cockpit, visual display, aeromodel, motion and G-force response, environmental, threats, and mission elements to stress the pilot in a manner similar to what he/she would experience in the aircraft.

Unlike G-cueing, DFS motion platforms can produce authentic, sustained G-forces. Although the visual scene and operational environment of the DFS system is "simulated", the G-forces are every bit as real as they are in the

airplane. A pilot pulling G's in a DFS cockpit will experience changes to the cardiovascular, cardiopulmonary, vestibular, proprioceptive and visual systems and *feel* their associated impacts on piloting performance and bio-mechanic function (Burton & Whinnery, 1986). Time spent training in a DFS system can therefore provide valuable and operationally significant benefits in the continued maintenance of acquired acceleration tolerance (van Patten, 1991) for pilots sidelined from operational flying.

Figure 1 shows a schematic of a typical DFS system. The system consists of a gondola positioned at the end of a centrifuge arm. Rotation of the arm about the central, planetary, axis produces a centrifugal force that is directed radially away from the center of rotation. This force is coupled with tangential and gravitational force to produce a resultant G-vector of predictable magnitude and direction. Powerful motors actively rotate the gondola in roll and pitch to precisely position this G-vector relative to a desired orientation or force environment. This process is commonly referred to as "precise G-force control" and "G-pointing" because the cab is actively pointed relative to the instantaneous acceleration vector of the centrifuge so that the three components of desired rectilinear acceleration in the aircraft (and vestibular) coordinate frame are obtained (Crosbie & Eyth, 1983).

