



**TOWARD A FLYING QUALITIES
STANDARD FOR UNMANNED AIRCRAFT**

DISSERTATION

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FOR UNMANNED AIRCRAFT

DISSERTATION

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Abstract

The topic of aircraft flying qualities has been pursued since even before the Wright Brothers' first flight. As aircraft have advanced, the understanding of flying qualities has progressed with it; however, a new field of aviation has been uncovered. Unmanned aircraft have garnered an increasing amount of attention and are well on the way to becoming a third major aircraft type next to manned fixed-wing and manned rotary-wing aircraft. The reason for the increased attention is unmanned aircraft have demonstrated operational usefulness and success in accomplishing missions that were too dull, dirty, or dangerous for manned aircraft. In spite of these accomplishments, the design and development cycle for unmanned aircraft has not achieved the level of sophistication observed in manned aircraft, to include a lack of a flying qualities standard. This research begins the discussion of how this unmanned aircraft flying qualities standard can be created to ensure the unique benefits of unmanned aircraft are upheld while still ensuring a necessary level of safety. Focusing on specific tasks accomplished during operational missions will alleviate the complications that arise with the current delineation for manned fixed-wing aircraft according to weight, air-speed, and operational altitude. Three hypothetical unmanned aircraft models are created to test this proposed flying qualities framework. Various criteria are used to validate this new methodology of approaching unmanned aircraft design.

*“How simple it seemed once found, yet unfound, most would have thought
impossible.” – John Milton*

This research is dedicated to my friends who were encouraging me to the end:

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List of Symbols

Symbol		Page
ξ_p	Phugoid damping ratio	27
T_{θ_2}	Ratio of high-frequency pitch attitude zero	27
CAP	Control Anticipation Parameter	27
ω_{sp}	Short-period undamped natural frequency	27
ξ_{sp}	Short-period damping ratio	27
τ_θ	Equivalent pitch time delay	27
$\dot{q}_o$	Instantaneous pitch acceleration	27
Δn_{ss}	Change in steady state load factor	27
$\frac{\Delta q_2}{\Delta q_1}$	Transient peak ratio	28
Δt	Rise time	28
t_1	Effective delay	28
T_R	Roll mode time constant	29
T_2	Time to double	29
ω_d	Dutch roll oscillation undamped natural frequency	29
ξ_d	Dutch roll oscillation damping ratio	29
ω_{RS}	Coupled roll-spiral oscillation undamped natural frequency	29
ξ_{RS}	Coupled roll-spiral oscillation damping ratio	29
p	Roll rate	29
q_{pk}	Peak pitch rate	34
$\Delta\theta$	Pitch angle	35
$\tau_{p\theta}$	Pitch phase delay	35

Symbol		Page
ω_{BW_θ}	Pitch bandwidth	35
t_d	Time to double	36
β	Sideslip angle	64
r_{gy}	Radius of gyration about the y-axis	65
r_{gx}	Radius of gyration about the x-axis	65
b	Wing span	65
α	Angle of attack	91
α_{stall}	Stall angle of attack	91
ω_{BW}	Bandwidth	96
$\omega_{BW_{Phase}}$	Phase bandwidth	96
$\omega_{BW_{Gain}}$	Gain bandwidth	96
τ_p	Phase delay	98
τ_t	Time delay	99
γ	Flight path angle	104

List of Abbreviations

Abbreviation		Page
RPV	Remotely Piloted Vehicle	3
UAV	Unmanned Aerial Vehicle	3
UCAV	Unmanned Combat Aerial Vehicle	3
ROA	Remotely Operated Aircraft	3
UA	Unmanned Aircraft	3
UAS	Unmanned Aircraft System	3
sUAS	small Unmanned Aircraft System	3
FAA	Federal Aviation Administration	4
ACTD	Advanced Concept Technology Demonstration	6
DoD	Department of Defense	10
EMD	Engineering and Manufacturing Development	11
HAE	High Altitude Endurance	12
NAS	National Airspace System	13
CFR	Code of Federal Regulations	13
SIGINT	Signals Intelligence Collection	14
VLOS	Visual Line-of-Sight	16
NPRM	Notice of Proposed Rulemaking	16
BIUG	Background Information and User Guide	23
LOES	Low Order Equivalent System	26
HOS	High Order System	26
SAS	Stability Augmentation System	26
PIO	Pilot Induced Oscillation	29

Abbreviation		Page
CAS	Command Augmentation Systems	30
MTEs	Mission Task Elements	31
UCE	Useable Cue Environment	31
VCRs	Visual Cue Ratings	31
SBIR	Small Business Innovative Research	37
HQR	Handling Qualities Rating	40
MCH-UVD	Modified Cooper-Harper for Unmanned Vehicles Displays	42
HUD	Head-Up Display	44
STEMS	Standard Evaluation Maneuvers Set	45
COTS	Commercial Off The Shelf	53
AST	Aerodynamic Strip Theory	54
VRML	Virtual Reality Modelling Language	55
ISR	Intelligence, Surveillance, and Reconnaissance	60
RSTA	Reconnaissance, Surveillance, and Target Acquisition	60
C3	Command, Control, and Communication	60
EOD	Explosive Ordnance Disposal	60
EW	Electronic Warfare	60
FP	Force Protection	60
TCS	Tactical Control System	60
A2/AD	Anti-Access and Area Denial	60
CAS	Control Augmentation System	75
VMC	Visual Meteorological Conditions	76

Abbreviation		Page
IMC	Instrument Meteorological Conditions	76
AR	Air Refueling	78
AGL	Above Ground Level	85

TOWARD A FLYING QUALITIES STANDARD FOR UNMANNED AIRCRAFT

I. Introduction

Over the past few decades, unmanned aircraft have garnered an increasing amount of attention, and are well on the way to becoming a major aircraft type along with manned fixed-wing and manned rotary-wing aircraft. The reason for this increased attention is that unmanned aircraft have demonstrated operational usefulness and success in accomplishing missions that were too dull, dirty, or dangerous for manned aircraft. Unmanned aircraft have some very unique benefits. They have the potential capability to do the same mission as a manned aircraft without putting the pilot or crew in danger. If an unmanned aircraft is lost there is no need to launch a rescue attempt for the pilot and crew. Furthermore, since there is no crew, life support equipment and similar items are not necessary. This allows for an increase in payload or the ability to decrease aircraft weight. Decreasing the weight is a benefit by itself, but this also decreases the maintenance, cost, and necessary support. With less required equipment, the aircraft can also be smaller and weigh less, and therefore need a smaller, less powerful engine. This also leads to reduced cost and maintenance.[1] In spite of these unique benefits, the research, design, and test cycle for unmanned aircraft has not received the same level of rigor and validation observed in the design of manned aircraft.

One particular area of technology for unmanned aircraft that remains underdeveloped and often overlooked is flying qualities. An accepted definition for flying qualities is noted in a report from Langley Aeronautical Laboratories published in

1949: “Flying qualities of an aircraft are those stability and control characteristics that have an important bearing on the safety of flight and on the pilots’ impressions of the ease of flying an airplane in steady flight and in maneuvers.” [2] These aircraft characteristics have been used to develop and enhance manned aircraft, both fixed-wing and rotary-wing. Standards have been published that manufacturers, investors, government, and industry must abide by not only for design requirements but also for safety of flight considerations. However, no such standards exist for unmanned aircraft. The development of flying qualities has aided manned aircraft in both their safety and performance. They allow for a better understanding of aircraft before any flight tests are accomplished. When flying qualities requirements are integrated throughout the research and design process, there is a better chance of success when actual flight testing begins and a greater potential for reducing the time from when flight test and evaluation begins to actual production and operational use of the aircraft. The field of flying qualities has not been fully researched or developed for unmanned aircraft. In fact, very little effort has been put into unmanned aircraft flying qualities research. Various reasons for this lack of effort include, but are not limited to, the fact that there is not an actual pilot in an unmanned aircraft, the need to get the technology into operational use as quickly as possible, and no government regulation requiring specific flying qualities for unmanned aircraft. Flying qualities research and analysis is extensive for manned aircraft. For the military, this research is consolidated in the manned flying qualities specification, MIL-STD-1797B for fixed-wing aircraft and ADS-33E-PRF for rotary-wing aircraft. However, since there is limited unclassified and releasable research on unmanned aircraft flying qualities, there is no requirement for unmanned aircraft to abide by either of these standards and there is no specific flying qualities standard or specification tailored to the unique mission and characteristics of unmanned aircraft.

The real question lies in determining if this lack of a flying qualities standard is acceptable. Or, instead, if we need to ensure the advancement of this innovative type of aircraft includes a flying qualities specification to ensure safety and reliability while still allowing mission accomplishment and performance. Reviewing the development cycle history compared to unmanned aircraft use and mishap rates will begin to address this question. Specifically, the development cycle for unmanned aircraft in terms of the military acquisition process will be addressed to determine if an unmanned aircraft flying qualities standard will aid in the process. Then reviewing the airspace restrictions placed on unmanned aircraft will further address this question. Specifically, a review of the requirements place on unmanned aircraft flying in the National Airspace System will be explained and how an unmanned aircraft flying qualities specification would help ensure safety and reliability throughout the National Airspace System. As we look into the future of unmanned aircraft, by setting a flying qualities standard, we have the potential to make a major impact on both the safety and mission accomplishment for the field of unmanned aircraft.

1.1 Origins of Unmanned Aircraft Terminology

Before the topic of current applications of unmanned aircraft is reviewed, there must be a discussion of the terminology used in the field in order to get a better understanding of the breadth and depth of unmanned aircraft. Throughout history, several different terms have been used to describe unmanned aircraft systems. A few worth mentioning here include the following: Drone, Remotely Piloted Vehicle (RPV), Unmanned Aerial Vehicle (UAV), Unmanned Combat Aerial Vehicle (UCAV), Remotely Operated Aircraft (ROA), Unmanned Aircraft (UA), Unmanned Aircraft System (UAS), and small Unmanned Aircraft System (sUAS). The specific discussion of terminology used for unmanned aircraft initially appears to have more technical-

ities; however, this distinction plays a major role in not only the development of unmanned aircraft throughout history but also assists in understanding the complex and diverse viewpoints of unmanned aircraft designers and operators.

Drones were developed as far back as the 1800's. A drone was described, according to Joint Publication 1-02, to be "a land, sea, or air vehicle that is remotely or automatically controlled".[3] The first well-known acronym used to describe unmanned aircraft was RPV. RPV became a commonly used term during the Vietnam War and was used to describe "an unmanned vehicle capable of being controlled from a distant location through a communication link. It is normally designed to be recoverable".[3] A distinguishable note in this definition is that RPVs were designed to be recoverable. Thus, making it different than ballistic, cruise, or artillery missile which were unmanned "vehicles" but had a one way mission with no intention of ever being recovered and used again. In other words, an RPV is equipped to land and fly future missions, it is not a one way flight. Another term that became common was UAV. This term is defined as "a powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload. Ballistic or semiballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles".[4] Another term that came into existence in the late 1990's was UCAV. This term describes a UAV with the unique mission of being primarily a strike attack vehicle. Some vehicles were made for a different mission (reconnaissance) and then missiles added onto the airframe afterwards; however, in a UCAV, the vehicle was made with the direct intention of primarily accomplishing strike and attack combat missions.[5]

The continuing development of UAVs has been limited some by the Federal Aviation Administration (FAA), the government agency that controls airspace. The FAA

developed the term ROA and used this instead of UAV. ROA distinguished between aircraft and air vehicle since the FAA regulated aircraft and required certification for aircraft, not necessarily air vehicles, to fly in airspace the FAA controls. This allowed the FAA to have more oversight on this developing field.[5] As this field progressed, the general term, UA, was defined as “an aircraft that does not carry a human operator and is capable of flight with or without human remote control”. [6] This was a general term that could apply to a wide range of aircraft. As unmanned flight progressed, another definition emerged, UAS. A UAS is nearly the same as UAV except that it furthers the definition from just the actual aircraft to the aircraft and “that system whose components include the necessary equipment, network, and personnel to control an unmanned aircraft” [6]. This term shows an understanding that there is more than just an aircraft involved in unmanned flight. Items such as the ground station, data link, and auxiliary systems on the aircraft need to be included for a full understanding of the complexity required to make unmanned flight successful. Recently, the Federal Aviation Administration created the term sUAS to define unmanned aircraft that weigh between 0.55 and 55 pounds. This new terms is used to help distinguish the necessary registration requirements for unmanned aircraft.

The history and development of all these terms demonstrates not only the changes within the field of unmanned flight, but also the understanding of how complex and diverse these systems can become. Each term has a specific definition and close attention must be paid to this. Depending on which term is used, a better understanding of the corresponding research, development, users, and potential obstacles can be observed. For the purposes of this research, the acronym UAV will be used to include all unmanned fixed-wing aircraft, and UAS to describe the unmanned fixed-wing aircraft plus the operator and ground based controller system, and the communication links between these two. Reviewing the changes in terminology leads to a discussion of the

current use of UAVs and how technology has advanced their development, roles, and future missions.

1.2 Current UAV Developments

UAV missions are expanding rapidly; however, as with any new technology, complications may arise. For unmanned aircraft, some of these complications can be directly attributed to flying qualities. The field of unmanned aircraft has been racked with high mishap rates, complications in procuring and developing the aircraft, and a lack of knowledge on how to properly operate these new and highly technical machines. The desire to overcome these complications is vital in order to ensure the full operational possibilities are reached, for both military and civilian operations.

1.2.1 Flight Hours and Mishap Rates.

As validation of the usefulness of UAVs to military operations, flight hours can be used as a metric. Several UAVs were developed under the Advanced Concept Technology Demonstration (ACTD) process which is described in detail in Section 1.2.2. The first ACTD process was initiated in the mid 1990's. The initial increase in UAV flight hours starting in 1998, seen in Figure 1, was due to the use of UAVs in the Kosovo Campaign. The first ACTD process was completed in 2000 and the UAV flight hours began to increase even more. An even larger increase in the flight hours can be correlated to the beginning of Operation Enduring Freedom in late 2001 followed by the beginning of Operation Iraqi Freedom in early 2003. By 2009, UAV flight hours had grown exponentially to almost 500,000 hours, mostly corresponding to increased missions in support of Operations Enduring Freedom and Iraqi Freedom. If the ACTD process had not been initiated, the increase in flight hours would

have been delayed 6 to 9 years. The fact that the flight hours continued to grow exponentially demonstrates the usefulness of these advanced systems.[7]

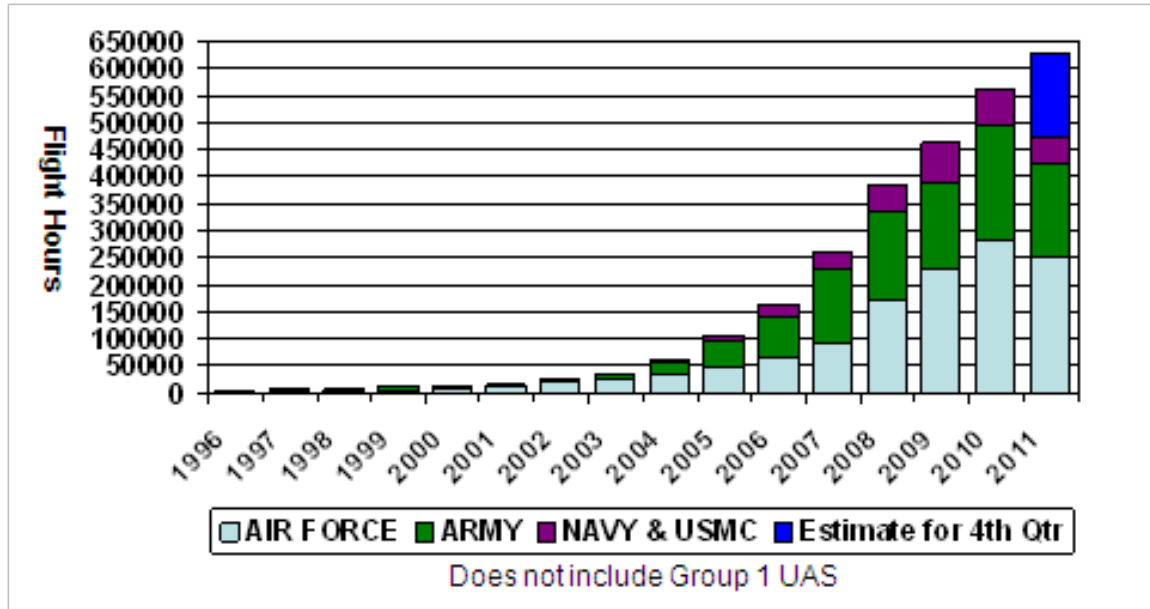


Figure 1. UAS Flight Hours (1996-2011)[7]

A complication did appear to arise with the expedited ACTD process. Without the typical research, analysis, and development cycles, to include analysis of state-of-the-art flying qualities typically required in the Defense Acquisition System, UAV accidents were commonplace. In the earlier stages of UAV operations, the Class A and B accident rate significantly exceeded that of manned aircraft by one to two orders of magnitude. As the number of flight hours increased, the accident rates began to close in on, but not eliminate, this gap between unmanned and manned aircraft, as seen in Figure 2.[8] Specifically, at around 5,000 cumulative flight hours, the F-16 had approximately 110 mishaps per 100,000 hours. The Global Hawk had 75, the Hunter had 150, and the Pioneer is off the chart with a trend showing around 770 mishaps per 100,000 hours. There are a few items to note from these data points. The Global Hawk actually had fewer mishaps per 100,000 hours compared to the F-16,

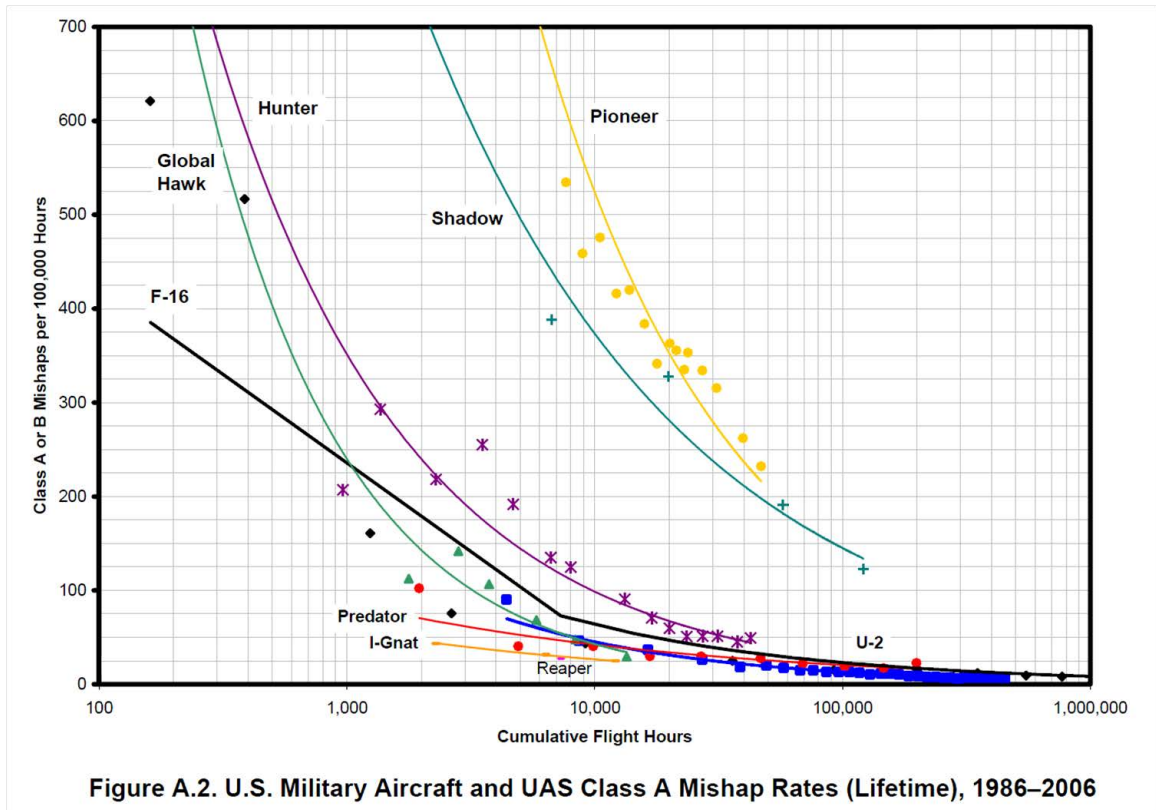


Figure 2. Mishap Rates of Manned and Unmanned Aircraft[8]

which is a positive trend. The Hunter had slightly above; however, the Pioneer had about seven times as many mishaps. A possible explanation for this large number of mishaps is discussed in more detail in Section 1.2.2. Examining the data at 10,000 cumulative flight hours, the F-16 had approximately 70 mishaps per 10,000 hours. The Global Hawk had 50, the Hunter had 100, and the Pioneer had 525 mishaps per 10,000 hours. The interesting information to gather from these data points are that all aircraft lessened their mishap rates. The Pioneer dramatically decreased their mishap rate while the other decreased by approximately the same percentage. However, there is still a significant trend for unmanned aircraft to have a higher mishap rate than manned aircraft. This is not only a demonstration of the “build-fly-fix-fly” mentality that has dominated the design of unmanned aircraft, but it also

shows room for improvement. Although not all the mishaps can be directly linked to a lack of flying qualities research or a flying qualities standard, it does show there is an unacceptable level of Class A and B mishaps leading to a concern of safety for both the aircraft and the environment in which it flies. Flying quality standards aim to manage the link between safety and performance. Successfully controlling this link leads to effective mission accomplishment.

Another important factor to understand the impact of mishap rates is realizing cost associated with these aircraft. According to the US Air Force Fact Sheets, an F-16 A/B costs \$14.6M and an F-16 C/D costs \$18.8M dollars.[9] In comparison, depending on the systems onboard, the Pioneer costs between \$250K to \$1M dollars. This is less than the F-16, but it is still a significant cost when an aircraft is lost. However, the Hunter, depending again on the systems onboard, ranges between \$1.2M and \$30M dollars.[10] This is up to almost double that of the F-16. Needless to say, the price point ranges slightly throughout depending on the different aircraft, sensors, and payloads, but they are all a significant financial loss when an aircraft has a mishap. Cost should not be the only factor in determining what is an acceptable mishap rate. Where the unmanned aircraft will be operating and what is its mission all need to be incorporated into the time, effort, and money allotted to unmanned aircraft research. Furthermore, there is a class of aircraft where returning from a mission is not a necessity. All of these possibilities need to be recognized and taken into the design process.

As new UAVs move beyond the drawing board and previous UAVs find new missions and capabilities, the need to not perpetuate this cycle of accident rates is obvious. A UAV flying qualities standard will assist in ensuring UAVs have an acceptable level of safety. Ensuring this safety, while still accomplishing the required missions, will aid in reducing the alarming mishap rate.

1.2.2 Advanced Concept Technology Demonstration (ACTD) Process.

In the Department of Defense (DoD), an extensive acquisition process is required. “The Defense Acquisition System is the management process by which the Department of Defense provides effective, affordable, and timely systems to the users.”[11] This acquisition system is used anytime the DoD is desiring to obtain a new system, anytime a current system receives an upgrade, or any other significant changes are implemented with respect to a given system.

In the early to mid 1990s, UAVs were showing their usefulness and ability to accomplish unique missions; however, the typical acquisition process was slow and delayed the operational implementation of this emerging technology. The Department of Defense Acquisition Program is thoroughly outlined in Department of Defense Directive Number 5000.01 [12] and Department of Defense Instruction Number 5000.02 [13]. In the mid 1990s, the Advanced Concept Technology Demonstration (ACTD) process was created and, as discussed in Section 1.2.1, several UAVs were procured through this process. The purpose of the ACTD program is to allow the ability to evaluate advanced technology early in the development process. The evaluation is accomplished operationally by the warfighter. However, the purpose of the ACTD process is not to replace the acquisition program, but more to provide the warfighter the opportunity to determine a project’s capability and usefulness in a realistic operational environment.[14] UAV development was one of the technologies that exploited this process. UAVs were developed as rapidly as possible, then the capability was put to use in the warfighter’s hands for evaluation. This began the “build-fly-fix-fly” concept that has been at the cornerstone of UAV development and has never quite been abandoned. The ACTD process allowed UAVs to be developed from the drawing board to implementation in only 3 to 4 years versus the typical 10 to 20 years for most aviation programs through the standard acquisition process.

The Pioneer UAV and the Predator UAV were two of the initial unmanned aircraft programs that went through the ACTD process and both had significant complications. The Pioneer was purchased as an “off the shelf” UAV from the Israelis. Soon after purchase, several limitations linked directly to flying qualities were discovered. There was no automatic operation so the aircraft had to be manually operated, leading to the high accident rates described in Section 1.2.1. The desire to quickly implement this UAV without a robust Engineering and Manufacturing Development (EMD) program led directly to the aircraft cost being 50% above the original purchasing price.[15]

The Predator UAV was another aircraft that began in the ACTD process. The Predator was developed rapidly. It only took 14 months from the beginning of the ACTD process for the first 10 UAVs and 3 ground stations to be delivered to the military. Initial testing in exercises led to the belief that the Predator was ready for operational use; however, as the Predator began production, complications arose. Debate on increased operational testing and defining the requirements of the Predator system delayed the production by 14 months.[15] Furthermore, during the beginning stages of the operational assessment, the aircraft was found to be “deficient in several areas, including mission reliability, documentation, and pilot training.”[14] These deficiencies are directly related to a high accident rate. Unfortunately, most of the complications with the Predator have been found by the warfighter during operational use. Then it is put on the warfighter to find a way to work around the problem, rather than return to the EMD stage to find a way to correct and eliminate the problem. As with the Pioneer, the Predator initially cost the ACTD program around \$15M and production costs are seen to be closer to \$30M.[15]

The drawbacks of the ACTD process were realized with aircraft like the Pioneer and Predator, and steps were taken to ensure the same complications were not re-

peated with newer aircraft such as the Global Hawk. The first step was to extend the ACTD process two to four year time line. Additionally the Global Hawk program (originally labeled the High Altitude Endurance (HAE) program) was reduced to a single requirement, cost. There was a cap of \$10M per aircraft and this was the only requirement. Any performance or operational desires could be ignored or altered in order to remain within the budget requirement.[15] Although the ACTD process was initially touted as reducing the implementation time, the Global Hawk post-ACTD program, beginning in June 2000, showed that there were no changes in the production rates.[16] The Global Hawk entered a formal EMD program after the ACTD and helped in the development and research process. These steps appear to have aided the accident rate reduction as discussed in Section 1.2.1; however, other complications, to include airworthiness certification, are still plaguing the program to this day.

