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A STUDY TO EVALUATE THE SUITABILITY OF A CENTRIFUGE AS A DYNAMIC FLIGHT
SIMULATOR FOR F/A-18 STRIKE FIGHTER MISSION TRAINING

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DEDICATION

This thesis is dedicated to my wife, Leigh.
Finishing this long journey would not have been possible without her.

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ABSTRACT

The purpose of this study was to evaluate the suitability of using an existing 25-ft radius centrifuge as a dynamic flight simulator for “full mission” F/A-18 strike fighter mission training with respect to the representativeness of pilot-perceived motion and acceleration cues.

The methodology employed in this study consisted of analyzing F/A-18 mission tasks, collecting pilot opinion surveys of important sensory cues needed in simulator training, and conducting an analysis of human pilot perceptual problems caused by centrifuge motion constraints.

This study identified a number of issues indicating that a centrifuge-based flight simulator shows limited potential for use in “full mission” F/A-18 training scenarios. Specifically, there is a fundamental mismatch between the 6 degree-of-freedom mission-representative acceleration environment experienced in the aircraft and the 3 degree-of-freedom acceleration environment the centrifuge is able to provide. The centrifuge is not optimized for the typical acceleration environment experienced during F/A-18 missions and has significant limitations in “near one g” and “near zero g” flight conditions. Additionally, the centrifuge causes a variety of undesired, unrealistic, and debilitating vestibular artifacts that are not consistent with what a pilot experiences in the aircraft when performing the same mission task, degrading the effectiveness of training.

Despite its limited suitability as a “full mission” F/A-18 simulator, the centrifuge is an essential physiological training device, shows good potential as a part-task trainer for departure/spin training, and should continue to play a role in the F/A-18 training continuum.

TABLE OF CONTENTS

1. INTRODUCTION	1
THE FUNDAMENTALS OF FLIGHT SIMULATION	2
2. DESCRIPTION OF F/A-18 STRIKE FIGHTER MISSION REQUIREMENTS	8
AIRCRAFT DESCRIPTION AND CAPABILITIES	8
STRIKE FIGHTER MISSION DESCRIPTIONS AND ANALYSIS OF STRIKE FIGHTER TRAINING MISSION DATA	12
F/A-18 STRIKE FIGHTER AIRCREW SURVEY RESULTS AND ANALYSIS	18
3. ANALYSIS AND DISCUSSION OF AN EXISTING CENTRIFUGE-BASED FLIGHT SIMULATOR	22
CENTRIFUGE-BASED FLIGHT SIMULATOR PERFORMANCE CAPABILITIES	22
PILOT QUALITATIVE EVALUATIONS OF THE ATFS 400	26
COMPARING THE MECHANICS OF AIRCRAFT FLIGHT AND CENTRIFUGAL MOTION	29
CENTRIFUGE-BASED FLIGHT SIMULATORS AS PART-TASK TRAINERS	36
4. CONCLUSIONS AND RECOMMENDATIONS	37
CONCLUSIONS	37
RECOMMENDATIONS	38
LIST OF REFERENCES	40
APPENDICES	47
APPENDIX A: Analysis of F/A-18E Aircraft Flight Data	48
APPENDIX B: Analysis of Strike Fighter Aircrew Survey Results	67
APPENDIX C: Review of Spatial Orientation and Human Sensory Perception	76
APPENDIX D: Review of the Mechanics of Aircraft Flight and Centrifuge Motion	79
VITA	83

LIST OF FIGURES

Figure 1. Three-View Diagrams of the F/A-18C/D Hornet and F/A-18E/F Super Hornet	9
Figure 2. Aircraft Reference Axes.....	9
Figure 3. Photograph of ATFS 400 Centrifuge Manufactured by ETC	23
Figure A-1. Pilot Seat Normal Acceleration Expressed as g and Aircraft Altitude Versus Elapsed Mission Time for the Air Combat Maneuvering Training Mission	50
Figure A-2. Histograms of Pilot Seat Normal Acceleration (G_z) Spectrum for the Air Combat Maneuvering Training Mission.....	52
Figure A-3(a). Pilot Seat Normal Acceleration Expressed as g and Aircraft Altitude Versus Elapsed Mission Time for the Air-to-Air Intercept Training Mission	54
Figure A-4. Histograms of Pilot Seat Normal Acceleration (G_z) Spectrum for the Air-to-Air Intercept Training Mission	58
Figure A-5. Pilot Seat Normal Acceleration Expressed as g and Aircraft Altitude Versus Elapsed Mission Time for the Close Air Support Training Mission.....	60
Figure A-6. Histograms of Pilot Seat Normal Acceleration (G_z) Spectrum for the Close Air Support Training Mission.....	62
Figure A-7. Pilot Seat Normal Acceleration Expressed as g and Aircraft Altitude Versus Elapsed Mission Time for the SACT Training Mission	64
Figure A-8. Histograms of Pilot Seat Normal Acceleration (G_z) Spectrum for the Surface-to-Air Countertactics Training Mission	66
Figure B-1. Histogram of Aircrew-Rated Realism of Existing Fixed-Base F/A-18 Simulator in Matching the Environment in the Actual Aircraft for Specific Mission Subsets.....	70
Figure B-2. Histogram of Aircrew-Rated Frequency of Head Movement in the Actual Aircraft During Specific Strike Fighter Mission Subsets.....	72
Figure B-3. Histogram of Aircrew-Rated Importance of Gravito-Inertial Based Cues During Various Strike Fighter Mission Tasks	74
Figure D-1. Required Bank Angle and Centrifuge Speed for a Pilot-Commanded G_z	82

LIST OF TABLES

Table 1: Basic Aircraft Parameters for F/A-18 Hornet and Super Hornet.....	9
Table 2: Typical Strike Fighter Mission Subsets	13
Table 3: ATFS 400 Parameters and Performance Characteristics.....	24
Table A-1: Air Combat Maneuvering Training Mission Acceleration Analysis	51
Table A-2: Air-to-Air Intercept Training Mission Acceleration Analysis.....	56
Table A-3: Air-to-Air Intercept Training Mission Acceleration Analysis.....	57
Table A-4: Close Air Support Training Mission Acceleration Analysis.....	61
Table A-5: SACT Training Mission Acceleration Analysis	65
Table B-1: Strike Fighter Aircrew Survey Demographics	68
Table B-2: Results of Aircrew Acceptance Ratings of Existing Fixed-Base F/A-18 Simulators....	69
Table B-3: Results of Aircrew-Rated Realism of Existing Fixed-Base F/A-18 Simulator in Matching the Environment in the Actual Aircraft for Specific Mission Subsets.....	71
Table B-4: Results of Aircrew-Rated Frequency of Head Movement in the Actual Aircraft During Specific Strike Fighter Mission Subsets	72
Table B-5: Results of Aircrew-Rated Importance of Gravito-Inertial Based Cues During Specific Strike Fighter Mission Subsets	75

LIST OF ABBREVIATIONS AND ACRONYMS

A/A	Air-to-Air
A/G	Air-to-Ground
ACM	Air Combat Maneuvering
AOA	Angle of Attack
ATFS	Authentic Tactical Fighting System
BVR	Beyond Visual Range
C-FET	Centrifuge-Based Flight Environment Trainer
CAS	Close Air Support
CCC	Coriolis Cross-Coupling
CRM	Crew Resource Management
DOF	Degrees of Freedom
ECS	Environmental Control System
EO	Electro-Optical
ETC	Environmental Technologies Corporation
F/A	Fighter-Attack
FAA	Federal Aviation Administration
FCS	Flight Control System
FOV	Field-of-View
FRS	Fleet Replacement Squadron
G	Gravito-Inertial Acceleration
GIF	Gravito-Inertial Force
GPS	Global Positioning System
HUD	Heads-Up Display
JHMCS	Joint Helmet-Mounted Cueing System
LEX	Leading Edge Extension
NAS	Naval Air Station
NASA	National Aeronautics and Space Administration
NATOPS	Naval Air Training and Operations Procedures Standardization
OCF	Out-of-Control Flight
P_s	Specific Excess Power
SA	Situational Awareness
SACT	Surface-to-Air Countertactics
SD	Spatial Disorientation

SO	Spatial Orientation
ToT	Transfer of Training
VID	Visual Identification
WSO	Weapon System Officer
WVR	Within Visual Range

1. INTRODUCTION

Within the United States Navy tactical aviation community, the sustained combat requirements for the prolonged Global War on Terror have outpaced the fatigue life expenditure estimates for the F/A-18 Hornet and Super Hornet, forcing U.S. Navy leadership to look to alternative methods to train and maintain combat readiness for strike fighter aircrew other than traditional in-aircraft training.¹ One of the initiatives sought by Naval Aviation leadership is to utilize flight simulators in a much more prominent role than in years past.² Faced with accelerating increases in life cycle costs and increased operational risk due to fatigue-related aircraft component failures, flight simulators offer an attractive alternative for maintaining combat readiness.

In recent years, advances in both the specification of human sensory, perceptual, and response mechanisms³ and also simulation technology including high-fidelity displays and powerful computers have significantly expanded what is possible with respect to simulating the flight experience.⁴ Nevertheless, it is nearly impossible to match all the cues experienced in the air in ground-based simulators because the cockpit displacement cues cannot be duplicated exactly.^{5,6} The question of how closely an earth-bound flight simulator can mimic the force and motion cues characteristic of aircraft flight has led to the development and deployment of different technologies to provide simulator force and motion realism, most notably those employing wide-view high-definition visual systems and 6 degree-of-freedom (DOF) synergistic platforms used for wide-body commercial and transport aircraft.

Providing accurate, timely, and effective force and motion cues in a simulator consistent with the dynamic, high g-force maneuvers typical during F/A-18 strike fighter missions is considerably more difficult. One alternative offered is to modify and refine existing human-rated centrifuge systems to be used as high performance dynamic flight simulators that match the performance capabilities of the F/A-18 Hornet and Super Hornet. This paper addresses the suitability of using an existing 25-ft radius centrifuge as a dynamic flight simulator for F/A-18 strike fighter mission training with respect to the representativeness of pilot-perceived motion and acceleration cues.

THE FUNDAMENTALS OF FLIGHT SIMULATION

Flight simulation is an essential component of both military and commercial aviation flight training, allowing pilots and crews to train safely and effectively without having to incur the high costs of operating and maintaining a fleet of training aircraft.^{7,8,9,10}

Merriam-Webster's Dictionary offers a simple, straightforward definition of simulation that frames the aviation training discussion very well: simulation is "the imitative representation of the functioning of one system or process by means of the functioning of another."¹¹ Very simply, a flight simulator is designed to provide an accurate, "imitative representation" of the conditions, characteristics, and events expected to be encountered in the actual aircraft such that the pilot learns skills that will be performed in the actual aircraft.¹² As McCauley describes: "flight simulators create the illusion of flight by simulating equipment, tasks, and environments and training simulators provide these capabilities for the purpose of accomplishing pilot or aircrew training without using the actual aircraft."⁸

Transfer of Training (ToT) in Flight Simulation

Transfer of training (ToT) in aviation refers to the measurable, beneficial effects of learning or practicing a skill, task, or combination of each in one device (i.e. the simulator) that can be directly applied to another device (i.e. the airplane).¹³ Transfer of training is based upon two key theories: American psychologist Edward L. Thorndike's "common elements" theory and Charles E. Osgood's theory of the concept of "transfer surface." These two theories suggest that transfer of training will occur to the extent that a simulator and the aircraft share common elements and where one can map an assumed relationship between elements or features of a simulator and the aircraft.¹⁴ Where there is one-to-one correspondence, ToT will be positive and high; less than one-to-one correspondence will result in decreasing ToT to the point that none will occur when correspondence is zero.¹⁴ These philosophies have guided the evolution of flight simulators and have resulted in a variety of technological advancements emphasizing high-fidelity and highly realistic representations of aircraft and their systems.¹⁴

While the requirement to achieve high levels of realism has driven flight simulator development and certification, there are two key principles that maximize ToT.¹² First, the characteristics and methods of using simulators should be based on their behavioral objectives.

Second, physical realism is not necessarily the only or optimal means for achieving the behavioral objectives of simulation. In the end, the success of flight simulation lies not just with improved physical realism, but instead with improved pilot learning or performance.¹² As stated by Ray, “If the simulation is to properly stimulate the physiology of the human being to achieve performance as it would occur in flight, it is very clear that simulation must faithfully address the cues upon which that flight performance is based.”¹⁵

With this in mind, the ToT from a flight simulator to the actual aircraft is highly dependent on the quality of the simulation, which provides sensory feedback.¹⁶ To obtain maximum training and habit transfer, the training mission must include as many of the pertinent features of the real mission as possible.¹⁷ A well-designed flight simulator, in replicating the physical interface between the pilot, aircraft, and external world, should provide an environment where the pilot can learn, practice, and perfect the skills and behavior necessary for successful completion of mission-representative tasks. Not surprisingly, the broad range of both aircraft and mission categories across the spectrum of military and commercial aviation has resulted in a wide variety of flight simulator design alternatives incorporating varying degrees of sensory fidelity and force or motion cueing.

What should be simulated is ultimately determined by the aircraft characteristics and mission profiles a simulator is designed to emulate. Designing a simulator to accurately emulate aircraft characteristics requires detailed analysis of:

1. Specific aircraft aerodynamic and performance capabilities including acceleration limits, excess power, maneuverability envelope, flying qualities, and stability and control characteristics; and
2. Human factors issues surrounding the man/machine interface such as layout and mechanization of controls and displays and field of view.

Designing a simulator to emulate the mission environment requires an understanding of:

1. How the pilots fly/performance the “full mission” in the actual aircraft, and
2. How the pilots interact with their external environment and what sensory cues they use while performing mission tasks. Examples of this interaction include how pilots perceive aircraft state changes, develop and modify aircraft control strategies, maintain intra- and inter-cockpit situational awareness, exercise decision making, and a perform a wide variety of mission-dependent cognitive tasks.

While the problems of simulating equipment and rehearsing tasks are relatively straightforward, the simulation of the in-flight environment is one of the most challenging tasks for

simulator designers.¹⁸ Specifically, it can be very difficult to accurately simulate the aircraft's gravito-inertial accelerations, maneuvering dynamics, external disturbance cues, and other types of aircraft motion that can be perceived by the human sensory system, particularly in high-performance, highly-agile tactical jet aircraft.

“Categories” of Sensory Cueing

Pilots depend upon sensory cues to assess the status and condition of their aircraft, to initiate actions, to guide their performance, and to signal when an action should be altered or ended.¹⁹ In other words, pilots interpret aircraft response solely on their perception of it. For every aircraft and mission, there are a wide variety of sensory cues that add realism to the simulated flight environment but these cues are highly dependent upon the mission subset and/or embedded tasks.

For the purposes on this study, the wide variety of different types of sensory cues were assigned to one of the following five 5 categories:

1. Visual cues, defined as changes in external scene including weather effects and in cockpit scene including HUD/sensor/display symbology changes.
2. Gravito-inertial acceleration cues, defined as any of the vestibular or somatosensory cues including positive and negative G forces, seat of the pants cues, any roll-pitch-yaw inner ear sensations, linear acceleration, sideforces, and G-suit inflation
3. Physical airframe cues, defined as high-frequency structural modes such as buffet, aerodynamic vortices, airframe vibration, and turbulence such that pilots perceive aircraft state or performance through airframe (aeromechanical) dynamic response.
4. Aural cues, defined as engine response, environmental control system (ECS) flow changes, ambient cockpit noise, external configuration changes (lowering/raising landing gear), and audible aircraft performance cues.
5. Environmental cues, defined as temperature, airflow, humidity, ambient pressurization, oxygen flow, and cockpit odor.

Force and Motion Cueing in High-Fidelity Flight Simulation

While the majority of sensory cueing in flight simulation comes through visual means, research has shown that force and motion cues, in effect, quicken pilot responses to displays of

attitude, altitude, and flight path changes.³ Force and motion cueing employed in high-fidelity simulators allows for the generation of gravito-inertial acceleration and physical airframe cues that are typically lacking in a traditional fixed-base, non-motion simulator.

Since it is highly unlikely that a ground-based simulator will be able to exactly duplicate actual aircraft motion (objective fidelity that matches aircraft displacement, velocity, and acceleration), the principle behind force and motion cueing in a flight simulator is to provide accurate, timely, and effective sensory cues (perceptual fidelity) via the predominant sensory receptors of the pilot in order to elicit the same performance and control strategy as would be used in the actual aircraft.^{7,20,21} This indicates that sensory cues used by pilots are strongly context-dependent, varying with different mission types, tasks, and workload.²²

The human nervous system is highly adaptable and helps bridge the gap to make flight simulation more realistic, even though the sensory cues may not be 100% accurate. As described by Chung, et al., “it is well known that human pilots will quite successfully adapt their behavior to many different control situations, and in the process optimize the pilot-to-vehicle performance for their task.”⁵ As Sinacori explains, “certain types of stimuli can evoke the same sensations and response even when the stimulus magnitude varies. In engineering terms, this means one-to-one motion reproduction in a simulator is not necessary and this is the basic reason why motion simulation is possible and works in practice.”²³ In other words, simulator designers have learned to tune visual and other methods of sensory stimuli and feedback to “fool” the pilot into thinking he/she is physically experiencing the sensation of flight by evoking nervous system responses consistent with those experienced while performing in-aircraft tasks.

Large commercial aircraft simulators currently employ force and motion cueing through the use of 6 degree of freedom (DOF) synergistic Stewart platforms to satisfy FAA Level D fidelity requirements.²⁴ These FAA-mandated force and motion cues are specifically tuned to the performance capabilities of large commercial aircraft and are designed to provide the pilot with high-fidelity feedback of aircraft response during demanding phases of flight such as takeoff, approach, and landing. Some examples of the force and motion cues required for commercial aircraft include the following:

- Runway rumble, oleo deflections, effects of ground-speed and uneven runway characteristics
- Buffets on the ground due to spoiler/speedbrake extension and thrust reversal
- Bumps after lift-off of nose and main gear
- Buffet during extension and retraction of landing gear

- Buffet in the air due to flap and spoiler/speedbrake extension
- Stall buffet to, but not necessarily beyond, the FAA certificated stall speed, V_S
- Representative touchdown cues for main and nose gear
- Nosewheel scuffing
- Thrust effect with brakes set.²⁴

These cues include both control cues (expected responses) and disturbance cues (unexpected responses) and are intended to assist the pilot in maintaining spatial orientation and managing aircraft state as he/she completes mission-representative tasks.

Tactical aircraft have a significantly larger flight envelope, dramatically more dynamic maneuvering and performance capabilities, and widely expanded mission subsets than commercial aircraft. These aircraft are capable of generating rapid onset, high magnitude accelerations that cause agile flight path changes and, as such, provide vastly different sensory cues to the pilot than those experienced from a commercial or transport aircraft during an approach and landing task. While a traditional simulator may provide sufficient fidelity for mimicking the motions and accelerations of larger aircraft in relatively benign phases of flight (like takeoff and landing), this fidelity begins to break down when attempting to mimic the complex and highly variable three-dimensional flight path possibilities and various combinations of linear and rotational acceleration cues experienced in tactical aircraft. Very simply, a traditional motion-based flight simulator like those used in commercial aviation has considerable difficulty in providing the gravito-inertial accelerations experienced in high-performance, highly agile strike fighter aircraft. As Gillingham explains, “the phenomenal ability of current high-performance aircraft to roll, pitch, accelerate, gain or lose altitude, and otherwise change spatial orientation parameters very quickly, presents a significant challenge to the pilot to maintain a continually accurate assessment of those parameters.”²⁵ This phenomenal ability also presents considerable challenges to any proposed simulator device that is supposed to generate accurate, timely, and effective cues of these dynamic aircraft parameters.

A human-rated centrifuge is one proposed alternative for providing force and motion cueing that can achieve the large magnitude, sustained normal acceleration (G_Z) accelerations and high G_Z onset/offload rates characteristic of highly agile fighters. Specifically, there are existing 25-ft radius centrifuges used in both physiological research and training applications that have the capability to provide the large magnitudes of sustained accelerations and onset rates.

Purpose, Limitations to Scope, and Methodology

Purpose

The purpose of this study is to evaluate the suitability of a 25-foot moment arm centrifuge for use in an expanded role as a dynamic flight simulator for “full mission” F/A-18 training scenarios.