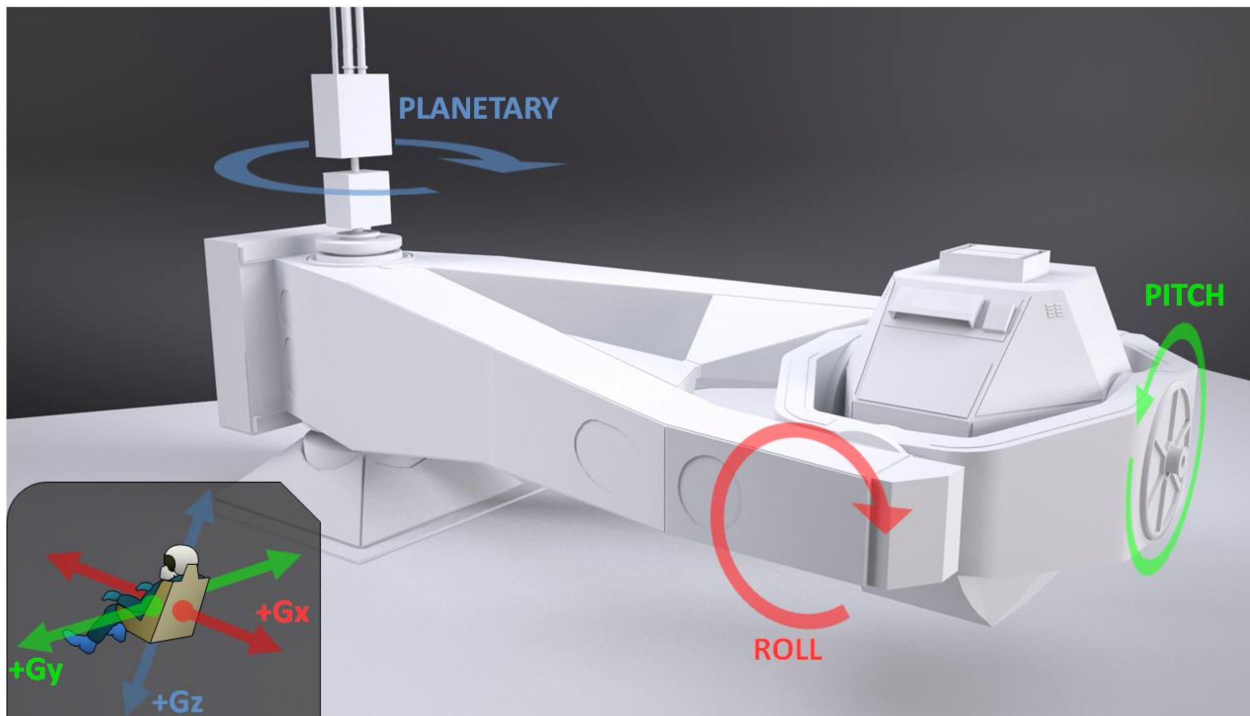

Figure 1. Authentic Tactical Fighting System (ATFS-400) Platform

During operation, a pilot sits in the gondola which is outfitted to resemble a particular aircraft cockpit. As he maneuvers his aircraft within the synthetic environment, advanced control computers synchronize the input of the pilot's control stick, throttle and rudder pedals with the visual imagery and time varying force environment of the expected flight condition. The resulting simulation both looks *and feels* like the real thing.

The Need for Stress

The desire to train in a realistically stressful and mission representative force environment is not new. During the early days of the manned space program, astronauts of Project Mercury trained in a high-fidelity Mercury capsule mockup that was mounted in the gondola of the human centrifuge at the NADC in Warminster, Pennsylvania (Chambers & Nelson, 1961). These astronauts performed control tasks and emergency procedures under the high G-loads that they would eventually experience during the launch and re-entry of the Mercury capsule.

Stress training is not limited to G-force and aerospace applications. Firefighters, law enforcement personnel, athletes and warfighters all incorporate stress scenarios into their training protocols. Studies have shown that such training encourages “automatic processing” and quicker recall when the skills are relied upon under future stressful conditions (Kivimaki & Lusa, 1994). Furthermore, Kivimaki and Lusa (1994) found that stress training enhances skill usefulness and decreases skill degradation over time.

It is somewhat obvious then, that centrifuge manufactures and aeromedical researchers have attempted to marry the flight simulator and centrifuge motion base for almost 45 years. The story of this integration, and the engineering developments that made it possible, will be the subject of the remainder of this paper.

THE DEVELOPMENT OF DYANMIC FLIGHT SIMULATION

The first attempt to create a simulator using hexapod technology in combination with sustained acceleration with a human centrifuge was the now-decommissioned Dynamic Environment Simulator (DES) located at Wright-Patterson Air Force Base (AFB) circa 1969. This machine featured a hexapod platform mounted on the pitch and roll-controlled gondola ring at the end of the centrifuge main arm. Unfortunately, due to design deficiencies it proved ineffective.

From Strength to Bandwidth

Like most centrifuges commissioned before 1990, the DES was designed for strength. Its arm was built to withstand a force load with a large factor of safety and considerations for cyclical operation. While sufficient from a safety perspective, this type of design criteria limits the controllability of arm response. During open-loop operation, such as classic G-training, this deficiency is not important. However, when one attempts to close the loop and “fly” the centrifuge with active control input from the gondola, precise arm response is essential to realistic operation.

A potential solution to this problem is to design the centrifuge for frequency rather than strength. Widely used in aircraft and automobile design, frequency domain engineering allows designers to maximize system bandwidth and control the modes and natural frequencies of operation. This ensures both structural integrity and dynamic responsiveness. By designing a system to increase total system bandwidth, one can tailor the response characteristics and “feel” of the simulation to suit the desired application. More recent advancements in material science and control software have further improved this process. The modern DFS arm is lighter, more rigid and able to attain the extreme capability and tracking performance that is necessary to simulate the advanced dynamics of 4th and 5th generation tactical aircraft.

In order to determine the efficacy of these engineering developments, we conducted an experiment to evaluate a DFS motion platform in comparison to actual flight data (Glaser & Newman, 2011). ETC’s ATFS-400 served as the DFS test platform at the National AeroSpace Training and Research (NASTAR) Center located in Southampton, PA.