Specifically to UAVs, the ACTD process allowed the warfighter to receive UAV technology and determine its usefulness, problems, and other potential advancements in real time. However, this development was not without complications. The quick implementation of these vehicles fostered a high mishap rate, as described in detail in Section 1.2.1. With each new aircraft and mission, the understanding of the technology and the corresponding capabilities increased dramatically. With the ACTD process, changes were having to be implemented post production or the pilot and/or operator procedures were adapted to account for, but not necessarily fix, any shortcomings.[5]

1.3 UAVs in National Airspace System

Further validation of the future of UAVs and the corresponding mission potential can be demonstrated by Congress creating the FAA Modernization and Reform Act of

2012. This act requires the FAA to create a plan to integrate civil unmanned aircraft into the National Airspace System (NAS). Several different tasks for the FAA to accomplish were listed in this act, but of particular interest are the following:

- Standards and certification for unmanned aircraft, to include a see and avoid system
- Best methods to enhance technologies
- Process to develop certification and flight standards for unmanned aircraft systems at test ranges
- Best method to ensure safe operation of civil unmanned aircraft systems in the national airspace

The deadline for these items was “as soon as practicable, but not later than September 30, 2015.”[17]

1.3.1 Certification Standards.

Currently, UAVs have minimal, if any, standards or requirements to ensure safe flying operations and adequate performance. However, UAVs needed to be integrated into the NAS so Congress enacted the FAA Modernization and Reform Act of 2012 which mandated that UAVs must be allowed to operate in the NAS.[17] This led to a review of how current aircraft are authorized to fly in the NAS. Title 14, Code of Federal Regulations (CFR) Part 21 describes the certification procedures for any aircraft wishing to fly in the FAA controlled airspace. Title 14, CFR Part 21 Subpart H explains airworthiness certificates and experimental certificates. Although UAVs are not explicitly listed, they fall under the definition of research and development for experimental certificates: “testing new aircraft design concepts, new aircraft equipment, new aircraft installations, new aircraft operating techniques, or new uses for

aircraft.”[18] As an example of how a currently operational aircraft validates that it is airworthy, Title 14, CFR Part 25 gives the requirements that transport category aircraft must comply with in order to be certified. Furthermore, Title 14, CFR Part 25 Subpart B describes the control and handling requirements to include trim, static stability, dynamic stability, and stall characteristics, and so forth.[19] All aircraft must either comply with these standards, or have their certification validated through the FAA, if they wish to fly in the NAS. For DOD manned aircraft, these control and stability requirements lead directly back to the flying qualities standard MIL-STD-1797B for fixed-wing aircraft and ADS-33E-PRF for rotary-wing aircraft which has been accepted by the FAA for certification purposes.

The certification requirements have caused complications not just for unmanned aircraft in the United States, but also for our NATO partners. The Euro Hawk is a similar airframe to the Global Hawk but has additional Signals Intelligence Collection (SIGINT) capabilities. The Euro Hawk program was initiated in 2006 with a system development contract in 2007. The first flight and delivery of the Euro Hawk to Germany was scheduled for 2010; however the FAA certification delayed delivery and pushed this time line back to July 2011. Eventually, the various flight certification complications became insurmountable and in May 2013 the program was terminated. The German Air Force initially planned to purchase four to five Euro Hawks and the airworthiness standards impeded the development of these additional UAVs which would keep the production line open and potentially reduce the cost of future aircraft.[20] With recent changes to the FAA’s categorization, registration, and certification process for larger UAVs, the Euro Hawk program has resurfaced with the hope of the program once again becoming operational.[21]

1.3.2 FAA's Incorporation of UAVs.

The concern of how to integrate UAVs into the NAS and ensure proper certification and the need for safety is understood. The first Integration of Civil Unmanned Aircraft Systems in the National Airspace System Roadmap was published in November of 2013. This document outlines a five year projection and specifically lists items that need to be addressed in order to allow manned and unmanned aircraft to operate safely in shared airspace. Some of these items are listed in Figure 3. In particular,

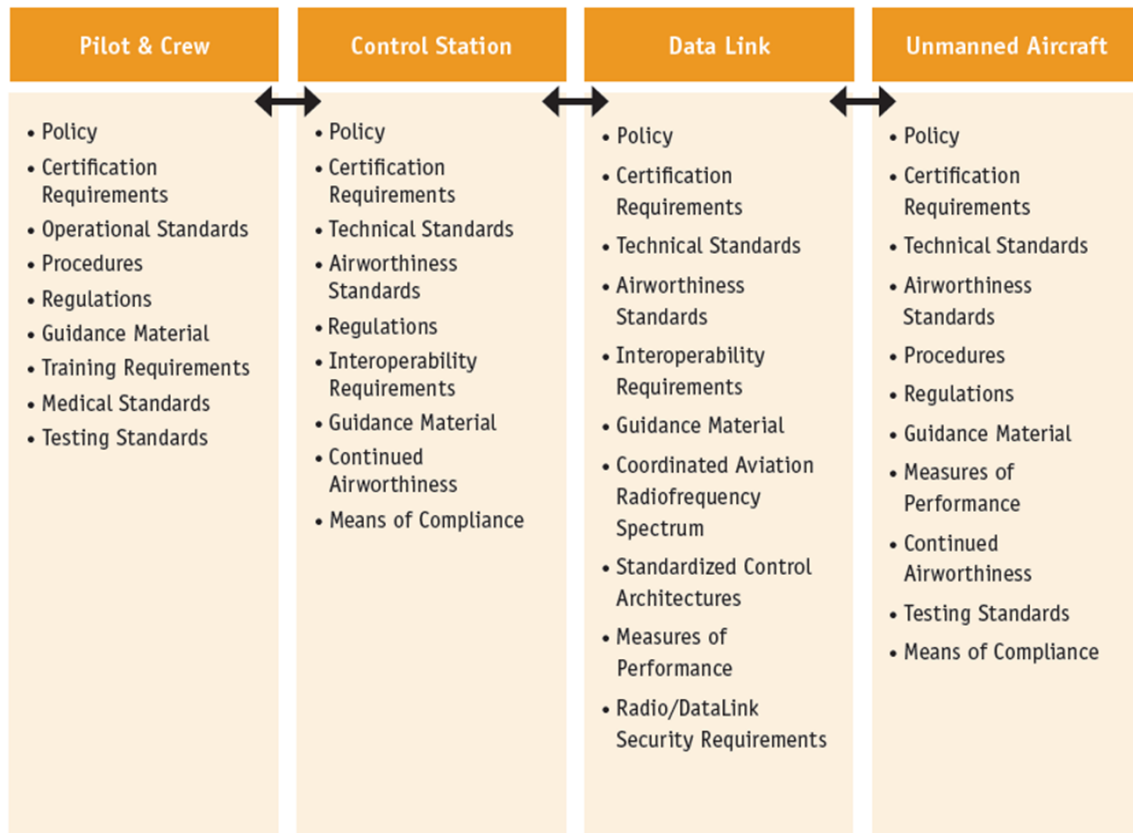


Figure 3. AVS Products to Regulate UAS Operations[22]

the document notes requirements for certification, technical standards, airworthiness standards, guidance material, and measures of performance.[22] All of these items are dependent on a standard for flying qualities.

Furthermore, the Joint Planning and Development Office created the UAS Comprehensive Plan. “The UAS Comprehensive Plan sets the overarching, interagency goals, objectives, and approach to integrating UAS into the NAS”. Six specific goals were outlined in this document:

- Routine Public Small UAS Visual Line-of-Sight (VLOS) Operations Conducted in the NAS (2015)
- Routine Civil Small UAS VLOS Operations Conducted in the NAS (2015)
- Routine Public UAS Operations in the NAS (2015)
- Routine Civil UAS Operations in the NAS (2020)
- Define, Determine, and Establish Acceptable Levels of Automation for UAS in the NAS (TBD)
- Foster U.S. International Leadership in UAS Capabilities and in Standards Development (Ongoing)

The plan also discusses national objectives which include establishing appropriate airworthiness certification requirements aligning with the third goal of UAS operations in the NAS.[23] Title 14, CFR 91 is the reference used to guide the FAA in accomplishing this goal. This CFR explains civil aircraft airworthiness and states that the pilot in command must deem if the aircraft is in a safe condition for flight.[24] This still leaves unanswered questions when working with unmanned aircraft. Who is the pilot? And what is deemed “safe” for unmanned aircraft?

The first goal listed in the UAS Comprehensive Plan, small UAS operations in the NAS, has had some forward traction. The Small UAS Notice of Proposed Rulemaking (NPRM) was released in February of 2015 and public comments on this document were closed in April of 2015. This document proposed a way to integrate small

UASs (less than 55 pounds) in the NAS. Reviewing the document, no discussion of airworthiness criteria were included. In fact, it specifically stated that the FAA Airworthiness Certificate was not required. The proposal put the responsibility for safety of flight on the operator, or pilot, and stated that they must, “maintain a small UAS in condition for safe operation and prior to flight must inspect the UAS to ensure that it is in a condition for safe operation.” The document does discuss the difference between performance standards (focusing on the outcomes) and design standards (focusing on specific ways to get the outcomes); however, it does not go into any further discussion on this topic.[25] This NPRM resulted in the creation of the Small Unmanned Aircraft Regulations, Title 14, CFR Part 107. This is the rules for non-hobbyist small, less than 55 pounds, unmanned aircraft operations. Included in this regulation are requirements to avoid manned aircraft, ensure the aircraft remains within sight, operating at a maximum altitude of 400 feet above the ground, and when air traffic control must be contacted. Part 107 also directs the operator to have a remote pilot airman certificate. Finally, the aircraft does not need to have an aircraft certificate. This is a step towards expanding UAV operations; however, there is still a need to look at UAVs operating in the NAS.

Since the Congressional Act mandating the FAA create a plan to integrate UAVs into the NAS, some progress has been made. First, the FAA has classified UAVs into three weight categories to clarify the registration requirements. The FAA states that “registration helps us ensure safety for you, others on the ground, and manned aircraft. UAS pose new security and privacy challenges and must be traceable in the event of an incident. It will also help enable the return of your UAS should it be lost.”[26] The weight categorization is based on the weight including everything onboard or attached to the aircraft. In order to be registered, the UAV must also be operated outdoors. The first type of UAV categorization is aircraft that weigh 0.55

pounds or less. Aircraft that fall into this category do not need to be registered. UAVs that weigh greater than 0.55 pounds and less than 55 pounds must be registered. The registration for this category of aircraft is somewhat simple, requires minimal data input, and can be completed online. For UAVs greater than 55 pounds, the registration must be completed under Title 14, CFR 47.

There are also three different types of UAV Operations: Public Operations, Civil Operations, and Model Aircraft Operations. Public Operations are operations where the aircraft is used only for or owned by the United States Government (including the military), by the government of a State, the District of Columbia, or a territory of the United States. Civil Operations are all of those UAV operations that are not Public Operations. When the UAV is used for Civil Operations, either a Section 333 Exemption or a Special Airworthiness Certificate is required. Finally, the FAA addresses Model Aircraft Operations which is meant for hobby or recreational purposes only. The FAA has taken steps to help classify and regulate UAV operations, but still there is no mention of UAV flying qualities.[27]

UAVs will continue to improve and increase in mission capability and versatility. The field has many commercial, combat, and government uses and their versatility potential is only now being realized. UAVs can perform missions such as reconnaissance, high altitude missions, strike and attack, surveillance, or a combination of all these missions for typical military operations. However, new applications are being employed which may help serve the civilian sector such as crop maintenance, security, disaster relief, fire fighting, and weather reporting. These missions can be compared to military missions, so the development of unmanned aircraft must be accomplished with the cooperation of both the military and civilian sectors. With each improvement comes an increase in capability and the need to ensure UAVs are safely operated. Furthermore, if UAV airspace is restricted, then the missions will likely be restricted

as well. A flying qualities standard can aid in the certification of UAVs to comply with any CFRs required to fly in the NAS. If the full utilization of this type of aircraft is to occur, the field of UAV flying qualities must be researched and developed. This will aid in determining the usefulness and validity of a flying qualities standard, specification, or guideline for future UAV operations and developments.

1.4 Research Goals and Objectives

UAVs have a unique potential that will continue to be used and developed. Their missions continue to expand and the allowable airspace is growing. The benefit of this field is understanding that UAVs have the ability to accomplish those tasks considered too dull, dirty, or dangerous for manned aircraft. Despite the fact that UAVs have such potential, minimal research and development has gone into the field of UAV flying qualities. The goal of this research is to expand the field of flying qualities related directly to UAVs. It will research, identify, and validate a paradigm that will support unmanned aircraft flying qualities.

1.4.1 Objective 1.

The first objective in this research is to determine the parameters that will bound this problem. In particular, aircraft, level of automation, and mission tasks will be defined. Then a discussion of how to best analyze the flying qualities for these parameters will be given. Specific methods and criteria from current flying qualities standards (MIL-STD-1797A and ADS-33E-PRF) will be the primary source for this analysis.

1.4.2 Objective 2.

The second objective is to propose a UAV flying qualities structure. Historical and current flying qualities standards will be reviewed as possible frameworks, as well as research that has proposed new structures for current manned aircraft flying qualities specifications.

1.4.3 Objective 3.

The third objective is to apply the proposed flying qualities structure from Objective 2. The parameters and criteria suggested in Objective 1 will be used in the modeling, creation, and validation of this flying qualities framework. It will focus on creating a process to be used in the first phase of the model validation in order to increase the success rate of UAV operations.

1.5 Summary

UAVs have the potential to aid both the civilian and government sectors. As time progresses, the use of UAVs has increased dramatically. They will undoubtedly be a priority for future military actions and the civilian population can see the benefits and possibilities of developing and exploiting this technology. The future of UAVs is wide open. Missions are continually expanding and changing. Furthermore, the concept of a UAV flying in the same airspace next to a civilian airliner is daunting. The field must be ready to help mold the standards needed to ensure safe flying operations, while not compromising the mission, yet fully exploiting the unique capabilities of these aircraft. This must be done before an unnecessarily restrictive standard is enforced which may limit the vast opportunities these aircraft provide. This is the way forward and now we must determine how best to implement a flying qualities standard that will allow for the flexibility of these aircraft to continue.

II. Literature Review

Unmanned aircraft have demonstrated their usefulness by successfully performing missions deemed too dull, dirty, or dangerous for manned aircraft. Currently, UAVs are designed using one of two development approaches. In the first, sophisticated autonomous and semi-autonomous control systems are designed for UAVs with minimal consideration of the flying qualities of the vehicle on which they will be implemented. Once the control systems are designed, the search for a suitable airframe commences. The second approach is the converse of the first. The vehicle is designed with generic flying quality capabilities, typically based on manned aircraft flying qualities. In this approach, it is assumed that those flying qualities will be suitable for executing the mission tasks it will be asked to perform. In both cases, mission tasks and flying qualities are not being developed in unison with one another, which leads to an inefficient “build-fly-fix-fly” development cycle. Given the state of unmanned aircraft design methods, several questions must be raised. What are the current flying quality standards? What is the current status of UAV flying qualities? And if no such flying qualities standard exists for UAVs, is there any additional guidance readily available? This literature review aims to answer these questions.

2.1 Flying Qualities Standards

“The director of the Air Force’s unmanned task force has compared ... UAV potential based on today’s systems to judging manned aircraft based on the Wright Brothers Flyer. Large numbers of increasingly capable UAVs - when integrated with our fifth-generation fighters – potentially give the United States the ability to disrupt and overwhelm an adversary using mass and swarming tactics, adding a new dimension to the American way of war.” [28]

– Robert M. Gates

To fully understand the topic of UAV flying qualities, one must look to the development of current manned aircraft flying qualities. Much research has been devoted to the topic of flying qualities since it is essential to understand for sustained flight, it supports an increase in performance in any aircraft, and it assists in having a successful EMD program. One viable approach that could be used to determine the best path for introducing new standards for UAV flying qualities is to see where the field of flying qualities has been and how it has progressed. Currently, there are two major flying qualities standards or references. MIL-STD-1797B, the flying qualities standard for manned fixed-wing aircraft, was released in 2006. ADS-33E-PRF, the flying qualities standard for manned rotary-wing aircraft, was released in 2000. Technically, there is an unmanned aircraft flying qualities standard, AFFDL-TR-76-125. However, this document is a flying qualities reference for RPVs that was released in 1976 and has not been updated since. In actuality, only the MIL-STD-1797B and ADS-33E-PRF are used by personnel designing new aircraft or updating existing aircraft, since the AFFDL-TR-76-125 is outdated and follows the same methodology as MIL-F-8785, a predecessor to MIL-STD-1797B.

MIL-STD-1797B and ADS-33E-PRF use two different approaches to classify the respective aircraft. MIL-STD-1797B, and therefore AFFDL-TR-76-125, focuses on aircraft gross weight and load factor to classify manned fixed-wing aircraft. Then the flying qualities are specified using metrics according to the assigned aircraft classification. Meanwhile, ADS-33E-PRF looks at mission tasks and the operational environment to define the manned rotary-wing aircraft classification. Then the flying qualities criteria are determined based on specified metrics and the assigned rotary-wing aircraft classification.

2.1.1 Manned Fixed-Wing Aircraft Standards.

A predecessor to the current flying qualities standard for manned fixed-wing aircraft, MIL-STD-1797B, is the MIL-F-8785 series, which was first published in 1954. It was the first time there was a multi-service flying qualities document that specified what was required for satisfactory operations.[29] The first revision, MIL-F-8785B, focused on the dynamic responses of aircraft in terms of natural frequencies and damping ratios. These criteria were used to give recommended ranges for the different flight dynamics modes (such as phugoid, short-period, etc.). This document also accounted for the pilot's ability and desire to control the flight path and added adjustments for turbulence.[30] With the MIL-F-8785B, a Background Information and User Guide (BIUG) was also released. The BIUG contained the detailed information needed to understand MIL-F-8785B, including how and why the criteria were created and how to apply the standards to aircraft.[31]

MIL-F-8785B transformed into the MIL-STD-1797 series and in 1990, MIL-STD-1797A was released. This document, which was updated in 2006 to MIL-STD-1797B, incorporated the BIUG into the standard. It also became more of a discussion of recommendations and allowed for the user to pick the most relevant and appropriate criterion.[32] MIL-STD-1797B is restricted to Department of Defense and US DoD contractors only; therefore, within the framework of this research, MIL-STD-1797A will be used. In order to determine the flying qualities required for an aircraft, MIL-F-8785 and MIL-STD-1797A determine which type, or category, of aircraft is being analyzed. The type is delineated by aircraft weight and aircraft attainable maneuverability. These specifications determine in which class the aircraft is placed. The current classes used in MIL-STD-1797A are listed in Table 1.[33]

Table 1. Classification of Aircraft in MIL-STD-1797A[33]

Class I – Small light aircraft such as:	Light utility Primary trainer Light observation
Class II – Medium weight, low-to-medium maneuverability aircraft such as:	Heavy utility/search and rescue Light or medium transport/cargo/tanker Early warning/electronic countermeasures/ airborne command, control, or communications relay Antisubmarine Assault transport Reconnaissance Tactical bomber Heavy attack Trainer for Class II
Class III – Large, heavy, low-to-medium maneuverability aircraft such as:	Heavy transport/cargo/tanker Heavy bomber Patrol/early warning/electronic countermeasures/ airborne command, control, or communications relay Trainer for Class III
Class IV – High-maneuverability aircraft such as:	Fighter-interceptor Attack Tactical reconnaissance Observation Trainer for Class IV

To clarify and put detailed boundaries on the classification given to any manned fixed-wing aircraft, MIL-STD-1797A plots specific aircraft with respect to gross weight and load factor. Per Figure 4, despite having specific boundaries, there is considerable overlap among the aircraft classes. For example, the C-20 used for airlift support, weighs between 70,000 and 75,000 pounds.[34] This weight puts the C-20 aircraft in both Class II and Class III. Aircraft that fall in an area of overlap may be classified as either class; however, the flying qualities requirements for one class may not address all aspects of the primary mission of the aircraft. Alternatively, if all aspects of the primary mission are not addressed, the flying qualities requirements for the aircraft may be a combination of two or more classes. Regardless of classification, the flying

[illegible]

2.1.1.1 MIL-STD-1797A Flying Qualities Criteria.

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maneuvers that involve high precision and rapid maneuvering such as air-to-air combat, air refueling, and so forth. Category B Flight Phase is nonterminal maneuvers without high levels of precision but still needing accuracy such as climb, descent, and loitering. Finally, Category C Flight Phase includes terminal maneuvers such as takeoff and landing. Once the Class and Flight Phase categories have been identified, then specific flying qualities criteria can be analyzed.

Aircraft control analysis is a complex area of research and much has been done to attempt to make a complex, dynamic aircraft simple. One of the techniques used in the past is the Low Order Equivalent System (LOES) analysis. This analysis takes High Order System (HOS) and eliminates small dynamic responses to simplify the model. This technique works well in classical aircraft control. In other words, aircraft with a Stability Augmentation System (SAS) Control, a control system that increases the stability of the actual aircraft. However, when using the LOES, some of the dynamic modes are eliminated which could prove to be critical and might need to be accounted for in a complex, highly non-linear system as seen in most modern manned aircraft and some advanced unmanned aircraft. Current UAVs range in system complexity and, therefore, the use of the LOES technique by UAVs could not consistently be applied since some UAVs could lose important dynamic responses.

2.1.1.2 MIL-STD-1797A Pitch Criteria.

Fixed-wing aircraft aim to control flight path to ensure mission success and MIL-STD-1797A[33] aims to classify this with flying qualities criteria. The first axis described is the pitch axis and there are two forms of pitch criteria. The long-term pitch criteria focuses on any oscillation that has a period of 15 seconds or greater. The short-term pitch criteria are for those oscillations where the period is less than 15 seconds.

The long-term pitch criteria include damping ratio of the phugoid oscillation, ξ_p , and the ratio of the high-frequency pitch attitude zero, T_{θ_2} . However, to determine these variables, the LOES must be determined. Unfortunately, this LOES technique might lose significant higher order dynamics which is concerning if this criteria is applied to a highly non-linear aircraft, such as some advanced UAVs. Therefore, this criterion will not be examined.

The short-term pitch criteria include several possible criteria: CAP or $\omega_{sp}^2 / (n/\alpha)$, ξ_{sp}, τ_{θ} ; $\omega_{sp} T_{\theta_2}$, ξ_{sp} , τ_{θ} ; transient peak ratio, rise time, effective delay; bandwidth, time delay; pilot-in-the-loop criteria; and Nichols chart boundaries. One problem with the short-term pitch criteria lies in the fact that minimal guidance is given for when to use the various criteria. In fact, MIL-STD-1797A states, “We strongly suggest using several or all of these criteria in an aircraft design, although that probably would not be practical in a specification.” [33]

Control Anticipation Parameter, CAP , is defined as the ratio of instantaneous acceleration, $\dot{q}_o$, to the steady state change in load factor, Δn_{ss} . The important item to note about CAP is that the pilot must guess from the initial response of the aircraft what the end result will be. If CAP is too small, the pilot will be unable to sense the acceleration and continue to make the necessary input. As a result, the change in the load factor is too large and the pilot will likely over-control the aircraft. In the other case, if CAP is too large, the pilot feels a large acceleration compared to the input to load factor and the pilot will reduce their input to avoid a large load factor change. This leads to the pilot undershooting the desired aircraft path. However, CAP is strongly correlated to what a pilot feels, therefore, it is not appropriate for unmanned aircraft which do not have a pilot onboard and will not be investigated during this research.[33]

$\omega_{sp}T_{\theta_2}$ is similar to the literal factor CAP . This requires a LOES analysis and consideration must be given if analyzing a highly non-linear aircraft. Given the potential complexity and non-linearities found in several UAVs, this criterion will not be examined.

The transient peak ratio, $\frac{\Delta q_2}{\Delta q_1}$, rise time, Δt , and effective delay, t_1 all have specific requirements in MIL-STD-1797A. It further qualifies these criteria for level 1, 2, and 3 flying qualities. Furthermore, the rise time, which in this case is similar to CAP , has requirements depending on the Flight Phase Category.[33]

Bandwidth and time delay quantify the stability margin when operated in a closed loop tracking task. A benefit of this criterion is the fact that the LOES is not necessary.[33] For complex non-linear aircraft, such as UAVs, this is very beneficial. Therefore, the bandwidth criterion will be one of the primary criteria used for the initial research into unmanned aircraft flying qualities.

Pilot-in-the-loop (otherwise known as Neal-Smith) criteria focuses on bandwidth again, this time it is defined as the frequency at a closed-loop phase of -90° . However, this criterion involves a pilot model so it is not pertain to UAVs in which every flight mode, including Human Operated, involves some level of automation.

The Nichols chart boundaries are using the open-loop transfer function in order to determine the closed-loop characteristics.[33] Once again, a pilot is necessary for this analysis and, therefore, the Nichols chart criterion will not be explored.

2.1.1.3 MIL-STD-1797A Lateral-Directional Criteria.

There are six main categories of lateral-directional criteria in MIL-STD-1797A[33]: roll mode, spiral mode, dutch roll, coupled roll-spiral oscillation, roll oscillation, and roll ratchet.

The requirement for the roll mode is necessary to ensure precise roll control. The criterion used for the roll mode is the roll mode time constant, T_R , which describes the roll damping.

The spiral mode is defined by a rolling and yawing motion when a roll disturbance affects the aircraft and primarily aims to ensure the aircraft does not diverge too quickly from level flight when the pilot is distracted. The criterion for this mode is the time to double, T_2 , the bank angle amplitude.

Dutch roll is an oscillation in sideslip, yaw, and roll when there is a yaw input. Any dutch roll response to a yaw control input needs to be sufficiently stable and well damped. The criteria used are the dutch roll oscillation undamped natural frequency, ω_d , dutch roll oscillation damping ratio, ξ_d , and the dutch roll damping coefficient, $\xi_d \omega_d$.

The coupled roll-spiral oscillation, similar to a lateral phugoid movement, affects the bank angle control and lateral stability when maneuvering. It typically results in turning flight and demonstrates a lack of roll control effectiveness and large forces on the aircraft. This mode is characterized by the coupled roll-spiral oscillation undamped natural frequency, ω_{RS} , and the coupled roll-spiral oscillation damping ratio, ξ_{RS} .

Roll oscillations take place when the yaw controls are free. The roll rate must be quantified. After a roll control step input, the “roll rate, p , at the first minimum following the first peak shall be of the same sign and not less than the percentage of the roll rate at the first peak” [33].

Roll ratchet is a term used to describe a limit cycle during roll “stop-to-stop” maneuvers. This is when the frequencies of the dutch roll mode and the roll mode are close enough together that they intensify each other. This has the ability to demonstrate and highlight roll Pilot Induced Oscillation (PIO) tendencies, if they ex-

ist. Typically this is seen in aircraft that have roll Command Augmentation Systems (CAS) such as the F-4 and F-16.

The complication of relating all of these lateral-directional criteria to unmanned aircraft is in the realization that unmanned aircraft are designed differently than manned aircraft. Control surfaces as common as ailerons are not always present on UAVs. When this occurs, any turning and rolling motion has to be accomplished solely by use of the rudder and horizontal tail, v-tail, or dihedral. The criteria in MIL-STD-1797A have been formulated with the expectation of common control surfaces. Smaller UAVs also have other unique traits to include a large thrust to weight ratio. The unique characteristics of UAVs cause several of these criteria recommendations to have difficulty translating from manned fixed-wing aircraft to unmanned aircraft.