Limitations to Scope

In order to focus discussion to the issue of whether or not a 25-ft moment arm centrifuge can be used as a dynamic flight simulator for “full mission” training scenarios, the following limitations to scope are offered:

1. The cockpit layout, visual displays, aircraft systems controls and operation, and aural and environmental cues for a centrifuge-based dynamic flight simulator are assumed to be the same as existing F/A-18 fixed-base flight training devices (any proposed centrifuge-based simulator will use the current state-of-the-art F/A-18 training devices as a starting point).
2. Discussion and analysis is based upon existing 25-foot planetary arm, 3 degree-of-freedom (DOF) centrifuge designs. There are many centrifuge design variables that can be modified to provide different force and motion cues, including varying centrifugal arm radius, baseline rotational speed, gondola degrees of freedom, gondola mass characteristics, and motor size and gearing.
3. Alternative methods to provide force and motion cueing (such as synergistic 6 DOF Stewart platforms, g-seats, g-suit inflation, helmet loading, light dimming systems, etc.) are not discussed.

Methodology

The methodology employed in this study consisted of analyzing F/A 18 mission tasks, collecting pilot opinion surveys of important sensory cues needed in simulator training, and conducting an analysis of human pilot perceptual problems caused by centrifuge motion constraints. Conclusions were drawn from this process and recommendations made for the concept of using a centrifuge-based simulator for full mission training.

2. DESCRIPTION OF F/A-18 STRIKE FIGHTER MISSION REQUIREMENTS

Before delving into detailed discussion and analysis on the suitability of a centrifuge-based dynamic flight simulator for F/A-18 mission training, there must be some understanding of the aircraft capabilities, strike fighter mission components, and current U.S. Navy aircrew (both pilot and weapon system officer) sensory cue (stimulus and feedback) expectations during flight. The following section provides:

- 1) A description of aircraft performance and capabilities,
- 2) A description of the strike fighter mission and an analysis of flight data from real-world mission training profiles, and
- 3) Results from pilot opinion surveys related to sensory cueing expectations.

A good understanding these three areas is needed to define the “requirements baseline” for a centrifuge-based dynamic flight simulator and its suitability for mission related training.

AIRCRAFT DESCRIPTION AND CAPABILITIES

Basic Aircraft Description

The Hornet and Super Hornet, shown in Figure 1, are twin engine, mid-wing, multi-mission and all-weather tactical aircraft that can be configured quickly to perform either fighter or attack roles or both, through selected use of external equipment to accomplish specific missions. The Hornet has been produced in four variants (single seat models A and C and two seat models B and D). The Super Hornet is a newer and larger version and is produced in two variants (a single seat E model and two-seat F model).²⁶ Table 1 details basic aircraft parameters for each aircraft. Figure 2 below reviews standard aircraft reference axes and sign conventions that will be used throughout this paper. The following paragraphs outline the acceleration and other performance capabilities of the aircraft.

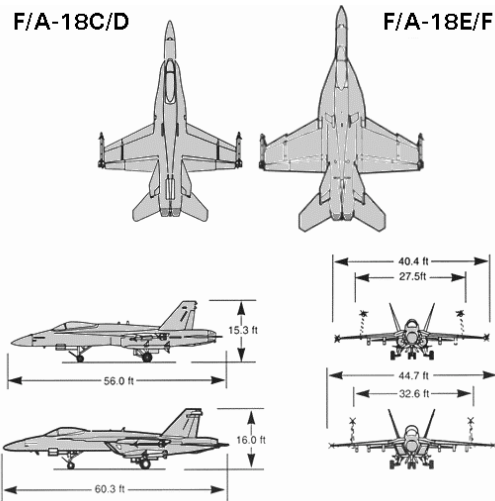


Figure 1. Three-View Diagrams of the F/A-18C/D Hornet and F/A-18E/F Super Hornet

Table 1: Basic Aircraft Parameters for F/A-18 Hornet and Super Hornet²⁶

Aircraft Parameter	Hornet	Super Hornet
Length	56 ft	60.3 ft
Height	15.3 ft	16 ft
Wingspan	40.4 ft	44.7 ft
Static Thrust per Engine	17,700 lbs	22,000 lbs
Max. Airspeed	> 1.8 Mach	> 1.8 Mach
Service Ceiling	50,000 ft	50,000 ft

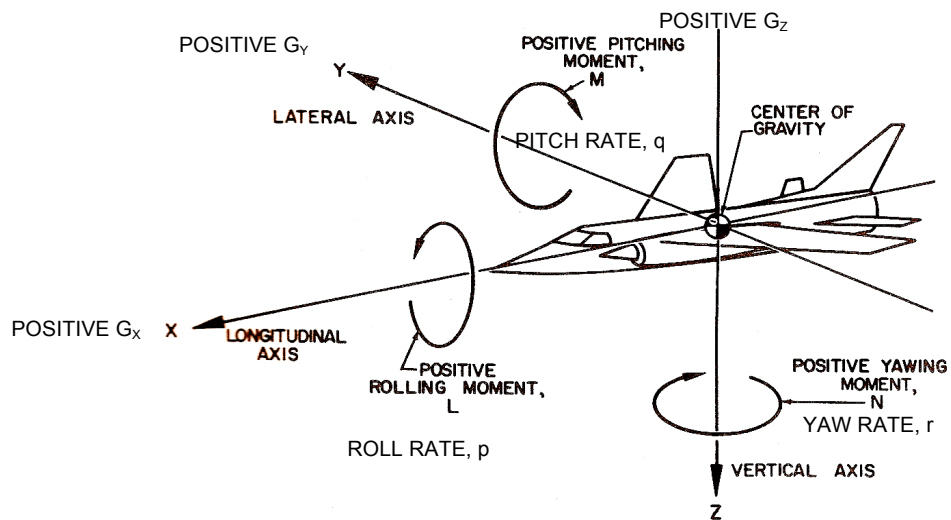


Figure 2. Aircraft Reference Axes²⁷

Acceleration and Performance Capabilities of the Hornet and Super Hornet

Normal acceleration (G_z)

The Hornet and Super Hornet have substantial positive and negative normal acceleration envelopes. Each aircraft FCS is designed to command maximum G_z accelerations of +7.5 g and -3.0 g for symmetrical maneuvers and +6.0 g / -1.0 g for unsymmetrical maneuvers such as rolling pullouts.^{28,29} In the fighter escort configuration the aircraft can achieve maximum G_z onset rates exceeding 10 g/sec.³⁰ Aircrew are specifically warned about this high onset rate capability via the following WARNING in each Naval Air Training Operations Procedures and Standardization (NATOPS) Flight Manual:

“Rapid aft stick movement, with or without g limit override, commands a very high g onset rate. This high g onset rate can cause immediate loss of consciousness without the usual symptoms of tunnel vision, greyout, and blackout. Consciousness may not return for more than 20 seconds after the g level is reduced to near 1 g.”^{28,29}

An important consideration in determining the suitability of a centrifuge-based flight simulator is whether or not it can generate the rapid onset rates and high G_z magnitudes experienced when aggressively maneuvering the aircraft during dynamic mission phases.

Aircraft Carrier Catapult and Arrestment Longitudinal Acceleration/Deceleration (G_x)

One unique consideration for U.S. Navy carrier based aircraft is the unique longitudinal accelerations/decelerations (G_x) experienced during launch from and recovery onboard the aircraft carrier. Both catapult launch and arrested landing are very dynamic phases of flight where the aircraft is accelerated to and decelerated from safe flying speed within relatively short durations (approximately 2-5 seconds). Catapult launches can generate rapid-onset G_x accelerations as high as +5.7 g and arrested landings can generate G_x decelerations as high as -4.10 g.³¹ An important consideration in determining the suitability of a centrifuge-based flight simulator is whether or not it can generate the same mission-representative high onset rate linear acceleration/deceleration (G_x) cues characteristic of carrier catapult launch and arrested landing.

Specific Excess Power (P_S) Capabilities

Both aircraft variants have considerable lift and thrust capability enabling the pilot to generate high normal accelerations (G_Z) along with impressive turn rates and small turn radii while maintaining sufficient excess power (P_S) to sustain those conditions during tactical maneuvering.^{28,29} Specifically, there are regions where the aircraft has sufficient P_S to sustain +5 to +6 g_Z in a level turn while maintaining airspeed.³⁰ Above this g level, the aircraft has negative excess power and will decrease in airspeed until reaching the maximum lift limit as the pilot attempts to maintain the accelerated condition. Below this level, the aircraft has positive excess power and will increase airspeed and energy state (experience G_X acceleration) in a continuous level turn.

An important consideration in determining the suitability of a centrifuge-based flight simulator is whether or not it can be tuned to match the performance capabilities of the aircraft such that it provides the same combination of G_Z and G_X acceleration cues as the aircraft maneuvers within its performance envelope.

Roll Rate Capabilities

The advanced FCS of both the Hornet and Super Hornet provides maximum roll rate for a given aircraft configuration with maximum lateral stick deflection maneuvers. Maximum roll rates for the fighter-escort configuration can exceed 220°/sec for the Hornet and 200°/sec for the Super Hornet.^{28,29,30} An important consideration in determining the suitability of a centrifuge-based flight simulator is whether or not it can be tuned to provide the same magnitude and duration of roll rate cues in response to pilot inputs during rapid rolling maneuvers.

The Role of Lateral Acceleration (G_Y) during Departures and Out of Control Flight (OCF)

While both aircraft variants have relatively benign flying qualities throughout most of the envelope, there are regions where departure from controlled flight can occur. F/A-18 pilots are taught to use tactile sideforce (G_Y) cues to recognize impending departure from controlled flight and when recovery has begun.^{28,29} Sideforce, felt in the cockpit as a sideways push, is a reliable indicator of continued departure and is accompanied by a vortex rumble sound as air passes sideways over the canopy. Once departed from controlled flight, post departure gyrations are characterized by large, uncontrollable changes in angle of attack and airspeed accompanied by

sideforces. Pilots are taught to recognize subsidence of sideforces as a reliable indicator of impending aircraft recovery.^{28,29} An important consideration in determining the suitability of a centrifuge-based flight simulator is whether or not it can represent the same magnitude and duration of sideforce cues (G_Y) to train pilots to recognize departure and recovery characteristics.

STRIKE FIGHTER MISSION DESCRIPTIONS AND ANALYSIS OF STRIKE FIGHTER TRAINING MISSION DATA

While the previous paragraphs provided details on the performance capabilities and limits of the Hornet and Super Hornet, they do not necessarily reflect what pilots routinely experience during mission-representative maneuvering. In order to determine the suitability of a centrifuge-based flight trainer for strike fighter mission training, it is also important to understand the broad spectrum of mission subsets and the dynamic force environment that imparts both advantageous and disadvantageous effects as the pilot completes mission-representative tasks within these mission subsets.³²

The following paragraphs describe typical strike fighter missions and explain how operational pilots fly the airplane during training missions.

Strike Fighter Mission Descriptions

Strike fighter aircraft perform a full spectrum of missions ranging from basic instrument and formation flight to the most complex, multi-aircraft warfighting scenarios. Table 2 below lists the F/A-18 mission areas and mission subsets. Within each of these mission subsets are a diverse set of embedded tasks including maneuvering the aircraft, maintaining formation position, making intra- and inter-cockpit communications, and operating aircraft and weapons systems.

In order to maximize pilot effectiveness across these diverse mission areas, both aircraft combine a vast array of technology including sophisticated propulsion and fuel systems, fully-digital flight control system (FCS), radar and electro-optical sensors, communication and navigation systems, and advanced weapons systems. The FCS is designed to provide both stability and controllability, resulting in excellent handling characteristics throughout the entire aircraft envelope and providing excellent departure resistance such that a pilot spends less time “flying the aircraft” and more time “flying the mission.” In addition, both variants utilize the Joint

Helmet Mounted Cueing System (JHMCS), a helmet visor-mounted display system that provides mission essential aircraft and weapon system information no matter where the pilot looks. The JHMCS capability allows the pilot to spend less “heads down” time looking inside the cockpit for time–critical information thus he/she can devote more “heads up” time to scanning outside the cockpit (looking for threats, maintaining formation, etc.).^{28,29}

Table 2: Typical Strike Fighter Mission Subsets

Mission Areas	Strike Fighter Mission Subsets
Air-to-Air (A/A) Warfare	Beyond Visual Range (BVR) Engagements
	Within-Visual-Range (WVR) Engagements
Air-to-Ground (A/G) Warfare	Precision Weapons (Laser/GPS Guided) Delivery
	Conventional Weapons Delivery
	Surface-to-Air Countertactics (SACT)
Basic Proficiency / Administrative Phase of Flight	Formation Flight
	In-flight Refueling
	Emergency Situations / Crew Resource Management (CRM) Scenarios
	Day/Night Carrier Approach and Landing

Within each of these many diverse mission areas, there are a variety of mission subsets and embedded tasks that require specific pilot skill sets and have distinct success/effectiveness criteria. During the performance of each mission, subset, and task pilots rely upon unique sets of input and output sensory cues to observe, orient, and make tactical decisions. In a typical tactical scenario, pilots are required to manage aircraft state, coordinate mission elements with other aircraft in a formation, and maintain situational awareness of enemy threats. This study thus offers the following two pillars upon which the pilot balances F/A-18 mission effectiveness:

1. Basic airmanship is defined as traditional stick and rudder skills and generally referred to the pilot’s ability to control aircraft state including airspeed, flight path, attitude, angle of attack, etc.
2. Overall aviation sense, also known as “skilled performance,”³³ is defined as flight leadership, situational awareness, and decision making. These are generally referred to as higher-level cognitive processes that are conducted at a supervisory level.

In short, within a “full mission” training or operational scenario, the F/A-18 pilot must continuously integrate basic airmanship and overall aviation sense in order to properly fly his/her aircraft (manage aircraft state) while simultaneously managing a complex set of mission tasks.

Strike Fighter Training Mission Acceleration Data

In order to better understand how pilots fly the Hornet and Super Hornet during strike fighter training missions, a total of 10 aircraft data files were obtained from an operational F/A-18E Super Hornet squadron conducting 4 different shore-based strike fighter training missions throughout 2008. As summarized in Appendix A, high sample rate (10 hertz) linear acceleration data was collected by onboard aircraft accelerometers and was corrected to the pilot seat along the three body axes: vertical/normal (G_z), longitudinal (G_x), and lateral (G_y). Training missions consisted of two A/A events and two A/G events. The A/A training missions were air combat maneuvering (ACM) and beyond-visual-range (BVR) air-to-air intercepts. A/G training missions were Close Air Support (CAS) and Surface-to-Air Countertactics (SACT). The pilot seat normal acceleration expressed as g and aircraft altitude versus elapsed mission time for each of the flight members from the four missions sampled are presented in Figure A-1 (ACM), Figure A-3(a) and (b) (A/A BVR intercepts), Figure A-5 (CAS), and Figure A-7 (SACT).

Mission time was the elapsed time from takeoff (initial brake release) until full-stop landing and included both transit time to and from the airfield to working airspace and actual tactical training mission time. Acceleration magnitudes are expressed the ratio of each resultant body axis acceleration to earth's gravitational acceleration. Positive accelerations were defined in accordance with the standard right hand rule for both vertical/normal (Z) and longitudinal (X) axes. Maximum lateral acceleration values were expressed as absolute values. In addition to maximum, minimum, and median acceleration values, Table A-1 through Table A-5 also provide an acceleration spectrum for vertical/normal acceleration (G_z), defined as the elapsed time and percentage of total mission time spent within a specific range of G_z values. Figure A-2 (ACM), Figure A-4 (A/A BVR intercepts), Figure A-6 (CAS), and Figure A-8 (SACT) are histograms summarizing the acceleration spectrum data for each of the strike fighter missions analyzed.

Strike Fighter Training Mission Acceleration Data Analysis

The flight data from the four training missions indicates the magnitude and duration of the three body axis-referenced linear acceleration vectors experienced by pilots while performing mission tasks and provides important clues for how pilots will likely "fly" the mission during centrifuge-based training events. The following paragraphs summarize the important factors to be considered when determining what acceleration profiles should be expected from a centrifuge-based flight simulator if it is used for F/A-18 strike fighter mission training.

Extended duration at G_z magnitudes near +1.0 g and large numbers of G_z onset and offload cycles

Although the Hornet and Super Hornet aircraft are capable of rapid onset to a sustained G_z magnitude of +7.5 g, analysis of aircraft flight data from each of the 4 missions indicates that pilots usually spend a majority of their mission time flying the aircraft near +1.0 g with frequent, short duration excursions to higher G_z levels. As shown in Figure A-1, Figure A-3(a) and (b), Figure A-5, and Figure A-7, the time history of G_z acceleration for every flight member during every mission analyzed indicates a highly dynamic profile consisting of hundreds of cycles of G_z onset and offload from some elevated G_z during maneuvering flight followed by a return to near +1.0 g flight. The histograms in Figure A-2, Figure A-4, Figure A-6, and Figure A-8 indicate the overwhelming majority (on average 90%) of mission time is spent operating near one g. These large numbers of onset and offload G_z cycles from a “steady-state condition” near +1.0 g characterize how pilots fly the aircraft during training missions where they are managing both aircraft state and complex mission variables. The flight data supports the notion that pilots fly the aircraft with an “Assess – Maneuver – Assess” mindset when performing mission tasks where they assess the task and determine how much to displace the aircraft, maneuver via high onset rate G_z inputs to position the aircraft, and then ease off to a lower G_z near +1.0 g to assess the effectiveness of the maneuver in accomplishing the mission task. This characterization of “how pilots fly the aircraft and manage the mission” is an important consideration for determining the suitability of a centrifuge-based flight simulator for F/A-18 training. Specifically, it is important to determine how well a centrifuge-based flight simulator can match this “mission representative” acceleration environment (spent mostly near +1.0 g_z) and whether or not there are adverse affects on accurate, timely, and effective sensory cues due to the large numbers of onload and offload cycles while performing mission tasks.

Limited duration at G_z magnitudes greater than +3.0 g

While the aircraft is capable of peak accelerations up to +7.5 g and has performance capabilities that permit sustained maneuvering while at elevated G_z , review of aircraft flight data indicates that pilots do not routinely fly the aircraft at elevated G_z magnitudes (greater than +3.0 g) for prolonged durations. The data indicates that for each of the missions sampled, the peak longitudinal accelerations experienced during maneuvering flight varied but were less than the aircraft G_z -limit of +7.5 g. In addition, the average time of exposure to G_z greater than +3.0 g during the different missions was less than 5% of the total mission time. The relatively limited

duration at elevated G_z levels in comparison to the total mission time and the median longitudinal acceleration value for the mission indicates that even during dynamic tactical maneuvering, there is a relatively limited amount of time spent at high normal accelerations and the overwhelming majority of the flight is spent at G_z levels less than 3.0 g's. An important consideration for determining the suitability of a centrifuge-based flight simulator is whether the centrifuge should be optimized for providing sustained high G_z accelerations at the limits of the aircraft or for providing accurate, timely, and effective acceleration cues at lower G_z magnitudes characteristic of how pilots fly the aircraft during mission representative scenarios. These mission representative acceleration cues consist of both control cues (initiated by the pilot) and disturbance cues (such as turbulence not initiated by the pilot).

G_z accelerations between -1.0 g and +1.0 g

There are times when strike fighter pilots target less than +1.0 g during mission-representative maneuvers. For example, when a pilot wants to regain aircraft energy as rapidly as possible, he/she will unload to close to zero g in order to maximize longitudinal acceleration while minimizing aerodynamic drag. Likewise, pilots will experience less than +1.0 g when aggressively unloading the aircraft in order to generate rapid nose-down pitch rates in order to point the nose of the aircraft for weapons employment when at high angle-of-attacks during air-to-air combat. Additionally, the pilot experiences less than +1.0 g when attacking a ground target in a stable dive delivery (resultant G_z is a function of aircraft dive angle, i.e. 45° dive is +0.707 g). The primary cues used by pilots are "lightness in the seat", lightness of the feet on the rudder pedals,⁶ and the strong surge of intracranial blood pressure ("head rush"). During these unloaded conditions, the pilot incorporates the magnitude of light-in-the-seat, floating cues into his/her overall sensory processing in order to assess the effectiveness and required duration of unaccelerated ("unloaded") flight control inputs.