Time histories of actual flight test data were input to the motion system of the ATFS-400 and the resulting accelerations at the pilot seat were measured. These measurements where then compared with the original flight test data from the aircraft. NASA Dryden Flight Research Center, Edwards Air Force Base, California, provided data from their Adaptive Aeroelastic Wing (AAW) program (Clarke et al., 2005). The AAW aircraft is a highly modified experimental F/A-18 which was tested through a wide range of flight conditions and maneuvers to determine potential wing structure design improvements. Aircraft normal accelerations, Nx, Ny and Nz, were provided for six examples of the classic G-performance quantification maneuver – the wind-up-turn (WUT). The target for each maneuver was 5G. The Nz from the AAW time histories was input directly into the Gz command of the ATFS-400 (see Figure 1 for a definition of the coordinate frame orientation). There were no noticeable excitations of Nx or Ny other than noise hence these values were set to zero. Comparisons of ATFS-400 performance to flight data for all maneuvers can be seen in Figure 2.

In all cases the ATFS-400 matched flight test data with the exception of the idle region between 1.0 and 1.4 G’s. In this idle region the ATFS-400 is programmed to scale all inputs such that the aircraft straight-and-level state (1.0Gz) corresponds to a simulator idle state. The idle state was set at 1.4Gz for all simulations throughout the experiment. Techniques to improve simulator fidelity within the idle region will be discussed in the next section of this paper.