2.1.2 Manned Rotary-Wing Aircraft Standards.

Manned rotary-wing aircraft initially used the same standard for flying qualities as manned fixed-wing aircraft until 1952 when MIL-H-8501 was created. This document based flying qualities criteria on aircraft weight and inertia. However, in the 1980s, the helicopter community began to realize that the current standards for manned rotary-wing aircraft, which mimicked manned fixed-wing aircraft, did not produce helicopters with flying qualities suitable for their specific and distinctive missions. With this understanding, the helicopter community began working on a new flying qualities standard that was specifically tailored for rotary-wing aircraft. The U.S. Army created a new specification for helicopters, ADS-33, in 1985. This new specification was the starting point to create a new standard with innovative criteria that catered to the unique mission of manned rotary-wing aircraft. One of the distinctive characteristics of rotary-wing aircraft is that the maneuvering requirements necessary to complete mission tasks are not specific to an aircraft's weight. There have been

some revisions and, as of 2000, ADS-33E-PRF [35] is the current standard for any manned rotary-wing aircraft. This document focuses on aircraft whose primary missions include scout, attack, utility, and cargo. The standard defines specific Mission Task Elements (MTEs) which may be linked to the entire operational mission scope of any manned rotary-wing aircraft. Just a few examples of MTEs to better understand this concept are hover, landing, and turn to target. Furthermore, this standard allows for an aircraft's flying quality criteria to be based on required agility and precision for a given MTE, without reference to weight.

MTEs are not the only difference between MIL-STD-1797A and ADS-33E-PRF. ADS-33E-PRF is considered to be a performance standard as well as a flying qualities standard. It correlates specific aircraft characteristics to required tasks. The maneuvers carried out by the aircraft are also separated by a speed regime. In general, rotary-wing aircraft can be separated into hover and low speed flight, or into forward flight. This separation allows for criteria to be more accurately defined and allows for the flight behavior to be characterized by different ranges of frequency and amplitude. This specification also allows for adjustments in the standards due to varying environments, known as the Useable Cue Environment (UCE). The UCE is based on Visual Cue Ratings (VCRs), where VCRs are obtained by the pilot through flight assessments. These VCRs will be designated for each axis, the pitch, roll and yaw attitude, lateral-longitudinal, and vertical translational rates evaluated for stabilization effectiveness by pilots. ADS-33E-PRF also has an adjustment in the required flying qualities for failed states. ADS-33E-PRF was a new approach to an aircraft classification system which was brought about due to the need to have a standard that can adapt to any manned rotary-wing aircraft regardless of shape, size, or mission. [36]

2.1.2.1 ADS-33E-PRF Flying Qualities Criteria.

There are four regions that manned rotary-wing aircraft responses are divided into when discussing flying qualities criteria. The variables that help categorize these regions are frequency and amplitude. The four dynamics regions, seen in Figure 5, are: trim; moderate to large amplitude with low to moderate frequency; small amplitude with moderate to high frequency; and small amplitude with low to moderate frequency.[37] For the three dynamic regions (trim is considered a static region), the

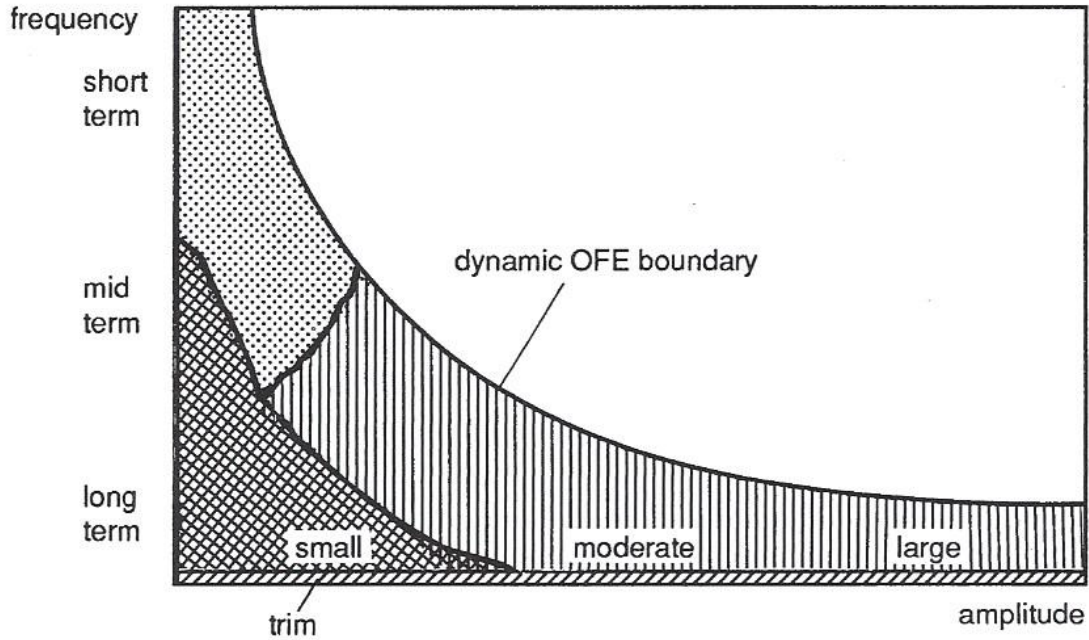


Figure 5. Characterization of Aircraft Response in Four Regions[37]

frequency is defined by bandwidth and phase delay. Small amplitude is defined as being less than 5° in pitch and 10° in roll. Moderate amplitude is between 5° and 30° in pitch and 10° and 60° in roll. Finally, large amplitude is defined as greater than 30° in pitch and greater than 60° in roll. This is shown in Table 2. In the trim region, the frequency is always defined as long term; however, trim can have small, moderate, or large amplitude. Any MTE described in ADS-33E-PRF can be separated into one

Table 2. ADS-33E-PRF Amplitude Definitions[35]

	Small Amplitude	Moderate Amplitude	Large Amplitude
Pitch	$<5^\circ$	$\geq 5^\circ \ \& \ \leq 30^\circ$	$>30^\circ$
Roll	$<10^\circ$	$\geq 10^\circ \ \& \ \leq 60^\circ$	$>60^\circ$

of the four regions shown in Figure 5. Using these regions, each axis is able to be looked at in terms of performance. In the manned fixed-wing aircraft analysis, it is accepted practice to separate the pitch axis from the roll and yaw axes. In contrast, in manned rotary-wing aircraft, there is a high degree of cross coupling. Therefore, the cross coupling dynamics must be looked at in depth and separating axes to remove the effects of other axes could quickly lead to lost dynamics.

A term that needs to be defined before going into detail on the rotary-wing aircraft flying qualities criteria is the term *quickness*. This term is defined as the ratio of maximum achievable rate value for a given attitude change. When performing large maneuvers, this is usually limited by the maximum achievable rate (rate limited) or the attitude control power. For simple responses, the maximum quickness is usually a close approximation to closed loop bandwidth, a commonly used parameter in manned fixed-wing aircraft.[37] Initially, this quickness criterion was termed “task signature” and was created to focus on the task being performed by the aircraft and the corresponding dynamics. As seen in Figure 6, there is a distinction between the “task dynamics” and the “pilot dynamics”. The task signature criterion aimed to focus on the task dynamics and not evaluate the pilot dynamics.[38] The peak rate to attitude change ratio allows for a focus on the task dynamics which is the pivotal feature of ADS-33E-PRF and what makes it such an innovative way of looking at manned rotary-wing flying qualities.

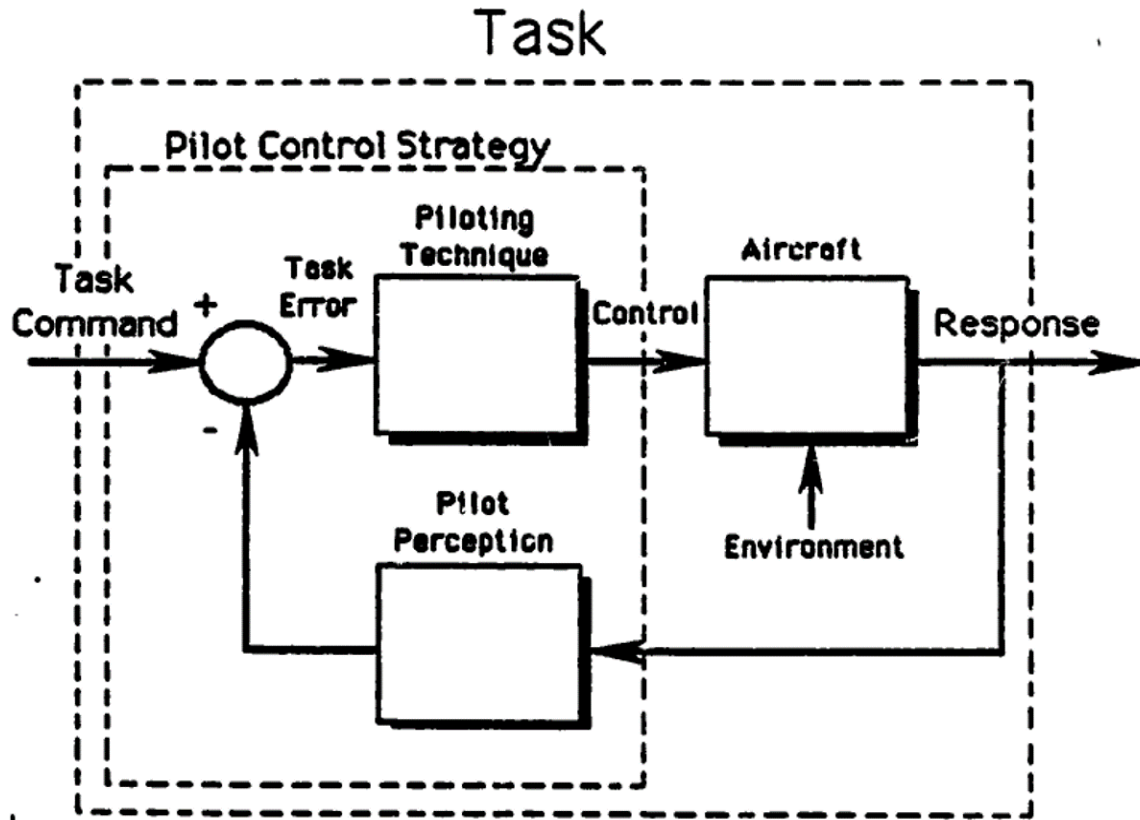


Figure 6. Block Diagram of Pilot-Vehicle-Task System[38]

2.1.2.2 Pitch and Roll Axis Response Criteria.

In manned rotary-wing aircraft flight dynamic analysis, pitch and roll criteria are very similar. With this being considered, the discussion will focus primarily on the pitch axis knowing a similar discussion could take place for the roll axis.

In order to have the ability to perform a given maneuver, the manned rotary-wing aircraft must have a minimum achievable pitch rate, which is defined as control power. This requirement is shown in Figure 7,[37] and is a valid criterion for the moderate to large amplitude with low to moderate frequency maneuvers. The best criterion for large amplitude maneuvers are control power available and quickness. For pitch maneuvers, quickness is defined as the ratio of maximum (or peak) pitch rate, q_{pk} , to

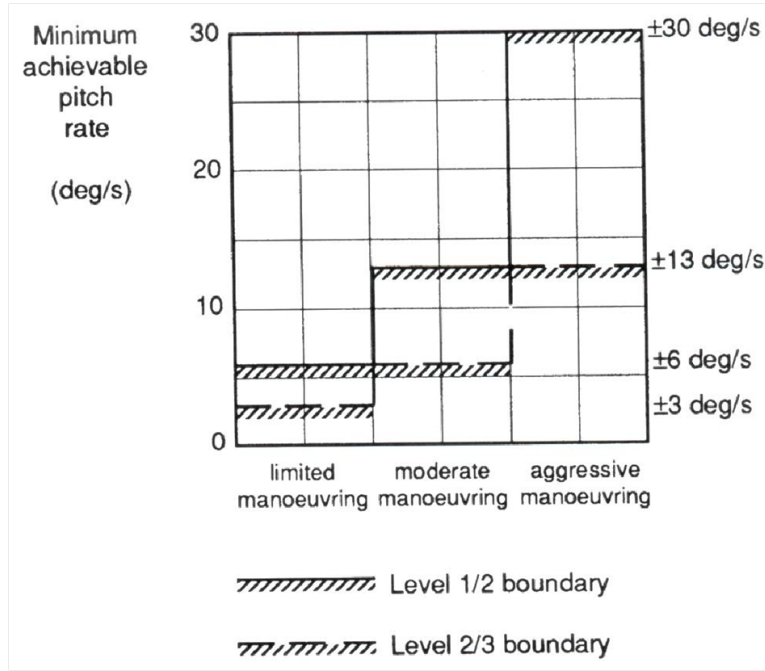


Figure 7. Minimum Pitch Control Power Requirements[37]

maximum change in pitch angle, $\Delta\theta$: [35]

$$\frac{Q_{pk}}{\Delta\theta}$$

This criterion has the possibility of being relevant to UAVs and will be examined further.

For the region of small amplitude with moderate to high frequency, the pitch phase delay, $\tau_{p\theta}$, is used to determine flying quality levels. As seen in Figure 8, the flying quality levels are determined using bandwidth, ω_{BW_θ} , and Pitch Phase Delay.[37][35] Since bandwidth is directly related to the frequency of a maneuver, it will be beneficial to investigate this criterion.

For the region of small amplitude with low to moderate frequency, the focus is to ensure the manned rotary-wing aircraft do not diverge from their trim condition if the pilot's attention is momentarily distracted and the controls are left free. There is

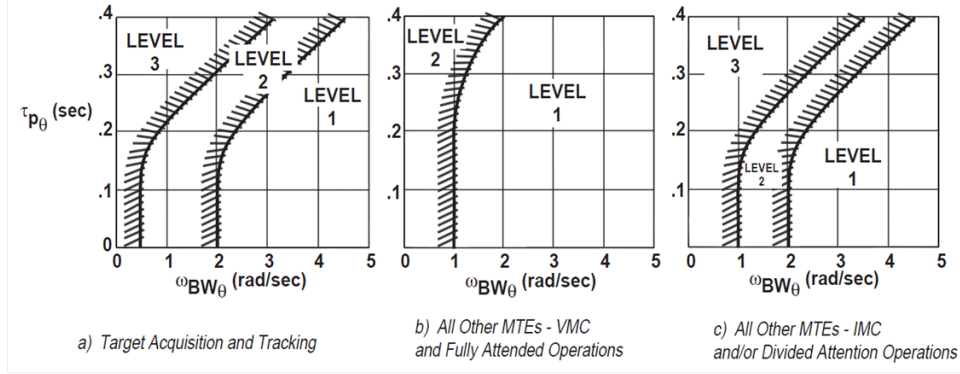


Figure 8. Parameters for Pitch Attitude Changes[35]

a tendency for a spiral mode to surface in this region. The criterion used to control this is the time to double, t_d , the amplitude of a roll input.[37][35] However, this is more focused on a pilot in the seat, which UAVs do not have. Thus, this criterion will not be studied.

Trim is a static region that requires adequate control margins to perform maneuvers; however, there must also be the ability to trim the aircraft to allow for minimal input to keep the three dimensional location in airspace. To ensure this region is acceptable, limits are put into place in terms of the amount of control used. The criterion is a percentage of control used per control force.[37][35] This criterion is geared primarily towards rotary-wing aircraft or aircraft that can hover. For the purposes of this initial unmanned fixed-wing aircraft flying qualities research, there is not much evidence to suggest investigation in this area would provide utility for this research. However, as research in this field expands to unmanned rotary-wing aircraft, it will be necessary to examine criteria fitting for aircraft that hover.

ADS-33E-PRF has additional criteria for the heave, yaw, and cross-coupling axes. However, the focus of this document is on unmanned fixed-wing aircraft and these additional rotary-wing axes do not have much correlation with fixed-wing axes. Once

again, as this research expands, so will the need to investigate additional flying qualities criteria.

2.1.3 Unmanned Vehicle Standards.

The only document that can be remotely classified as a flying qualities standard for unmanned vehicles is AFFDL-TR-76-125 [39], which was published in 1976. However, it is not a true standard. It is actually Phase II of a three-phase Small Business Innovative Research (SBIR). The intention was for Phase II to determine a set of flying qualities criteria for RPV design, and then have Phase III flight test the criteria. Upon completion, the objective would be to develop a tri-service RPV flying qualities specification with a background information and user guide, similar to MIL-F-8785 and the corresponding BIUG.[40]. Since the publication of AFFDL-TR-76-125, there has been little to no work performed to update the document. The manned fixed-wing aircraft flying qualities standard at the time was MIL-F-8785B, which is significant because the two documents are very similar in organization, scope, and substance. Furthermore, AFFDL-TR-76-125 only addresses stability augmentation, and not command and control augmentation or automation which modern UAVs use. The standard does state that the entire system must be considered, an insightful observation since the full spectrum of interaction between all components of unmanned systems had yet to be fully investigated and understood. The entire system is described to include the bare airframe, the airframe with augmentation, automatic and manual control, command, control, and communication data link subsystems, and the pilot consoles, displays, and controls. Today, this “entire system” would be referred to as a UAS.

To determine the flying qualities needed for a RPV, AFFDL-TR-76-125 tailors each requirement by four items:[39]

- The kind of vehicle (Class)
- The job to be performed (Flight Phase)
- How the job is performed (Automatic, Manual Control)
- How well or easily the job must be performed (Level of Flying Qualities)

There are four classes by which RPVs are grouped and they are separated mainly by maneuvering capability and size. The RPV classifications that each aircraft is placed into are specified as follows:

- Class I – Small, light mini RPVs
- Class II – Low-maneuverability RPVs
- Class III – Medium-maneuverability RPVs
- Class IV – Highly maneuverable RPVs

AFFDL-TR-76-125 reviews several different approaches for distinguishing aircraft classes including weight versus maneuverability, weight versus mission, and maneuverability levels. According to the document, the first approach, weight versus maneuverability, is not desirable since RPV's with similar weight can perform missions requiring low to high maneuverability ranges. Therefore, there is little correlation between weight and maneuverability. The second approach, weight versus mission, results in too many classifications since every possible mission needs to be analyzed. The concern was also raised of what to do with unusual or new RPV missions. Furthermore, when investigating aircraft based solely on their weight and mission, the approach appears to discount maneuverability which was believed to be a primary variable in flying qualities. According to the document the third and final approach, maneuverability levels, appears to be most applicable for RPVs. Maneuverability

played the largest role in determining the mission, leading to the classifications listed above. There are also four flight phase categories which are “based on maneuvering, tracking, and flight path control requirements”. [39] The categories are as follows:

- Category A – Flight phases requiring rapid maneuvering, precision tracking, and/or precise flight path control
- Category B – Flight phases requiring gradual maneuvers without precision tracking, although accurate flight path control may be required
- Category C – Launch/recovery flight phases that require rapid maneuvering, precision tracking or precise flight-path control
- Category D – Launch/recovery flight phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required

The manned fixed-wing aircraft standards prior to this document, MIL-F-8785B, only had three categories. For AFFDL-TR-76-125, the launch and recovery phase was separated into two different categories. This allowed for precision requirements, such as need to use an arresting gear versus using a parachute to land. The two control mechanizations include automatic and manual. The automatic control is described as “autonavigation, sensor following, or autopilot” while the manual control allows for the pilot to be in the loop and have direct control of the aircraft. [39] AFFDL-TR-76-125 is outdated and not used as a reference for current unmanned aircraft; however, it had insight into the complexity of this unique type of aircraft.

2.2 Handling Qualities Rating Scales

An important part of determining flying qualities criteria is the need to bound the criteria. Currently, in both MIL-STD-1797A and ADS-33E-PRF, flying qualities

criteria have boundaries for level 1, 2, and 3 handling qualities. The term handling qualities was defined by George E. Cooper and Robert P. Harper as, “those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.”[41]. The terms handling qualities and flying qualities are very similar with a minor distinction being that flying qualities relates more toward concrete criteria while handling qualities involves the pilots interpretation of the criteria. Level 1 is satisfactory handling qualities; “Satisfactory flying qualities are clearly adequate for the mission flight phase. Desired performance is achievable with no more than minimal pilot compensation.” Level 2 is acceptable handling qualities; “Acceptable flying qualities are adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.” Level 3 is controllable handling qualities; “Controllable flying qualities are such that the aircraft can be controlled in the context of the mission Flight Phase, even though pilot workload is excessive or mission effectiveness is inadequate, or both.” [33] The flying qualities criteria and the corresponding level is an objective data point. Aircraft characteristics are analyzed and plotted to determine if they fall into level 1, 2, or 3 handling qualities. However, the determination of the boundaries for the various levels are created from subjective data.

2.2.1 Cooper-Harper HQR Scale.

The Cooper-Harper Handling Qualities Rating (HQR) Scale, seen in Figure 9 was created to standardize the process a pilot goes through to give their subjective opinions on the handling characteristics of an aircraft. It attempts to evaluate an aircraft’s handling qualities purely from qualitative data. By sequentially going through the Cooper-Harper Scale, engineers hope to get specific diagnostic comments about how

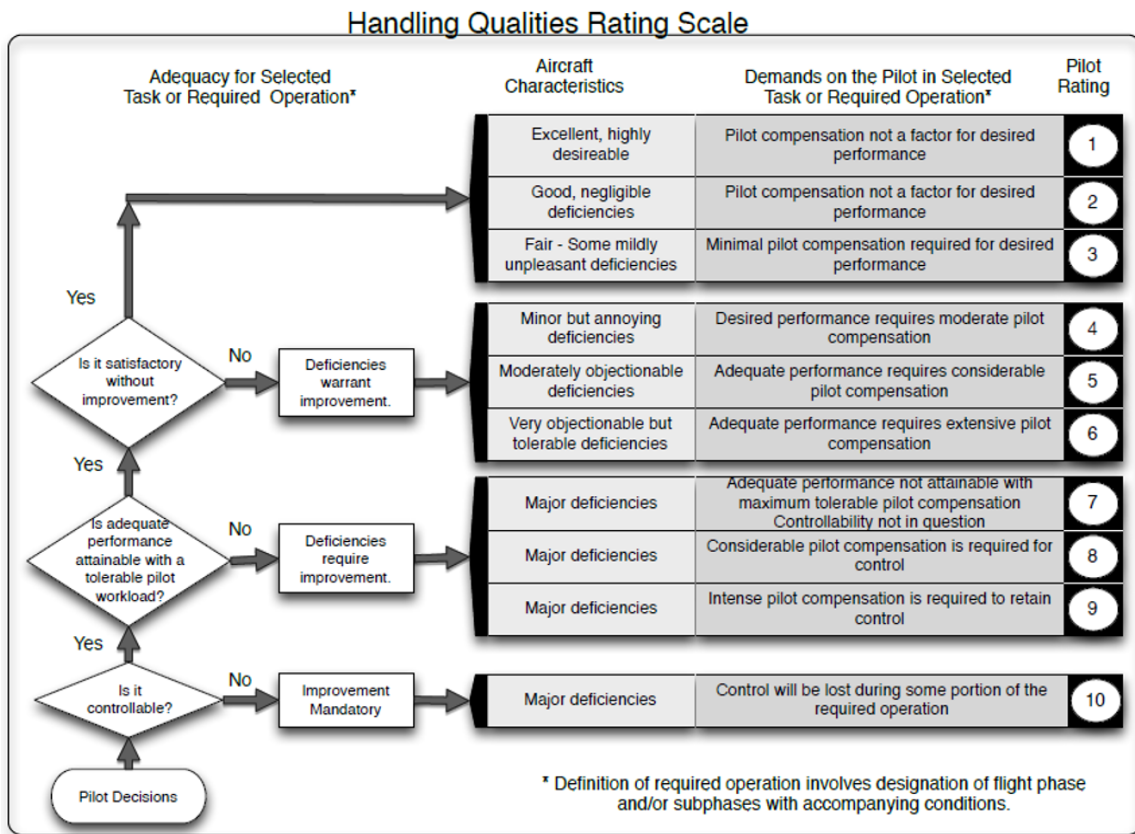


Figure 9. Cooper Harper HQR Scale[41]

the aircraft performed a specific task. [41] In fact, quite often, the comments the pilot makes on how the aircraft flies are far more valuable than any objective criteria. [42] Several different scales have been used in the past; however, the one seen in Figure 9 became widely accepted in 1966 within the flying quality community. Then in 1970 it was used in MIL-F-8785B and is currently used in MIL-STD-1797A. [42] This scale forces the pilot to answer some specific questions with either a concrete “yes” or a “no”. This eventually leads to the pilot rating ranging from 1 to 10. A pilot rating of 1, 2, or 3 equates to a level 1 handling quality. Similarly, a pilot rating of 4, 5, or 6 equates to a level 2 handling quality and a pilot rating of 7, 8, or 9 equates to a level 3 handling quality. This is a beneficial process for manned aircraft, both fixed-wing

and rotary-wing; however, it is difficult to apply to unmanned aircraft since there is no pilot in the seat to give their subjective opinions on how well the aircraft flies.

2.2.2 Modified Cooper-Harper for Unmanned Vehicles Displays (MCH-UVD).

Some research has been accomplished to find a way to subjectively evaluate unmanned aircraft displays. Figure 10 shows one attempt at evaluating displays, the Modified Cooper-Harper for Unmanned Vehicles Displays (MCH-UVD). It takes the Cooper-Harper Scales from Figure 9 and instead of evaluating the pilot's ability to control the aircraft, this scale focuses more on the evaluation of how well the displays allow the operator to process information.[43] This is a beneficial scale; however, it does not address the aircraft's ability to perform a mission.