Review of aircraft flight data from each mission indicated every flight member experienced G_z accelerations between -1.0 g and +1.0 g throughout each mission. The flight data does not specify if these accelerations were control or disturbance cues and how the magnitude and duration of these accelerations varied between missions and flight members, but it can be inferred from the time histories that these small magnitude G_z accelerations/perturbations were experienced during both administrative phases (transit, cruise, approach, and landing) and tactical maneuvering phases. The longest exposures to G_z values between -1.0 g and +1.0 g were experienced during the ACM and SACT training missions (in fact the time spent at these

unloaded normal acceleration levels was the same as the time spent at normal acceleration levels greater than +5.0 g for these two missions).

An important consideration for determining the suitability of a centrifuge-based flight simulator is whether or not the centrifuge can generate accurate, timely, and effective G_z accelerations between -1.0 g and +1.0 g that mimic both the control and disturbance cues characteristic of a pilot flying the aircraft in a realistic air mass while managing mission representative tasks.

Limited sideforce (G_y) exposure

As discussed above, sideforces are primarily used as warning cues for impending departure from controlled flight. Departure from controlled flight is obviously not something that is expected or desirable and pilots are trained to fly the aircraft safely within the maneuvering envelope.

As provided in Table A-1 through Table A-5, the peak and median lateral/sideforce accelerations (G_y) experienced during the training missions indicate pilots do not experience high levels of sideforce while maneuvering. Therefore, a centrifuge-based flight simulator should be designed to generate pilot-perceived sideforces that do not exceed the peak values attained during dynamic maneuvering in the actual aircraft. Two important considerations for determining the suitability of a centrifuge-based flight simulator are (1) how well the centrifuge limits unwanted sideforce accelerations while reorienting the gondola pitch and roll axes in response to pilot control inputs; and (2) how well the centrifuge is tuned to generate the accurate, timely, and effective sideforce acceleration cues characteristic of impending departure from controlled flight should the pilot “fly” into a departure-prone region of the flight envelope.

Positive and negative G_x exposure

Longitudinal acceleration (G_x) data from the training missions indicate pilots do experience both positive (accelerating airspeed) and negative (decelerating airspeed) G_x accelerations during both steady-state (non-maneuvering) and dynamic flight. It is important that a centrifuge-based flight simulator generate accurate, timely, and effective G_x cues to provide the pilot with cues that help recognize a change in aircraft energy state and airspeed during one g

and dynamic high-G maneuvering flight. Additionally, the centrifuge should be tuned to provide high onset rate and large magnitude G_x accelerations characteristic of those experienced during both aircraft carrier catapult launch and arrested landing.

F/A-18 STRIKE FIGHTER AIRCREW SURVEY RESULTS AND ANALYSIS

The capability of meeting the sensory expectations of the aircrew is another important component in determining the suitability of a centrifuge-based flight trainer for the strike fighter mission. Specifically, it is important to quantify the different types of sensory cues and their importance to the aircrew when performing typical mission flight tasks.

The previous section provided analysis of actual F/A-18 aircraft flight data flown by operational pilots during four different tactical training missions. These data yielded important factors which must be considered when designing a centrifuge-based dynamic flight simulator so it can better match or mimic “real-world” acceleration cues. This next section will review and analyze aircrew survey responses on a number of sensory cueing issues pertaining to flying the aircraft and managing mission tasks. While the survey answers are subjective, they nonetheless provide a valuable framework for understanding how aircrew “interact” with the aircraft during tactical missions. This study does not attempt to use survey results to establish objective sensory requirements or suggest what sensory cues are necessary in order to maximize transfer of training from a simulator to the aircraft; it merely offers some subjective insight into what aircrew expect in terms of sensory cues while performing flight tasks.

Survey Group Composition and Size

A survey was conducted at Naval Air Station (NAS) Lemoore, CA, from 24 February through 06 March 2009. Seventy eight (78) F/A-18 pilots and weapon system officers (WSOs) were surveyed, varying in F/A-18 flight hour experience from less than 500 hours to over 2000 hours in model and all currently assigned to operational units at NAS Lemoore. Table B-1 details the demographics of the surveyed aircrew.

Survey Questions and Method of Survey

The survey consisted of 9 Likert Scale questions eliciting aircrew opinions on a variety of in-simulator and in-aircraft sensory issues as they related to different mission subsets and tasks. Each question was subdivided into specific mission “phases” (A/A, A/G, and administrative phases) and further subdivided into mission-representative embedded tasks. The five categories of sensory cues considered in the survey were visual, gravito-inertial acceleration, physical airframe, aural, and cockpit environmental stimuli and feedback, as described in Section 1.

Table 2 detailed the mission areas, subsets, and embedded tasks included in the survey. Survey results were analyzed by performing modal analysis and histograms were generated to graphically depict respondent’s answers, shown in Figure B-1 through Figure B-3. Table B-2 through Table B-5 depict numerical survey results.

Survey Results and Analysis

Survey data indicated that aircrew have specific sensory expectations that need to be considered when determining the suitability of a centrifuge-based flight simulator. These expectations and the considerations for centrifuge-based simulation are summarized below.

General Aircrew Acceptance of the Realism and Effectiveness of Fixed-Base Flight Simulation

As shown in Figure B-1 and Table B-3, a majority (>50%) of aircrew indicated that the current fixed-base simulator provides a “very good,” “good,” or “acceptable” training environment that is representative of the actual aircraft for all of the surveyed mission subsets except formation flight and in-flight refueling. Likewise, as shown in Table B-2, more aircrew agreed than disagreed that basic airmanship and overall aviation sense (skilled performance) were improved by performing tasks in the simulator for all of the surveyed mission subsets except for formation flight and in-flight refueling. This indicates aircrew generally accept the realism and effectiveness of a fixed-base flight simulator for many of the mission subsets even though the simulator does not provide the force and motion cues encountered in the actual aircraft.

The two notable exceptions to aircrew acceptance of simulator realism and effectiveness, formation flight and in-flight refueling, are high gain mission tasks characterized by precise, small magnitude flight control inputs that result in small variations in G_z sensed by the aircrew.

Similarly, the precision or effectiveness of these high-gain tasks can be significantly degraded by small G_z perturbations (such as turbulence, jet wash, etc.) that cause unacceptable flight path deviations. Survey results for formation flight and in-flight refueling indicate that the lack of precise cueing of G_z variations/perturbations while performing precise, high-gain tasks in the fixed-base simulator reduces the realism and effectiveness of the training.

Given the general aircrew acceptance of fixed-base simulators that do not generate force and motion cueing, an important consideration in determining the suitability of a centrifuge-based flight simulator is whether aircrew will have higher levels of acceptance in the realism and effectiveness of the force and motion cues generated by the centrifuge. Particular emphasis should be given to determining the effectiveness of force and motion cues during high-gain mission tasks like formation flight and in-flight refueling that rely upon precise cueing of G_z variations/perturbations.

Head Movement is Extremely Common During Strike Fighter Mission Tasks

As summarized in Figure B-2 and Table B-4, survey data indicates aircrew head movements away from the central axis of the aircraft (the center of the HUD) are extremely common during nearly all mission tasks, particularly during A/A and A/G missions. The survey did not quantify the magnitude, rate of movement, or duration of head movement, only that head movement away from the HUD display occurred while the pilots performed mission tasks. Two important considerations for head movement issues affecting the suitability of centrifuge-based flight simulators are:

1. Whether or not pilots experience adverse sensory stimuli while making mission- or task-specific head movements under centrifugation; and,
2. If head movements result in adverse sensory stimuli, what is the impact on the overall training effectiveness of the centrifuge-based flight simulator.

Visual and Gravito-Inertial Cues Are Valued Most by Aircrew for the Majority of Mission Tasks

In general, survey data indicates visual and gravito-inertial based cues are the most valued sources of sensory stimuli and feedback by pilots in the management and completion of mission tasks across the spectrum of strike fighter mission profiles flown in the actual aircraft. Consistent with results from other survey questions, aircrew responses indicated a strong task

dependency among the different types of sensory cues. In other words, aircrew indicated they value different types of sensory stimuli and feedback depending upon what specific mission task or mission phase is in progress. Since the purpose of this study is to determine the suitability of a centrifuge as a dynamic flight simulator for F/A-18 mission training, the aircrew-rated importance of gravito-inertial cues in the aircraft are particularly pertinent and are specifically broken out in Figure B-3. Survey data indicates, not surprisingly, that the more dynamic the maneuvering phase, the more important aircrew considered gravito-inertial cues. Two important considerations related to dependency on visual and gravito-inertial cues which affect the suitability of centrifuge-based flight simulators are:

1. How well the centrifuge-based simulator provides a proper combination of accurate, timely, and effective visual and gravito-inertial sensory cues to cover the broad range of accelerations experienced while flying the missions; and,
2. Whether or not the centrifuge-based flight simulator is capable of generating all of the gravito-inertial cues experienced during those missions.

3. ANALYSIS AND DISCUSSION OF AN EXISTING CENTRIFUGE-BASED FLIGHT SIMULATOR

For many years, centrifuges have been used successfully to generate large magnitude linear acceleration vectors for aerospace research and physiological training scenarios.^{34,35,36,37} Long known as a relatively safe and reliable method for generating both high G onset rates and high levels of sustained G, centrifuges nonetheless are limited in their ability to provide the same displacement and motion cues experienced at the pilot-seat of a highly maneuverable tactical aircraft.^{34,35,38} The mechanics of circular motion impose considerable limitations on what a centrifuge-based simulator can attain when compared to the highly agile, three dimensional flight path possibilities of an actual aircraft in maneuvering flight. As stated by Crosbie and Kiefer, existing centrifuges “are confined to move in a horizontal plane about a fixed radius circle. This confinement dictates the physical impossibility for [the centrifuge] to match both the linear and angular accelerations of an aircraft which flies in an unlimited six DOF flight regime.”³⁴

With this in mind, this section will review the performance capabilities of an existing 25-ft moment arm centrifuge-based flight simulator, review the results from two qualitative evaluations of the centrifuge-based flight simulator during mission-representative scenarios, and identify the differences between the mechanics of aircraft flight and centrifuge motion.

CENTRIFUGE-BASED FLIGHT SIMULATOR PERFORMANCE CAPABILITIES

The following section will briefly describe the design characteristics and performance capabilities of an existing 25-foot planetary arm centrifuge modified to function as a flight simulator. The centrifuge-based flight simulator considered and reviewed for this study was the Authentic Tactical Fighting System (ATFS) 400, built and operated by the Environmental Technologies Corporation (ETC) located in Southampton, PA. Figure 3 below is a photograph of the ATFS 400 centrifuge.

ATFS 400 Description and Performance Capabilities

The ATFS 400 centrifuge has a 25-ft planetary arm with an advertised 15 g/sec acceleration onset rate with a maximum capability of 25 g. At the end of the planetary arm, the

ATFS 400 uses gimbals that allow the gondola/cockpit section to be articulated 360° in pitch and roll. The ATFS 400 has an advertised capability to provide rapid onset roll and pitch rates as listed in Table 3.^{39,40}



Figure 3. Photograph of ATFS 400 Centrifuge Manufactured by ETC

The gondola/cockpit section contains a realistic replica of a single seat cockpit that can be reconfigured to match different tactical fighter aircraft, and was modified with an F/A-18C cockpit (with production hardware control stick, rudder pedals, and throttles) during the two evaluations considered in this study. A 120° by 70° partial dome color visual system projects external scenery in the pilot's forward field-of-view (FOV). The HUD is projected onto the visual display and currently there is no JHMCS capability.^{41,42}

During a simulation profile, the ATFS 400's planetary arm (with attached gondola/cockpit) is always in motion, resulting in the minimum resultant cockpit G_z of +1.4 g's (the "G Floor" equivalent to "one g" straight and level conditions). The simulation utilizes a "g-mapping" algorithm that is designed to translate aerodynamic model G , which is based upon level flight at 1g to the centrifuge characteristic of 1.4 g's or greater. The pilot-commanded and simulation normal acceleration are blended to equal the "real-world" resultant gondola acceleration at approximately 3 g's. The ATFS 400 centrifuge is designed to incorporate both a roll acceleration/sideforce cueing feature and an "anti-tumble" feature.^{41,42}

The ATFS 400 is limited to 3-DOF motion. Referenced to the gondola/cockpit body frame of reference, the three degrees of freedom available are:

1. Linear translation (along the centrifugal circumference in the form of tangential velocity and acceleration caused by centrifuge angular velocity and acceleration),
2. Angular rotation about the lateral (y_{BODY}) axis (body roll rate – p), and
3. Angular rotation about the longitudinal (x_{BODY}) axis (body pitch rate – q).

Of particular note, the ATFS 400 centrifuge does not incorporate gimbals to control gondola/cockpit yaw angle and was unable to provide angular rotation about the vertical (z_{BODY}) axis (body yaw rate – r).

Table 3 below summarizes the performance capabilities of the ATFS 400.

Table 3: ATFS 400 Parameters and Performance Characteristics⁴¹

Parameters	Characteristics
Centrifugal Arm Length	25 ft
Main Drive Motor	High torque, 1250 HP DC Motor
Gondola Positioning System	Dual, synchronized electric motor gearboxes for pitch and roll
Gondola Pitch Control Limits	+180° to -180°
Gondola Roll Control Limits	+180° to -180°
Maximum Gondola Pitch Axis Angular Speed and Acceleration	100°/sec and 250°/sec ²
Maximum Gondola Roll Axis Angular Speed and Acceleration	100°/sec and 200°/sec ²
Maximum G_z Level ¹	25 g
Maximum G_z Onset Rate	15 g/sec from “G-floor” of +1.4 g
Maximum G_x Level	- 10 to +10 g
Maximum Absolute G_y Level	0 to 8 g

Note 1: Maximum G_z limits are limited by software-based controllers to match aircraft-representative G_z levels.

Of note, the U.S. Navy operates a similar 25-ft moment arm device called the Centrifuge-based Flight Environment Trainer (C-FET) device also manufactured by ETC. Although not designed specifically as an F/A-18 tactical flight simulator, the C-FET device nonetheless mimics the basic cockpit layout and seat geometry of a tactical high performance aircraft so the acceleration forces are anthropometrically distributed in the same manner as those experienced

during high G flight. In this role, the C-FET device operated by the U.S. Navy physiologically trains tactical aircrew in improving their flight performance by enhancing their tolerance to positive normal accelerations (G_z) and the resultant forces associated with high performance flight. The Navy's C-FET device has an advertised G_z onset rate of 6.0 g per second with a range from +1.4 to +15.0 g.³⁷ The C-FET gondola contains a simplified cockpit station with inert, adjustable ejection seat, simulated flight controls and throttles, and a forward-quarter visual display system. The C-FET is designed to allow the occupant to control G_z acceleration levels via the center or side stick controllers during single axis (pitch) closed loop target tracking tasks against a computer-generated target projected on the visual display.³⁷

Comparison of Centrifuge Performance to Aircraft Capabilities

By comparing the advertised performance capabilities to the G_z limits and P_s characteristics of the F/A-18 Hornet and Super Hornet presented in Section 2, the following conclusions can be drawn about the capabilities of the ATFS 400 centrifuge:

1. The ATFS 400 has the capability to provide large magnitude G_z and G_x sustained linear accelerations and high onset/offload rates that meet (in fact exceed) the maximum G_z limits of the Hornet and Super Hornet, but is designed with constraints that match aircraft capabilities by a simulation model based upon F/A-18C aerodynamic and performance data.
2. The ATFS 400 does not have the excess power (P_s) limitations of the Hornet and Super Hornet, allowing it to sustain high magnitude G_z accelerations nearly indefinitely. In operation, it is designed to match aircraft capabilities of the F/A 18C simulation model.
3. The ATFS 400 has the capability to roll and pitch the gondola/cockpit at angular rates comparable to those experienced in the Hornet and Super Hornet.
4. The ATFS 400 has the capability to roll and pitch the gondola/cockpit to distribute the resultant acceleration vector along the three gondola/cockpit body axes, suggesting that it should be able to generate sustained G_y (sideforce) accelerations such as those experienced during departure from controlled flight in the Hornet and Super Hornet.
5. The ATFS 400 rotates in only one direction (clockwise looking down along the rotational axis) and cannot reverse it's direction of turn. Accordingly, the centrifuge control system must provide well-tuned manipulation of gondola/cockpit pitch and roll angles in order to provide pilot-perceived differentiation between left and right turns.

With these performance capabilities and limitations in mind, there are notable differences between the accelerations generated in the aircraft and those replicated with a centrifuge-based simulator. These differences significantly impact the accuracy, timeliness, and effectiveness of sensory cues and provide the foundation for understanding the challenges of using a centrifuge-based simulator to mimic an in-flight environment.

The following paragraphs review the results of two previous evaluations of the ATFS 400 during mission-representative scenarios and identify a number of vestibular artifacts that highlight these differences. From these results, it seems that a centrifuge-based flight simulator has limited potential to generate accurate, timely, and effective sensory cues for “full mission” F/A-18 training scenarios. Appendix C summarizes the basic components and mechanisms involved in maintaining spatial orientation (SO) in-flight and the limitations of the vestibular system.

PILOT QUALITATIVE EVALUATIONS OF THE ATFS 400

2004 Evaluation of the ATFS 400

Evaluation Background and Methods

An evaluation of the ATFS 400 was conducted in 2004 and is detailed in reference 42. Participants represented military and aeronautical organizations from several different countries and included experienced fighter pilots from the United States Air Force, United States Navy, and NASA. The 2004 ATFS 400 evaluation consisted of a series of one-on-one A/A WVR engagements, with one pilot flying inside the centrifuge and the other flying in a non-motion simulator.

Evaluation Results

The evaluation identified a variety of centrifuge characteristics that highlight the challenges associated with using a centrifuge-based flight simulator to provide the sensory cues characteristic of high-G, high-performance flight. From the results of this study, the author concluded the following:

- The physics of the centrifuge motion introduced error between the forces the pilot felt in the centrifuge simulator as compared to what he/she would feel in the actual aircraft due to vestibular artifacts.
- There were complaints of an overwhelming tumbling sensation while under motion cueing as a result of head movement. Also, some participants complained of the same sensation during G_z offset.
- Vestibular artifacts could be distracting to the pilot and may hinder his/her ability to perform the tasks required of them in the simulator, and thus may interfere with progress in training.
- Vestibular artifacts were causes for such phenomena as spatial disorientation and motion sickness.
- When a pilot moved his/her head in order to maintain visual contact with the enemy aircraft while in motion in the centrifuge, he/she experienced an overwhelming tumbling sensation that is disruptive to flight and therefore decreased the effectiveness of the training.

Author Assessment of 2004 ATFS Centrifuge Testing:

- The centrifuge cannot be effective for tactical flight training such as close in air-to-air engagements.
- The concept of centrifuge-based full motion flight simulation should continue to be developed. Provided that a high level of fidelity can be reached with high-G motion based flight simulation, significant value can be seen in training pilots in the operation of aircraft systems in a tactical aircraft while under high G.⁴²

2008 U.S. Navy Evaluation of the ATFS 400

Evaluation Background and Methods

The purpose of the U.S. Navy's 2008 evaluation of the ATFS 400 was to assess the potential of using a man-rated centrifuge as a force and motion base to generate flight representative instantaneous and sustained g-forces for a tactical aircraft training device to meet fleet proficiency and tactical training requirements.

The test profiles completed in September 2008 included maneuvers to gather both qualitative and quantitative data to evaluate simulation fidelity within the F/A-18C flight envelope. Two F/A-18 test pilots, two F/A-18 fleet replacement squadron (FRS) instructor pilots, and one F/A-18 FRS student pilot participated in this evaluation with F/A-18 experience levels ranging

from greater than 1,800 flight hours to less than 50 flight hours. Time in the centrifuge for each pilot ranged from 13 minutes to 67 minutes and totaled 2.5 hours for the complete evaluation.

Testing consisted of open- and closed-loop maneuvers to provide both qualitative pilot comments as well as quantitative data to compare against existing F/A-18 data. The maneuvers included level accelerations and decelerations, basic aerobatics, close formation flight, A/G attack profiles, high angle of attack (AOA) flying qualities, and A/A mission tasks.