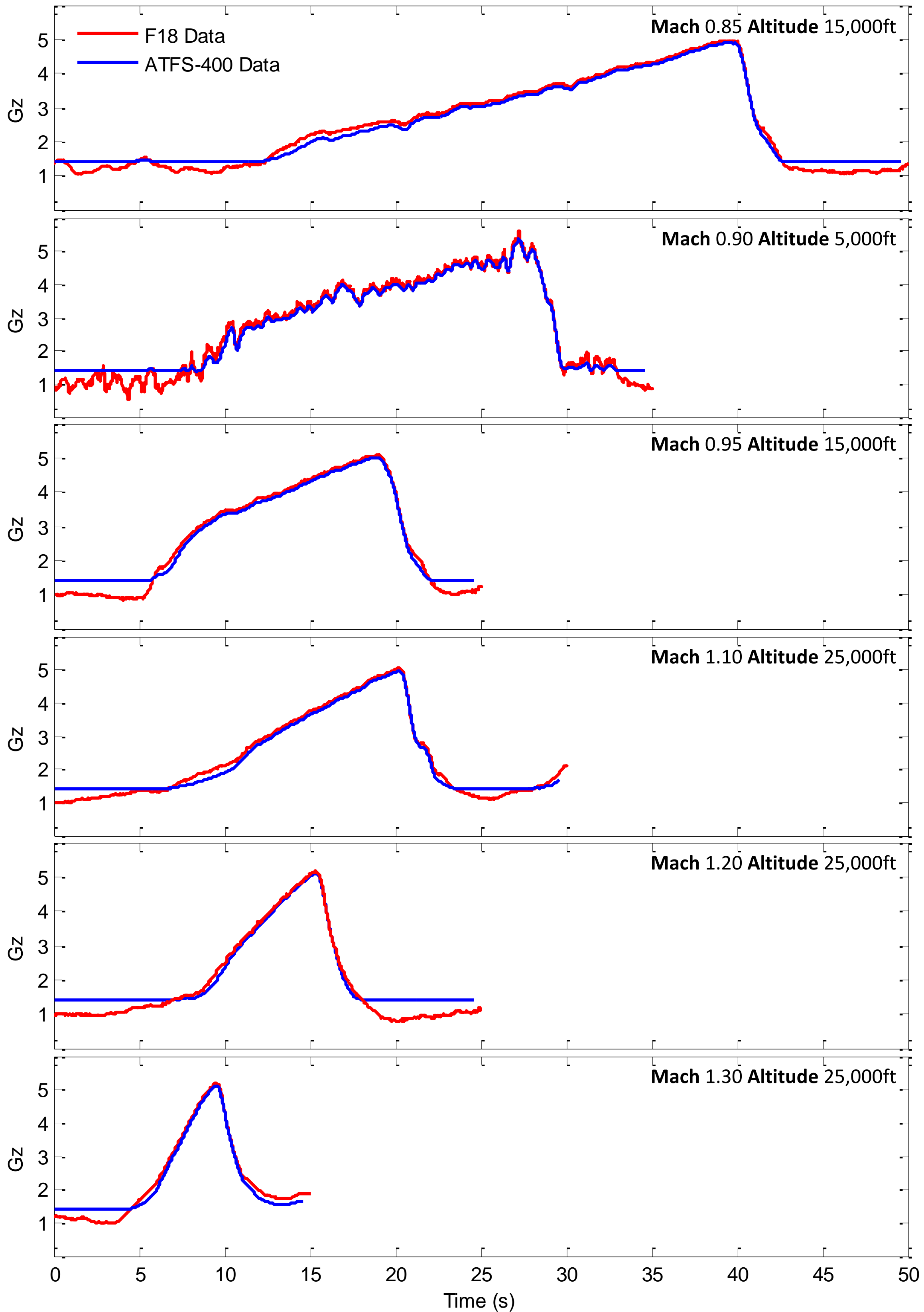

Figure 2. ATFS-400 vs. Flight Data for Six Wind-Up-Turn Maneuvers

Root-mean-squared error values were calculated for all six (6) maneuvers and are shown in Table 1. These error values represent the average G-level the ATFS-400 differed from the actual flight data throughout the simulation.

Table 1. RMS Error Values for all WUT Maneuvers

Mach (M)	Altitude (FT)	Root Mean Squared Error (G)
0.85	1,5000	0.12058
0.90	5,000	0.12526
0.95	15,000	0.11386
1.10	25,000	0.13071
1.20	25,000	0.11776
1.30	25,000	0.15828

Only values above the 1.4Gz centrifuge idle level were used to calculate the RMS values. Values under the idle level do not reflect true ATFS-400 dynamic performance and were thus excluded from the analysis.

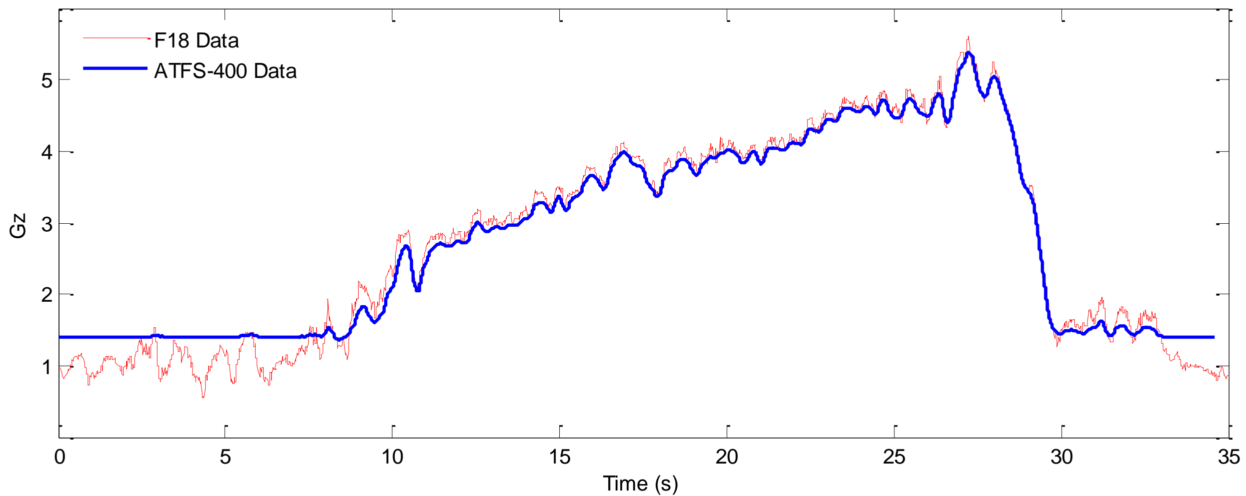

Figure 3. AAW WUT Maneuver Mach 0.90, Altitude 5,000ft.

One maneuver was selected as the most difficult to match due to G-level and transients in the AAW Nz trace. The 5G WUT at 0.9M, 5,000 ft (see Figure 3) showed slight variations in aircraft G and was the least smooth of all of the example runs. Still the ATFS-400 was able to reproduce the F/A-18 flight dynamics within an average of ±0.158Gz for all G levels above idle.