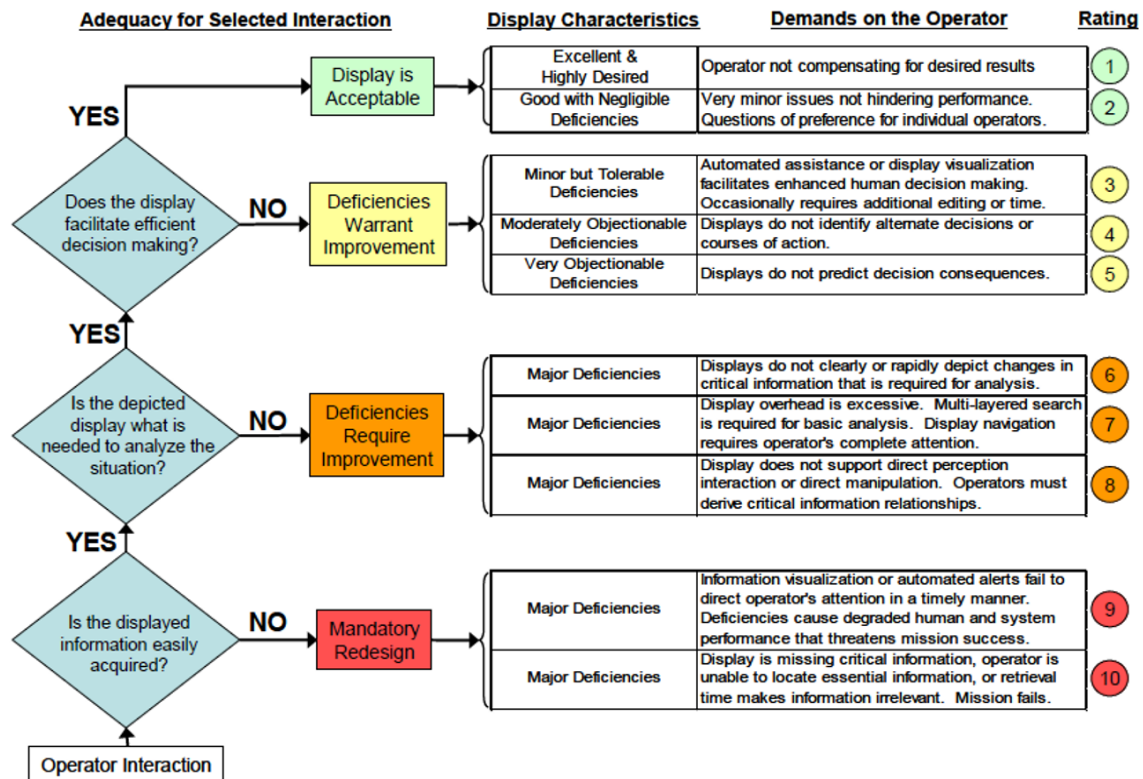


Figure 10. Modified Cooper-Harper (MCH-UVD) Scale[43]

2.2.3 Modified Cooper-Harper HQR Scale.

The most widely accepted handling qualities rating scale for unmanned aircraft systems is seen in Figure 11 [44]. This rating scale modifies the Cooper-Harper HQR

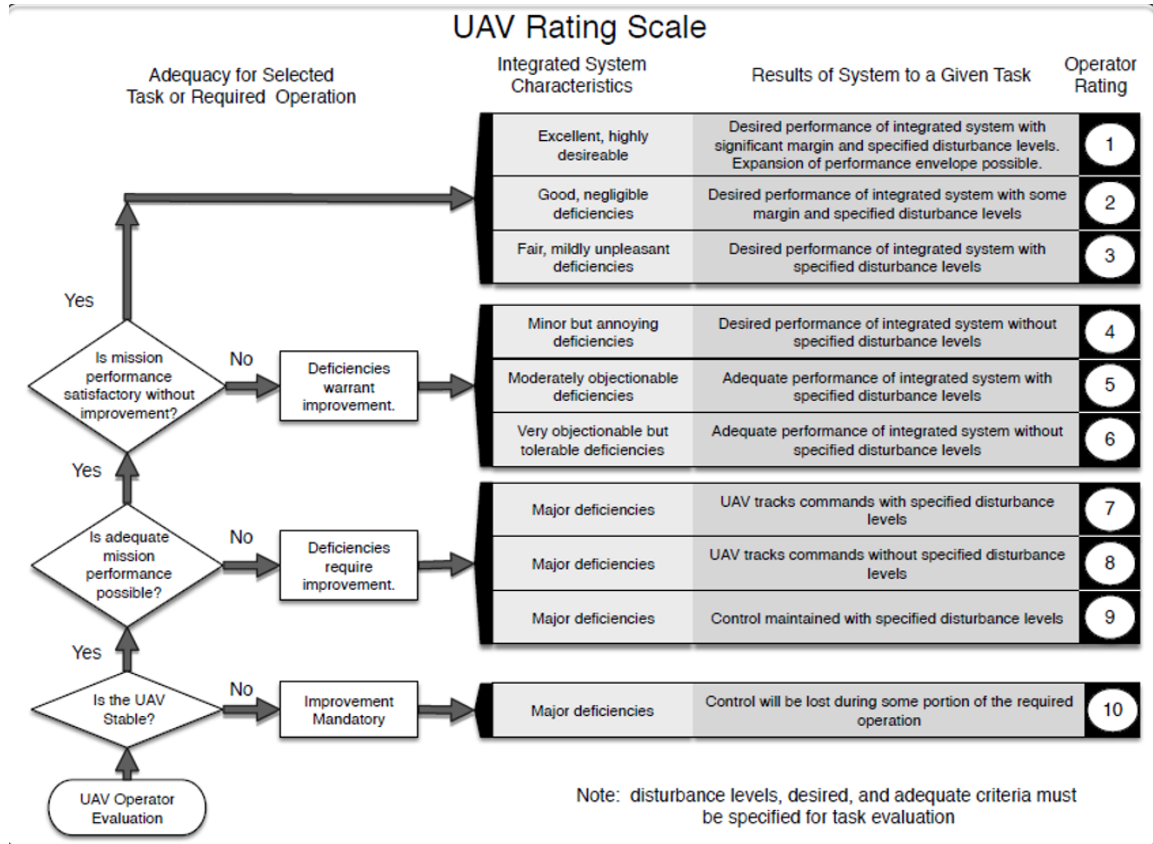


Figure 11. Modified Cooper Harper Scale for use in UAV Evaluation[44]

Scale and adjusts it to incorporate the unique characteristics and operations of UAVs. The focus is on the UAV operator and on UAV mission performance. This modified Cooper Harper scale is adjusted to be generic for any UAV task flown. Additionally, the sensor system is included in the mission performance evaluation descriptions. The rating of 7, 8, and 9 are solely dependent on the UAV, not the sensor. This is a start to understanding on how to rate handling qualities for unmanned aircraft.

Despite the various rating scales available, there does not appear to be a cohesive agreement on what “good” UAV performance entails. Various concepts have included the UAV mission performance, the operator workload, and the workload placed on the aircraft. Despite the research already accomplished, there does not appear to be an agreed upon standard and this is a field that is viable for further research and development.

2.3 Related Research

2.3.1 Mission Task Research.

ADS-33E-PRF took an innovative approach towards classifying flying qualities. Instead of considering the aircraft first, the performance and flying qualities standard looks at mission first and, in particular, the specific tasks required to accomplish a mission. Although this is an innovative approach for flying qualities, the MTE concept has been used successfully in the past to aid in the evaluation and investigation of aircraft and aircraft related systems.

One area of research[45] that used the mission task approach for evaluation was for Head-Up Display (HUD) designs. One of the primary reasons this approach was taken is due to the understanding that modern HUDs interact with aircraft dynamics, to include handling qualities. In this investigation, 5 MTEs were chosen for design evaluation. The tasks were specifically selected to ensure they were appropriate for missions the aircraft, and therefore the display, would perform. The tasks were also chosen to include aggressive pilot tracking. During this kind of maneuver, trends are highlighted and this is where the aircraft and its displays are performing at their maximum capacity. The final item to note from this research is the acknowledgment of the need for performance criteria from which to compare the various displays which are tested.

Another study[46] was completed to understand high angle of attack handling qualities on the F-18. This research also used the MTE approach. Since the testing was accomplished in an uncommon flight regime, unconventional maneuvering and dynamics were expected. Therefore, an initial list of necessary maneuvers were gathered from the Standard Evaluation Maneuvers Set (STEMS) created by McDonnell Douglas Aerospace. The STEMS were a starting point and then ground testing was used to develop and refine the maneuvers. It was the goal of the various maneuvers to ensure both good and poor handling qualities were demonstrated. Another approach this research took was a pyramid of maneuvers seen in Figure 12. This approach

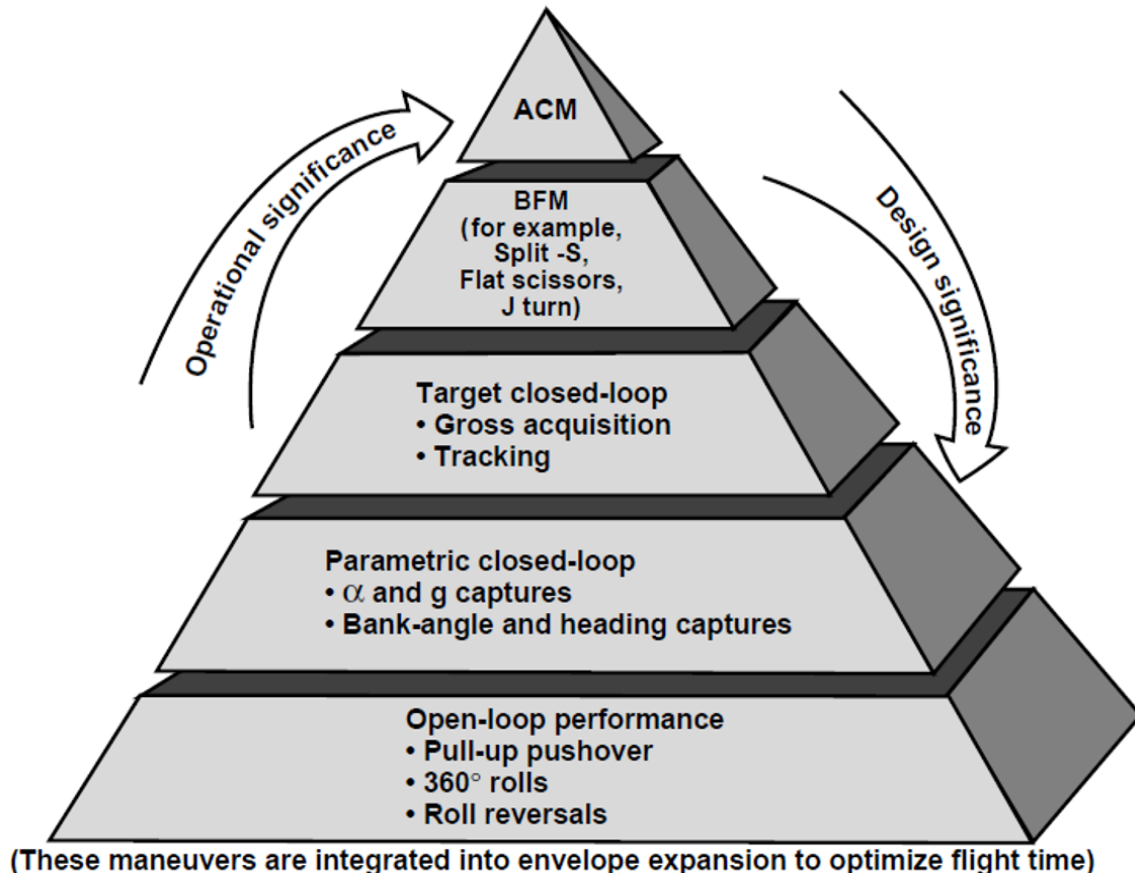


Figure 12. Maneuver Pyramid Handling Qualities Evaluation[46]

grouped together maneuvers with more maneuvers in the bottom group of the pyra-

mid and less maneuvers towards the groups at the top of the pyramid. Starting with maneuvers at the bottom of the pyramid, the focus was on repeatability, ease of flight, easy to accurately perform in simulation. There were several maneuvers that fit into the bottom group and the maneuvers would have results that could be easily related to design characteristics. As the maneuvers move up in the pyramid, they become more specific. They are smaller in number, difficult to fly, less repeatable, and more difficult to translate to aircraft design characteristics. This study benefited from the use of a MTE approach, as it had the ability to concretely examine high angle of attack flight while minimizing the cost and danger to the aircraft and pilot.

2.3.2 Flying Qualities Research.

In 1994, the results from a Phase II SBIR[47] recommended changing MIL-STD-1797A from a Flight Phases approach to a MTE approach. The chosen MTEs were based on realistic mission tasks that correlated with a flight test demonstration maneuver. The SBIR also recommended that the reference to aircraft size and weight (similar to the class category in MIL-STD-1797A) should be eliminated. The reasoning behind this was that if an aircraft is required to complete a specified mission, regardless of the size of the aircraft, that mission requires a certain level of aggressiveness and precision. The aircraft should be required to attain these criteria regardless of its size. The obvious concern is when a large aircraft (heavy-type aircraft, Class III) has the mission necessity to perform a task that has level 1 flying qualities associated with small maneuverable aircraft (fighter-type aircraft, Class IV). The large aircraft may not be able to perform to a level 1 standard. For example, both fighter aircraft and heavy aircraft perform air refueling. Both aircraft have the same task; however, it would be illogical to assume both aircraft need the same performance criteria for this task. When this situation occurs, the SBIR recommends that a new mission task

be created. The new task would be similar to the first, but with relaxed demands, to allow the large aircraft the ability to meet the level 1 criterion. This research also clarified some of the MIL-STD-1797A short term pitch criteria and what is the best situation to apply the respective criteria. These recommendations are seen in Figure 13 and are similar to the discussion in Section 2.1.1.2.

Another interesting suggestion from this research[47] was to redefine the flight phase categories used in MIL-STD-1797A. The recommendation suggested to define new flight phase categories in terms of precision and aggressiveness. The MIL-STD-1797A Flight Phase Categories A and C would be considered “precision tasks” and the Flight Phase Category B would be considered the “non-precision tasks”. Further distinctions would take the precision tasks and separate them into “precise aggressive tasks”, taken and modified from the previous Category A maneuvers, and “precise non-aggressive tasks”, taken and modified from the previous Category C maneuvers. Likewise, the non-precision tasks would be separated into “non-precise non-aggressive tasks”, taken and modified from the previous Category B maneuvers, and “non-precise aggressive tasks”, created from a new Category D maneuvers. This separation is similar to the MTE agility orientation of ADS-33E-PRF. Examples of the MTE and flight phase categorization of maneuvers are seen in Figure 14. Figure 14 also demonstrates a technical separation of the categories based on bandwidth, ω_{BW} , and phase delay, τ_p .

Some initial research has been done on the possible avenues for UAV flying qualities. In 2008, one study[48] looked at UAV flying qualities from two perspectives. The first was adjusting piloted specifications for use with UAVs. The second was developing new criteria for UAV flying qualities based on mission performance requirements. Several different items were discussed to include: aircraft classes, flight phases, levels of flying qualities, degraded levels of flying qualities, and flight envelopes. The re-

1. CAP or MIL-F-8785C Criteria ("Preferred Form")
— Developed for Conventional "Classical" Airplanes — Difficult or Impossible to Apply for Unusual Modes and attitude Augmentation — Data Bases for Highly-Augmented Aircraft (Neal-Smith, LAHOS) Are in Conflict With the Requirements
2. $\omega_{sp} T_{\theta_2}$, ζ_{sp} , τ_{θ} Criteria
— Closely Related to CAP, Same Observations Apply
3. Transient Peak Ratio, Rise Time, Time Delay Criteria
— Applicable Only to Speed-Constrained Response for Rate Systems — Specify Pitch Rate Only, Not Flight Path — May Be Incorrect Since Limits Were Based on Mapping CAP (a Flight Path/Attitude Requirement) into Attitude-Only Limits — Time-Domain Criteria Are Highly Subject to Interpretation
4. Bandwidth, Phase Delay
— Specify Attitude Only (Requires an Additional Flight Path Requirement) — In Combination With Dropback, More Effective in Specifying Flying Qualities Than Any Other Criteria — Only Criteria That Are Applicable to All Response-Types
5. Pilot-in-the-Loop Criteria (Neal-Smith)
— Application Requires Extensive Closed-Loop Analysis That is Impossible for a Specification — Applicable to Attitude Response (Not Flight Path) for Rate and Conventional Response-Types Only — Proper Application Specifies Unrealistic Closed-Loop Pilot/Vehicle Operations (Low Closed-Loop Resonance and High Phase Margins) That Are Counter to Actual Piloted Operations (e.g., Ref. 3) — Continued Use as a Criterion Will Require Considerable Refinements
6. Dropback and Nichols Chart Boundaries
— Not Actually "Criteria" — i.e., No Levels, No bases for Comparison, No Data Correlations to Indicate Effectiveness of Methods — Phase-Rate is Closely Related to Phase Delay in Bandwidth — Dropback Has Shown Sufficient Promise to Include it as a Supplement to Bandwidth and CAP for Rate Response-Types

Figure 13. Alternative Short Period Pitch Response Criteria in MIL-STD-1797A[47]

search put forward the proposition that the final standard should be a combination of adapted manned aircraft flying qualities criteria and new performance-based criteria that are directly linked to mission tasks. The study noted that current UAV guidance

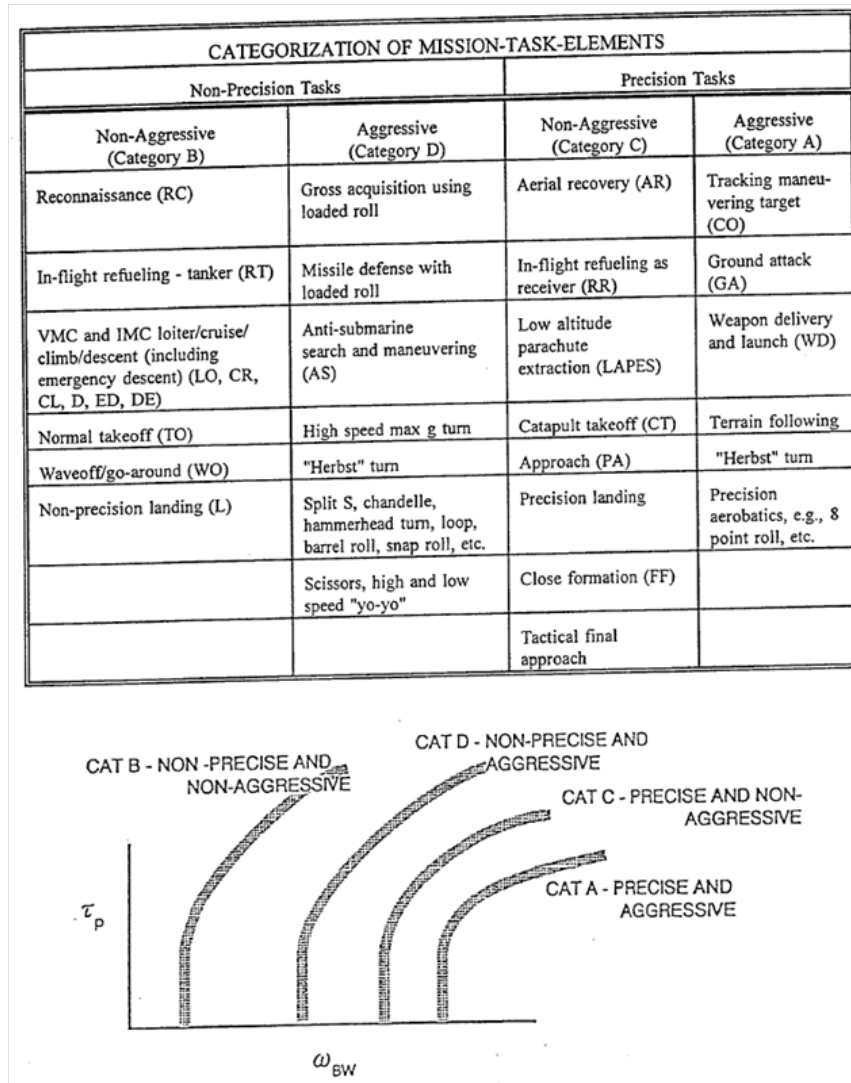


Figure 14. SBIR Categorization of MTEs and Relationship Between Maneuver Boundaries[47]

does not account for sensor and payload mission requirements. It is only focused on the aircraft stability and control performance, not on the mission that the aircraft needs to accomplish. In particular, the study points out that stall warning devices that provide a margin of safety are not as applicable to UAVs; however, this margin of safety may be applied to requirements to ensure compliance with required limits for sensors and software. The manned fixed-wing flying qualities also have requirements that are not applicable at all to UAVs, for example stick force gradients. The

study also looks at deficiencies in the manned fixed-wing standard when applied to UAVs. Most importantly, the paper notes that there is a large need for data and research. The criteria used for manned aircraft flying qualities have been created by decades of research, flight testing, and industry collaboration. This is something missing from the UAV community. The study recommends several areas for future research to include: “developing UAV mission task elements, payload/sensor and flying qualities tradeoffs, upset recovery, simulation and data analysis requirements, and cost/expendability/reliability relationships.” [48]

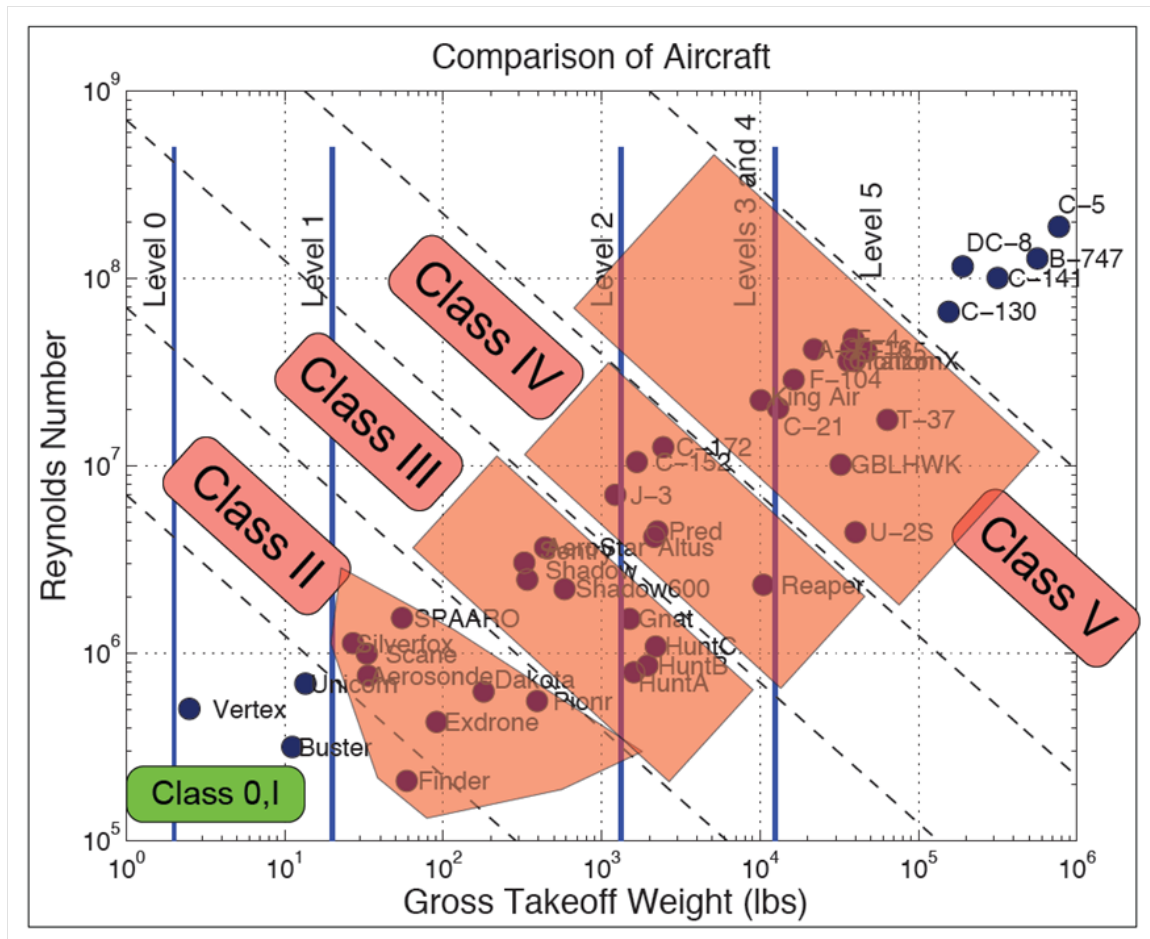
Another study [44] suggested that the size and weight of UAVs do not correspond directly to certain missions, as they do in manned aircraft. Therefore, UAVs would not easily fit into similar classifications as seen in Figure 4 and used in MIL-STD-1797A; however, there is not enough unmanned aircraft flying qualities research, or a database of flight test data, to validate the proposed mission based approach. Effort was then put into ensuring a gross weight versus maneuverability classification system could work until a UAV flying qualities database became more robust to allow for the new mission based approach. This effort was able to recommend an adjustment to the grouping classification system described in the FY 2009-2034 Unmanned Systems Integrated Roadmap. The Unmanned Systems Integrated Roadmap grouping system can be seen in Figure 15. The research recommended a slight change in the classifications that did not correlate directly to just gross weight. This new proposal recommended a classification system based on Reynold’s number and weight, as seen in Figure 16. Another significant result of this research was the Modified Cooper Harper HQR Scale that was described in Section 2.2.3.

A final study [49] again approached the idea of a UAV standard for flying qualities. This report was directed by the US Naval Air Systems Command due to the expansion of the field of unmanned aircraft. It stated that the current design process for

UAS Category	Maximum Gross Takeoff Weight (lbs)	Normal Operating Altitude (ft)	Speed (KIAS)	Current/Future Representative UAS
Group 1	0-20	< 1,200 AGL	100 kts	WASP III, Future Combat System Class I, TACMAV RQ-14A/B, BUSTER, BATCAM, RQ-11B/C, FPASS, RQ-16A, Pointer, Aqua/Terra Puma
Group 2	21-55	< 3,500 AGL	< 250 kts	Vehicle Craft Unmanned Aircraft System, ScanEagle, Silver Fox, Aerosonde
Group 3	< 1,320	< 18,000 MSL		RQ-7B, RQ-15, STUAS, XPV-1, XPV-2
Group 4	> 1,320		Any Airspeed	MQ-5B, MQ-8B, MQ-1A/B/C, A-160
Group 5		> 18,000 MSL		MQ-9A, RQ-4, RQ-4N, Global Observer, N-UCAS
Note: Lighter than air vehicles will be categorized by the highest level of any of their operating criteria.				
(1) Group 1 UA: Typically weighs less than 20 pounds and normally operates below 1200 feet AGL at speeds less than 250 knots.				
(2) Group 2 UA: Typically weighs 21-55 pounds and normally operates below 3500 feet AGL at speeds less than 250 knots.				
(3) Group 3 UA: Typically weighs more than 55 pounds but less than 1320 pounds and normally operates below 18,000 feet MSL at speeds less than 250 knots.				
(4) Group 4 UA: Typically weighs more than 1320 pounds and normally operates below 18,000 feet MSL at any speed.				
(5) Group 5 UA: Typically weighs more than 1320 pounds and normally operates higher than 18,000 feet MSL at any speed.				

Figure 15. UAV Group Classifications[8]

unmanned aircraft was not controlled or standardized. This study validated a need for a unified standard for flying quality characteristics. Scaling analysis was reviewed



(keeping the MIL-STD-1797A classification system) and there were some complications. In one case, a scaled vehicle produced unacceptable roll control sensitivity. Another concern was that a scaled aircraft could produce an abrupt short-period or roll response dynamic. More research needs to be conducted in order to determine the full scope of the benefits and complications of scaling. This study also recommended future research should aim to develop mission tasks that measure flight dynamics and response characteristics.

2.4 j2 Software

The research proposed in this thesis would normally require either flight test or extensive flight simulator analysis, both being very costly and time consuming tasks. In order to accomplish the extensive research in a compressed timeline, it was necessary to find a Commercial Off The Shelf (COTS) software that would allow for the rapid construction of various math models of the UAV platforms under study and provide the capability to put these models through actual flight maneuvers within the software and then collect data at each time step without compromising the analytical accuracy. The j2 Universal Tool-Kit[50] is able to deliver this capability for any fixed wing aircraft platform and does this by running off-line analysis at 1000 Hz removing any need to accommodate variation between each time step. Previous research discussed either the use of flight tests data for the analysis or the writing and recompiling of code using MatLab to simulate flight test data. This was neither practical nor possible.