Evaluation Results

All five pilots who participated in the 2008 evaluation experienced spatial disorientation while attempting to perform mission tasks under centrifugal motion and agreed that vestibular artifacts were very pronounced, disorienting, and at times overwhelming during pilot closed-loop mission tasks. Specific observations included:

- Pilots experienced uncommanded rolling sensations when making out-of-plane head movements.
- Pilots experienced a debilitating tumble sensation during G_z offload or planetary arm angular deceleration. The effect of these simulator characteristics was observed in the pilots' head nodding and eye motion (i.e. rapid blinking) in an attempt to compensate for the tumble perception. Following a rapid G_z unload to idle conditions (+1.4 g) during mission tasks, pilots stated their concentration was limited to one cockpit task for up to 15 seconds due to the disorientation caused by the tumbling sensation associated with G_z unload.
- Pilots noted some disorientation caused from the subtle mismatch between cockpit instruments (HUD), visual scene, and centrifuge-based motion cueing.
- When asked to compare the centrifuge motions to the actual airplane, all of the pilots stated they were unable to adapt or otherwise compensate to a level consistent with their "nominal" performance within the allotted evaluation time and the disorientation contributed to pilot fatigue much more rapidly than in an aircraft.⁴¹

Based upon these pilot observations, the U.S. Navy evaluation concluded the following:

1. Due to the prolonged presence of vestibular artifacts while performing mission-representative tasks (like frequent head movement), there was a potential for pilots to accept spatial disorientation vice recognize and initiate corrective action of it.
2. Centrifugal acceleration creates vestibular artifacts that significantly degrade pilot effectiveness and result in negative transfer of training.

3. Navy researchers recommended no further Navy testing of full spectrum tactical aircraft training systems using a man-rated centrifuge to generate cockpit acceleration cueing until sufficient research and progress has been made to mitigate vestibular artifacts and a positive transfer of required skills has been demonstrated.⁴¹

COMPARING THE MECHANICS OF AIRCRAFT FLIGHT AND CENTRIFUGAL MOTION

The pronounced and disorienting vestibular artifacts experienced by pilots within the centrifuge-based flight simulator environment of the ATFS 400 are due to fundamental differences between the mechanics of aircraft flight and centrifugal motion. The following paragraphs review these differences and identify the significant challenges of using a centrifuge-based flight simulator to generate accurate, timely, and effective sensory cues for mission training.

Mathematical Comparison of the Mechanics of Aircraft Flight and Centrifuge Motion

While a detailed analysis of the aircraft mechanics, performance variables, and stability and control derivatives that govern an aircraft's flight path are beyond the scope of this study, it is important to understand the fundamental role the pilot-perceived linear and angular acceleration and velocity cues play in maintaining spatial orientation, monitoring aircraft state, and generating properly timed and sized control inputs in order to maintain precise aircraft control. Steady-state and maneuvering flight are characterized by a complex interplay of both gravitational and inertial forces acting upon the aircraft. What matter most to the pilot as he/she performs mission tasks, however, are the resultant linear and angular accelerations experienced at the pilot seat, whether due to gravitational or inertial effects. Appendix D briefly reviews the physical principles and mathematical formulas that comprise the resultant linear accelerations experienced during both steady state and circular motion within a centrifuge.

From the equations D-1 thru D-4, it is clear that aircraft turn radius and turn rate vary as a function of the airspeed and load factor capability of the aircraft. In other words, the resultant aircraft flight path and turn radius during maneuvering flight are functions of the airspeed and pilot-commanded G_z .

In contrast, centrifugal motion, while governed by the same basic principles, nonetheless is constrained to maintain a fixed, 25-ft radius circle. Reviewing equations D-5 through D-9, it is clear that the centrifuge uses fundamentally different mechanisms than the aircraft to generate G_z accelerations in response to pilot commands.

To exemplify the differences between the mechanics of aircraft flight and centrifuge motion, consider the following: an F/A-18E aircraft at 420 knots at 15,000 ft MSL has sufficient P_s to rapidly transition within 1 second from non-maneuvering flight at one g to maneuvering flight at +5 g while maintaining constant airspeed, generating a resultant turn radius of approximately 3,300 ft.³⁰ The centrifuge, constrained to a 25-ft turn radius, must, within the same 1 second, nearly double the centrifuge's tangential speed from approximately 34 ft/sec (it's "G-Floor" speed) to 64 ft/sec while also coordinating a bank angle change of approximately 34° in order to properly resolve the resultant acceleration along the new G_z axis.

The following paragraphs identify some of the specific, significant challenges that limit a centrifuge-based flight simulator's ability to generate accurate, timely, and effective sensory cues for F/A-18 mission training.

The Challenge of Translating 6-DOF Aircraft Motion to a 3-DOF Centrifuge

Existing centrifuges like the ATFS 400 have only 3-DOF available but must somehow attempt to provide linear and angular acceleration cues of a 6-DOF aircraft. Since this is physically impossible,³⁴ existing centrifuges employ a "G-pointing" control strategy that attempts to match aircraft rectilinear accelerations as close as possible, trading off angular acceleration fidelity as required.³⁶ The ATFS 400 uses a "G-pointing" method to continuously and actively point the gondola/cockpit relative to the instantaneous acceleration vector of the centrifuge so that the three components of desired linear acceleration in the "aircraft representative" coordinate frame are obtained (usually as a single G_z acceleration along the gondola "lift vector").³⁶ This resultant acceleration vector, a combination of normal and tangential accelerations of the planetary arm and gravity that vary with time, is distributed along the three components of the "aircraft-representative" frame of reference by proper selection of gondola/cockpit pitch and roll angles. High G_z onset and offload rates generate rapid increases in tangential velocity combined with simultaneously reorienting of gondola pitch and roll angles. Unfortunately, there are Coriolis cross-coupled (CCC) effects generated by this complicated combination of centrifuge motion.³⁶

Experimental data indicates the threshold of perception of rotation about X and Z axes were $0.41^\circ/\text{sec}^2$ and about Y axis was $0.67^\circ/\text{sec}$, suggesting that humans are extremely sensitive to angular acceleration in all three axes.^{41,42} With this in mind, changes in centrifuge tangential speed and pitch/roll rotations that must be imparted to the gondola to generate resultant linear accelerations along “aircraft-representative” axes as precisely as possible actually produce CCC effects that degrade angular acceleration fidelity.³⁶ Without some means of filtering these CCC effects, a centrifuge is severely limited for use as a flight simulator.³⁴

In an effort to minimize CCC effects, the “G-Pointing” control strategy incorporates washout algorithms in order to coordinate the complex combination of centrifugal and gondola pitch/roll angular accelerations (necessary to provide resultant G_z accelerations) at levels below what the pilot can detect.^{43,44} These washout algorithms, in order to reduce CCC effects while still providing correct force and motion cues, tradeoff objective fidelity (where the simulator is exactly matching the linear and angular acceleration and motion cues experienced in the aircraft) for perceptual fidelity (where the pilot experiences timely sensory feedback that may not exactly match exact magnitude or duration experienced in the aircraft).

Unfortunately, washout algorithms utilized by the “G-Pointing” control strategy cannot completely eliminate these CCC effects. The effectiveness of these washout algorithms is significantly reduced during rapid changes in commanded G_z (such as during rapid G_z offload). As Crosbie and Eyth explain, unrealistic angular motions are most pronounced “particularly during transient G periods which could severely interfere with the pilot’s ability to fly the simulator.”³⁸ The Navy’s C-FET program specifically limits the rate of G_z offload in order to reduce the negative impact of Coriolis tumbling on the quality of training as follows: “Because a slower deceleration rate is more tolerable to the occupant, the Emergency Stop ($-2.0 \text{ g}_z/\text{sec}$) is preferred over the Medical Stop ($-3.0 \text{ g}_z/\text{sec}$) as the stopping modality for most situations dictating immediate cessation of manned dynamic operations.”³⁷ Both the 2004 and 2008 evaluations of the ATFS 400 correlate the known negative effects of rapid G_z offload in a centrifuge as indicated by the debilitating tumbling sensations experienced by pilots during rapid G_z offload.

As indicated by the acceleration spectrum from actual F/A-18 missions in Appendix A, dynamic missions like SACT and ACM are characterized by long durations spent near one g with frequent, short duration excursions to higher G_z levels. This highly dynamic profile consisting of hundreds of cycles of G_z onload and offload supports the notion that pilots fly the aircraft with an “Assess – Maneuver – Assess” mindset when performing mission tasks where they assess what they need to go/where they need to displace the aircraft, maneuver via high onset rate G_z inputs

to position the aircraft, and then ease off to a lower G_z near +1.0 g to assess the effectiveness of the maneuver in accomplishing the mission task. The debilitating tumbling sensation experienced during G_z offload in the centrifuge will likely disrupt this “Assess – Maneuver – Assess” mindset. The centrifuge-based flight simulator will therefore provide a sensory environment that is not consistent with what is experienced in the aircraft, suggesting that mission tasks will not be accomplished with the same perceptual cues in the centrifuge as they would be in the aircraft.

Similarly, the centrifuge, when generating the rapid onset G_x deceleration characteristic of arrested landing aboard an aircraft carrier, will likely introduce debilitating tumbling sensations that will significantly disorient the pilot and delay the completion of time-critical control inputs required during carrier landing tasks.

A 3-DOF centrifuge, in trying to provide accurate and timely rectilinear accelerations experienced in a 6-DOF aircraft, generates unwanted angular artifacts that are most noticeable during rapid changes in commanded G_z . As indicated by pilot qualitative evaluations, these disorienting angular artifacts are particularly debilitating during G_z offload. These disruptive vestibular artifacts are not representative of the aircraft environment and interfere with the “normal” pilot responses that would be used while conducting mission-representative tasks in the aircraft. This limitation indicates that a centrifuge-based flight simulator has limited potential for use in “full mission” F/A-18 training scenarios.

More research is needed to determine if there are alternative centrifuge designs that have more than 3-DOF available in order to reduce or eliminate unwanted angular artifacts. Specifically, more research is needed to determine the optimum “G-pointing” and washout algorithms that will reduce or eliminate the debilitating tumbling sensation associated with centrifugal deceleration.

The Challenge of One-g Flight in a Centrifuge

As indicated in Equations D-7a and 7b, the magnitude of resultant acceleration of a rotating centrifuge is always greater than one g. Thus the centrifuge can only provide sensations of true “one-g” flight when it is stopped (not rotating). As shown in Figure D-1, the gradients of required centrifuge speed and required gondola/cockpit bank angle per commanded G_z (assuming no resultant sideforces) from +1.0 to +7.5 g are non-linear and have the highest gradients near one g. The steeper gradients near one g indicate that CCC angular artifacts are

more pronounced when accelerating the centrifuge from a stopped condition (“true one g”) to resultant G_z levels just above one g.³⁴

As a tradeoff to minimize these CCC angular artifacts as the centrifuge rotation is stopped and started, the centrifuge maintains a minimum rotational speed that yields a resultant “G floor” or “G-bias”⁴⁵ greater than one g (this “G floor” or “G-bias” represents the centrifuge equivalent of straight and level flight in an aircraft and will be displayed as +1.0g in the cockpit display or HUD). The “G floor” of the ATFS 400 is +1.4 g (generated by an idle speed of approximately 10.8 rpm with a gondola/cockpit roll angle of approximately 45° referenced to earth’s vertical). Between +1.4 g (the “G-floor”) and approximately +3.0 g, there is not one-to-one correspondence between pilot-commanded G_z and gondola/cockpit resultant G_z . Above approximately +3.0 g, the slope of required bank angle and centrifuge speed per commanded G_z in Figure D-1 is essentially constant and there is one-to-one correspondence of pilot-commanded G_z to gondola/cockpit resultant G_z . This indicates that the centrifuge is optimized to operate at sustained G_z accelerations greater than +3.0 g where the “G-pointing” control strategy produces minimal CCC effects. Because most of the time spent in training missions is at acceleration levels below +3.0 g, the centrifuge is not optimized for most F/A-18 mission tasks.

As indicated by the aircrew survey data in Appendix B, aircrew value the presence of gravito-inertial acceleration cues when maneuvering, which suggests that these cues in conjunction with high-quality visual cues are relied upon to perform various mission tasks. Gravito-inertial cues are therefore useful for developing and refining basic airmanship and overall aviation sense skills.

While performing a “near one g” non-maneuvering flight task, pilots can sense small magnitude positive and negative G_z changes. These changes are caused by perturbations from aircraft response to control inputs, or disturbances such as turbulence. These small acceleration cues are beneficial to the pilot for sensing small changes in flight path. In particular, when precision is required to maintain level flight, flying in formation, or when executing an instrument approach and landing, a pilot uses these cues to form a control strategy for task performance.

Experimental data indicates the perception threshold for linear acceleration for X and Y axes is 0.005-0.01 g and for Z axis is 0.01-0.1 g, suggesting that humans have a very low threshold for detecting changes in G_z and would likely perceive small G_z perturbations.⁴⁶ In utilizing the “G floor” of +1.4 g, the centrifuge has no mechanism for generating small magnitude G_z perturbations at less than +1.4 g that are characteristic of mission-representative maneuvering

in the “near one g” environment. The cockpit visual display system and HUD will, however, indicate changes in G_z even though there is no physical change in resultant G_z , introducing a mismatch between visual and vestibular sensory information.

Existing 3-DOF centrifuges, in utilizing a “G-Floor” designed to control CCC effects, are unable to generate an accurate “near one g” acceleration environment that is experienced during the majority of F/A-18 mission time, including the small G_z perturbations resulting from control and disturbance cues during highly-precise mission tasks. This limitation indicates that a centrifuge-based flight simulator, specifically designed to provide sustained large magnitude G_z accelerations and optimized for use above +3.0 g, has limited potential for use in “full mission” F/A-18 training scenarios where the majority of time is spent operating in the near one g environment.

More research is needed to determine alternative methods for generating small magnitude G_z control and disturbance cues in a simulated flight environment. Additionally, a ToT experiment should be conducted to determine the effect these cues have on improving basic airmanship and overall aviation sense during F/A-18 mission training.

The Challenge of Unloaded and Ballistic Flight in a Centrifuge

As provided in Equations D-7a and 7b, Earth-fixed centrifuges cannot provide resultant acceleration less than the combination of centripetal, tangential, and Earth’s gravitational accelerations. Even when the centrifuge is not rotating (i.e. no centripetal or tangential accelerations), there is still a one g component due to Earth’s gravity that defines a minimum resultant acceleration of one g.³⁴ While the gondola/cockpit can rotate in both pitch and roll to distribute a resultant acceleration vector along the three body axes, it still cannot reduce its absolute magnitude to less than one g. By definition, centrifuges cannot experience resultant G accelerations between -1.0g and +1.0g that are characteristic of unloaded or ballistic flight. In reality, as described above, a centrifuge like the ATFS 400 does not generate G_z magnitudes less than the “G-Floor” of +1.4g.

The centrifuge is therefore not capable of providing normal acceleration cues between -1.0 g and +1.0 g which are beneficial to the pilot when performing non-maneuvering flight tasks (where he/she typically experiences small magnitude accelerations just less than one g) or highly dynamic unloaded flight tasks (where he/she typically experiences accelerations near zero g).

Head Movement: A Source of CCC Effects

The problem of head motion while under centrifugation is well known. As stated by Bischoff, et al, "certain tasks were not well-suited to centrifuge-based flight simulators; notably any task requiring the pilot to move his/her head around the cockpit."⁴⁵ When the pilot moves his/her head out of alignment of the gondola/cockpit axes, the resultant CCC angular acceleration cannot be corrected for by the centrifuge washout algorithms and will consequently introduce an angular sensation that is not representative of aircraft motion. Pilot-perceived roll, yaw, and pitch motion associated with head movement can lead to unpleasant and nauseogenic sensations culminating in motion sickness.^{9,47,48,47} These disorienting and unrealistic vestibular sensations are most noticeable at the "G-floor" near one g and tend to diminish at elevated G_z levels greater than +3 g.⁴⁷ The disorienting and unrepresentative sensation caused by head movement in the centrifuge is not normally experienced in an aircraft primarily due to the relatively large instantaneous turn radius.⁴⁷ The findings from the 2004 and 2008 evaluations of the ATFS 400 were consistent with previous observations and centrifuge research.

As indicated by the survey data in Figure B-2, pilots (very frequently, frequently, or sometimes) make head movements while performing mission tasks. These head movements are essential for scanning within and outside the cockpit for visual information, and is especially the case when a JHMCS is worn.

When head movement occurs while decelerating from a steady turn or under rapid G transition, spatial disorientation due to the cross-coupled effects are exacerbated and the disorientation becomes more intense.⁴⁸ These effects will significantly increase the likelihood of motion sickness, distract/disrupt the pilot's normal cockpit habit patterns, and decrease the effectiveness of the training. Head motion problems limit the use of centrifuge-based flight simulation for use in "full mission" training scenarios.

Mitigating the disorienting vestibular artifacts experienced when making head movements in the centrifuge may be possible if an optimum acceleration level or maneuvering profile in the centrifuge could be identified where pilots are able to adapt to the vestibular effects caused by mission-representative head movement. Research should determine if pilot adaptation to CCC effects caused by head motion in the centrifuge results in negative habit transfer to the actual aircraft. Specifically, this research should determine if adaptation to vestibular artifacts in the

centrifuge results in incorrect and potentially dangerous habit patterns that may result in human error in the actual aircraft.

CENTRIFUGE-BASED FLIGHT SIMULATORS AS PART-TASK TRAINERS

The centrifuge is currently used to train pilots for the highly accelerated flight conditions which the F/A 18 can achieve. This training plays an essential role in safety by allowing pilots to experience very rapid onset G_z rates and learn, practice, and perfect physiological defenses against G-LOC.⁴⁹ In this same sense, a centrifuge-based simulator may have further advantages as a part-task trainer by offering unique training capabilities that cannot be simulated in other ground-based trainers or are infeasible to train in an actual aircraft due to the hazards to crew and aircraft.⁵⁰ Specifically, previous research has identified that a centrifuge-based flight simulator can be effective in generating the dynamic and disorienting motions characteristic of departure from controlled flight, post-stall gyrations, spins, and recovery to controlled flight, allowing pilot to recognize the cues and provide correct control inputs to recover from OCF.⁵¹

4. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based upon a number of issues identified in this study, a centrifuge-based flight simulator shows limited potential for use in “full mission” F/A-18 training scenarios.

There is a fundamental mismatch between the mission-representative acceleration environment experienced in the aircraft and the acceleration environment the centrifuge is able to provide. The majority of mission time during F/A-18 missions is spent operating near one g with relatively limited durations spent above +3.0 g and between -1.0 and +1.0g. The centrifuge, designed to generate large magnitude sustained linear accelerations and high g onset rates and optimized to operate above +3.0 g, has significant limitations when operating near one g. It cannot generate accurate G_z perturbations below its “G-floor” of +1.4 g. In addition, the centrifuge is physically incapable of generating resultant accelerations between -1.0 and +1.0 g.

In addition, while the ATFS 400 has the capability to generate large magnitude G_z and G_x sustained linear accelerations and high onset/offload rates the centrifuge uses fundamentally different physical mechanics to generate these accelerations. Because it is limited to 3-DOF and constrained within a fixed, 25-ft radius circle, the centrifuge causes a variety of undesired, unrealistic, and debilitating vestibular artifacts that are not consistent with what a pilot experiences in the 6-DOF aircraft when performing the same mission task. These effects are particularly apparent during rapid changes in G_z where washout algorithms are less effective. Pilot survey comments indicated that these sensations interfered with “normal” pilot responses and degraded the effectiveness of training.

Frequent head movement, which is an essential pilot requirement in order to maintain situational awareness and manage mission tasks, provides another source of undesired, unrealistic, and debilitating vestibular artifacts in the centrifuge that are not consistent with what is experienced in the aircraft. Pilot comments indicate these sensations also interfere with “normal” pilot responses and degrade the effectiveness of the training.

RECOMMENDATIONS

Based upon its limited potential for use in “full mission” F/A-18 training scenarios, a centrifuge-based flight simulator is not considered a suitable alternative for F/A-18 strike fighter mission training. Given the high level of user acceptance of existing fixed-base simulators and generally negative opinion of centrifuge-unique vestibular artifacts and disorientation, this study recommends the continued use of fixed-base simulators for the bulk of “full mission” F/A-18 training scenarios, supplemented with part-task training in the centrifuge for physiological training and departure/spin training.