Overall, these results indicate that a frequency design can allow centrifuges to accurately emulate the G-profile of tactical aircraft without compromising safety. The one notable condition which we were not able to closely emulate in this experiment is the 1.0 G condition. The ATFS-400 maintained a minimum of 1.4G throughout experimental runs to ensure rapid response to higher G-onset. Overcoming the need for this artificiality was the next challenge we investigated.

To G or Not to G

In order to generate the high-G onset rates required during many tactical missions, traditional DFS systems utilize an "idle" G-level that is greater than 1.0Gz. This idle level keeps the centrifuge arm constantly rotating and helps the drive system overcome the inertial load of the gondola and centrifuge arm. Straight-and-level flight in the simulator

therefore corresponds to a G-load that is superficial to the aircraft and a rotation component that is not present during actual flight. It was within this idle region that the majority of the deviations between the ATFS-400 and F/A-18 occurred (see Figure 2, third pane from the top for a clear illustration of this discrepancy). Typical idle levels range from 1.2-1.4Gz and as a result, expose the pilot to planetary rotation rates of up to 65°/sec (assuming an arm length of 7.6m and 1.4Gz idle level). Prolonged rotation at these rates and G-loads can cause motion sickness (MS) and make even subtle head movements disorienting. Thus, designers of DFS systems face a tradeoff between accurately emulating forces during tactical maneuvering and exposing trainees to MS and unrealistic forces during straight and level flight.

To solve this conundrum, we observed that the periods within a mission that require high-G maneuvering are limited and somewhat predictable. Consequently, we investigated abandoning the use of a constant idle G-level throughout the entire scenario.

Instead, we integrated three separate motion states of operation into a single training profile. These states are full motion, partial motion and non-motion. During full motion operation the system is able to move in two degrees of freedom (pitch, roll) and about the planetary axis in order to generate G forces. The full motion mode retains the 1.2-1.4Gz idle level. During partial motion operation all planetary motion is eliminated, however the gondola retains the ability to rotate about the roll and pitch axes. This mode of operation is particularly useful during near 1.0Gz operation where realistic angular motion cues are essential to accurate simulation. Finally, during the non-motion mode the gondola remains fixed about all axes.

Although this approach ensures that a centrifuge provides the best possible force representations during discrete periods of the scenario, it raises the question of how to transition between periods without motion on-set or off-set artifacts. Taking advantage of thresholds in the human vestibular system, we developed algorithms to transition the centrifuge between motion states without the trainee perceiving the change. The transition out of full motion mode, for example, is accomplished by triggering a sub-threshold deceleration algorithm during centrifuge operations that brings a subject down to zero planetary velocity. Because the deceleration is below the threshold for human detection, the pilot is unaware that he/she is no longer rotating. Since the occupant does not need G-forces for this portion of the event, he/she remains pleasantly immersed in the simulation without the accumulating effects of planetary motion. Subsequently, when G forces are desired during the mission, the reverse process can be accomplished. This flexibility enables an unlimited number of transitions between full, partial, and non-motion modes.

Using this technology, pilots can acclimate and adapt to the DFS environment more comfortably and extend their time in the centrifuge without experiencing MS. When planetary motion is blended out (partial or non-motion mode), sensory conflict between the semicircular canals and the visual system is reduced and both the fast and slow rising components of MS will begin to rapidly subside. During this period, occupants can also conduct normal operations and head movements without a Coriolis Cross-Coupling (CCC) stimuli.

Motion Sickness and Coriolis Cross-Coupling

Although MS and CCC have been minimized with the technologies and methods discussed herein, they remain the two biggest physiological challenges that limit the acceptance and perceived practicality of centrifuge-based DFS training.

MS is provoked, to varying degrees, during all types of flight simulation and flight training. It is caused primarily by a conflict between the different sensory systems (e.g., visual, vestibular and proprioceptive) (Guedry, 1970; Steele, 1968). For example, during training in a non-motion wide field-of-view flight simulator, a sensory mismatch exists between the visual system (indicating motion) and the muscular and vestibular systems (indicating a standstill). Given time, this mismatch can manifest itself as nausea, disorientation or one of the many other common symptoms of MS. In a DFS system sensory conflict occurs during virtually all maneuvers that involve planetary motion.