The j2 Universal Tool-Kit[50] software gives the user the capability to create models for any use including this research which require more than just a point mass to be used. The models produced also needed to have a recognisable level of fidelity to allow for complete analytical envelope providing both linear and non-linear analysis at each time step. Following a thorough review of various software programs, the decision to go with j2 Aircraft Dynamic's, "j2 Universal Tool-Kit" was made. This COTS software allows the user to take any data into a model framework within the j2 software and run them through various maneuvers and model configurations anywhere in their operating envelope. The aircraft can also be viewed in flight in a three dimensional viewing environment running directly off the calculation engine. This is all achieved in a fully version controlled environment using a highly flexible working sandbox environment to conduct "many to many" analyses prior to final

acceptance of a version. This greatly enhances quality control and reduces any risk of working on the wrong version.

The j2 Universal Tool-Kit creates a six degree of freedom model with all the standard equations of motion. To create a model, first the aircraft geometry and parameters must be entered to include, but not limited to, span, length, center of gravity, moments of inertia, and so forth. Once the geometry has been determined, the next step is to input aerodynamic characteristics such a lift, drag, and moment coefficients. In addition to the aircraft static components, the control surfaces are also added in a similar manner. The j2 Universal Tool-Kit then takes the created model and uses Aerodynamic Strip Theory (AST) to approximate the model's lifting surface. This is accomplished by creating airfoil strips along the aircraft's wing, tail, and any other lifting surface. Each strip has a local angle of attack that is calculated based upon the strip's individual aerodynamics. This methodology is well documented and allows the user to get much nearer the end point at a much earlier point in the overall process. From the analysis of the dynamic motions and angular rates, using AST allows for quick analysis of the effects of geometry and airfoil sections. It also eliminates the need to input aerodynamic derivatives.

Instead, the aerodynamic derivatives are calculated within the j2 software giving the model characteristics. This is a major difference with other aircraft model programs which require the derivative coefficients first before then calculating the aircraft performance characteristics. The j2 software uses response modelling. This is the technique of predicating the aircraft's response to various inputs, e.g., control surface deflections, atmospheric disturbances, configuration changes, failures etc. This procedure takes the accelerations from the standard equations of motion and numerically integrates them to supply the aircraft with updated velocities and positional

information. The speed of calculation means this can be run in seconds and makes this a realtime process.

One of the most beneficial capabilities of using j2 Universal Tool-Kit is the ability to visualize the aircraft flight/maneuver in a three dimensional viewing screen. As a model is run through extended maneuvers or flight, the data outputs can become overwhelming. This is when the visualization capability becomes essential. The software uses Virtual Reality Modelling Language (VRML). It allows for the input of any visual model for both the aircraft and the environment over which the aircraft is flying. Then the aerodynamic characteristics are input into the three dimensional environment for a visual picture of how the aircraft model is performing. Each maneuver can be observed from different viewpoints of the aircraft, such as a chase plane, as a wing man, or any other viewpoint that can provide insight into the dynamics of the model.

The j2 Aircraft Dynamics website has several white papers that validate analysis accomplished with the j2 Universal Tool-Kit. One reference[51] demonstrates not only the ability to use this software for air accident investigation for which it is already receiving recognition, but also provides insight into the usefulness of the j2 Universal Tool-Kit for the purposes of UAV flying qualities analysis. This white paper describes the process used to build a model of a Piper Navajo aircraft and provides an approach for UAV model building for this study and into the future. The next portion of the white paper describes some initial analysis and sanity checks including flight test data flight matching after the Piper Navajo Aircraft model was built. This is a necessary step to ensure the model performs as expected and imparts a high degree of fidelity to the model right through to a full flight tests data matched model. The flight test data flight matching capability is a significant advance and has already been adopted by L3-Link in application on USAF platforms.

The j2 Universal Tool-Kit has been used in various research endeavors. One study[52] used this software for flightpath reconstruction in the hopes of increasing the fidelity of the model’s performance when compared to other reconstruction methods and actual flight test. The common method of flight parameter reconstruction is a process created by NASA in the late 1970s. This method has several limitations that j2 Universal Tool-Kit has the ability to eliminate. The end result is the determination that j2 Aircraft Dynamic’s Software has the ability to reconstruct a flight path using a high fidelity model and fits the flight data within acceptable tolerances and ensuring aircraft dynamics and performance adheres to the laws of physics. This study provides yet another example demonstrating the usefulness and validity of models created in the j2 Universal Tool-Kit and demonstrates that this software is a useful tool in the development of the methodology for evaluating the flying qualities of UAVs.

2.5 Summary

In the past, UAV flying qualities has been more of an adaptation of manned fixed-wing flying qualities. It has not been it’s own standard tailored to the unique mission of the UAV. In general, most research has recommended a new approach for evaluating UAV flying qualities. Several recommendations from various sources suggest researching specific UAV mission tasks and the corresponding aircraft characteristics to determine if there is a trend. Despite this constant recommendation, minimal research has attempted to further this innovative idea. This research will focus on the UAV mission task approach. The objective is to build a database of UAV characteristics during specific mission tasks. A software program that will provide a way to quickly analyze various models performing several maneuvers is the starting point for this database. This research begins the discussion of a valid and pertinent UAV

flying qualities standard which will allow UAVs to maximize mission success while ensuring a necessary level of safety is still attained.

III. Methodology

Chapter I illustrated a need to research UAV flying qualities. With the background information presented in Chapter II, now the proposed methodology of how to interpret UAV flying qualities will be discussed. First, there will be a discussion on the different facets to consider when examining UAV flying qualities: aircraft type, levels of automation, and mission tasks. Then there will be a discussion on how to apply various flying quality criteria across these facets. Finally, there will be a discussion of the method used to analyze and rate UAV flying qualities.

The various flying quality criteria and methods used in MIL-STD-1797A (Section 2.1.1.1) and ADS-33E-PRF (Section 2.1.2.1) do not provide a definitive approach to the field of UAV flying qualities. However, two common facets between MIL-STD-1797A and ADS-33E-PRF stand out: aircraft type and maneuvers. In addition to these two facets, when considering the specific nature, unique mission, and method of UAV operation, the level of automation is another feature that needs to be taken into account when analyzing flying qualities criteria. This results in three main facets that vary depending on the specific unmanned aircraft being used for a mission. Varying these three facets and investigating how the UAV responds will begin the creation of an unmanned aircraft flying qualities database. Furthermore, approaching these three facets in a methodical, repeatable, and documented manner will allow the discovery and analysis of some possible trends.

3.1 Aircraft Type

UAVs are a different type of aircraft than seen in the past because no human is on the aircraft and control inputs are delayed due to the remoteness of the operator. Knowing that, in order to demonstrate the flying qualities analysis methodology, it

will take time to consolidate a comprehensive database of all different kinds of UAVs and the corresponding simulation or flight data. This research must find a way to pick a few aircraft that span the spectrum of facets of interest. MIL-STD-1797A groups the aircraft according to weight and maneuverability. This is a logical approach for manned fixed-wing aircraft because aircraft that perform the same mission (with the necessary corresponding maneuverability) tend to weigh approximately the same. All fighter aircraft, for example, are of similar weight. The same goes for cargo aircraft, training aircraft, etc. If UAVs were similar, this would lead down a path of choosing which UAV aircraft to study based on weight and mission, with a corresponding maneuverability. A possible grouping scheme using this methodology from the FY 2013-2038 Unmanned Systems Integrated Roadmap Groups is shown in Figure 17.

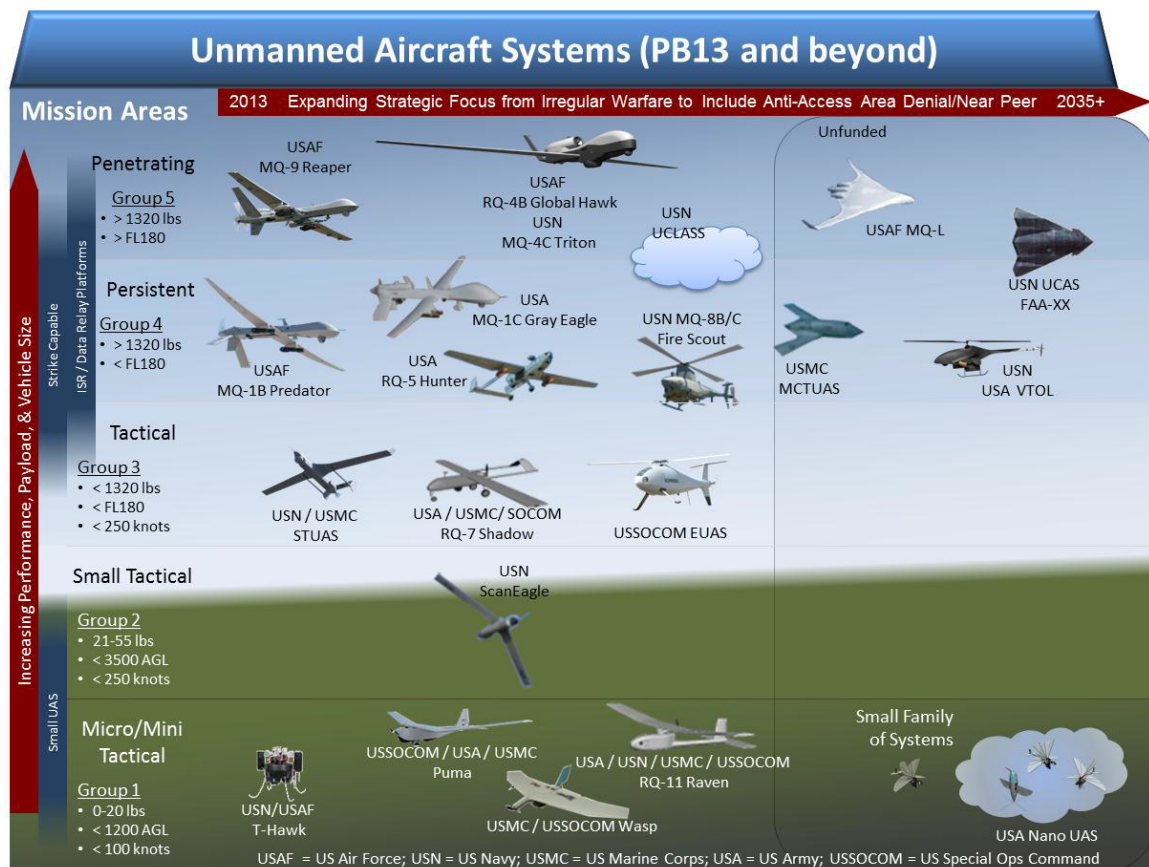


Figure 17. UAV Group Classifications[53]

The primary parameter for this grouping is weight; however, using a classification scheme based purely on weight has some disadvantages. For example, since UAVs have a wide array of missions to include, but not limited to, Intelligence, Surveillance, and Reconnaissance (ISR); counterterrorism; Reconnaissance, Surveillance, and Target Acquisition (RSTA); counter-weapons of mass destruction; Command, Control, and Communication (C3); Explosive Ordnance Disposal (EOD); Electronic Warfare (EW); Force Protection (FP); Tactical Control System (TCS); and Anti-Access and Area Denial (A2/AD). Figure 18 demonstrates that with a wide range of UAVs in both physical appearance and weights, the assigned operational missions also span the entire weight spectrum. The various missions are not restricted to just one Group.[7][53] For example, consider the Global Hawk, RQ-4, and Hunter, MQ-5B. The Global Hawk has a gross weight of 32,250 pounds while the Hunter has a gross weight of 1,950 pounds.[54] Both aircraft have ISR missions yet fall in different aircraft Group Classifications according to the FY 2013-2038 Unmanned Systems Integrated Roadmap and Figure 17. This leads to a belief that UAV flying quality groupings should not be chosen based on weight, but rather chosen on mission requirements. It will be important to research aircraft with various weights and in different Group Classifications to help validate this hypothesis.

Another factor to consider when discussing UAVs is the classified, proprietary, or sensitive nature of the aircraft and everything associated with it, from performance to control systems. Even discussing something as simple as the center of gravity, can be sensitive to the manufacturers or the government. Due to this limitation, the following research creates models of UAVs. By creating models, all of this research and the findings will be releasable. This will not diminish or dismiss any results found, it will just give the opportunity for broader dissemination of the results. Therefore, these models will use only open source information on currently active UAVs; however,

AIRCRAFT					
System	Lead Service	Primary JCA	Mission Capabilities	ACAT	Acquisition Status
GROUP 1					
RQ-16B T_Hawk	US Navy	N/A	ISR/RSTA, EOD	Non-ACAT	Other
Wasp	US Air Force	BA	ISR/RSTA	Non-ACAT	Other
RQ-11B Raven	US Army	BA	ISR/RSTA	IV(T)	Production
Puma AE	USSOCOM	N/A	ISR/RSTA, FP	III	Production/Sustainment
GROUP 2					
Scan Eagle	US Navy , US Marines	N/A	ISR/RSTA, Force Protection	Non-ACAT	Other
GROUP 3					
RQ-7B Shadow	US Army, US Marines	BA	ISR/RSTA, C3, Force Protection	II	Production
S 100	USSOCOM	N/A	ISR/RSTA, EW, Force Protection	III	Design &Development
STUAS RQ-21A	US Navy , US Marines	BA	ISR/RSTA, EOD, Force Protection	III	Design &Development
Viking 400	USSOCOM	N/A	ISR/RSTA, EW, Force Protection	III	Design &Development
GROUP 4					
MQ-5B Hunter	US Army	N/A	ISR/RSTA, C3, Log, PS/TCS, FP	N/A	Other
MQ-1C Gray Eagle	US Army	BA	ISR/RSTA, C3, Log, PS/TCS, FP	I D	Production
MQ-1B Predator	US Air Force	BA	ISR/RSTA, PS/TCS, FP	I D	Sustainment
MQ-8B VTUAV	US Navy		ISR/RSTA, ASW, SUW/ASUW,	I C	MS-C
GROUP 5					
MQ-4 BAMS	US Navy		ISR/RSTA, EW, PS/TCS, SUW/ASUW, FP	I D	Design &Development
MQ-9A Reaper	US Air Force	FA	ISR/RSTA, EW, PS/TCS, FP	I D	Production
RQ-4A Global Hawk	US Air Force	BA	ISR/RSTA, C3, PS/TCS	I D	Sustainment
RQ-4B Global Hawk	US Air Force	BA	ISR/RSTA, C3, PS/TCS	I D	Production/Sustainment
MR UAS	US Navy	N/A	TBD	N/A	Concept
UCLASS	US Navy	N/A	TBD	N/A	Concept
MQ-X	US Air Force	FA	ISR/RSTA, PS/TCS, FP	N/A	Concept
Group 4	US Marines	N/A	TBD	N/A	Concept

Figure 18. DoD Unmanned Capabilities by Program[7]

the models will **NOT** be actual operational UAVs. As much as possible, realistic information was used to create the model, therefore ensuring the aircraft behaves and performs in a manner consistent with the respective operational unmanned aircraft; however, there was no comparison to flight test data since the models created for this research are not actual operational UAVs. Not using flight test data to validate the model kept this research from taking advantage of one of the largest benefits of the j2 Universal Took-Kit; however, it allowed this research to be fully releasable to all groups interested in unmanned aircraft flying qualities. This does not diminish

the value of this research or the results and conclusions drawn. There are countless UAVs yet to be designed and the models used in the following research are viable aircraft. In fact, this research can actually hold more relevance since these models can represent several different current UAVs instead of just one specific aircraft.

The aircraft models chosen for this research span the FY 2013-2038 Unmanned Systems Integrated Roadmap Groups seen in Figure 17. The first two models fall into Group 5, while the third model is in Group 4. To help categorize the models, they will be referred to as Group 5 Aircraft A, Group 5 Aircraft B, and Group 4 Aircraft. Groups 1, 2, and 3 are left for future research. The weight requirement for Group 4 and Group 5 aircraft is defined as greater than 1,320 *lbs*. To aid in the hypothesis that weight does not play a major role in aircraft flying qualities classification, the three aircraft chosen had significantly different gross weights:

- Group 5 Aircraft A: 32,250 *lbs*
- Group 5 Aircraft B: 10,500 *lbs*
- Group 4 Aircraft: 2,250 *lbs*

These three aircraft are modeled after actual UAVs in aid in the identification of aircraft mission; however, only open-source information was used to create the models. The important part to note is that despite the wide range of weights, these models have in common some missions but also have missions associated with only one aircraft. This allows for an excellent spread of flying qualities analysis. The missions are as follows:

- Group 5 Aircraft A: ISR, RSTA, C3, and TCS
- Group 5 Aircraft B: ISR, RSTA, EW, TCS, and FP
- Group 4 Aircraft: ISR, RSTA, TCS, and FP

These three models have other unique traits that could demonstrate some additional trends. Models from two different FY 2013-2038 Unmanned Systems Integrated Roadmap Groups were chosen. Aircraft in Group 5 and Group 4 have an unlimited range of weights since they are defined as greater than 1,320 *lbs*; however Group 5 aircraft operate at an altitude greater than 18,000 feet while Group 4 aircraft operate at an altitude less than 18,000 feet. Due to this wide range of weights for both groups, two aircraft were chosen to test in Group 5 that had a large difference in their weights and designs, yet fell into the same Group Classification. The Group 4 Aircraft and the Group 5 Aircraft B are similar in design yet significantly different in weight by almost 8,000 lbs. This will allow for a good view of flying quality criteria and possible trends may be visible with these aircraft comparisons.[55]

To ensure the aircraft chosen were good representations of the full spectrum of UAV classifications, other grouping systems are taken into account. The UAV groups listed in the FY 2013-2038 Unmanned Systems Integrated Roadmap use weight, operational altitude, and airspeed to separate the UAVs, as seen in Figure 17.[53] The class distinctions suggested in Figure 16, focused on grouping aircraft by weight and Reynolds Number.[44] Finally, the classification system used in MIL-STD-1797A focuses on weight and load factor.[33] Although maximum load factors were not found for the given UAVs, a reasonable assumption is they will all be under the 4.5G line which separates Classes I, II, and III from Class IV. Each aircraft used in this research was classified using these three groupings and the results are shown in Table 3. The Unmanned Systems Integrated Roadmap and MIL-STD-1797A use different criteria to organize their respective classification schemes. Yet, the Group 5 Aircraft A and Group 5 Aircraft B fall into the same class for both grouping systems. A difference in aircraft classification appears between the Reynolds Number classification scheme and the other two methods. The difference is seen with Group 5 Aircraft B. This

Table 3. Aircraft Classification Comparison

Aircraft	Unmanned Systems Integrated Roadmap[53]	Reynolds Number Classification[44]	MIL-STD-1797A[33]
Group 5 Aircraft A	5	5	2
Group 5 Aircraft B	5	4	2
Group 4 Aircraft	4	4	1

classification variation is noted and the comparison of the Group 5 Aircraft B with the other two aircraft might provide some insightful information, not only on UAV flying qualities, but also how best to classify UAVs in the future.

3.1.1 Aircraft Model Construction.

All three aircraft models were created using the same method. First, open-source information was collected on operational UAVs. Parameters, such as weight, size, moments of inertia, and aerodynamic coefficients were input into the j2 Universal Tool-Kit aircraft model design template. Once the model had all necessary parameters, some initial sanity checks, and stability and control derivatives were reviewed. Of particular note, the lift, drag, and moment curves were reviewed over a range of longitudinal step inputs to ensure a comparison could be made to operational UAVs. Other derivative checks were performed including C_{n_β} , C_{l_β} , and C_{y_β} . This was accomplished by performing a sideslip angle, β , sweep. The sideslip angle ranged between -25° and 25° . A further analysis was accomplished by performing a lateral-directional input step. At each lateral-directional input, a rudder step input was also performed. The sideslip angle had 26 different positions, the lateral-directional input had 11 different step sizes, and the rudder input also had 11 different sizes. This equates to a total of 3,146 different combinations analyzed. This extensive analysis was accomplished in just a few minutes and demonstrates one of the main reasons

the j2 Universal Tool-Kit was chosen as the software for this research. The various derivative coefficients were calculated to determine stability. The derivative slope values were compared to values for known aircraft of similar shape and weight. Each aircraft model also had the radius of gyration about the y-axis, r_{gy} , and about the x-axis, r_{gx} , calculated. The equations used were:

$$r_{gy} = \sqrt{\frac{I_y}{m}} \quad \text{or} \quad r_{gx} = \sqrt{\frac{I_x}{m}}$$

The radius of gyration provides a metric for the resistance to rotation and can provide some insight into the mass property effects. Then the radius of gyration is nondimensionalized with respect to the wing span, b .

After the sanity checks were accomplished, an initial analysis of the bare airframe was performed and, with each model, it was verified there was a need for loop closure to ensure a stable platform. The magnitude of the necessary gains, and various damping coefficients, were determined by performing control doublets. First a longitudinal doublet at a moderate control input was performed to determine the necessary longitudinal axis control system. The longitudinal doublet was performed by commanding a positive vertical speed, holding that vertical speed for one second, and then commanding a negative vertical speed of the same magnitude. This negative vertical speed was held for one second, and then a zero vertical speed was commanded. The magnitude of this control input was adjusted and refined as the analysis was accomplished to ensure the aircraft would not have significant changes in the other control parameters of airspeed and bank angle. Then a lateral-directional doublet at a moderate control input was performed to determine the lateral-directional axis control system. Once again, this lateral-directional doublet was accomplished by commanding a positive bank angle, holding this command in for one second, immediately commanding a negative bank angle of the same magnitude, holding the negative bank

angle for one second, and then commanding a zero bank angle. The magnitudes of the lateral-directional control input were adjusted and refined as needed to ensure the other control parameters, airspeed and vertical speed, were able to be controlled to their desired input. The intention was to have the three different aircraft respond to the doublets at moderate control inputs in the same manner, despite the moderate control input having a different magnitudes for each aircraft. When this was accomplished, any results obtained during the aircraft performance of maneuvers should be similar. Any data that is unique or different must be attributed to the specific aircraft's airframe or ability to perform a maneuver.

This process led to putting in control measures to ensure the aircraft was stable but also able to maneuver as necessary for any given performance task. The general control system used was the same for each model; however, the gains were adjusted to account for the unique characteristics of each individual aircraft. The control measures put in place include a pitch rate, roll rate, and yaw rate controller. An outer loop autopilot was also created to aid in performing the maneuvers. The autopilot was a simple controller with inputs of airspeed, vertical speed, and bank angle.

To further validate the model, a frequency sweep was performed in the longitudinal and lateral-directional planes to analyze the closed loop bandwidth of the chosen aircraft and control system. The frequency sweep used was defined as:

$$M \sin(0.5 \cdot \pi \cdot e^{0.061257 \cdot t} \cdot t)$$

Where M is defined as the moderate control input and t is time. The amplitude of the sweep varied until an acceptable value of bandwidth was achieved. This process of adjusting the amplitude will aid in defining an acceptable value for the moderate control input in each axis. From there, the small and large control inputs will be offset

from the moderate in order to get a wide range of maneuver analysis and increase the data available to begin a UAV flying qualities database.

After completion of all the sanity checks, the operating envelope was established. Creating the operating envelope provided straight and level, trim conditions from which to start the maneuvers.

3.1.2 Group 5 Aircraft A.

The primary information used to create the Group 5 Aircraft A model is shown in Table 4. The lift, drag, and moment curves are shown in Figure 19 and the complete

Table 4. Group 5 Aircraft A Model Parameter Inputs

Parameter	Value
Wing Span, b	130.9 <i>ft</i>
Mean Chord, $\bar{c}$	5.05 <i>ft</i>
Planform Area, S	621.7 <i>ft</i> ²
Mass with Fuel, m	32,500 <i>lbs</i>
Moment of Inertia, I_x	1,471,282 <i>lb</i> · <i>ft</i> ²
Moment of Inertia, I_y	3,559,554 <i>lb</i> · <i>ft</i> ²
Moment of Inertia, I_z	6,169,894 <i>lb</i> · <i>ft</i> ²
Aircraft Drag Coefficient, C_D	0.01

list of parameters and analysis of the bare airframe is in Appendix A. The derivative chart for C_{n_β} , C_{l_β} , and C_{y_β} can be seen in Appendix A, Figure 77. The closed loop Group 5 Aircraft A longitudinal and lateral-directional doublets can be seen in Figure 20. The careful analysis of these doublets led to the gain selections for Group 5 Aircraft A control system. The controller can be seen in Appendix A, Figure 75. Finally, the frequency sweep performed at moderate control inputs resulted in the bandwidths seen in Table 5.

After all of the sanity checks were complete, the operating envelope, seen in Figure 21, was established. Once the boundaries were defined, an initial condition of 20,000 feet and 200 knots was chosen as a location in the middle of the operating en-

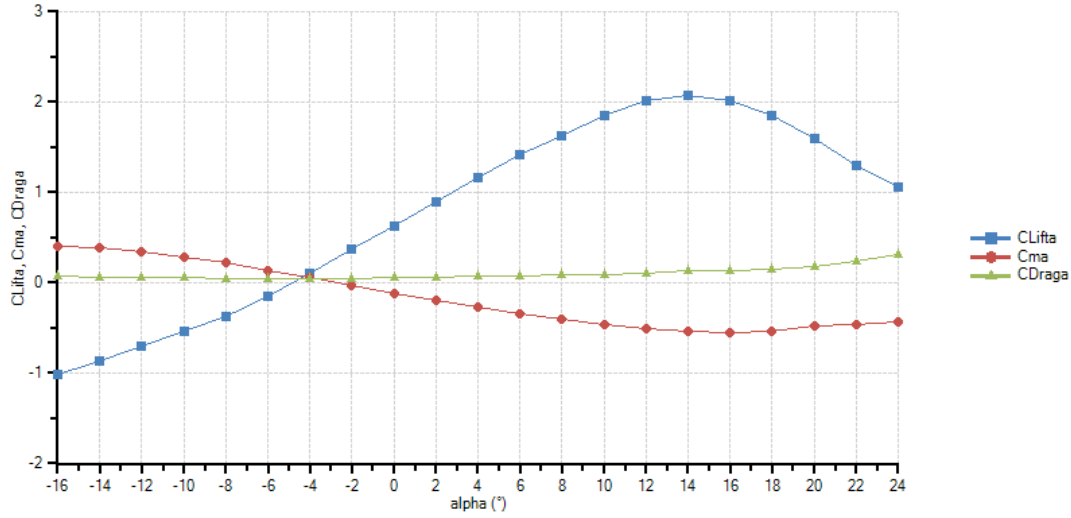


Figure 19. Group 5 Aircraft A Lift, Drag, and Moment Curves

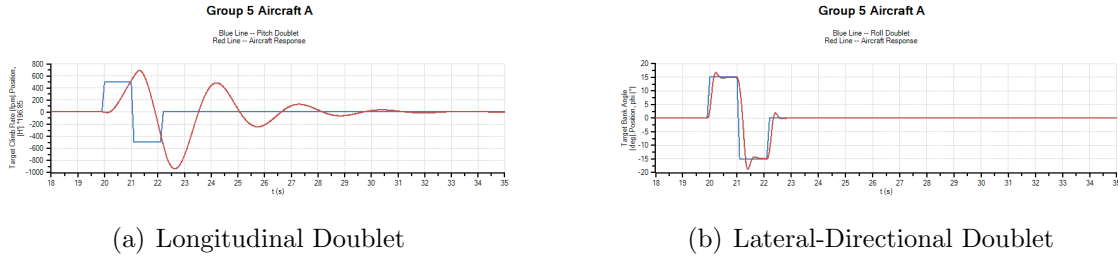


Figure 20. Group 5 Aircraft A Longitudinal and Lateral-Directional Doublets

velope. The initial condition of 2,000 feet and 110 knots was chosen as an additional initial condition when performing a final approach maneuver.