The problem of mismatch between gravito-inertial acceleration cues in the centrifuge-based flight simulator and those in the aircraft for the same maneuver may be addressed in a number of ways:

1. Investigate alternative centrifuge designs that have more than 3-DOF available in order to reduce or eliminate unwanted angular artifacts, with particular emphasis on optimum “G-pointing” and washout algorithms that will reduce or eliminate the debilitating tumbling sensation associated with centrifugal deceleration.
2. Investigate alternative methods for generating small magnitude G_z control and disturbance cues “near one g” such as g-seat technology in order to provide some proprioceptive/tactile cueing to G_z perturbations below the centrifuge “G-floor” of 1.4g.
3. Investigate alternative methods for providing proprioceptive/tactile cueing of unloaded, “near zero g” flight conditions. While it is not possible for a centrifuge-based flight simulator to generate accelerations that physically match unloaded, “near zero g” flight conditions, alternative methods such as g-seat technology may be able to generate proprioceptive/tactile cues that elicit the same responses as those expected in the aircraft during unloaded, “near zero g” flight conditions.

The vestibular artifacts caused by head motion in a centrifuge limit user acceptance and training effectiveness. Since these vestibular artifacts cannot be eliminated because of the physical constraints of the centrifuge, further research is needed to identify methods to mitigate this problem:

1. Determine if there is an optimum acceleration level or maneuvering profile in the centrifuge where pilots can adapt to vestibular effects caused by mission-representative head movement.

2. Determine if pilot adaptation to CCC effects caused by head motion in the centrifuge results in negative habit transfer to the actual aircraft. Specifically, determine if adaptation to vestibular artifacts in the centrifuge results in incorrect and potentially dangerous habit patterns that may result in human error in the actual aircraft.

While a centrifuge-based flight simulator has limited potential for “full mission” F/A-18 training scenarios, there are specific part-task training applications where a centrifuge-based flight simulator provides significant value and should continue to play an important part in the training continuum for F/A-18 pilots, most notably physiological training and departure/spin training. More research is needed in order to optimize the role and design of a centrifuge-based flight simulator as a part-task trainer for high-G physiological training and departure/spin training. Specifically:

1. Determine the optimum profile and frequency of exposure to high-onset rate, high G acceleration environments of the centrifuge that will improve the physiological protection and increase performance in the actual aircraft.
2. Quantify the force and motion cues experienced during departure, spin, and other OCF modes in the actual aircraft and determine if and how accurately the centrifuge can replicate these cues.
3. If the centrifuge is capable of accurately replicating OCF force and motion cues, determine the optimum profile for teaching OCF mode recognition and proper recovery controls in order to maximize transfer of training to the actual aircraft.

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APPENDICES

APPENDIX A: Analysis of F/A-18E Aircraft Flight Data

ACM Training Mission Acceleration Results

Pilot seat normal acceleration and aircraft altitude versus elapsed mission time are shown in Figure A-1. During ACM mission training, the average mission duration for the flight lead and wingman was approximately 59 minutes. As depicted in Table A-1, both the flight lead and wingman experienced maximum pilot-seat G_z accelerations of +6.60 g and +7.20 g and minimum G_z accelerations of +0.25 g and -0.05 g, respectively. The median G_z accelerations experienced throughout the entire mission were +1.31 g for the flight lead and +1.40 g for the wingman. As depicted in Figure A-2, throughout the 59 minutes of elapsed mission time, the G_z acceleration spectrum indicated the following:

- Less than 1% was spent between -0.5 g and +0.5 g for both members of the flight (12 seconds for the flight lead and 29 seconds for the wingman)
- 87.1% (flight lead) and 83.8% (wingman) were spent between +0.5 g and +2.0 g
- 6.6% (235 seconds) for the flight lead and 7.8% (277 seconds) for the wingman were spent between +2.0 g and +3.0 g
- 3.9% (140 seconds for the flight lead and 138 seconds for the wingman) was spent between +3.0 g and +4.0 g
- 1.1% (39 seconds) for the flight lead and 1.7% (59 seconds) for wingman were spent between +4.0 g and +5.0 g
- 0.6% (23 seconds) for the flight lead and 1.3% (46 seconds) for wingman were spent between +5.0 g and +6.0 g
- Less than 0.5% was spent at G_z accelerations greater than +6.0g for both members of the flight (4 seconds for the flight lead and 18 seconds for the wingman).

Longitudinal (G_x) accelerations varied from a maximum of +1.26 g for the flight lead and +1.69 g for the wingman and minimum of -0.54 g for the flight lead and -0.63 g for the wingman. The median G_x accelerations experienced throughout the entire mission were +0.16 g for the flight lead and +0.18 g for the wingman.

Sideforce (G_y) accelerations varied from an absolute maximum of 0.42 g for the flight lead and 0.44 g for the wingman. The median absolute G_y accelerations experienced throughout the entire mission were 0.00 g for the flight lead and 0.01 g the wingman.

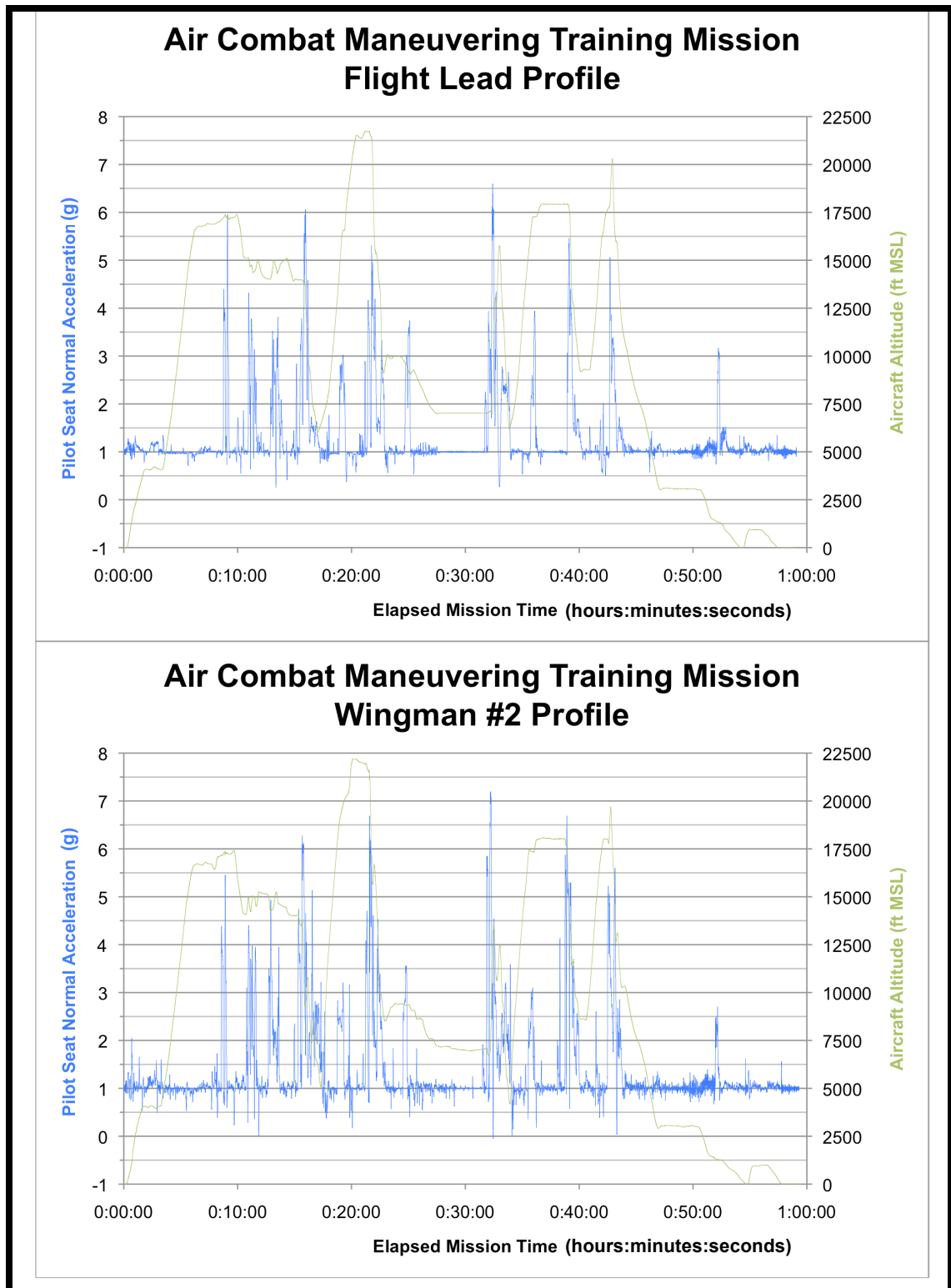


Figure A-1. Pilot Seat Normal Acceleration Expressed as g and Aircraft Altitude Versus Elapsed Mission Time for the Air Combat Maneuvering Training Mission

Table A-1: Air Combat Maneuvering Training Mission Acceleration Analysis

Air Combat Maneuvering Training Mission Acceleration Analysis						
	Flight Lead			Wingman #2		
	Acceleration Level	Elapsed Time	Percent of Total Time	Acceleration Level	Elapsed Time	Percent of Total Time
Vertical (Normal) Acceleration – G _z						
Mission Time		0:59:05			0:59:18	
Maximum G _z	+6.60			+7.20		
Minimum G _z	+0.25			-0.05		
Median G _z	+1.31			+1.40		
Spectrum	-0.5 to +0.5	0:00:12	0.3%	-0.5 to +0.5	0:00:29	0.8%
	+0.5 to +2.0	0:51:28	87.1%	+0.5 to +2.0	0:49:42	83.8%
	+2.0 to +3.0	0:03:55	6.6%	+2.0 to +3.0	0:04:37	7.8%
	+3.0 to +4.0	0:02:20	3.9%	+3.0 to +4.0	0:02:18	3.9%
	+4.0 to +5.0	0:00:39	1.1%	+4.0 to +5.0	0:00:59	1.7%
	+5.0 to +6.0	0:00:23	0.6%	+5.0 to +6.0	0:00:46	1.3%
	+6.0 to +8.0	0:00:04	0.1%	+6.0 to +8.0	0:00:18	0.5%
Longitudinal Acceleration – G _x						
Maximum G _x	+1.26			+1.69		
Minimum G _x	-0.54			-0.63		
Median G _x	+0.16			+0.18		
Lateral (Sideforce) Acceleration - G _y						
Max Abs G _y	0.42			0.44		
Median G _y	0.00			0.01		

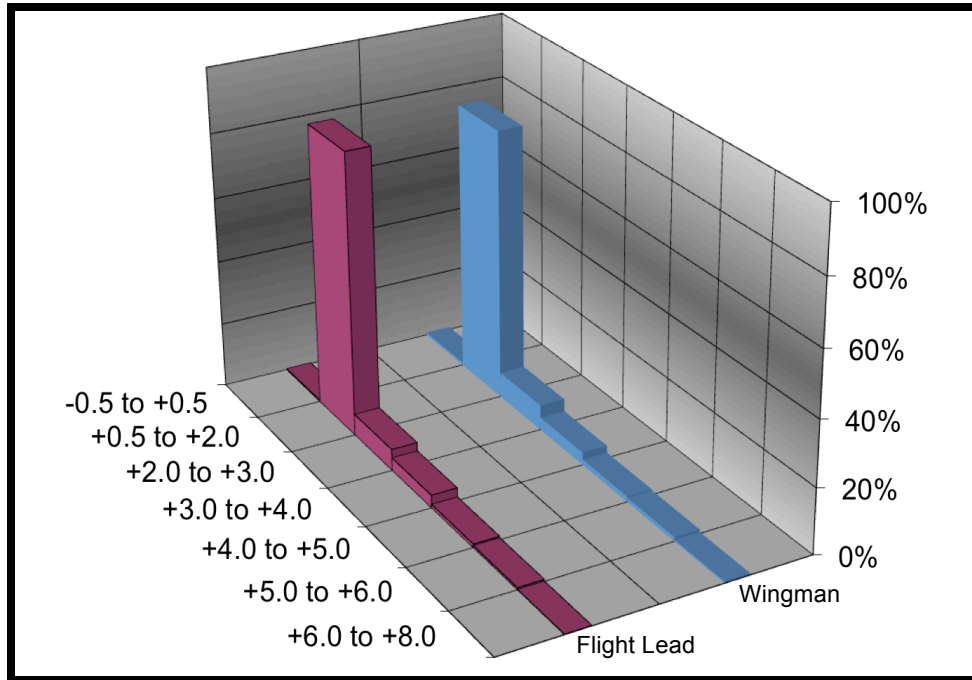


Figure A-2. Histograms of Pilot Seat Normal Acceleration (G_z) Spectrum for the Air Combat Maneuvering Training Mission

Air-to-Air Intercept Training Mission Acceleration Results

Pilot seat normal acceleration and aircraft altitude versus elapsed mission time are shown in Figure A-3(a) and Figure A-3(b). During Air-to-Air Intercept mission training, the average mission duration for the flight lead and 3 wingmen was approximately 62 minutes. As depicted in Table A-2 and Table A-3, the flight lead and wingman #2 through 4 experienced maximum pilot-seat G_z accelerations of +6.16 g, +4.69 g, +5.58 g, and + 5.48 g and minimum G_z accelerations of +0.54 g, +0.29 g, -0.28 g, and -0.04 g, respectively. The median G_z accelerations experienced throughout the entire mission were +1.15 g for the flight lead, +1.19 g for wingman #2, +1.20 g for wingman #3, and +1.24 g for wingman #4. As depicted in Figure A-4, throughout the 62 minutes of elapsed mission time, the G_z acceleration spectrum indicated the following:

- Less than 1% was spent between -0.5 g and +0.5 g for all members of the flight (0 seconds for the flight lead, 4 seconds for wingman #2, 16 seconds for wingman #3, and 33 seconds for wingman #4)
- Over 90% was spent between +0.5 g and +2.0 g for all flight members of the flight (95.2% for the flight lead, 93.0% for wingman #2, 92.5% for wingman #3, and 90.1% for wingman #4)

- 1.8% (66 seconds) for the flight lead, 4.1% (149 seconds) for wingman #2, 3.3% (124 seconds) for wingman #3, and 4.1% (156 seconds) for wingman #4 was spent between +2.0 g and +3.0 g
- 1.5% (54 seconds) for the flight lead, 2.2% (82 seconds) for wingman #2, 2.5% (96 seconds) for wingman #3, and 3.4% (130 seconds) for wingman #4 was spent between +3.0 g and +4.0 g
- Less than 1.5% was spent at G_z accelerations greater than +4.0g (52 seconds for the flight lead, 19 seconds for wingman #2, 45 seconds for wingman #3, and 54 seconds for wingman #4).

Maximum G_x accelerations were +1.15 g for the flight lead, +0.97 g for wingman #2, +0.99 g for wingman #3, and +1.02 g for wingman #4. Minimum G_x accelerations were -0.92 g for the flight lead, -1.15 g for wingman #2, -1.02 g for wingman #3, and -0.52 g for wingman #4. The median G_x accelerations experienced throughout the entire mission were +0.08 g for the flight lead, +0.08 g for wingman #2, +0.07 g for wingman #3, and +0.10 g for wingman #4.

Sideforce (G_y) accelerations varied from an absolute maximum of 0.23 g for the flight lead, 0.26 g for wingman #2, 0.54 g for wingman #3, and 0.28 g for wingman #4. The median absolute G_y acceleration experienced throughout the entire mission was 0.00 g for all members of the flight.

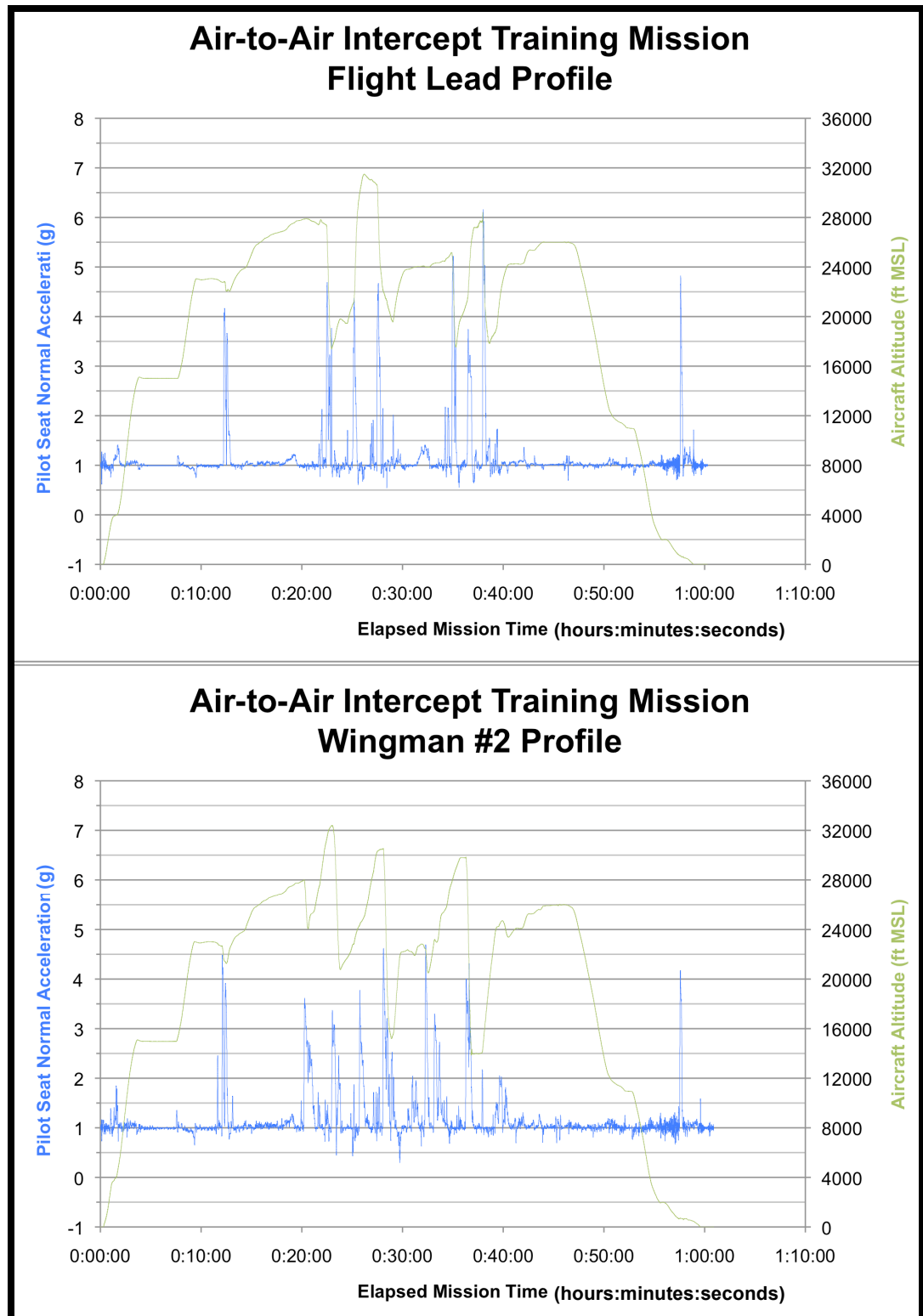


Figure A-3(a). Pilot Seat Normal Acceleration Expressed as g and Aircraft Altitude Versus Elapsed Mission Time for the Air-to-Air Intercept Training Mission