CCC is an unusual pattern of vestibular stimulation that occurs when an individual tilts his head while rotating (Schubert, 1932). The resultant perceptual response can be disorienting and induce strong sensations of illusory tumbling (Peters, 1969). These sensations can produce and exacerbate nausea and MS (Bles, 1998). In a DFS system this occurs when planetary motion is "coupled" with either *active motion* of the head or *passive motion* of the

gondola as the G-Pointing algorithm moves the gondola to properly align the G vector. Although CCC can occur in flight, it is seldom perceived by pilots (Guedry & Benson, 1978). This is due to the fact that an airplane has a significantly larger turning radius than a centrifuge (e.g., 1000m vs. 7.6m), and thus requires a substantially lower turning rate to produce an equivalent G-load. The angular rate of the aircraft, along with the rate and magnitude of the coupled rotation (e.g., the head or the banking motion of a turn) drives the intensity of the tumbling response (Peters, 1969). Innovation to address the physiological challenges pilots face during training in a DFS system has focused both on the use and optimization of vestibular adaptation protocols to diminish MS and CCC, and the development of new motion technologies.

Adaptation as a Means of MS and CCC Mitigation

Adaptation protocols to minimize MS and CCC have been researched and implemented for many applications including air desensitization (Stott, 1990), seasickness and artificial gravity using short radius centrifugation (Sheehan, Young, & Jarchow, 2008). Although the degree and rate of adaptation tend to vary depending on the motion stimuli, most experiments have found that the human neuro-vestibular link is indeed plastic, and that adaptation to alternate motion environments is possible. In response to repeated CCC stimulation, studies have shown a reduction of the gain and time constant of the human vestibulo-ocular reflex (VOR) (Adenot, Jarchow, & Young, 2005), a decrease in the severity and onset rate of MS, a decrease in the intensity of the perceived illusory tumbling response of CCC, and an increase in the duration of time one can withstand a given stimuli (Young et al., 2003). Although disputed and not fully understood, most researchers agree that adaptation is specific to the sensory paradigm being investigated and does not transfer to alternate motion environments or planes of sensory input (Garrick-Bethell, Jarchow, Hecht, & Young, 2008). For example, Garrick-Bethell (2008) found that adaptation to CCC head movements does not transfer between the roll and pitch planes.

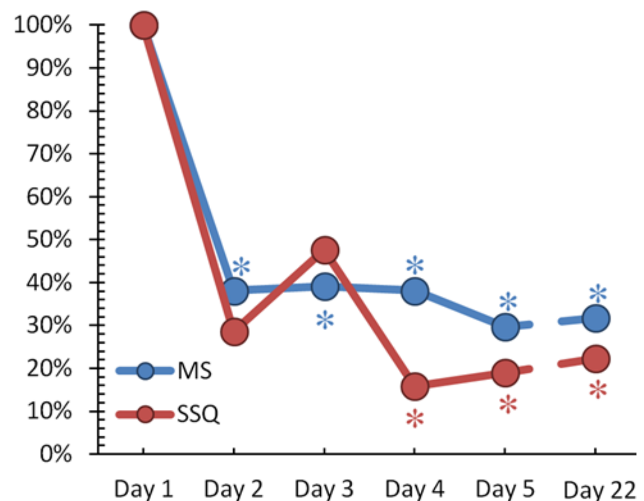

Figure 4. Mean MS and SSQ Score as a Percentage of Day 1 Intensity.

With this in mind, many questions about adaptation and its potential implications for DFS training remain. Will the dynamic, multisensory environment of the DFS preclude subjects from obtaining significant adaptation benefits? Will adaptation to MS differ from adaptation to CCC due to head movements? Will this in turn differ from CCC due to passive motion of the gondola? Will any potential adaptation benefits remain following an extended break in DFS exposure? All of these questions are essential to the efficacy of adaptation as a plausible method for CCC and MS mitigation.