3.1.3 Group 5 Aircraft B.

The notable information used to create the Group 5 Aircraft B model is shown in Table 6. As with the previous model, after the design was complete, some initial sanity checks, and stability and control derivatives were reviewed. The lift, drag, and moment curves are shown in Figure 22 and the complete parameter listing and bare

Table 5. Closed-Loop Frequency Sweep Bandwidth for Group 5 Aircraft A at Moderate Control Inputs

Pitch Bandwidth	Roll Bandwidth
$\omega_{BW_{Pitch}} \text{ (rad/sec)}$	$\omega_{BW_{Roll}} \text{ (rad/sec)}$
2.35	15.70

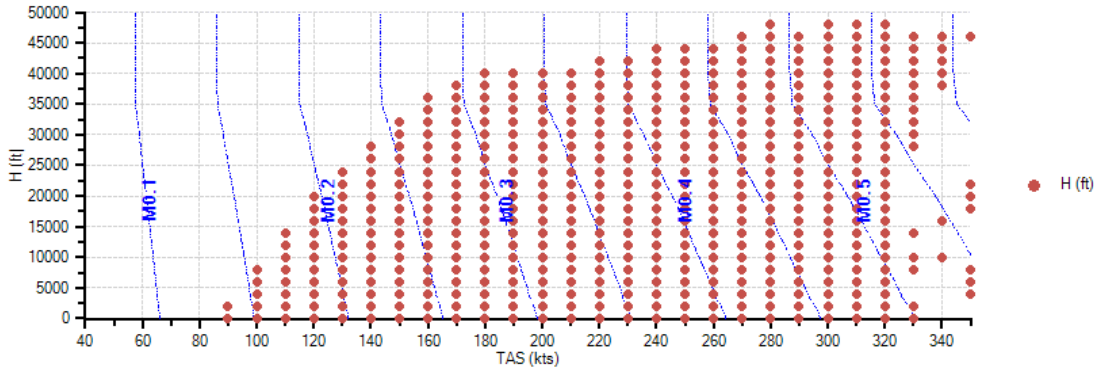


Figure 21. Group 5 Aircraft A Operating Envelope

airframe analysis is in Appendix B, Figure 86 and Figure 87. The longitudinal and

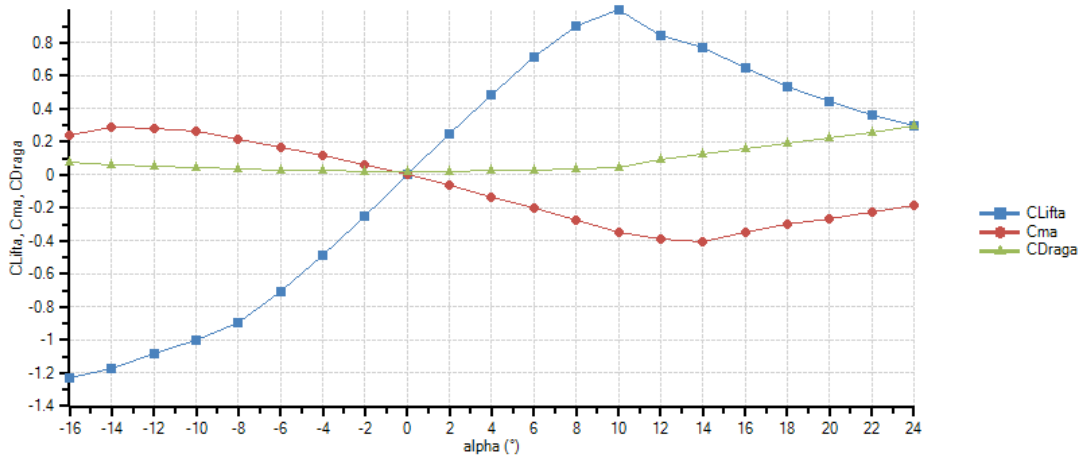


Figure 22. Group 5 Aircraft B Lift, Drag, and Moment Curves

lateral-directional doublets performed at moderate control inputs were used to verify

Table 6. Group 5 Aircraft B Model Parameter Inputs

Parameter	Value
Wing Span, b	66.01 ft
Mean Chord, $\bar{c}$	3.90 ft
Planform Area, S	255.97 ft^2
Mass with Fuel, m	10,500 lbs
Moment of Inertia, I_x	522,353 $lb \cdot ft^2$
Moment of Inertia, I_y	1,275,578 $lb \cdot ft^2$
Moment of Inertia, I_z	1,752,250 $lb \cdot ft^2$
Aircraft Drag Coefficient, C_D	0.01

the need for loop closure and aid in defining gain values, can be seen in Figure 23.

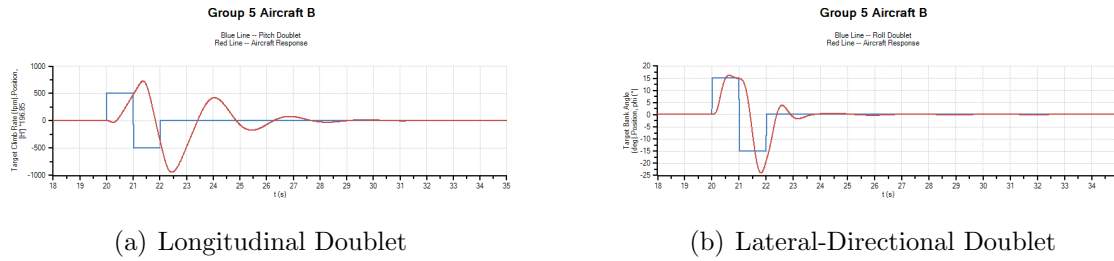


Figure 23. Group 5 Aircraft B Longitudinal and Lateral-Directional Doublets

The full control system with respective gains is seen in Appendix B, Figure 85. The frequency sweep performed resulted in the bandwidths seen in Table 7.

Table 7. Closed-Loop Frequency Sweep Bandwidth for Group 5 Aircraft B at Moderate Control Inputs

Pitch Bandwidth	Roll Bandwidth
$\omega_{BW_{Pitch}} (rad/sec)$	$\omega_{BW_{Roll}} (rad/sec)$
3.38	4.55

After completion of all the sanity checks, the operating envelope was established, as seen in Figure 24. Once the boundaries were defined, an initial condition of 16,000 feet and 220 knots was chosen as a location in the middle of the operating envelope. The initial condition of 2,000 feet and 150 knots was chosen as the starting point when performing a final approach maneuver.

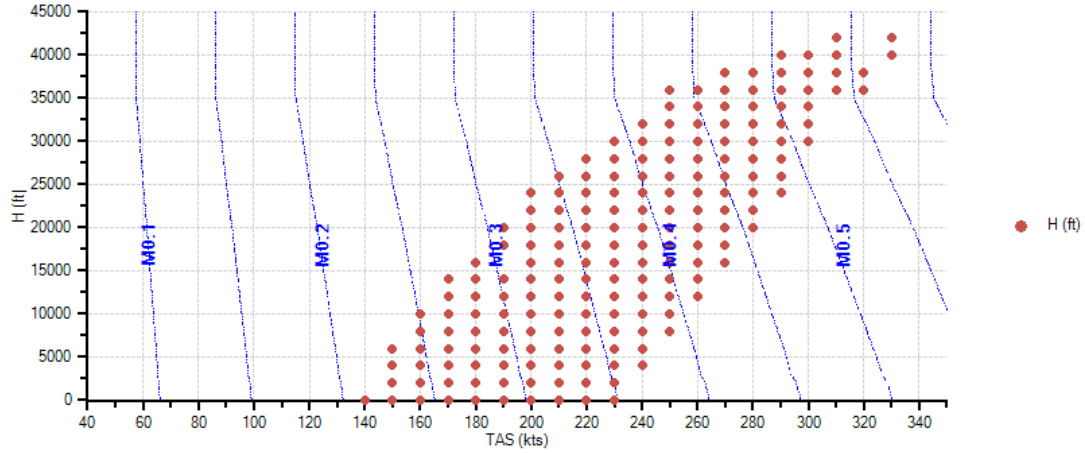


Figure 24. Group 5 Aircraft B Operating Envelope

3.1.4 Group 4 Aircraft.

The final model created is the Group 4 Aircraft. The primary information for this aircraft is shown in Table 8. The lift, drag, and moment curves are shown

Table 8. Group 4 Aircraft Model Parameter Inputs

Parameter	Value
Wing Span, b	55.25 ft
Mean Chord, $\bar{c}$	2.46 ft
Planform Area, S	128.84 ft^2
Mass with Fuel, m	2,250 lbs
Moment of Inertia, I_x	33,721 $lb \cdot ft^2$
Moment of Inertia, I_y	49,074 $lb \cdot ft^2$
Moment of Inertia, I_z	66,113 $lb \cdot ft^2$
Aircraft Drag Coefficient, C_D	0.01

in Figure 25. The full parameter listing and bare airframe analysis can be found in Appendix C. The control system produced longitudinal and lateral-directional control doublets seen in Figure 26. Once again, the full control system with the respective gains can be seen in Appendix C, Figure 95. The frequency sweep performed resulted in the bandwidths seen in Table 9.

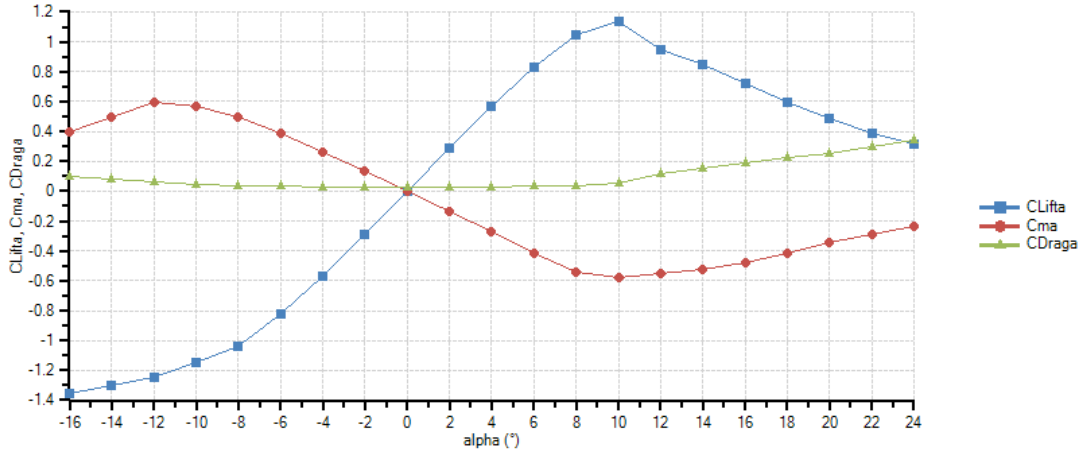


Figure 25. Group 4 Aircraft Lift, Drag, and Moment Curves

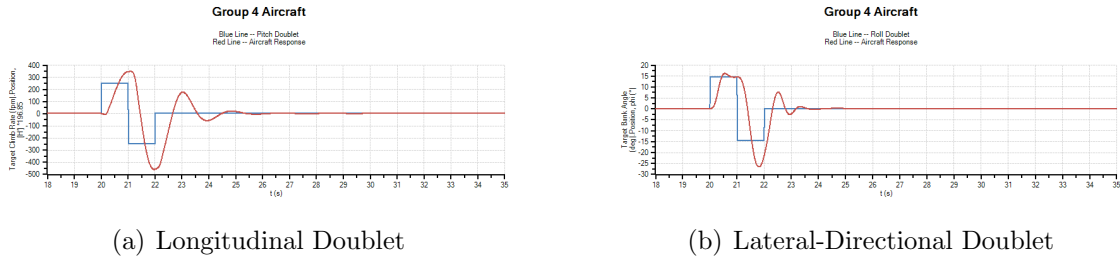


Figure 26. Group 4 Aircraft Longitudinal and Lateral-Directional Doublets

After completion of all the sanity checks, the operating envelope was established, as seen in Figure 27. An initial condition of 10,000 feet and 120 knots was chosen as a location in the middle of the operating envelope with 2,000 feet and 95 knots being chosen as an additional initial condition for a final approach maneuver.

3.2 Levels of Automation

The level of automation is an essential factor in unmanned aircraft flying qualities analysis. The definition of automation is changing with technology. Initially, automation was correlated with an autopilot and possibly an autothrottles. However, now

Table 9. Closed-Loop Frequency Sweep Bandwidth for Group 4 Aircraft at Moderate Control Inputs

Pitch Bandwidth	Roll Bandwidth
$\omega_{BW_{Pitch}} (rad/sec)$	$\omega_{BW_{Roll}} (rad/sec)$
4.82	3.67

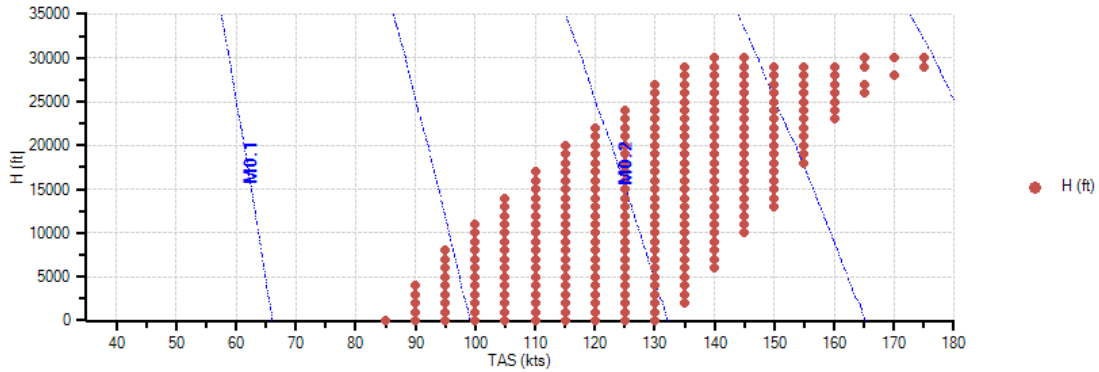


Figure 27. Group 4 Aircraft Operating Envelope

there are “smart” aircraft that can use preexisting code logic and hierarchies to make decisions autonomously. Regardless, depending on the type of UAV automation used, or lack of automation used, a key factor will be the time delay associated with the respective level of control. Figure 28, taken from the Unmanned Systems Integrated Roadmap FY 2011-2036, demonstrates the complexity of this level of automation facet[7].

Level	Name	Description
1	Human Operated	A human operator makes all decisions. The system has no autonomous control of its environment although it may have information-only responses to sensed data.
2	Human Delegated	The vehicle can perform many functions independently of human control when delegated to do so. This level encompasses automatic controls, engine controls, and other low-level automation that must be activated or deactivated by human input and must act in mutual exclusion of human operation.
3	Human Supervised	The system can perform a wide variety of activities when given top-level permissions or direction by a human. Both the human and the system can initiate behaviors based on sensed data, but the system can do so only if within the scope of its currently directed tasks.
4	Fully Autonomous	The system receives goals from humans and translates them into tasks to be performed without human interaction. A human could still enter the loop in an emergency or change the goals, although in practice there may be significant time delays before human intervention occurs.

Figure 28. Four Levels Of Autonomy[7]

Level 1 is defined as “Human Operated” which includes some sort of operator-in-the-loop control analysis. This is similar to hands on flying for manned aircraft so there is the typical “pilot” delay. However, since the UAV operator is not actually in the UAV, there is an added time delay due to the electronic path the signal must travel to and from the operator before they can see what effects their control inputs have on the aircraft.[56] For this level of automation, time delay plays a significant factor and needs to be incorporated into any aircraft performance requirements.

Level 2 is defined as “Human Delegated”. In this level of automation, the operator is actively controlling the aircraft; however, both the inner and outer loops are closed and the operator is using an “autopilot”. The aircraft is making the control inputs, but the pilot is directing the desired outcome. This level of automation has the possibility of time delays similar to that discussed for Level 1, depending on how and where the aircraft is operated. Time delay consideration should be assessed during aircraft performance analysis.

Level 3 is defined as “Human Supervised”. This is similar to the automation in Level 2; however, in this level either the operator or the system can make decisions and input commands to adjust the controls and the concern of time delays is reduced even further.

Level 4 is defined as “Fully Autonomous”. This is truly autonomous flight where the system is making all of the decisions on the control of the aircraft and making changes to the mission depending on changes in the operating environment or new intelligence received. There is always the chance the operator can insert a command; however, there will most likely be a significant time delay between the input and the aircraft response, especially with this level of automation. Automation Levels 3 and 4 are unique to UAVs versus manned aircraft.[7]

The varying amount of automation given to the UAV is an important factor; however, there is also the discussion of which control loops are closed during UAV automation. The inner loop, Stability Augmentation System (SAS) Control, is a control system that increases the stability of the actual aircraft and is typically closed loop for all UAV operations; yet, it is worthwhile to consider opening this loop to determine the fundamental aircraft characteristics. The closure of the SAS Control loop may also play a significant role in the FAA's requirement for sense and avoid. If only this inner loop is closed, then the research would be focusing on Level 1 automation. However, when the aircraft models were created in the j2 Universal Took-Kit, all maneuvers were accomplished with this SAS Control engaged. Therefore, Level 1 automation was not analyzed. When the outer loop, the Control Augmentation System (CAS) Control, is closed the aircraft is trying to shape a particular response to a given input. Since the response is actuated through the CAS Control, it does matter where the input is directed from: the operator, the ground control system, or the aircraft itself. The response is always actuated through the CAS Control loop automation. This loop closure is representative of automation Levels 2, 3, and 4. In fact, for the specific purpose of unmanned aircraft flying qualities, automation Levels 2, 3, and 4 are extremely similar with the only difference being the time delay between a control command and the actual aircraft responding. So, for the purposes of unmanned aircraft flying qualities analysis, Levels 2, 3, and 4 can be considered to be equivalent and only one analysis is necessary to encompass all three levels. This comprehensive singular level is the focus of this research in order to keep the emphasis on the aircraft capabilities, safety, and performance.

3.3 Mission Tasks

To determine the tasks for these UAVs to accomplish, the research discussed in Section 2.3.2 was used as a guideline. Specifically, the research suggesting the incorporation of mission oriented flying qualities into MIL-STD-1797A[47] was used to select maneuvers. In Figure 14, the recommended classification scheme is demonstrated and corresponding tasks are provided. The mission tasks are split into four categories: non-precision non-aggressive demonstration maneuvers, non-precision aggressive demonstration maneuvers, precision non-aggressive demonstration maneuvers, and precision aggressive demonstration maneuvers. To get a wide understanding of these tasks and what is required in terms of flying qualities to perform them, one task from each category provided in Figure 14 was chosen and refined to create the initial framework for this research's UAVs MTEs. These specific MTEs were chosen due to the ability to cover all the missions of the aircraft listed in Section 3.1.

The non-precision non-aggressive demonstration maneuver includes Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) loiter, cruise, climb, and descent. The non-precision non-aggressive MTE chosen for this research was a climbing spiral. It is also a maneuver which appears to be simple enough to perform with certainty and can act as a verification of the j2 Universal Tool-Kit simulation. Furthermore, the climbing spiral will offer up the opportunity to evaluate the aircraft's ability to accurately change heading, accurately change altitude, and identify potential flightpath and airspeed coupling. The climbing spiral maneuver is performed in all of the missions for the three UAVs. In particular, this maneuver could be performed during the ISR, RSTA, C3, EW, or TCS missions.

The non-precision aggressive demonstration maneuver includes gross acquisition using loaded lateral-direction control. The air-to-ground gross acquisition MTE was chosen for the non-precision aggressive analysis. The air-to-ground gross acquisition

MTE is a task where the aircraft is at altitude and is tracking a fixed target on the ground. This allows for the ability to evaluate flying qualities during elevated load factors and low altitude flight. It also enables the ability to evaluate the aircraft's ability to descend and to roll onto a target at steep dive angles. This MTE could be necessary in the ISR, RSTA, or FP missions.

The precision non-aggressive demonstration maneuver is defined as an approach and the MTE chosen was the precision offset landing. The precision offset landing is a requirement for any UAV landing sequence. It also provides the ability to analyze quick maneuvers with a required level of precision at low airspeeds and close to the ground. Furthermore, this task evaluates an aircraft tendency to PIO. Although PIO is a "pilot" induced oscillation, a similar attribute has been seen in UAVs with either the operator hand-flying the aircraft or inputting control commands continuously during a maneuver. There will also be the ability to evaluate precise horizontal and vertical control of both flight path and airspeed. The analysis will be able to evaluate the aircraft's ability to precisely control sink rate and attitude in the flare and evaluate the tendency for nose bobble or operator induced oscillations and control sensitivity in landing.

Finally, the precision aggressive demonstration maneuver includes tracking a maneuvering target. For the precision aggressive maneuver, pitch and roll discrete tracking MTE was chosen to analyze. In this maneuver, the aircraft is required to track a given input as closely as possible. During the maneuver, there will be the ability to evaluate handling qualities in a tight, closed-loop tracking task and the control sensitivity characteristics. Furthermore, there will be the opportunity to identify bobble or operator induced oscillation tendencies. While this pitch and roll discrete tracking task can loosely correlate to the RSTA and FP missions, this maneuver was chosen to identify with potential future missions. There is the possibility of air-to-air

tracking as an operation mission requirement. However, more realistic is the mission of autonomous Air Refueling (AR) which is an airborne tight tracking task. All of these four MTEs, are directly related to mission accomplishment for all four aircraft. More specifically, in Table 10 all the planned MTEs are correlated with the chosen aircraft and respective missions.

Table 10. Demonstration Maneuvers with Corresponding Aircraft Missions

	Chosen Demonstration Maneuvers			
	Climbing Spiral	Air-to-Ground Gross Acquisition	Precision Offset Landing	Pitch and Roll Discrete Tracking
Group 5 Aircraft A	ISR, RSTA C3, TCS	ISR RSTA	Landing AR	RSTA
Group 5 Aircraft B	ISR, RSTA, EW, TCS	ISR RSTA, FP	Landing AR	RSTA, FP
Group 4 Aircraft	ISR, RSTA TCS	ISR RSTA, FP	Landing AR	RSTA, FP

An important aspect of this research is that the control system gains were not changed for each maneuver. Some aircraft keep the same gains for the entire flight while others adjust the control gains depending on which maneuver is being accomplished. For the purposes of this research, each aircraft's respective gains remained constant throughout all four maneuvers.

The procedures used to perform these four MTEs must be specifically defined. This is necessary in order to ensure repeatability for each aircraft. As aircraft inputs are changed, the maneuver must be performed in the same manner to ensure the ability exists to compare the various input maneuvers. A rigidly defined maneuver is also necessary to be able to compare the analysis of the same maneuver between different aircraft. In Section 2.3.2 the Phase II SBIR[47] was discussed. This research effort used similar maneuvers on manned fixed-wing aircraft and was referenced for

verification and validation of the MTEs and procedures used. During each maneuver, the longitudinal-only plane, lateral-directional only plane, and coupled maneuver is investigated. Furthermore, variations of the control inputs for both longitudinal and lateral-directional are adjusted for different analyses. A small, moderate, and large control input is available for each maneuver. This will provide approximately 15 data points for each maneuver performed. The culmination of this data is a perfect starting point for the build up of a UAV flying qualities database.

3.3.1 Non-Precision Non-Aggressive Maneuver.

The non-precision non-aggressive maneuver is a climbing spiral. This maneuver might be used to gain altitude while remaining within a certain area for either terrain clearance, a zone of safety, or for increased communication. As described previously, small, moderate, and large control inputs were defined for each aircraft. The longitudinal control inputs can be seen in Table 11 and the lateral-directional control inputs can be seen in Table 12. Before executing the maneuver, specific parameters were

Table 11. Non-Precision Non-Aggressive Pitch Data Points

Aircraft	Elapsed Time	Small Longitudinal Control	Moderate Longitudinal Control	Large Longitudinal Control
Group 5 Aircraft A	255 <i>sec</i>	500 <i>fpm</i> Climb	1000 <i>fpm</i> Climb	1500 <i>fpm</i> Climb
Group 5 Aircraft B	265 <i>sec</i>	250 <i>fpm</i> Climb	500 <i>fpm</i> Climb	800 <i>fpm</i> Climb
Group 4 Aircraft	150 <i>sec</i>	100 <i>fpm</i> Climb	250 <i>fpm</i> Climb	500 <i>fpm</i> Climb

defined to ensure consistency and repeatability of the maneuver. Steady flight for 100 seconds was flown prior to any maneuver beginning to ensure the aircraft was in trim and level flight. Upon the initiation of the maneuver, the aircraft begins a climb and turn at the specified control input for both longitudinal and lateral-directional. The

Table 12. Non-Precision Non-Aggressive Roll Data Points

Aircraft	Elapsed Time	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
Group 5 Aircraft A	255 <i>sec</i>	6.75nm Turn Radius $\approx 5^\circ$ AOB 0.47°/sec	2.25nm Turn Radius $\approx 13^\circ$ AOB 1.42°/sec	1.0nm Turn Radius $\approx 30^\circ$ AOB 3.19°/sec
Group 5 Aircraft A	265 <i>sec</i>	8nm Turn Radius $\approx 5^\circ$ AOB 0.44°/sec	2.6nm Turn Radius $\approx 15^\circ$ AOB 1.35°/sec	1.5nm Turn Radius $\approx 25^\circ$ AOB 2.34°/sec
Group 4 Aircraft	150 <i>sec</i>	2.5nm Turn Radius $\approx 5^\circ$ AOB 0.76°/sec	0.8nm Turn Radius $\approx 15^\circ$ AOB 2.39°/sec	0.45nm Turn Radius $\approx 25^\circ$ AOB 4.25°/sec

aircraft continues the climbing spiral until a given amount of time had passed. The duration of the maneuver was set by taking into account the moderate longitudinal and lateral-directional input. The time it takes for the aircraft to complete one 360° turn at these moderate inputs is the elapsed time used for all the maneuvers for a given aircraft. This elapsed time is shown in Table 11 and Table 12.

The primary constraints during the maneuver were to maintain a constant climb rate, turn radius, and airspeed. A generalized top down view of the maneuver is shown in Figure 29. The side view is shown in Figure 30 and the complete maneuver in three dimensions is shown in Figure 31. The maneuver is initiated at the same time step for each control input variation, and is denoted with a “o” in the figure. The termination point is denoted with a “*” in the figure.