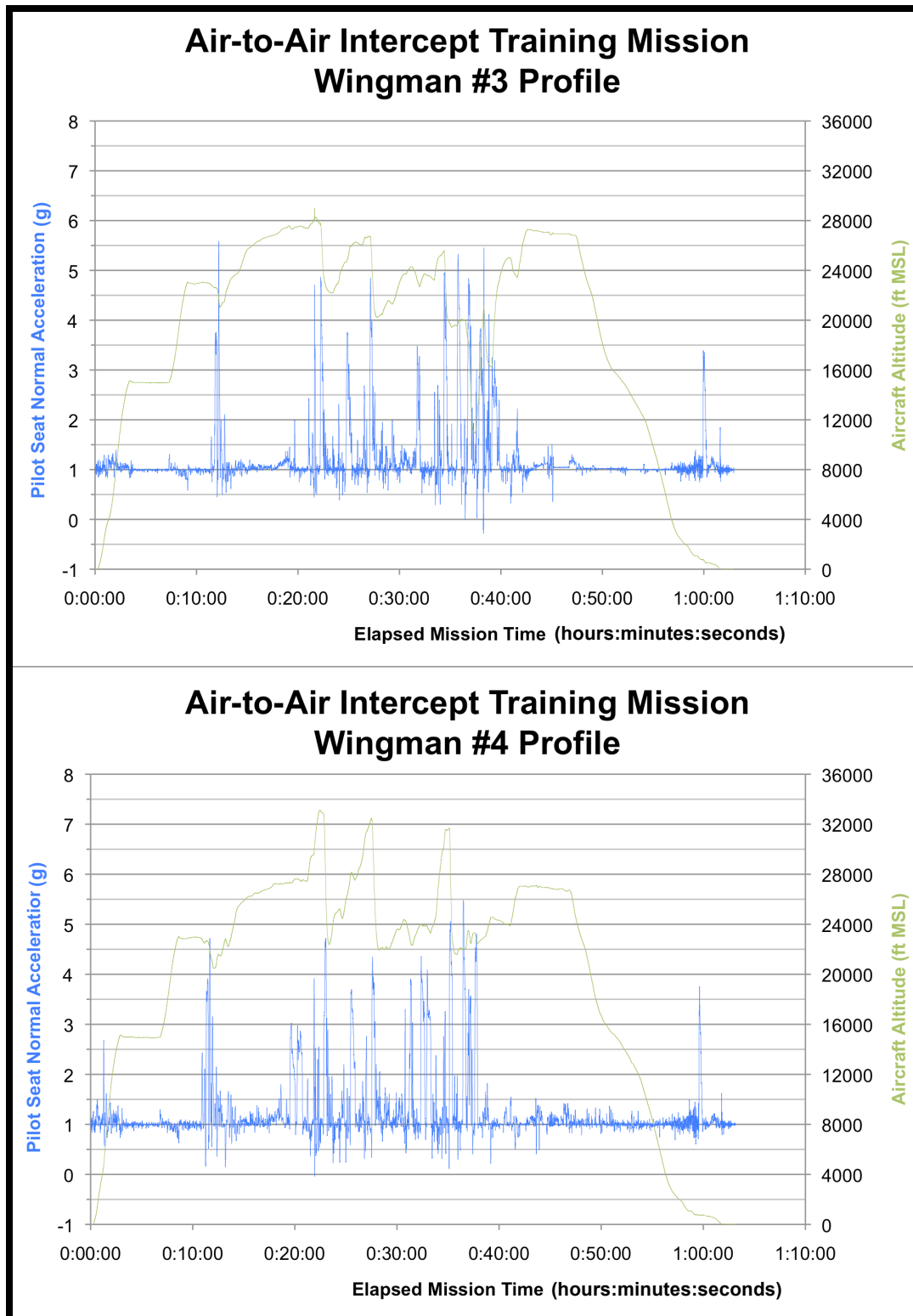


Figure A-3(b). Pilot Seat Normal Acceleration Expressed as g and Aircraft Altitude Versus Elapsed Mission Time for the Air-to-Air Intercept Training Mission

Table A-2: Air-to-Air Intercept Training Mission Acceleration Analysis

Air-to-Air Intercept Training Mission Acceleration Analysis						
	Flight Lead			Wingman #2		
	Acceleration Level	Elapsed Time	Percent of Total Time	Acceleration Level	Elapsed Time	Percent of Total Time
Vertical (Normal) Acceleration - G _z						
Mission Time		1:00:17			1:00:54	
Maximum G _z	+6.16			+4.69		
Minimum G _z	+0.54			+0.29		
Median G _z	+1.15			+1.19		
Spectrum	-0.5 to +0.5	0:00:00	0.0%	-0.5 to +0.5	0:00:04	0.1%
	+0.5 to +2.0	0:57:23	95.2%	+0.5 to +2.0	0:56:37	93.0%
	+2.0 to +3.0	0:01:06	1.8%	+2.0 to +3.0	0:02:29	4.1%
	+3.0 to +4.0	0:00:54	1.5%	+3.0 to +4.0	0:01:22	2.2%
	+4.0 to +5.0	0:00:39	1.1%	+4.0 to +5.0	0:00:19	0.5%
	+5.0 to +6.0	0:00:12	0.3%	+5.0 to +6.0	0:00:00	0.0%
	+6.0 to +8.0	0:00:00	0.0%	+6.0 to +8.0	0:00:00	0.0%
Longitudinal Acceleration - G _x						
Maximum G _x	+1.15			+0.97		
Minimum G _x	-0.92			-1.15		
Median G _x	+0.08			+0.08		
Lateral (Sideforce) Acceleration - G _y						
Max Abs G _y	0.23			0.26		
Median G _y	0.00			0.00		

Table A-3: Air-to-Air Intercept Training Mission Acceleration Analysis

Air-to-Air Intercept Training Mission Acceleration Analysis						
	Wingman #3			Wingman #4		
	Acceleration Level	Elapsed Time	Percent of Total Time	Acceleration Level	Elapsed Time	Percent of Total Time
Mission Time		1:02:57			1:03:08	
Vertical (Normal) Acceleration - G _Z						
Maximum G _Z	+5.58			+5.48		
Minimum G _Z	-0.28			-0.04		
Median G _Z	+1.20			+1.24		
Spectrum	-0.5 to +0.5	0:00:16	0.4%	-0.5 to +0.5	0:00:33	0.9%
	+0.5 to +2.0	0:58:14	92.5%	+0.5 to +2.0	0:56:53	90.1%
	+2.0 to +3.0	0:02:04	3.3%	+2.0 to +3.0	0:02:36	4.1%
	+3.0 to +4.0	0:01:36	2.5%	+3.0 to +4.0	0:02:10	3.4%
	+4.0 to +5.0	0:00:39	1.0%	+4.0 to +5.0	0:00:50	1.3%
	+5.0 to +6.0	0:00:06	0.2%	+5.0 to +6.0	0:00:04	0.1%
	+6.0 to +8.0	0:00:00	0.0%	+6.0 to +8.0	0:00:00	0.0%
Longitudinal Acceleration - G _X						
Maximum G _X	+0.99			+1.02		
Minimum G _X	-1.02			-0.52		
Median G _X	+0.07			+0.10		
Lateral (Sideforce) Acceleration - G _Y						
Max Abs G _Y	0.54			0.28		
Median G _Y	0.00			0.00		

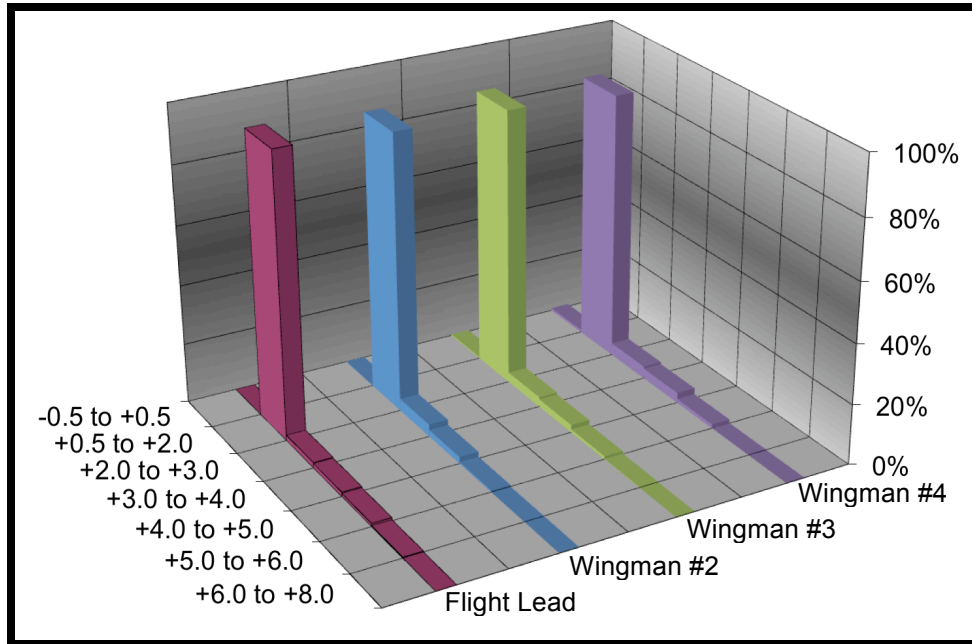


Figure A-4. Histograms of Pilot Seat Normal Acceleration (G_z) Spectrum for the Air-to-Air Intercept Training Mission

Close Air Support Training Mission Acceleration Results

Pilot seat normal acceleration and aircraft altitude versus elapsed mission time are shown in Figure A-5. During Close Air Support mission training, the average mission duration for the flight lead and wingman was approximately 92 minutes. As depicted in Table A-4, both the flight lead and wingman experienced maximum pilot-seat G_z accelerations of +7.13 g and +7.46 g and minimum G_z accelerations of +0.20 g and -0.18 g, respectively. The median G_z accelerations experienced throughout the entire mission were +1.24 g for the flight lead and +1.23 g for the wingman. As depicted in Figure A-6, throughout the 92 minutes of elapsed mission time, the G_z acceleration spectrum indicated the following:

- Less than 1% was spent between -0.5 g and +0.5 g for both members of the flight (3 seconds for the flight lead and 23 seconds for the wingman)
- 92.5% (flight lead) and 93.2% (wingman) were spent between +0.5 g and +2.0 g
- 5.3% (294 seconds) for the flight lead and 5.2% (287 seconds) for the wingman were spent between +2.0 g and +3.0 g
- 1.4% (77 seconds) for the flight lead and 1.1% (60 seconds) for the wingman were spent between +3.0 g and +4.0 g

- Less than 1% was spent at G_z accelerations greater than +4.0g (32 seconds for the flight lead and 43 seconds for the wingman).

Longitudinal (G_x) accelerations varied from a maximum of +0.98 g for the flight lead and +0.99 g for the wingman and minimum of -0.52 g for the flight lead and -0.59 g for the wingman. The median G_x accelerations experienced throughout the entire mission were +0.08 g for the flight lead and +0.07 g for the wingman.

Sideforce (G_y) accelerations varied from an absolute maximum of 0.51 g for the flight lead and 0.54 g for the wingman. The median absolute G_y accelerations experienced throughout the entire mission were 0.01 g for both the flight lead and the wingman.

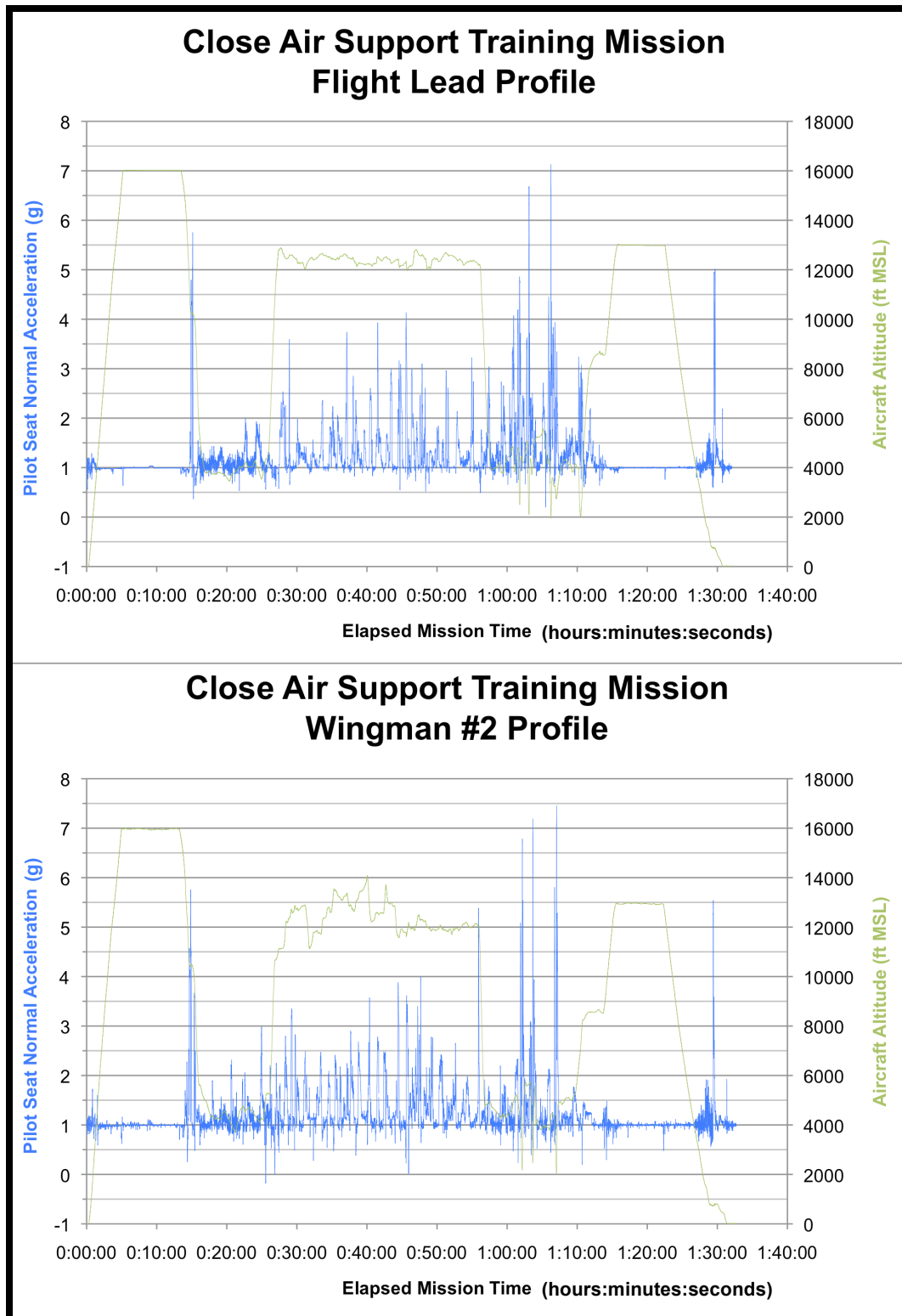


Figure A-5. Pilot Seat Normal Acceleration Expressed as g and Aircraft Altitude Versus Elapsed Mission Time for the Close Air Support Training Mission

Table A-4: Close Air Support Training Mission Acceleration Analysis

Close Air Support Training Mission Acceleration Analysis						
	Flight Lead			Wingman #2		
	Acceleration Level	Elapsed Time	Percent of Total Time	Acceleration Level	Elapsed Time	Percent of Total Time
Vertical (Normal) Acceleration – G _Z						
Mission Time		1:32:03			1:31:59	
Maximum G _Z	+7.13			+7.46		
Minimum G _Z	+0.20			-0.18		
Median G _Z	+1.24			+1.23		
Spectrum	-0.5 to +0.5	0:00:03	0.1%	-0.5 to +0.5	0:00:23	0.4%
	+0.5 to +2.0	1:25:07	92.5%	+0.5 to +2.0	1:25:41	93.2%
	+2.0 to +3.0	0:04:54	5.3%	+2.0 to +3.0	0:04:47	5.2%
	+3.0 to +4.0	0:01:17	1.4%	+3.0 to +4.0	0:01:00	1.1%
	+4.0 to +5.0	0:00:25	0.5%	+4.0 to +5.0	0:00:28	0.5%
	+5.0 to +6.0	0:00:04	0.1%	+5.0 to +6.0	0:00:10	0.2%
	+6.0 to +8.0	0:00:03	0.1%	+6.0 to +8.0	0:00:05	0.1%
Longitudinal Acceleration – G _X						
Maximum G _X	+0.98			+0.99		
Minimum G _X	-0.52			-0.59		
Median G _X	+0.08			+0.07		
Lateral (Sideforce) Acceleration – G _Y						
Abs Max G _Y	0.51			0.54		
Median G _Y	0.01			0.01		

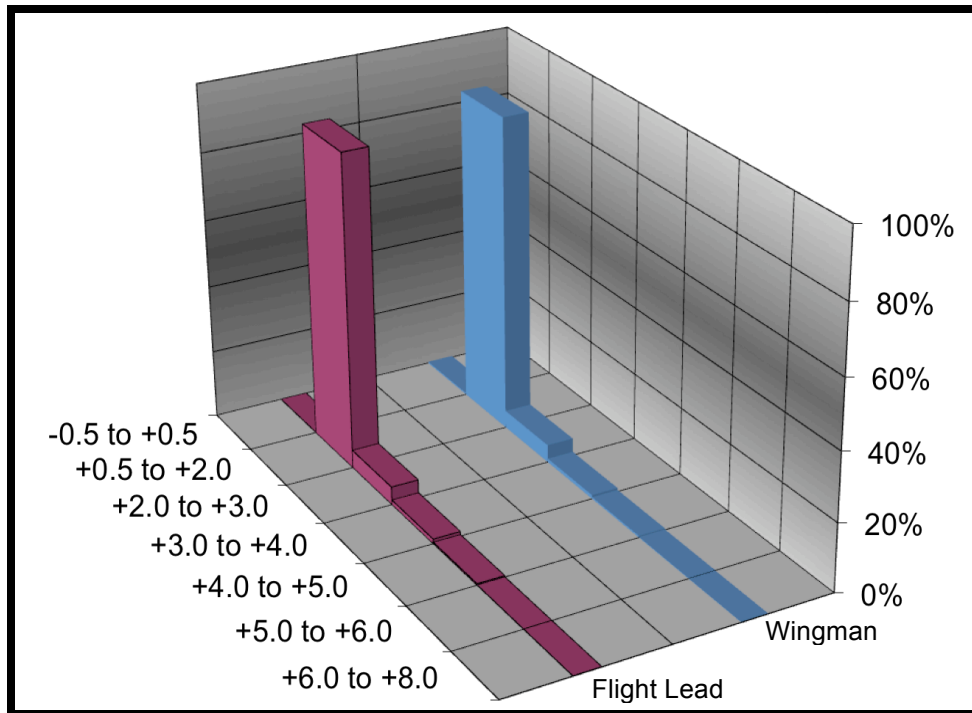


Figure A-6. Histograms of Pilot Seat Normal Acceleration (G_z) Spectrum for the Close Air Support Training Mission

SACT Training Mission Acceleration Results

Pilot seat normal acceleration and aircraft altitude versus elapsed mission time are shown in Figure A-7. During SACT mission training, the average mission duration for the flight lead and wingman was approximately 65 minutes. As depicted in Table A-5, both the flight lead and wingman experienced maximum pilot-seat G_z accelerations of +6.62 g and +7.06 g and minimum longitudinal accelerations of -0.16 g and -0.42 g, respectively. The median G_z accelerations experienced throughout the entire mission were +1.30 g for the flight lead and +1.37 g for the wingman. As depicted in Figure A-8, throughout the 65 minutes of elapsed mission time, the G_z acceleration spectrum indicated the following:

- Approximately 1% (flight lead) and 1.5% (wingman) was spent between -0.5 g and +0.5 g (32 seconds for the flight lead and 61 seconds for the wingman)
- 88.3% (flight lead) and 85.6% (wingman) were spent between +0.5 g and +2.0 g
- 4.6% (181 seconds) for the flight lead and 5.1% (202 seconds) for the wingman were spent between +2.0 g and +3.0 g
- 3.6% (143 seconds) for the flight lead and 3.8% (151 seconds) for the wingman were spent between +3.0 g and +4.0 g

- 1.6% (63 seconds) for the flight lead and 2.6% (104 seconds) for wingman were spent between +4.0 g and +5.0 g
- Approximately 1% was spent at G_z accelerations greater than +5.0g for both members of the flight (32 seconds for the flight lead and 44 seconds for the wingman).

Longitudinal (G_x) accelerations varied from a maximum of +1.14 g for the flight lead and +1.05 g for the wingman and minimum of -0.59 g for the flight lead and -0.61 g for the wingman. The median G_x accelerations experienced throughout the entire mission were +0.10 g for the flight lead and +0.11 g for the wingman.