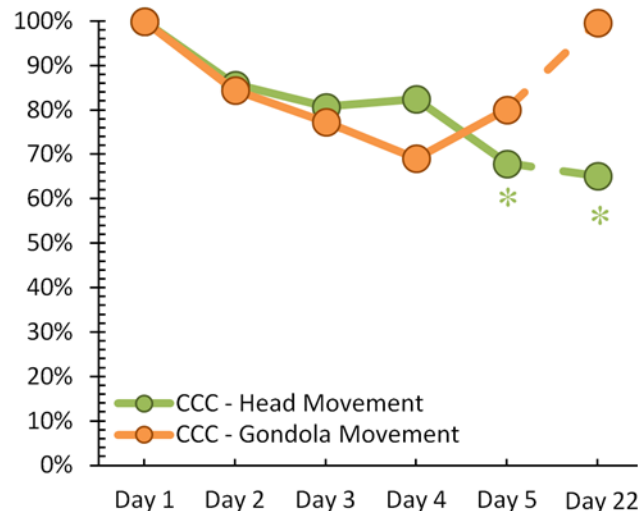

Figure 5. Mean CCC Score as a Percentage of Day 1 Intensity.

In order to answer these questions we conducted a study to determine how humans adapt to MS and CCC in a DFS training environment (Newman et al., 2013). Experienced pilots made 14 predetermined head movements (up to 90° in yaw and 45° in pitch) at +3.0Gz on five consecutive days and 22 days after initial training. ETC's ATFS-400 was used as the test platform. MS and CCC symptoms were measured after each head turn using subjective intensity scales. The Simulator Sickness Questionnaire (SSQ) was also administered before and after each daily training

session. We observed that MS symptoms adapt rapidly (after one (1) session), significantly (with 40-90% reduction), and with benefits that are retainable for more than 2 ½ weeks without subsequent centrifuge exposure (see Figure 4). Note that the stars shown in Figures 4 & 5 indicate a statistically significant decline from Day 1 values at the $p<0.05$ level. Rapid adaptation was observed both in terms of overall wellbeing inside the ATFS-400 and intensity of individual MS symptoms (e.g., nausea, sweating, and fatigue as measured by the SSQ; red trace in Figure 4).

During retesting 22 days after the initial exposure, nearly all scores indicated 90-100% retention of training benefits. The reduction of unpleasant MS effects associated with DFS using an adaptation training protocol may enhance the effectiveness of simulation. Practical use of sustained-G simulators is also likely to be interspersed and complimented with other types of ground and in-flight training. Hence, it would be undesirable and unpleasant for trainees to lose adaptation benefits after a short gap in DFS use. However, these results suggest that training gaps in excess of two weeks may be permissible with almost no loss of adaptation training benefits. Studies investigating the retention of adaptation benefits beyond two weeks are fairly limited. Wang and colleagues (2011) utilized a similar, five day, adaptation schedule with a simple Coriolis training device and found that pilots were able to retain reduced MS levels for up to five weeks while non-pilots were able to retain their adapted state for two weeks. The long term retention of such adaptation benefits is an area that requires further investigation.

Adaptation to CCC tumbling artifacts due to head motion and passive gondola motion did not show as substantial and rapid a decline (see Figure 5). CCC motion artifacts from active head movements (green trace in Figure 5) tend to persist for a much longer period of time than MS symptoms. Only after five (5) days of repeated CCC exposure were active CCC intensity ratings significantly different than their initial intensity. The overall decline in CCC intensity was small, especially when compared to the dramatic decline reported for MS symptoms. Passive CCC intensity ratings showed no statistically significant decline throughout the entire study (orange trace in Figure 5). These results suggest that it may be impossible to adapt to the tumbling sensations produced by passive motion of the gondola.