The purpose of this non-precision non-aggressive maneuver is to evaluate the ability of the aircraft to accurately change heading (lateral-directional plane) and altitude (longitudinal plane). In addition, execution of the fully-coupled maneuver allows potential flightpath and airspeed coupling issues to be identified.

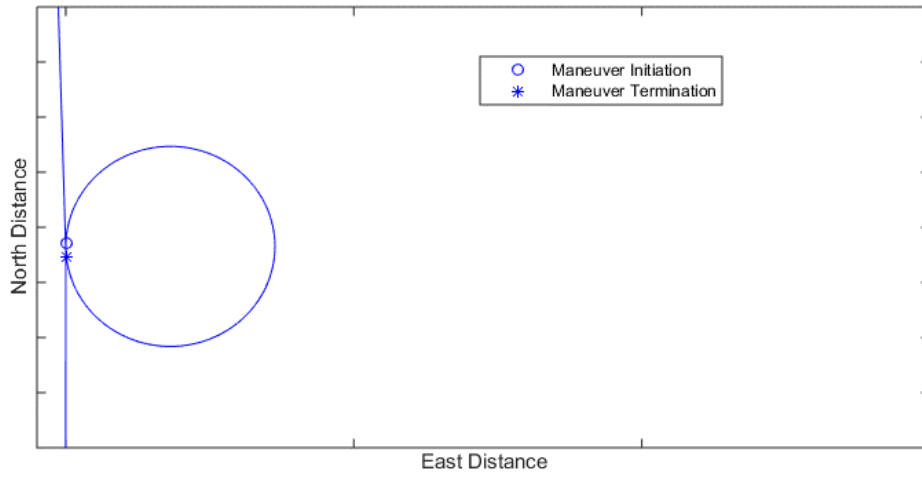


Figure 29. Top View of Non-Precision Non-Aggressive Maneuver

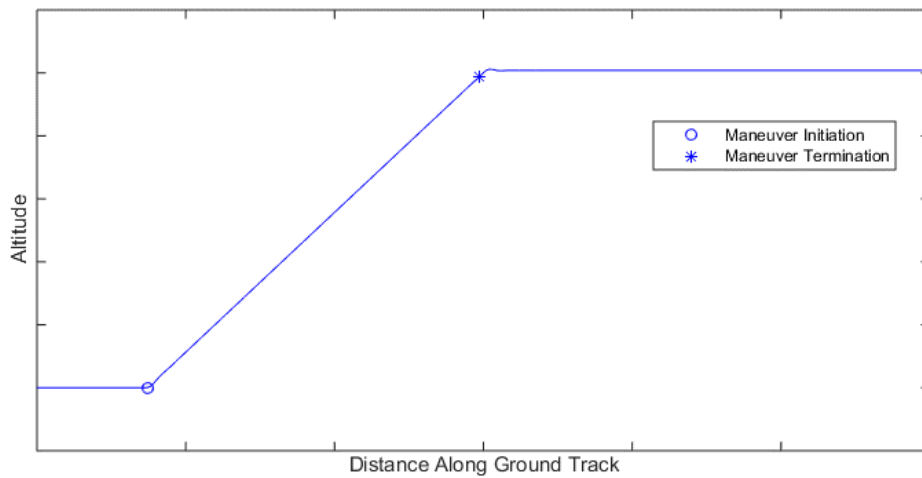


Figure 30. Side View of Non-Precision Non-Aggressive Maneuver

3.3.2 Non-Precision Aggressive Maneuver.

The non-precision aggressive maneuver is an air-to-ground gross acquisition task. It involves descending to an specified altitude and turning to acquire a non-moving target on the ground. Before performing the maneuver, specific parameters were defined to ensure consistency and repeatability of the maneuver. As described pre-

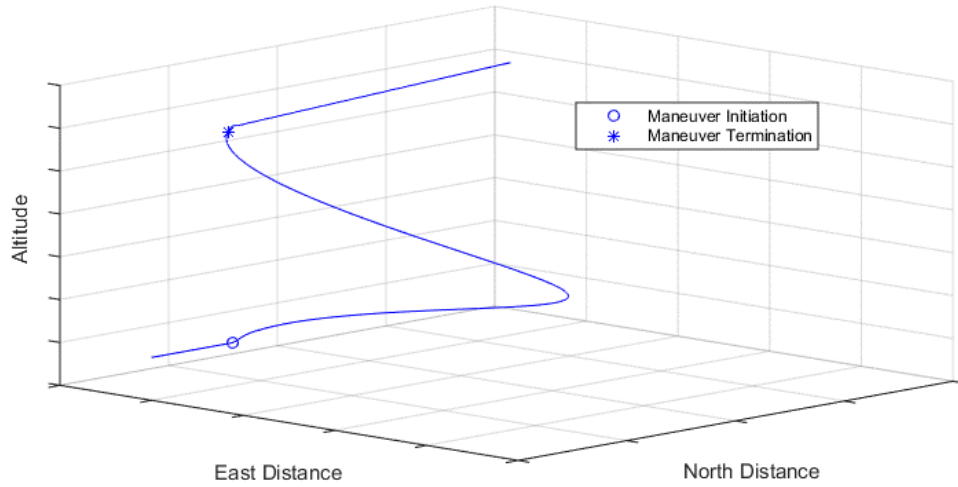


Figure 31. 3-Dimensional View of Non-Precision Non-Aggressive Maneuver

viously, small, moderate, and large control inputs were defined for this maneuver and can be seen in Table 13 and Table 14. The air-to-ground acquisition maneuver

Table 13. Non-Precision Aggressive Pitch Data Points

Aircraft	Altitude Change	Small Longitudinal Control	Moderate Longitudinal Control	Large Longitudinal Control
Group 5 Aircraft A	3000 <i>ft</i>	500 <i>fpm</i> Descent	800 <i>fpm</i> Descent	1400 <i>fpm</i> Descent
Group 5 Aircraft B	3000 <i>ft</i>	500 <i>fpm</i> Descent	800 <i>fpm</i> Descent	1400 <i>fpm</i> Descent
Group 4 Aircraft	1500 <i>ft</i>	250 <i>fpm</i> Descent	500 <i>fpm</i> Descent	700 <i>fpm</i> Descent

begins after 100 seconds of flight to ensure the aircraft is trim and level. Then the aircraft initiates a decent, and continues this decent until a pre-determined level-off altitude is achieved. During this decent, a 90° right turn is executed. This turn to target is defined to be half-way through the decent. Since the turn is in the middle of the descent, this maneuver can be seen as four different control inputs: beginning of the descent, beginning of turn, end of turn, end of descent. These different control

Table 14. Non-Precision Aggressive Roll Data Points

Aircraft	Altitude Change	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
Group 5 Aircraft A	5000 <i>ft</i>	5° AOB 0.49°/sec	15° AOB 1.53°/sec	30° AOB 3.27°/sec
Group 5 Aircraft B	3000 <i>ft</i>	5° AOB 0.44°/sec	15° AOB 1.43°/sec	25° AOB 2.54°/sec
Group 4 Aircraft	1500 <i>ft</i>	5° AOB 0.83°/sec	15° AOB 2.81°/sec	25° AOB 5.29°/sec

inputs must be referenced when looking at the various flying qualities criteria. The decomposition of this maneuver includes a descent in the longitudinal plane, and a pointing maneuver in the lateral-directional plane.

The primary constraints during the maneuver were to maintain constant descent rate, bank angle, and airspeed. The generalized top-down view of the maneuver is shown in Figure 32. The side view and three dimensional view can be seen in Figure 33 and Figure 34 respectively. The maneuver is always initiated at 100 seconds and is denoted with a “o” in the figure. The target is denoted with a “*” in the figure and depicts the capture of the descent altitude.

The purpose of this non-precision aggressive maneuver is to evaluate flying qualities during maneuvers at elevated load factors. It also provides the opportunity to evaluate short-term response characteristics with aggressive pitch pointing (longitudinal plane) and lateral-directional pointing (lateral-directional plane). Concerns regarding the coupling between longitudinal and lateral-directional motion can be addressed by examining the response of the fully-coupled maneuver.

3.3.3 Precision Non-Aggressive Maneuver.

The precision non-aggressive maneuver is an offset landing task. This maneuver involves a landing approach where, initially, the aircraft is offset from the runway

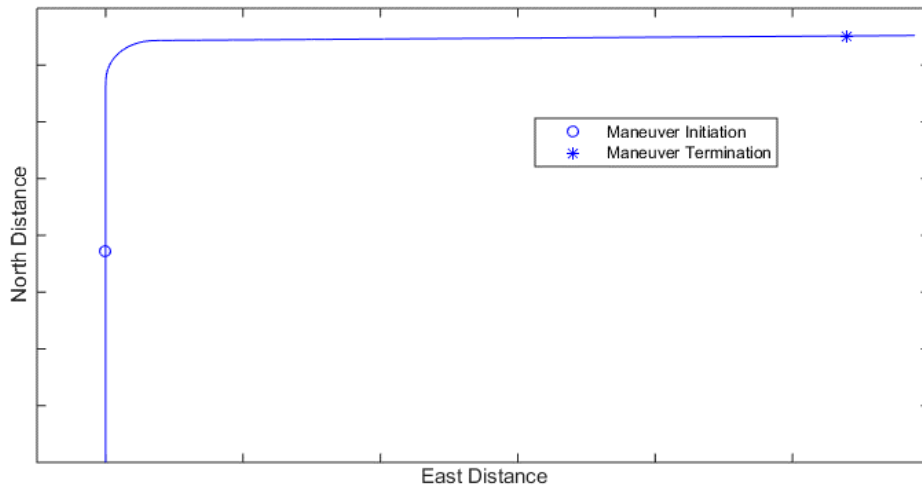


Figure 32. Top View of Non-Precision Aggressive Maneuver

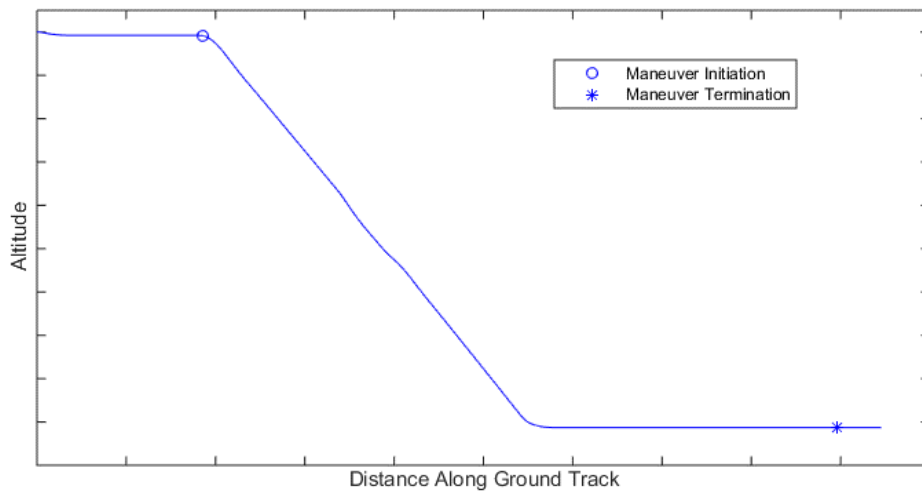


Figure 33. Side View of Non-Precision Aggressive Maneuver

centerline. This maneuver is common during either a non-precision approach (to include circling), or an approach with strong crosswinds and incorrect, or not enough, control input is applied. After initiation of the descent, the aircraft makes a lateral-directional control input to correct to runway centerline. As described previously, small, moderate, and large control inputs were defined for this maneuver but only for

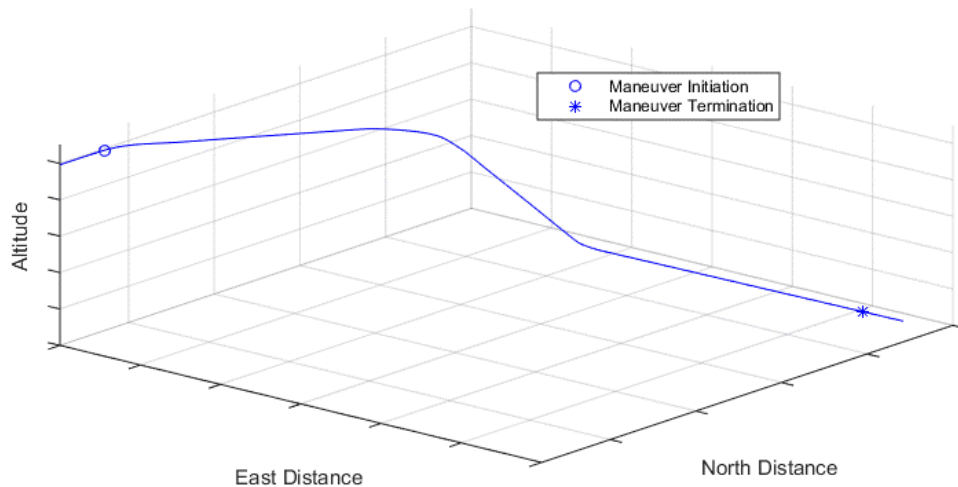


Figure 34. 3-Dimensional View of Non-Precision Aggressive Maneuver

the lateral-directional input. The descent was set to a 500 to 600 foot per minute descent rate, which approximately correlates with the commonly seen 3° glidepath. The lateral-directional input variations can be seen in Table 15. As with the previous

Table 15. Precision Non-Aggressive Roll Data Points

Aircraft	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
Group 5 Aircraft A	5° AOB	15° AOB	22° AOB
Group 5 Aircraft B	5° AOB	15° AOB	22° AOB
Group 4 Aircraft	5° AOB	15° AOB	25° AOB

maneuvers, the offset landing maneuver begins after 100 seconds of flight. First the aircraft began the 600 foot per minute descent. The lateral-directional command was input to maneuver the aircraft onto centerline. The aircraft was required to be stable on centerline by 200 feet Above Ground Level (AGL).

The primary constraints during the maneuver were to maintain a constant decent rate, and airspeed while not over commanding the lateral-directional input. The generalized top-down view of the maneuver is shown in Figure 35. The side view and three dimensional view can be seen in Figure 36 and Figure 37 respectively. The sidestep maneuver initiation is denoted with a “o” and the landing is denoted with a “*”.

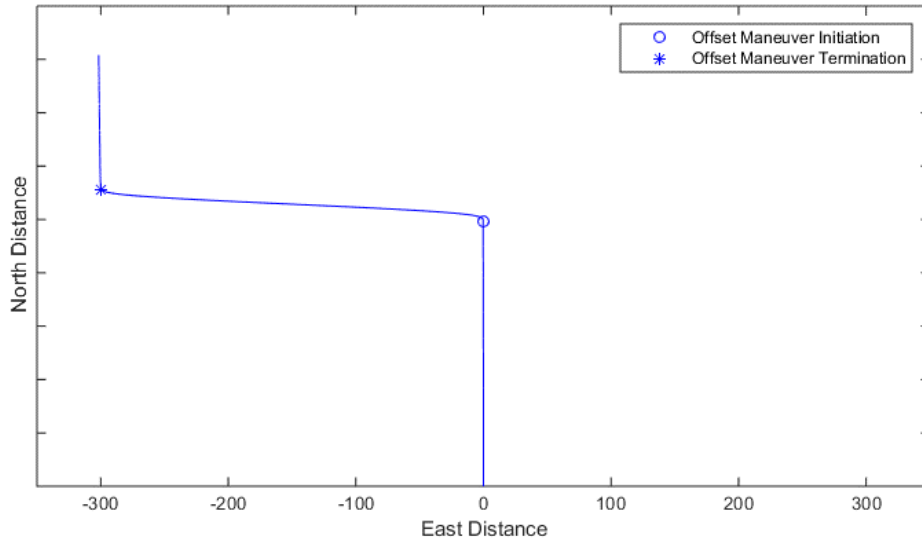


Figure 35. Top View of Precision Non-Aggressive Maneuver

The purpose of this precision non-aggressive maneuver is to evaluate flying qualities during maneuvers which require precise control of both the horizontal and vertical flightpath. It also evaluates the aircraft’s ability to maintain precise airspeed control. The ability to control sink rate is also analyzed. If there is a tendency for the aircraft’s nose to bobble, or if there is a tendency for the operator to induce oscillations, this can be observed, isolated, and addressed. Finally, this maneuver can evaluate the control sensitivity during landing.

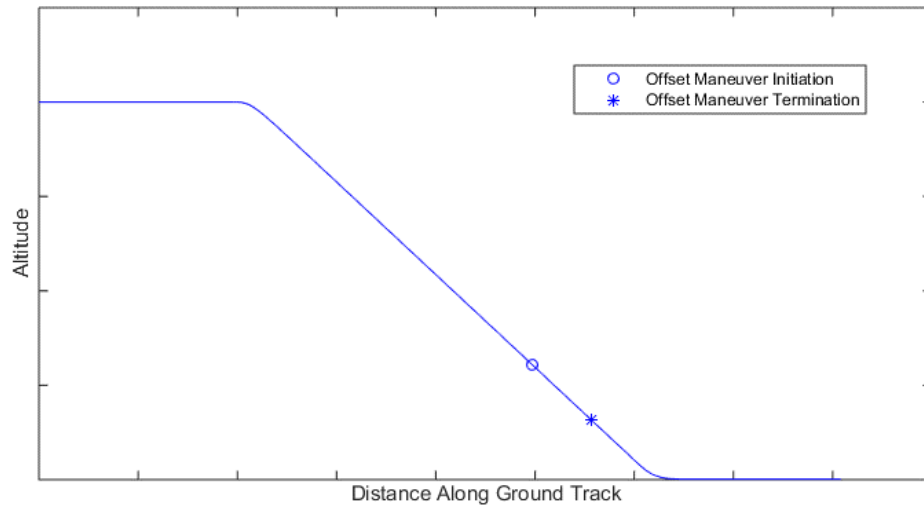


Figure 36. Side View of Precision Non-Aggressive Maneuver

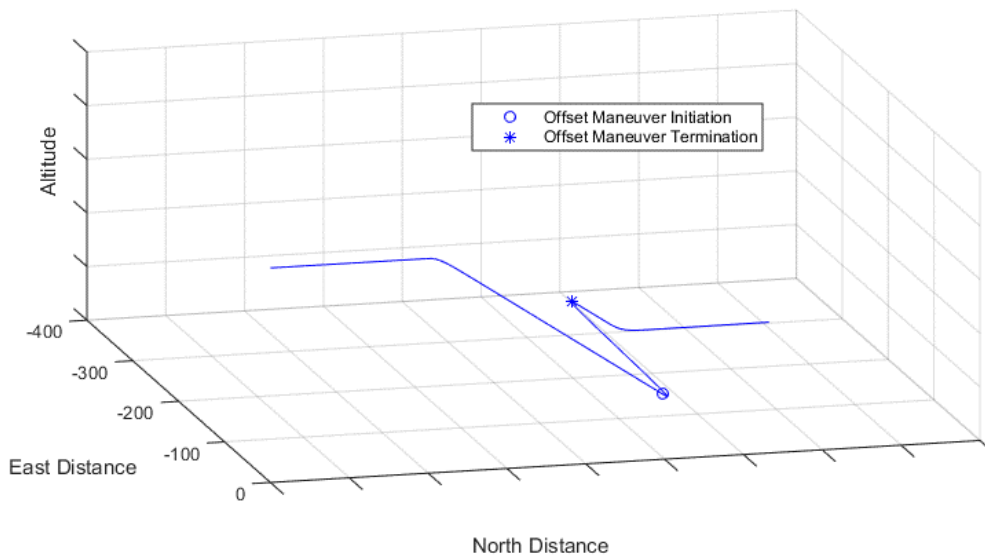


Figure 37. 3-Dimensional View of Precision Non-Aggressive Maneuver

3.3.4 Precision Aggressive Maneuver.

The precision aggressive maneuver is a pitch and roll discrete tracking task. This maneuver simulates tracking a moving airborne target, to include tracking a boom

during air refueling operations. The target is maneuvering and follows the vertical speed and bank angle paths seen in Figure 38 and Figure 39. The small, moderate,

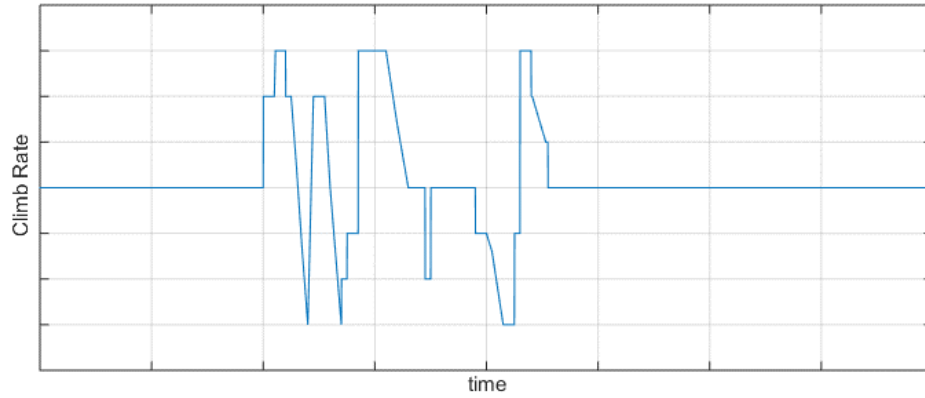


Figure 38. Discrete Tracking Target Pitch Path

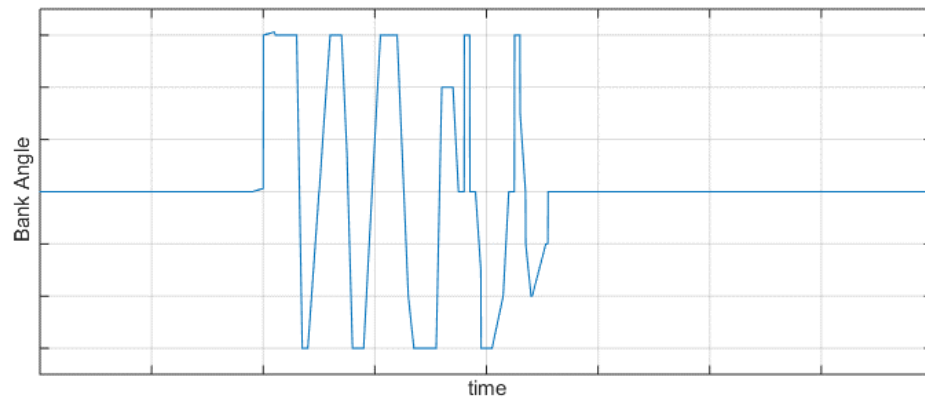


Figure 39. Discrete Tracking Target Roll Path

and large control inputs follow the same target track, just the maneuvers are more or less aggressive. The maximum longitudinal control input for the various aircraft can be seen in Table 16 and the maximum lateral-directional control input can be seen in Table 17. Once again, the pitch and roll discrete tracking maneuver does not begin until after 100 seconds of flight to ensure trim and level conditions exist at the onset of the maneuver.

Table 16. Maximum Precision Aggressive Pitch Data Points

Aircraft	Small Longitudinal Control	Moderate Longitudinal Control	Large Longitudinal Control
Group 5 Aircraft A	500 <i>fpm</i>	1000 <i>fpm</i>	1500 <i>fpm</i>
Group 5 Aircraft B	250 <i>fpm</i>	500 <i>fpm</i>	800 <i>fpm</i>
Group 4 Aircraft	150 <i>fpm</i>	300 <i>fpm</i>	500 <i>fpm</i>

Table 17. Maximum Precision Aggressive Roll Data Points

Aircraft	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
Group 5 Aircraft A	5° AOB	15° AOB	30° AOB
Group 5 Aircraft B	5° AOB	15° AOB	25° AOB
Group 4 Aircraft	5° AOB	15° AOB	25° AOB

The primary constraint during the maneuver was to track the target as closely as possible. The generalized top-down view of the maneuver is shown in Figure 40. The side view and three dimensional view can be seen in Figure 41 and Figure 42 respectively. The beginning of the tracking denoted with a “o” and the tracking completion is denoted with a “*”.

The purpose of this precision aggressive maneuver is to evaluate flying qualities during tight, closed-loop tracking maneuvers. It also evaluates the aircraft’s sensitivity characteristics and identifies any potential tendencies to bobble, in the longitudinal or lateral-directional planes, or the tendency for operator or aircraft induced oscillations.

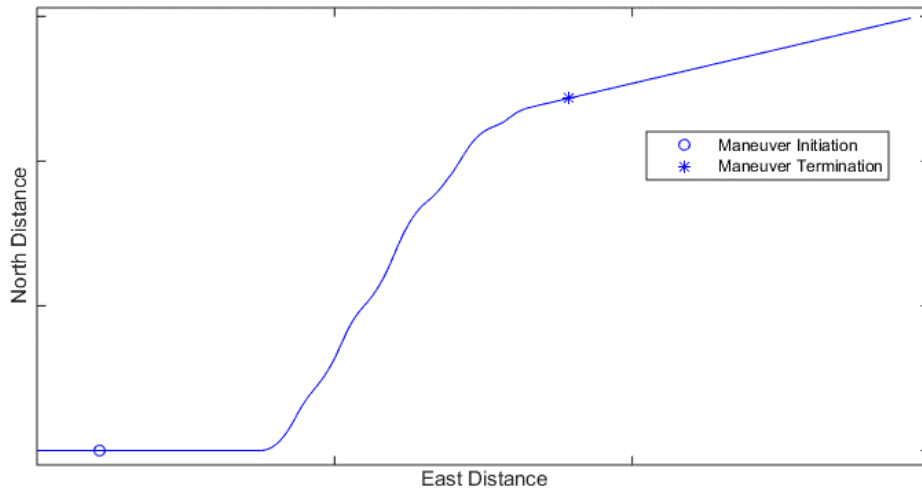


Figure 40. Top View of Precision Aggressive Maneuver

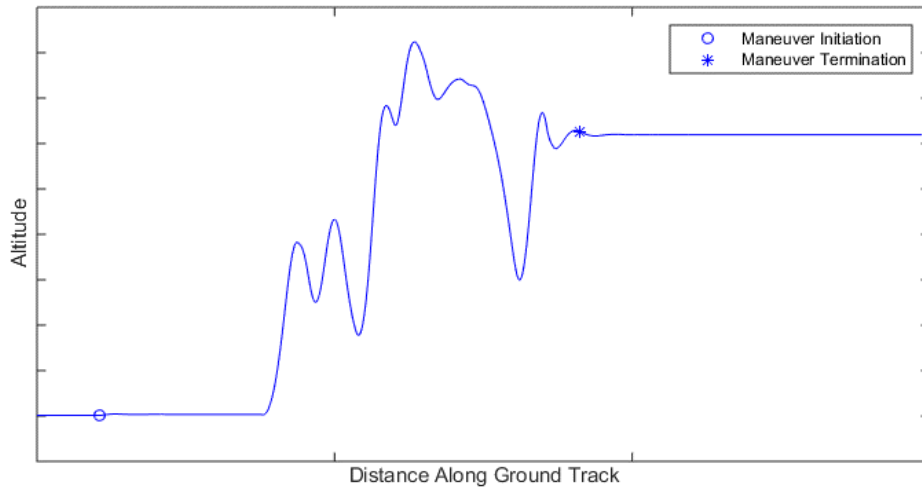


Figure 41. Side View of Precision Aggressive Maneuver

3.4 Criteria

The factors identified for this research have been carefully defined. Now the flying qualities analysis needs to incorporate the similarities and differences provided by each of the factors. The background information provided in Chapter II guides

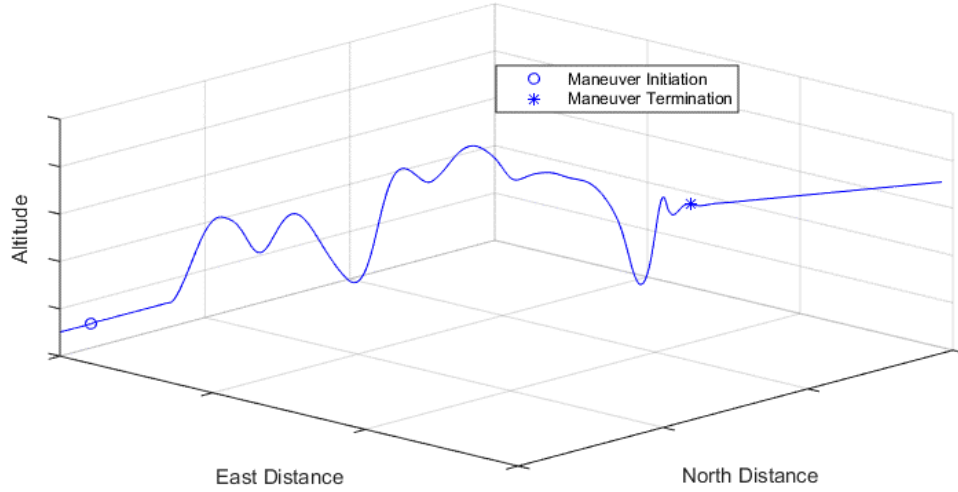


Figure 42. 3-Dimensional View of Precision Aggressive Maneuver

this discussion which focuses on six specific flying qualities criteria: angle of attack, attitude change, peak attitude rate, quickness, bandwidth, and time delay.