Sideforce (G_y) accelerations varied from an absolute maximum of 0.53 g for the flight lead and 0.42 g for the wingman. The median absolute G_y accelerations experienced throughout the entire mission were 0.01 g for both the flight lead and the wingman.

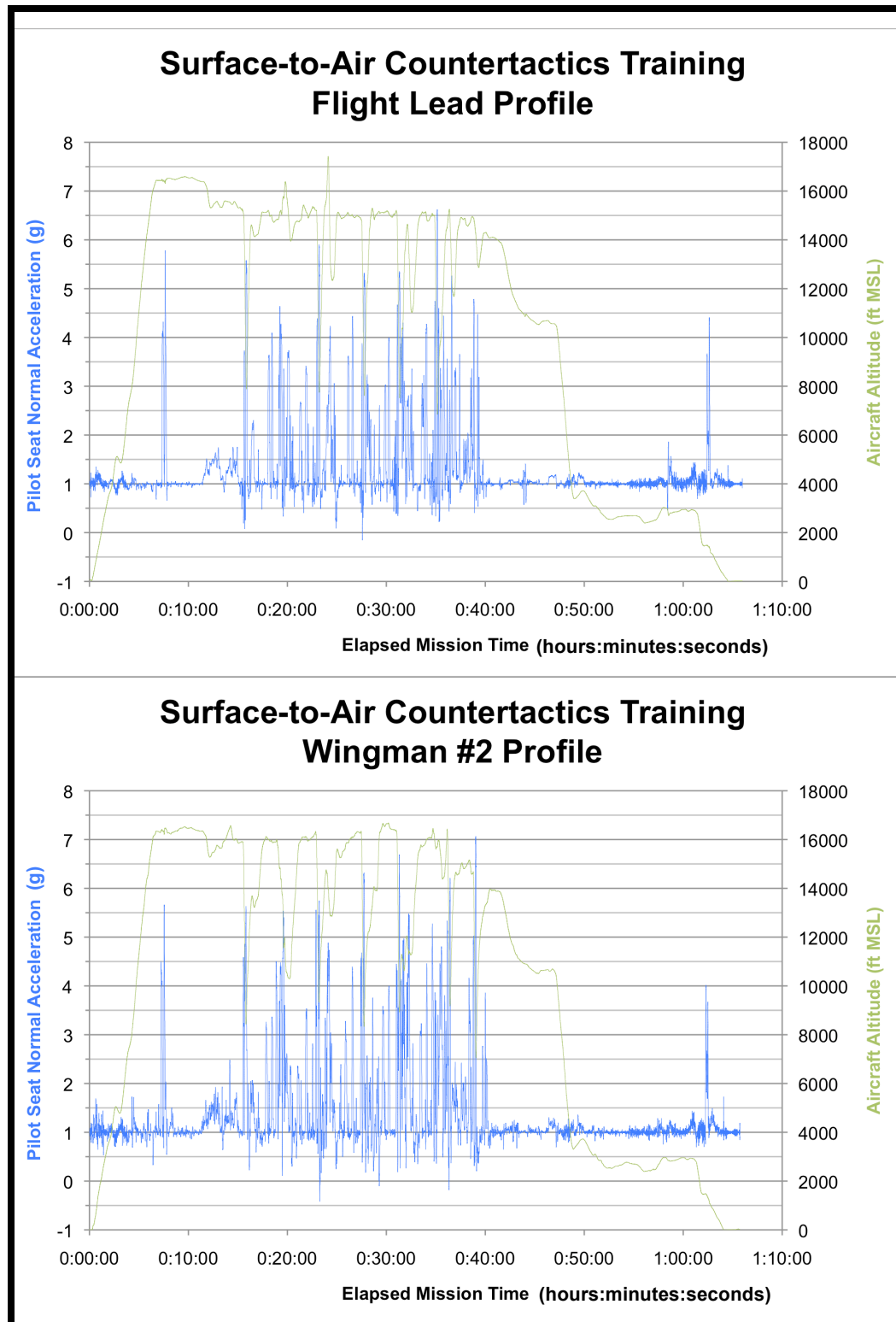


Figure A-7. Pilot Seat Normal Acceleration Expressed as g and Aircraft Altitude Versus Elapsed Mission Time for the SACT Training Mission

Table A-5: SACT Training Mission Acceleration Analysis

Surface-to-Air Countertactics Training Mission Acceleration Analysis						
	Flight Lead			Wingman #2		
	Acceleration Level	Elapsed Time	Percent of Total Time	Acceleration Level	Elapsed Time	Percent of Total Time
Vertical (Normal) Acceleration – G _Z						
Mission Time		1:05:58			1:05:43	
Maximum G _Z	+6.62			+7.06		
Minimum G _Z	-0.16			-0.42		
Median G _Z	+1.30			+1.37		
Spectrum	-0.5 to +0.5	0:00:32	0.8%	-0.5 to +0.5	0:01:01	1.5%
	+0.5 to +2.0	0:58:15	88.3%	+0.5 to +2.0	0:56:16	85.6%
	+2.0 to +3.0	0:03:01	4.6%	+2.0 to +3.0	0:03:22	5.1%
	+3.0 to +4.0	0:02:23	3.6%	+3.0 to +4.0	0:02:31	3.8%
	+4.0 to +5.0	0:01:03	1.6%	+4.0 to +5.0	0:01:44	2.6%
	+5.0 to +6.0	0:00:30	0.8%	+5.0 to +6.0	0:00:33	0.8%
	+6.0 to +8.0	0:00:02	0.1%	+6.0 to +8.0	0:00:11	0.3%
Longitudinal Acceleration - G _X						
Maximum G _X	+1.14			+1.05		
Minimum G _X	-0.59			-0.61		
Median G _X	+0.10			+0.11		
Lateral (Sideforce) Acceleration - G _Y						
Abs Max G _Y	0.53			0.42		
Median G _Y	0.01			0.01		

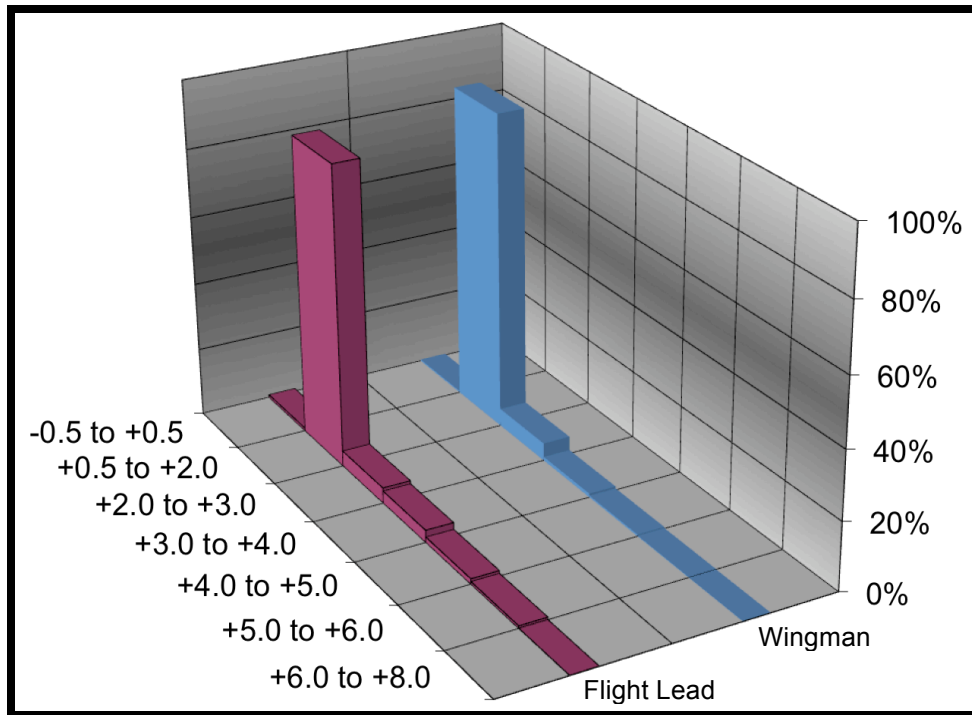


Figure A-8. Histograms of Pilot Seat Normal Acceleration (G_z) Spectrum for the Surface-to-Air Countertactics Training Mission

APPENDIX B: Analysis of Strike Fighter Aircrew Survey Results

Purpose of Survey and Tabulated Results

A Likert scale survey using rating scales 1 through 5 and consisting of 9 questions was conducted at Naval Air Station (NAS) Lemoore, CA, from 24 February through 06 March 2009. Seventy-eight (78) F/A-18 pilots and weapon system officers (WSOs) were surveyed from operational squadrons and Fleet Replacement Squadron (FRS)/training squadrons. Table B-1 details survey demographics including designator, paygrade, total and F/A-18 flight hours, and current Strike Fighter Weapons and Tactics (SFWT) level.

Table B-1: Strike Fighter Aircrew Survey Demographics

Category	Survey Question Detail	Median	Mode	% of Responses				
				%1	%2	%3	%4	%5
Designator	1 = Pilot 2 = WSO	1	1	57%	21%	-	-	-
Paygrade	1 = O-1 2 = O-2 3 = O-3 4 = O-4 5 = O-5 & Up	3	3	0%	12%	67%	18%	4%
Total Flight Hours	1 = ≥ 500 , <1000 2 = ≥ 1000 , <1500 3 = ≥ 1500 , < 2000 4 = ≥ 2000 . < 2500 5 = N/A	2	1	37%	29%	15%	18%	-
F/A-18 Model Hours	1 = ≥ 500 , <1000 2 = ≥ 1000 , <1500 3 = ≥ 1500 , < 2000 4 = ≥ 2000 . < 2500 5 = N/A	1	1	56%	28%	9%	6%	-
Current SFWT Level	1 = FRS Student 2 = Wingman 3 = Section Lead 4 = Division Lead 5 = N/A	4	4	6%	22%	12%	60%	-

As shown in Table B-1, the majority ($\geq 51\%$) of surveyed aircrew were pilots with a paygrade of O-3 (Navy Lieutenant) who had less than 1,500 total (all aircraft) flight hours and less than 1000 F/A-18 flight hours and who had attained their division lead qualification. The survey group

consisted of a statistically representative mixture of aircrew from the Navy's strike fighter community.

The survey questions elicited aircrew opinions on a variety of in-simulator and in-aircraft sensory issues as they related to different mission subsets and tasks and pertinent results are provided below.

Aircrew Acceptance of Existing Fixed-Base F/A-18 Flight Simulators

Survey questions 1 and 2 asked aircrew to indicate their level of agreement with the statements that their "basic airmanship" (BA) and "overall aviation sense" (AS) are improved by performing mission tasks in the current F/A-18 simulator. "Basic airmanship" was defined as traditional stick and rudder skills and generally referred to the aircrew's ability to control aircraft state including airspeed, flight path, attitude, angle of attack, etc. "Overall aviation sense" was defined as flight leadership, situational awareness, and decision making skills and generally referred to higher-level cognitive processes whereby the aircrew managed "mission parameters" vice just the aircraft's state.

Table B-2 below summarizes aircrew level of agreement that basic airmanship and overall aviation sense were improved by performing specific missions or tasks in the existing fixed-base simulator. The first percentage in the columns reflects basic airmanship and the second percentage reflects overall aviation sense.

Table B-2: Results of Aircrew Acceptance Ratings of Existing Fixed-Base F/A-18 Simulators

Mission Phase / Task	Strongly Agree		Agree		Undecided		Disagree		Strongly Disagree	
	BA	AS	BA	AS	BA	AS	BA	AS	BA	AS
A/A Missions	9%	25%	39%	62%	18%	7%	24%	6%	10%	0%
A/G Missions	11%	13%	47%	71%	17%	6%	17%	7%	9%	3%
Formation Flight Tasks	0%	0%	23%	29%	32%	35%	34%	26%	11%	10%
In-flight Refueling Tasks	0%	0%	2%	15%	42%	38%	25%	22%	32%	25%
Emergency Situations and CRM Scenarios	44%	50%	39%	42%	13%	8%	0%	0%	5%	0%
Carrier Approach and Landing Tasks	13%	20%	34%	55%	27%	15%	6%	5%	11%	5%

Aircrew Rating of Realism of Existing Fixed-Base F/A-18 Simulators

Question 3 asked aircrew to indicate their level of agreement with the statement that the current fixed-base simulator provided a training environment representative of the actual “in-aircraft” environment, broken into specific mission phases and tasks. As indicated in Figure B-1 and Table B-3, aircrew responses rated the quality of the existing fixed-base simulator as acceptable, good, or very good for the majority of surveyed mission subsets, indicating a general level of acceptance of current F/A-18 simulators for mission training. Notable exceptions to this trend were respondent opinions of A/A Within Visual Range tasks (42% rated poor or very poor), formation flight (56% rated poor or very poor), and in-flight refueling (64% rated poor or very poor).

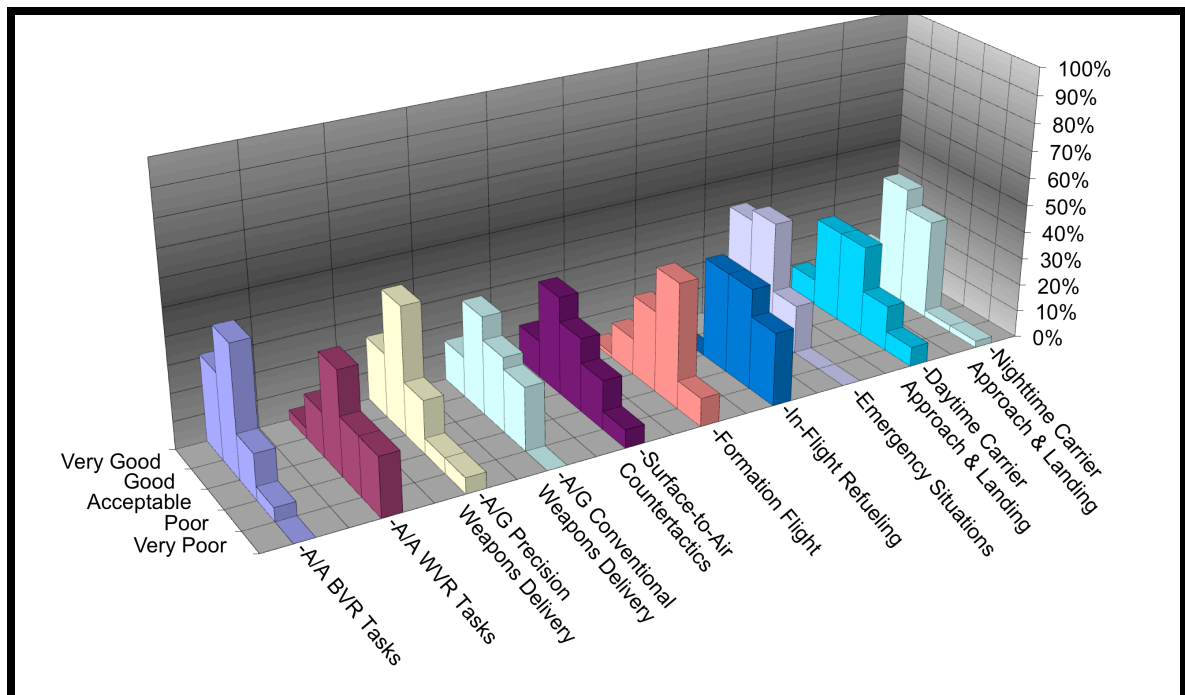


Figure B-1. Histogram of Aircrew-Rated Realism of Existing Fixed-Base F/A-18 Simulator in Matching the Environment in the Actual Aircraft for Specific Mission Subsets

Table B-3: Results of Aircrew-Rated Realism of Existing Fixed-Base F/A-18 Simulator in Matching the Environment in the Actual Aircraft for Specific Mission Subsets

Mission Subset	Very Good	Good	Acceptable	Poor	Very Poor
A/A Beyond Visual Range Tasks	31%	48%	16%	5%	0%
A/A Within Visual Range Tasks	4%	16%	38%	21%	21%
A/G Precision Weapons Delivery	23%	46%	19%	6%	6%
A/G Conventional Weapons Delivery	15%	35%	27%	23%	0%
Surface-to-Air Countertactics	13%	36%	27%	18%	7%
Formation Flight	1%	13%	29%	46%	10%
In-Flight Refueling	0%	0%	37%	37%	27%
Emergency Situations	39%	43%	18%	0%	0%
Daytime Carrier Approach & Landing	10%	33%	33%	17%	7%
Nighttime Carrier Approach & Landing	15%	44%	37%	2%	2%

Frequency of Head Movement While Performing Mission Tasks

Question 4 asked aircrew to quantify how frequently they move their head away from the Heads-Up Display (HUD) while performing mission tasks in the aircraft. Head movement was defined as rotating, raising, or lowering the sight axis away from the HUD so HUD symbology was no longer within the visual field-of-regard. Survey results indicate the frequency of head movement varies according to the type of mission task being performed, with A/A within visual range tasks having the highest frequency of head movement (71% Very Frequently, 19% Frequently). The majority of survey respondents also indicated they make Very Frequent or Frequent head movements during Air-to-Air Beyond Visual Range (20%, 47%), Air-to-Ground Precision Weapons Delivery, (17%, 35%), Air-to-Ground Conventional Weapons Delivery (34%, 42%), SACT (54%, 31%), Formation Flight (49%, 44%), In-Flight Refueling (41%, 36%), and Daytime Carrier Approach and Landing tasks (19%, 38%). Only during Nighttime Carrier Approach and Landing tasks did the majority of respondents indicate they Sometimes (32%), Seldom (24%), or Never (7%) make head movements. Survey results on the frequency of head movement during various mission phases are summarized in Figure B-2 and Table B-4.