Technological Developments for MS and CCC Mitigation

It is important to note that not all head or gondola movements during centrifugation cause a CCC tumbling response. For example, tumbling during accelerated rotation (G-onset) is seldom reported and, if reported, is usually rated at the lowest end of the intensity scale. Tumbling during decelerated rotation (G-Offset) is almost always reported and almost always rated at the highest end of the intensity scale. Guedry provided a framework to understand this phenomenon (Guedry & Benson, 1978). He demonstrated that the intensity of the illusory tumbling response depends upon the orientation of the resultant angular velocity vector of the head with respect to the gravito-inertial force direction. As this vector drifts away from the axis of primary rotation (a Barany chair rotating in yaw in his experiment) the perceived tumbling sensation tends to intensify. Many other mathematical models of vestibular Coriolis also predict this phenomenon (Holly, 2004). Likewise, anyone who has ridden in a passive centrifuge can most definitely attest to the accuracy of these findings.

LEFT 90°	LEFT 45°		RIGHT 45°	RIGHT 90°
3.6	2.2	UP 45° 0.6	1.7	2.7
3.7	2.0	0.0	2.4	4.0
2.9	1.8	0.7 DOWN 45°	2.3	3.8

Figure 6. Mean CCC Intensity for Head Movements to Various Cockpit Locations at +3Gz

During the adaptation experiment mentioned previously, we measured CCC intensity for head movements to various locations within the cockpit. These locations ranged from ± 90° left-right (yaw) and ± 45° up-down (pitch). All head movements were made at a nominal rate of 90°/s. Figure 6 shows mean CCC intensity for all cockpit locations averaged across all six (6) days of the experiment.

At the +3Gz level tested, pitching head movements, within a substantial range of head-neck motion, produce very minimal CCC tumbling sensations (a score of 0.6-0.7 out of 10). At the same G level, yaw head movements at identical rates and to identical angles produce sensations that are more than three (3) to four (4) times as intense. Additionally, half of the subjects tested during the experiment reported no tumbling during either the pitch up or pitch down condition.

These observations suggest that not all cross-coupled motions produce tumbling sensations or disorientation. Instead, CCC appears to be a particular phenomenon whose intensity and characteristics can be controlled and manipulated by head and centrifuge augmentation. Modern DFS systems should attempt to exploit these observations in order to mitigate CCC in response to passive gondola motion.

An experiment is underway to determine the efficacy of these techniques using a developmental ATFS-400 system at ETC's Southampton, PA facility. This experimental DFS motion platform utilizes an advanced G-Pointing algorithm to minimize CCC intensity during G-offset maneuvers. The algorithm combines mathematical models of vestibular physiology and centrifuge dynamics to minimize the cross-coupled forces that act on a pilot's vestibular system during decelerated rotation. Using the vector framework described by Guedry (1978), the algorithm works by shifting the resultant angular velocity vector towards the axis of planetary rotation. This thereby minimizes the intensity of the CCC tumbling response. Pilot testing has demonstrated a significant reduction of CCC intensity with minimal loss of ATFS-400 dynamic performance. Results from the full experiment, which will be completed in 2014, will help determine the true efficacy of this new algorithm.

CONCLUSION

From its initial incarnation in 1969, the modern DFS motion platform represents a quantum leap in terms of both performance capability and pilot comfort in the system. These systems can replicate the force environment of 4th and 5th generation tactical aircraft and mitigate many of the unwanted physiological artifacts that plagued previous DFS implementations.

There is still room for future development. Although positive efforts have been made to mitigate the effects of CCC during passive gondola motion, head movement contingent CCC requires additional research. Since fighter pilots routinely move their heads during tactical air combat, it is essential to develop new technologies and training scenarios that minimize CCC during active head motion. For example, it may be possible to develop mission specific scenarios that exploit the fact that at certain G-levels specific planes of head motion do not provoke a strong CCC tumbling artifact (see Figure 6). Enemy targets or other visual input could be dynamically positioned to the pilot such that the necessary range of head movement is within the envelope of least CCC provocation. Head and eye tracking technology could also be integrated into the training environment to help determine target positioning and provide feedback to the pilot on CCC and head range-of-motion. Adaptive tactical training scenarios represent one solution for high value training using DFS. Other solutions will likely hinge on the intersection of physiological research and advanced motion engineering that has been essential to DFS development over the past 45 years.

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