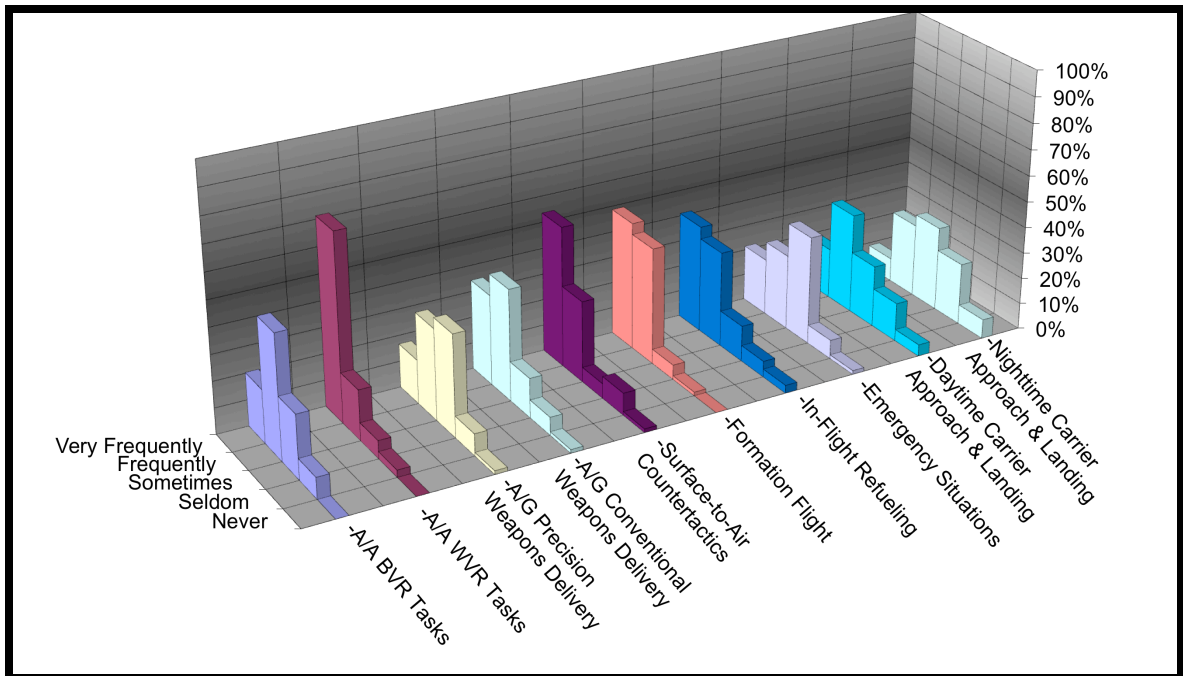


Figure B-2. Histogram of Aircrew-Rated Frequency of Head Movement in the Actual Aircraft During Specific Strike Fighter Mission Subsets

Table B-4: Results of Aircrew-Rated Frequency of Head Movement in the Actual Aircraft During Specific Strike Fighter Mission Subsets

Mission Subset	Very Frequently	Frequently	Sometimes	Seldom	Never
A/A Beyond Visual Range Tasks	20%	47%	24%	8%	0%
A/A Within Visual Range Tasks	71%	19%	7%	3%	0%
A/G Precision Weapons Delivery	17%	35%	39%	8%	1%
A/G Conventional Weapons Delivery	34%	42%	15%	7%	1%
Surface-to-Air Countertactics	54%	31%	6%	8%	1%
Formation Flight	49%	44%	6%	1%	0%
In-Flight Refueling	41%	36%	14%	6%	3%
Emergency Situations	21%	29%	41%	7%	1%
Daytime Carrier Approach & Landing	19%	38%	24%	15%	4%
Nighttime Carrier Approach & Landing	9%	28%	32%	24%	7%

Aircrew Ratings of In-Aircraft Sensory Cues

Questions 5 through 9 asked aircrew to indicate the level of importance of different types of sensory cues (stimuli and feedback) during different mission tasks performed in the actual aircraft. Visual stimuli and feedback (question 5) were defined as changes in external scene including weather effects and in cockpit scene including HUD/sensor/display symbology changes. Gravito-inertial (G) based stimuli and feedback (question 6) were defined as any of the vestibular or somatosensory cues including positive and negative G forces, seat of the pants cues, any roll-pitch-yaw inner ear sensations, linear acceleration, sideforces, and G-suit inflation. Physical airframe stimuli and feedback (question 7), while in reality cues that could be considered either gravito-inertial or aural-based, were defined as buffet, leading edge extension (LEX) vortices, airframe vibration, and turbulence in an effort to isolate aircrew perception of aircraft state or performance through airframe (aeromechanical) dynamic response. Aural stimuli and feedback (question 8) were defined as engine response, environmental control system (ECS) flow changes, ambient cockpit noise, external configuration changes (lowering/raising landing gear), and audible aircraft performance cues such as “LEX hum” (a low altitude, high dynamic pressure phenomenon) and vortex rumble (at high angle of attack). Cockpit environmental stimuli and feedback (question 9) were defined as temperature, airflow, humidity, ambient pressurization, oxygen flow, and cockpit odor.

In general, survey data indicated visual and gravito-inertial (G) based cues were the most valued sources of sensory cues by aircrew in the management and completion of mission tasks across the spectrum of F/A-18 strike fighter mission profiles in the actual aircraft. Survey data also indicated aircrew assign different relative values for the different categories of sensory cues depending upon what specific mission task or mission phase is in progress (i.e. task dependency). Of note, cockpit environmental stimuli and feedback were rated as “Of Little Importance” across the spectrum of mission subsets and embedded tasks, indicating aircrew do not currently consider high-fidelity simulation of the in-cockpit environment to be important in improving their management and completion of mission tasks.

Since the purpose of this study was to determine the suitability of a centrifuge as a dynamic flight simulator for F/A-18 mission training, the aircrew-rated importance of gravito-inertial cues in the aircraft are particularly pertinent and are specifically broken out in Figure B-3 and Table B-5. The mission subsets with the highest overall ratings of importance were A/A WVR tasks (80% Very Important, 12% Important), A/G Conventional Weapons Delivery tasks

(51% Very Important, 37% Important) , and SACT tasks (74% Very Important, 22% Important) had the highest ratings of all mission subsets. Survey data indicates, not surprisingly, that the more dynamic the maneuvering phase, the more important aircrew considered gravito-inertial cues while flying the F/A-18. However, even in the more benign non-maneuvering mission subsets such as formation flight, in-flight refueling, and carrier approach and landing, the majority of aircrew rated gravito-inertial cues as Moderately Important, Important, or Very Important, indicating that aircrew value gravito-inertial cues even when operating at lower G_z magnitudes.

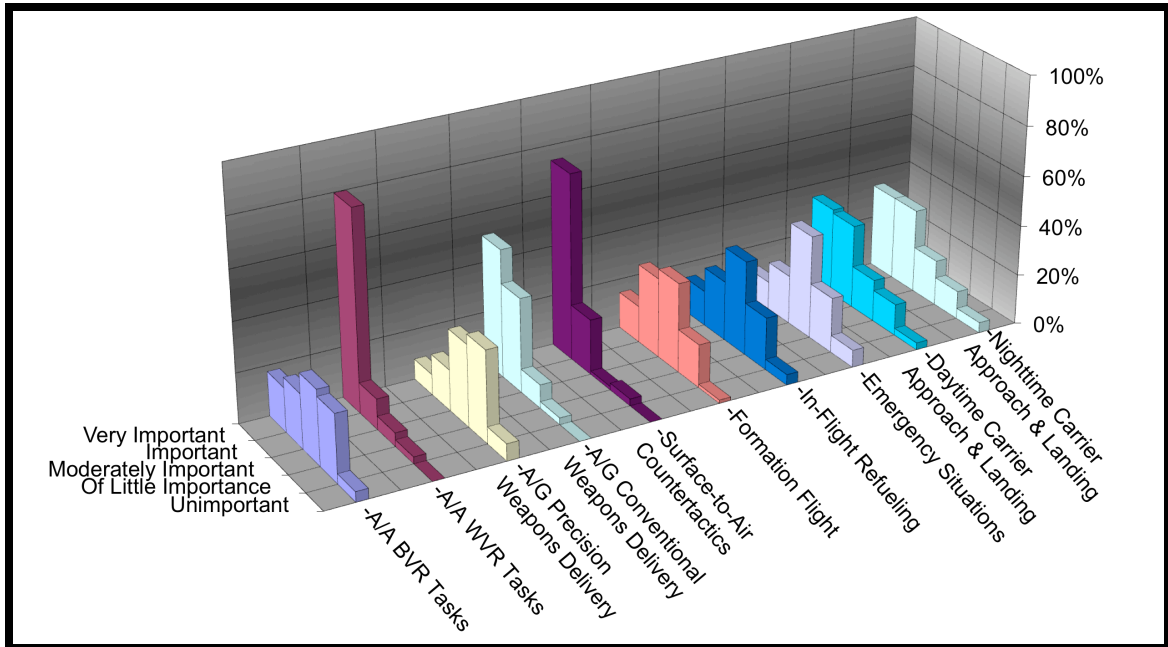


Figure B-3. Histogram of Aircrew-Rated Importance of Gravito-Inertial Based Cues During Various Strike Fighter Mission Tasks

Table B-5: Results of Aircrew-Rated Importance of Gravito-Inertial Based Cues During Specific Strike Fighter Mission Subsets

Mission Subset	Very Important	Important	Moderately Important	Of Little Importance	Unimportant
A/A Beyond Visual Range Tasks	18%	22%	30%	27%	4%
A/A Within Visual Range Tasks	80%	12%	5%	3%	0%
A/G Precision Weapons Delivery	8%	16%	32%	36%	7%
A/G Conventional Weapons Delivery	51%	37%	9%	3%	0%
Surface-to-Air Countertactics	74%	22%	1%	3%	0%
Formation Flight	14%	32%	36%	17%	1%
In-Flight Refueling	14%	24%	38%	21%	4%
Emergency Situations	11%	19%	41%	22%	7%
Daytime Carrier Approach & Landing	35%	33%	17%	13%	3%
Nighttime Carrier Approach & Landing	33%	33%	18%	11%	4%

APPENDIX C: Review of Spatial Orientation and Human Sensory Perception

A Review of Spatial Orientation and the Human Sensory System

Spatial orientation (SO) is defined as the ability to correctly sense the position, motion, or attitude of the aircraft or the pilot within the fixed coordinate system provided by the surface of the Earth and the Earth's gravitational vector.²¹ Maintaining SO and detecting aircraft acceleration and motion involves a large number of different and complex overlapping sensory mechanisms, namely the visual, vestibular, and somatosensory systems.^{20,52,53,54,55,56} Spatial disorientation (SD) is defined as the failure to maintain SO, which in the flight environment all too frequently proves catastrophic.⁵⁷

Visual System

The visual system, which predominates all other senses,^{23,58} consists of photoreceptors in the eye which respond to changes in size, shape, texture, and relative position of targets and physical features outside of the cockpit and changes in flight instruments, cockpit displays, and other symbolic data. The brain cognitively processes this information and as such determines changes in aircraft state (velocity/displacement and acceleration) by indirect means.^{16,20,48,59} One important limitation of the visual system is it cannot directly sense gravito-inertial acceleration changes; consequently, the central nervous system combines vision with other sources of complementary sensory stimuli (including vestibular and somatosensory stimuli) in order to produce overall sensations of velocity/displacement and acceleration.²⁰

Vestibular System

The vestibular system within the inner ear contains mechanoreceptors that send direct signals to the brain in response to 6 DOF head accelerations. The three roughly orthogonal semicircular canals sense head angular accelerations similar to a rate gyro. The otoliths sense linear accelerations and head tilt (orientation towards gravity) similar to a linear accelerometer.⁶¹

Somatosensory System

The somatosensory system contains mechanoreceptors distributed throughout the body. Commonly known as "seat of the pants" cues, these mechanoreceptors perceive changes in aircraft state through tactile nerve receptors (in the skin) and kinesthetic/proprioceptive nerve

receptors (in the joints, muscles, and tendons) distributed throughout the body and generally complement the vestibular system.^{19,61}

Vestibular System Limitations

It is well known that the vestibular system provides inadequate cues both in-flight and within the centrifuge.^{60,61} Within the terrestrial environment, sensory organs generally provide concordant, complementary, and redundant sensory information to the central nervous system which, in turn, maintains proper spatial orientation.^{48,62} The altered gravito-inertial environment encountered in-flight and within the centrifuge confuses the vestibular organs and provides conflicting or discordant information to the central nervous system, complicating the task of maintaining spatial orientation.⁶²

An important distinction between visual and vestibular sensory processing is that visual information, unlike vestibular cues, does not decay over time during constant velocity motion. Consequently, human perception of orientation and motion begin to break down in the absence of visual input. With respect to centrifuge-based flight simulators, the most significant vestibular system limitations reside within the semicircular canals and their inability to correctly perceive angular acceleration, as follows:

1. There is an absence of sensation of rotation during constant velocity rotation.
2. There is an apparent sensation of rotation in the opposite direction during angular deceleration.
3. There is a persistent sensation of rotation in the opposite direction after physical rotation has stopped.⁴⁸

The predominant SD illusions caused by the inadequacies of the semicircular canals are somatogyral illusions, which are the false sensation of rotation, or absence of rotation caused by misperceiving the magnitude and direction of an actual rotation.⁴⁸

Comparing these limitations to the results of previous centrifuge testing, it is clear that the semicircular canals were responsible for the following:

1. The debilitating tumbling sensation during G_z offload in the centrifuge (caused by centrifuge tangential deceleration).
2. The Coriolis cross-coupling (CCC) illusion which stems from the sensation of angular motion in response to an inclination or movement of the head while the head is undergoing a passive rotation about an axis not aligned with the tilt axis.⁴⁸

APPENDIX D: Review of the Mechanics of Aircraft Flight and Centrifuge Motion

Review of the Mechanics of Aircraft Flight and Centrifuge Motion

The following paragraphs review the basic mechanics of level turning aircraft flight and centrifuge motion and were drawn from reference 62.

The following formulas govern the aircraft flight path dynamics during level turns and serve as a starting point for understanding the differences between aircraft flight path dynamics and the physics of centrifugal motion (the following formulas assume coordinated flight where the resultant force used to turn the aircraft is provided entirely as a function of lift with no resultant body axis side forces i.e. no skidded turns):

Eq. D-1a - Centripetal Acceleration:
$$a_{\text{centripetal}} = \frac{V_{\text{tangential}}^2}{R},$$

where $a_{\text{centripetal}}$ is resultant centripetal acceleration (in ft/sec²), $V_{\text{tangential}}$ is the instantaneous tangential velocity (in ft/sec) along a circle of radius R (in ft). $a_{\text{centripetal}}$ can also be expressed as a function of angular velocity ω (in rad/sec) as follows:

Eq. D-1b:
$$a_{\text{centripetal}} = R\omega^2;$$

Eq. D-2 - Load Factor:
$$n = \frac{1}{\cos \phi},$$

where n is the load factor and ϕ is the aircraft bank angle;

Eq. D-3 - Radius of Turn:
$$R = \frac{V^2}{g \tan \phi} = \frac{V^2}{g \sqrt{n^2 - 1}},$$

where R is radius of turn (in ft), V is true airspeed (in ft/sec), and g is Earth's gravitational acceleration (32.174 ft/sec²); and,

Eq. D-4 - Turn Rate:
$$\omega = \dot{\Psi} = \frac{V}{R} = \frac{g \tan \phi}{V} = \frac{g \sqrt{n^2 - 1}}{V}$$

The governing equations for the linear acceleration components of centrifugal motion are developed below as a review. The centrifuge, when in steady-state rotation at a constant angular velocity, will always have a resultant acceleration magnitude greater than one g as determined by the following formula:

Eq. D-5:
$$a_{\text{constant } \omega} = \sqrt{g^2 + (a_{\text{centripetal}})^2},$$

where $a_{\text{constant } \omega}$ is the resultant acceleration vector during constant angular velocity (in ft/sec²).

When the centrifuge increases or decreases its angular velocity (in order to change the resultant linear acceleration to match commanded G), it generates an instantaneous acceleration component that acts perpendicular to both the centripetal acceleration and Earth's gravitational acceleration as determined by the following formula:

Eq. D-6:
$$a_{\text{tangential}} = R\dot{\omega},$$

where $a_{\text{tangential}}$ is the instantaneous tangential acceleration along the centrifugal circumference (in ft/sec²) and $\dot{\omega}$ is the angular acceleration of the centrifuge axis (in rad/sec²). Combining Eq. D-5 and D-6 yields a total resultant linear acceleration with a magnitude as determined by the following formula:

Eq. D-7a:
$$a_{\text{resultant}} = \sqrt{g^2 + (a_{\text{centripetal}})^2 + (a_{\text{tangential}})^2} \text{ or}$$

Eq. D-7b:
$$a_{\text{resultant}} = \sqrt{g^2 + R\omega^2 + R\dot{\omega}}$$

The non-dimensional form of this resultant acceleration is expressed as follows:

Eq. D-8:
$$G_{\text{resultant}} = \frac{a_{\text{resultant}}}{g},$$

where $G_{\text{resultant}}$ is the ratio of resultant acceleration to Earth's gravitational acceleration.

$G_{\text{resultant}}$ can be distributed along the three body axes of the gondola/cockpit as determined by the following formula:

Eq. D-9:
$$G_{\text{resultant}} = \sqrt{G_{\text{X-body}}^2 + G_{\text{Y-body}}^2 + G_{\text{Z-body}}^2}.$$

Coordinate transformation of resultant linear and angular acceleration vectors into specific gondola/cockpit axis components can be developed via in-depth analysis of vector products and matrix manipulation and is provided in reference 63.

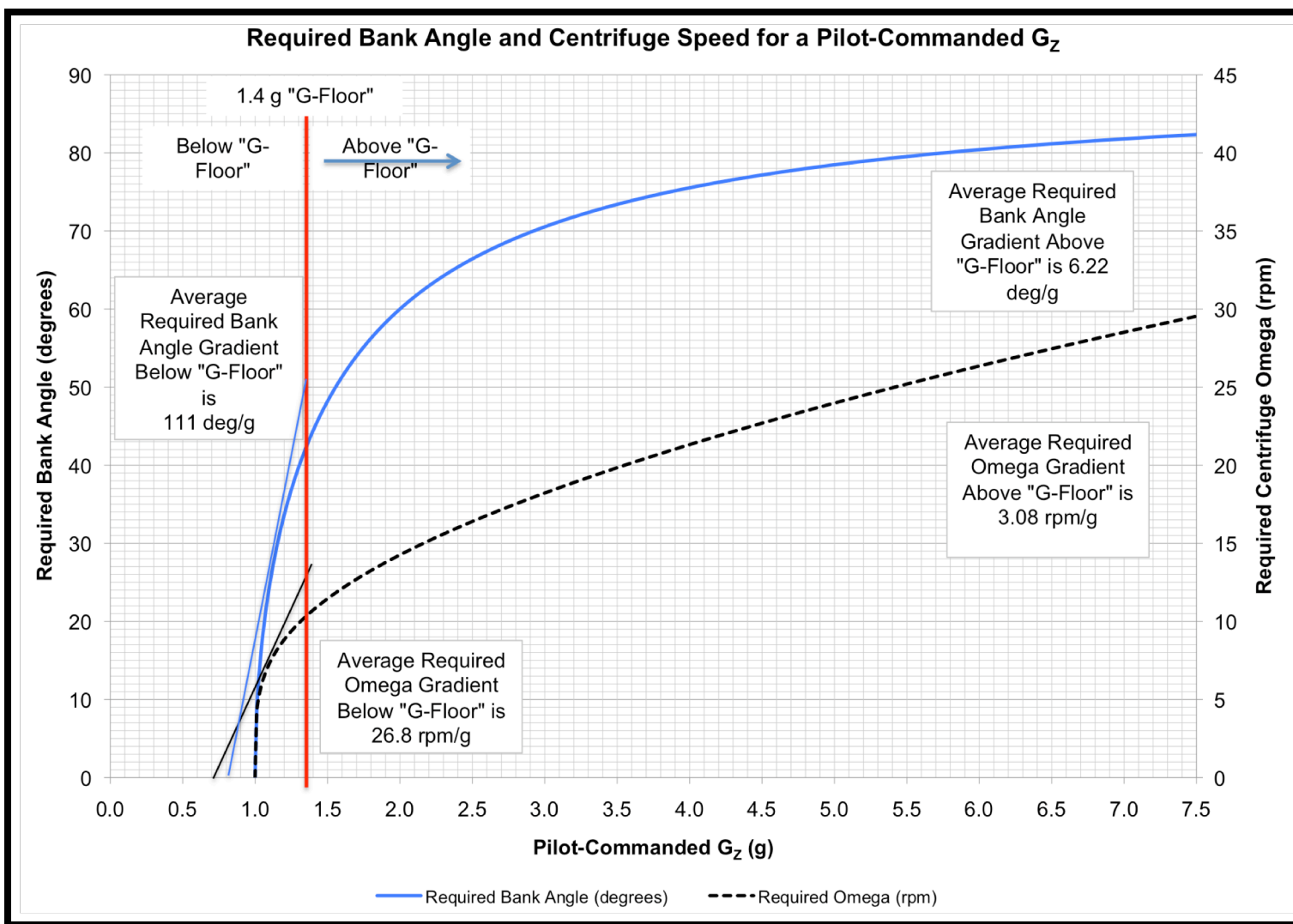


Figure D-1. Required Bank Angle and Centrifuge Speed for a Pilot-Commanded G_z

VITA

Richard Michael Masica was born in Pensacola, FL, in 1973. Raised in Sarasota, FL, he graduated from Pine View School in 1991. He was appointed to the United States Naval Academy in Annapolis, MD, where he earned a Bachelor of Science degree in Ocean Engineering and graduated with distinction in 1995. Following graduation, he was commissioned an Ensign in the United States Navy and was selected for pilot training. He completed fixed-wing flight training and was designated a Naval Aviator in 1997. After completing a three-year operational F/A-18 tour in Japan, he attended the United States Naval Test Pilot School as a member of Class 122, graduating in 2002. He then served over 2 years as a developmental test pilot at NAS Patuxent River, MD. From 2005 to 2008, he again served as an operational F/A-18 pilot in Japan. He resumed developmental test pilot duties in 2008 at NAS Patuxent River, MD. Throughout his military career, he has flown 17 different types of aircraft and logged more than 2,400 flight hours and 570 aircraft carrier arrested landings. He is a member of the Society of Experimental Test Pilots. He is currently completing his Master of Science degree in Aviation Systems from the University of Tennessee Space Institute, Tullahoma, TN.