3.4.1 Angle of Attack.

Angle of attack, α , is the angle between the relative wind and a reference line on the aircraft.[57] Not only does this criteria aid in the understanding of how the aircraft is maneuvering, it also can lead to verifying aircraft performance limits. The stall angle of attack, α_{stall} , can be referenced to determine if the aircraft is not performing as desired or commanded due to being near an aerodynamic limit or if it is operating near a thrust performance limit.

3.4.2 Attitude Change.

Attitude change in the longitudinal plane can be inferred from the angle of attack analysis since the vertical speed is the commanded longitudinal control input. In the lateral-directional plane it is the exact analysis of the commanded lateral-directional

control input. During each maneuver, the time history is documented and the largest attitude and smallest attitude values are found. The attitude change is just the difference between these two values. In general, this would not be a criterion used for flying qualities purposes; however, it can allow for better understanding of the pitch quickness values as it is the denominator in the quickness equation that will be described in Section 3.4.4.

3.4.3 Peak Attitude Rate.

Peak attitude rate is a criterion that can aid in the understanding of an aircraft's control characteristics. In particular, it can help analyze trends seen in the quickness criterion. Since it is the numerator in the quickness equation, if the same trends are seen in the quickness as in the peak attitude rate, then an understanding of the quickness trends can be attained. However, if different trends are noted, then the attitude change will be an important factor in the quickness value. There is also the consideration of the maneuvers when quickness is not a good criterion to use. Peak pitch rate can still provide some information on the aircraft's ability to perform a given maneuver, particularly when a control input reversal is seen.

Furthermore, the peak attitude rate can help provide insight into an aircraft's actual ability to perform a maneuver. Attitude rates are criteria used in the current manned rotary-wing flying qualities standards, as described in Section 2.1.2. The peak attitude rate has the ability to describe how quickly the aircraft can track within a given plane. It can provide some much needed insight into an aircraft's ability to perform a maneuver and how aggressively that maneuver can be performed. This can assist in the definition of maneuver categorizations.

3.4.4 Quickness.

Quickness is a relatively new criterion to the flying qualities community. The method used to obtain the quickness criterion is seen in Figure 43. In this example, a roll maneuver is used to first gather time history information for the roll rate and bank angle change. Then a comparison of the bank angle change of the peak roll rate is shown. These two criteria can be cross-plotted to show a single discrete point. This point is the term described as quickness. Furthermore, this quickness value is approximately proportional to the closed-loop bandwidth, where bandwidth is described to be the frequency at which the bode phase response of the system is 45° . For an extensive range of closed-loop damping ratios, the bandwidth is approximately two times the size of the quickness criterion.[38] An example of how the quickness values can be analyzed from the discrete maneuver time histories can be seen in Figure 44.

During this research, quickness is evaluated throughout several maneuvers. The benefit of the j2 Universal Tool-Kit in this analysis is demonstrated in the data extraction. When an aircraft is flown through a maneuver, the j2 Universal Took-Kit provides a time history for the parameters the user selects. In this case, during every maneuver pitch rate, Q , pitch attitude, θ , roll rate, P , and roll attitude, ϕ , were recorded for each time step. All of this information was exported into Microsoft ExcelTM where the peak rates and attitude change were calculated. Then the quickness was determined with one of the following equations:

$$\frac{Q_{pk}}{\Delta\theta} \quad \text{or} \quad \frac{P_{pk}}{\Delta\phi}$$

An important item to note is that quickness should be focused on “one-sided control inputs”. When significant control input reversals are performed, the peak

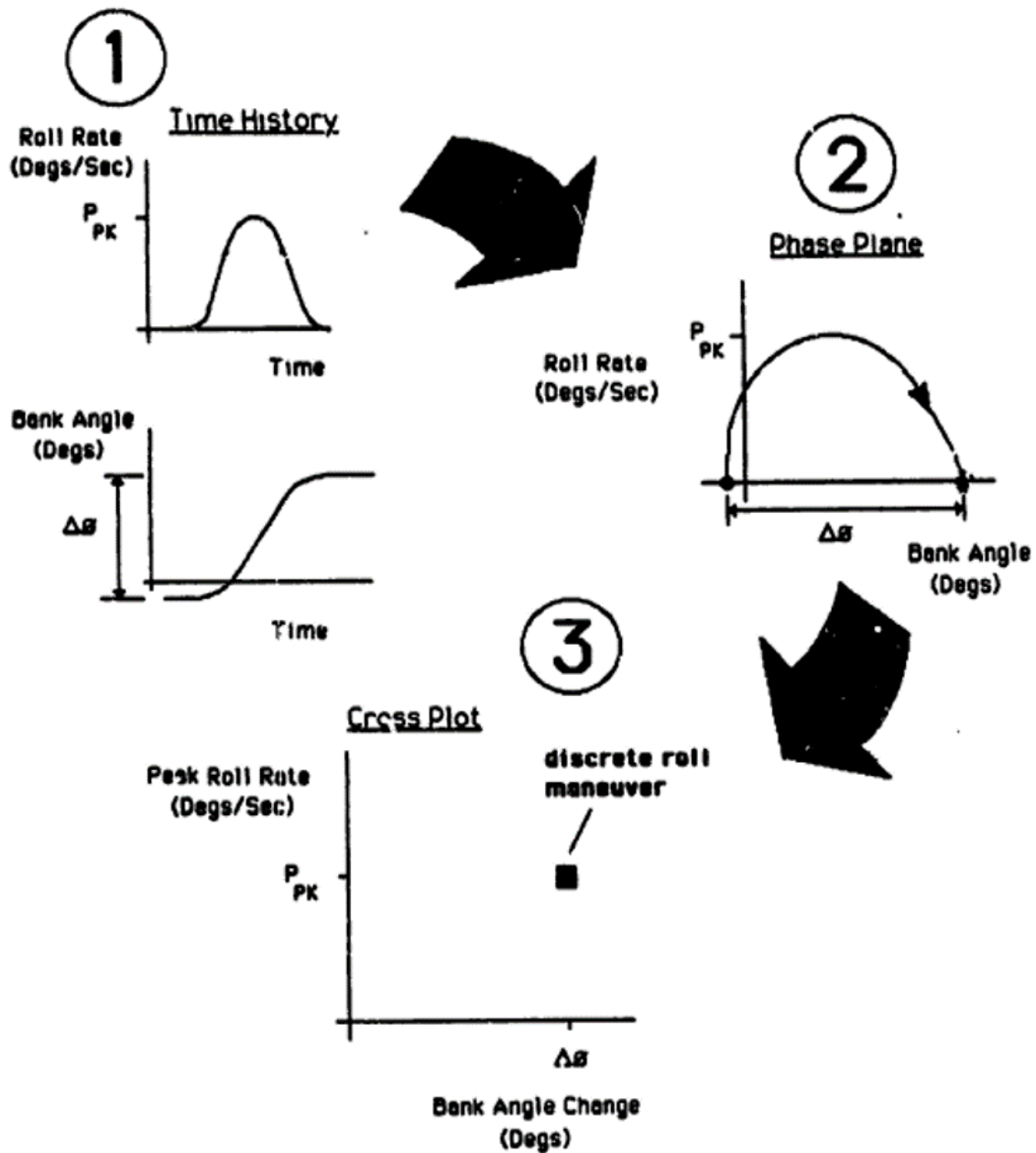


Figure 43. Analysis Technique for Discrete Roll Maneuver Data[38]

attitude rate tends to overshoot the desired input compared to a single control input. Then, as the peak attitude rate starts to reduce for the reversal, the input is already returning to the initial attitude rate. This causes a very large peak attitude rate with approximately the same attitude change and, therefore, leads to an inaccurately large

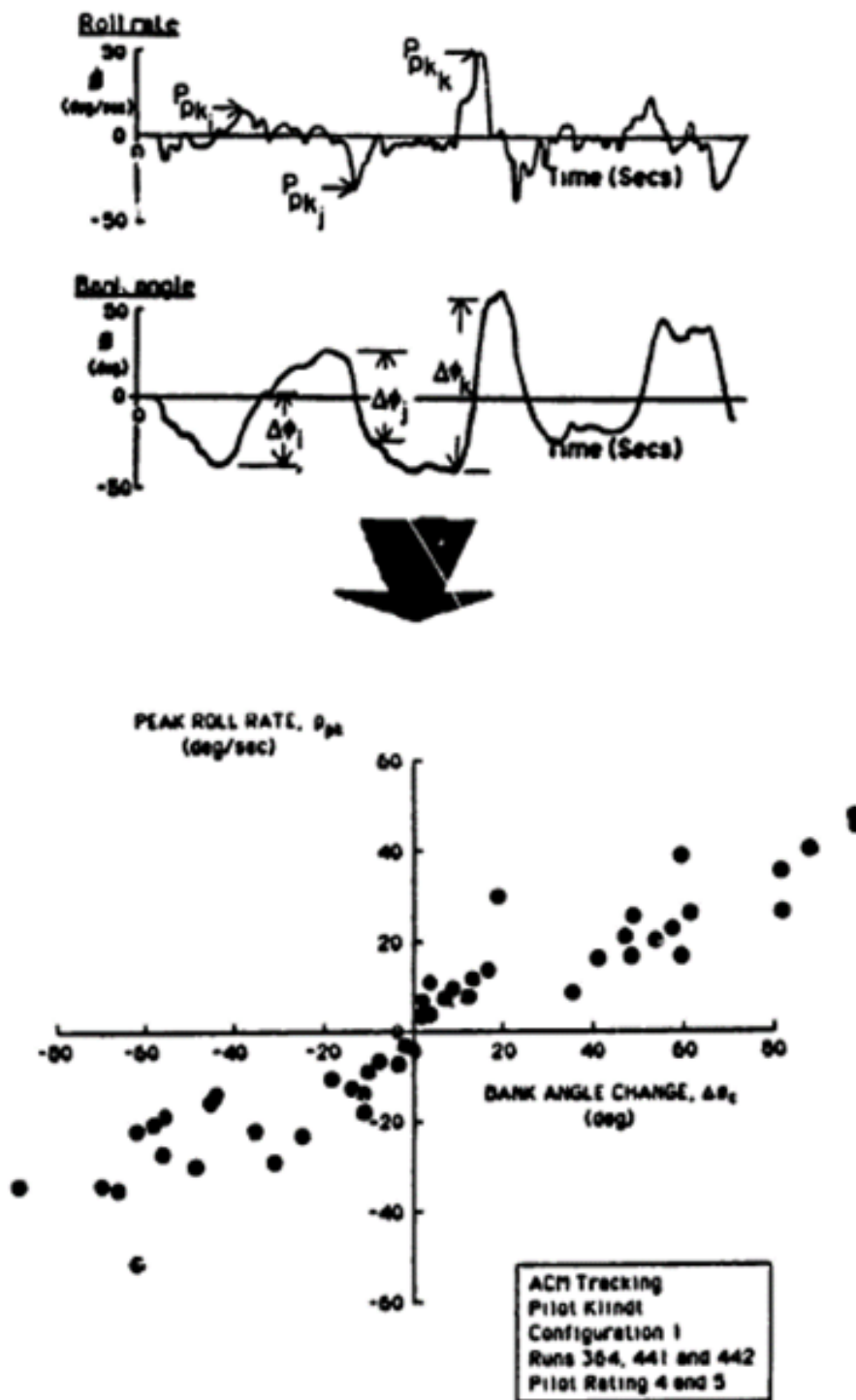


Figure 44. Definition of Task Signature From Discrete Maneuver Time Histories[38]

quickness value that does not correlate to bandwidth.[38] With this understanding in mind, the pitch quickness will not be evaluated for the pitch and roll discrete tracking maneuver and the roll quickness will not be evaluated for the precision offset landing or the pitch and roll discrete tracking maneuvers.

3.4.5 Bandwidth.

Bandwidth, ω_{BW} , is a frequency domain criterion that has been used to help quantify flying qualities criteria in both MIL-STD-1797A and ADS-33E-PRF. In fact, almost all criteria in either standard can be related back to bandwidth.[33]. Bandwidth is a frequency criterion aiming to quantify how fast the aircraft can respond to a given input. Bandwidth is further described to be the lesser of the phase bandwidth, $\omega_{BW_{Phase}}$, or the gain bandwidth, $\omega_{BW_{Gain}}$. The natural stability of the aircraft is when the phase is equal to -180° . The phase bandwidth, $\omega_{BW_{Phase}}$, is defined as the frequency where there is a phase margin of 45° . In other words, the frequency found when the phase is -135° . To determine the gain bandwidth, $\omega_{BW_{Gain}}$, first the amplitude at ω_{180} is found and 6 dB is added to that. The corresponding frequency is the gain bandwidth, $\omega_{BW_{Gain}}$. The resulting lesser value of $\omega_{BW_{Gain}}$ or $\omega_{BW_{Phase}}$ determines the bandwidth frequency, ω_{BW} . This process is depicted in Figure 45. Important to note, this is the same definition of bandwidth frequency that both manned fixed-wing and manned rotary-wing aircraft use.

$$\omega_{BW} = \text{Lesser of } \omega_{BW_{Gain}} \text{ and } \omega_{BW_{Phase}}$$

The results of a maneuver were downloaded and the time history of input to output was uploaded into MatLab. Then a discrete Fourier transform was performed to obtain the gain and phase of the system. Next the “fmincon” function in MatLab, which finds the minimum of a cost function of several variables. In this case, the cost

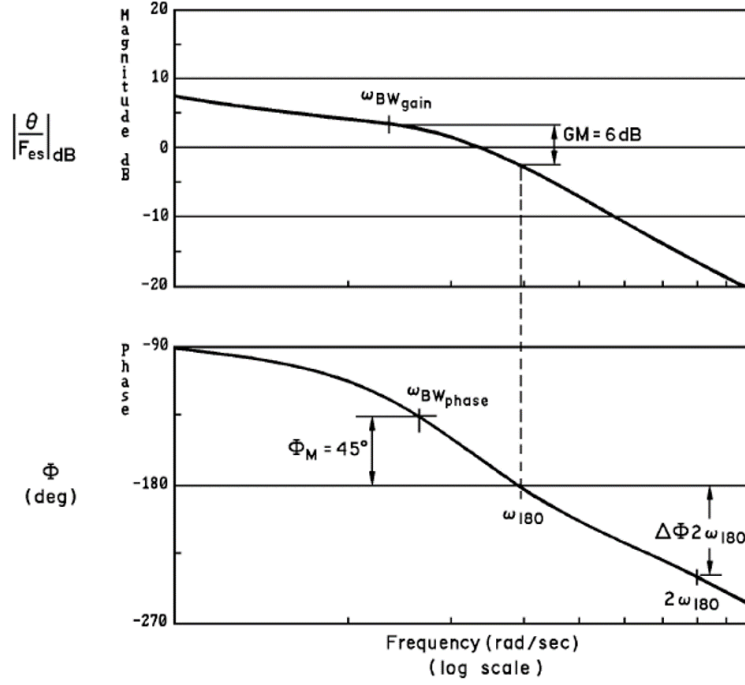


Figure 45. Bandwidth Definition[33]

function was an unknown second order transfer function created from the aircraft's input and output time history. The desire was to find a transfer function of the form:

$$\frac{x_4}{1 + 2 \cdot x_2 \cdot x_3 + x_3^2}$$

The initial conditions of (0, 0.5, 3,4) were defined. There were no linear constraints. The lower bounds of the array were (-0.1, -1000, 0, -100) while the upper bounds of the array were (0.1, 1000, 100, 100). Using the fmincon function, a transfer function performing a response very similar to the actual aircraft response was calculated. An example of the Group 5 Aircraft A precision aggressive, pitch discrete tracking, best fit transfer function is shown in Figure 46. The transfer function associated with this best fit is of the form:

$$\frac{2.235}{s^2 + 0.7534 \cdot s + 2.442}$$

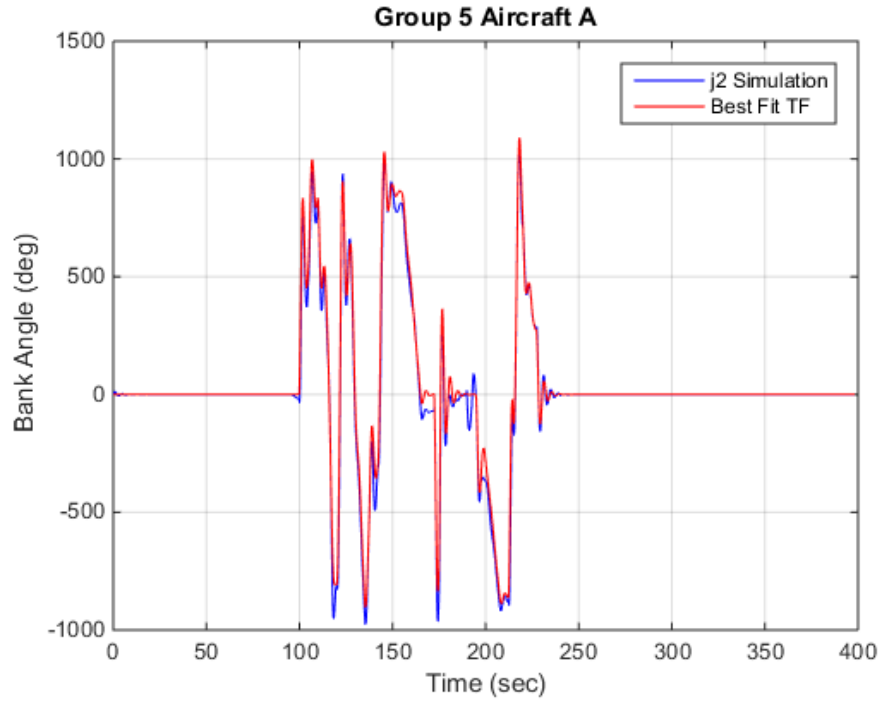


Figure 46. Group 5 Aircraft A, Pitch Discrete Tracking, Best Fit Transfer Function

With this best fit transfer function, the aircraft's longitudinal and lateral-directional bode plots were created, as seen in Figure 47. Then the bandwidth values were calculated.

3.4.6 Time Delay.

In both MIL-STD-1797 and ADS-33E-PRF, the bandwidth is typically displayed with reference to the phase delay, τ_p . The phase delay compares the rate of change of the phase with the frequency above the crossover frequency. Both MIL-STD-1797 and ADS-33E-PRF use the following equation to calculate phase delay:

$$\frac{\Delta\phi_{2\omega_{180}}}{57.3 \cdot 2\omega_{180}}$$

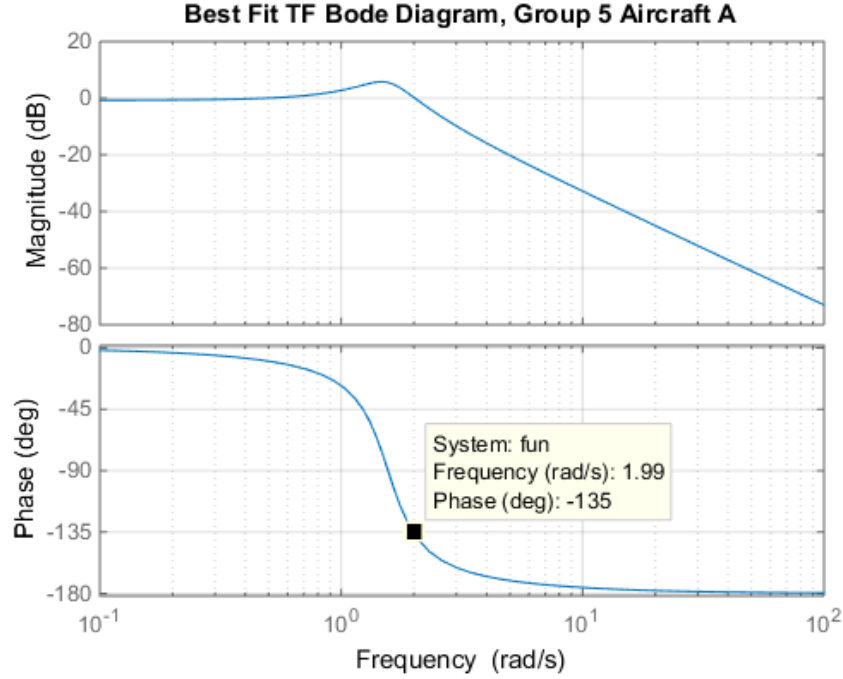


Figure 47. Group 5 Aircraft A, Pitch Discrete Tracking, Bode Plot

However, phase delay is also approximately equivalent to time delay, τ_t . Time delay is the time between control input and the aircraft's response.[37] This is a beneficial metric in determining an aircraft's performance and ability to accomplish a maneuver. In this research, the j2 Universal Tool-Kit exports a time history of the maneuver, so time delay will be the criterion used.

3.5 Summary

The field of UAV flying qualities is extensive; however, to make a complex problem more manageable, we must first carefully choose aircraft types, mission tasks and flying qualities criteria that can span various categories, allowing a flying qualities framework to be realized. Three UAVs were chosen that spanned various aircraft groupings due to operating altitude and weight: Group 5 Aircraft A, Group 5 Aircraft B, and Group 4 Aircraft. These UAVs also had specific missions that correlate with

specific MTEs chosen. Four MTEs were chosen due to varying amounts of precision and aggressiveness: climbing spiral, air-to-ground tracking, precision offset landing, and pitch and roll discrete tracking. With all of these facets defined, flying qualities criteria, to include angle of attack, attitude change, peak attitude rate, quickness, bandwidth, and time delay, can be analyzed and a full spectrum of results will be collected. These results will be analyzed and trends will be noted with the intention of verifying the speculation that flying qualities criteria should not be grouped by aircraft weight, but should instead be classified according to which mission an aircraft performs. This analysis will set the stage for a proposed framework for an unmanned aircraft flying qualities standard.

IV. Results

During this research, three validated models of hypothetical UAVs discussed in Section 3.1 were created and run through the four maneuvers discussed in Section 3.3. Each maneuver was also iterated with varying amounts of longitudinal and lateral-directional control inputs. The result is a very large amount of data that has been compiled and fully documented in the appendices for each aircraft. The purpose of this section is to highlight the significant results, comparisons, and findings of this research. Each maneuver will be looked at individually, comparing the different aircraft results. Then a comparison across maneuvers for each aircraft will be reviewed. Finally, there will be a discussion on possible methods for evaluating a UAV's performance during a specified maneuver.

4.1 Aircraft Comparisons on Common Maneuver

The following discussion takes each maneuver individually and compares the criteria magnitudes and tendencies among the three aircraft. This information will provide insight into a possible classification scheme for UAV flying qualities. Several times throughout the following paragraphs, the radius of gyration nondimensionalized by the wing span is referenced. To aid in understanding and for reference, Table 18 lists these ratios for the three different aircraft. The smaller the nondimensionalized radius

Table 18. Radius of Gyration Nondimensionalized by Wing Span

	$\frac{r_y}{b}$, Longitudinal Plane	$\frac{r_x}{b}$, Lateral-Directional Plane
Group 5 Aircraft A	0.0800	0.0514
Group 5 Aircraft B	0.1670	0.1069
Group 4 Aircraft	0.0845	0.0701

of gyration, the less resistance to rotation created by the aircraft’s mass properties. Group 5 Aircraft A and Group 4 Aircraft have very similar nondimensionalized radius of gyrations in the longitudinal plane. Group 5 Aircraft B has a nondimensionalized radius of gyration approximately two times as large as the other two aircraft; however, this is not true in the lateral-directional plane. Group 5 Aircraft A has the smallest nondimensionalized radius of gyration in the lateral-directional plane. Group 4 Aircraft has a ratio that is 1.36 times larger. Finally, Group 5 Aircraft A has a ratio 2.08 times as large as Group 5 Aircraft A’s ratio. The fact that there are differences in the nondimensionalized radius of gyration is correlated in this analysis.

4.1.1 Non-Precision Non-Aggressive Maneuver Results.

The non-precision non-aggressive climbing spiral maneuver was discussed in Section 3.3.1. Each aircraft performed this maneuver fifteen different times at varying longitudinal and lateral-directional control inputs. The full analysis for each aircraft is listed in the appendices; however, the specific items of interest for the coupled maneuvers are noted in the following discussion.

4.1.1.1 Angle of Attack and Pitch Attitude Change.

The angle of attack, α , criterion was documented throughout each variation of this maneuver. For all three aircraft, even at combined large longitudinal and lateral-directional control inputs, the largest angle of attack performed was not near the stall angle of attack, α_{stall} . Therefore, any unusual characteristics must be related to the airframe or possibly a thrust limitation.

The pitch attitude change criterion, $\Delta\theta$, is worth discussion. All three aircraft have similar tendencies when increasing the longitudinal control input, but differences

when increasing the lateral-directional control input. Therefore, all three sets data are shown in Tables 19, 20, and 21.

Table 19. Group 5 Aircraft A, Climbing Spiral, Pitch Attitude Change Values (rad)

$\Delta\theta$	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
500 fpm Climb	0.0308 (1.7631°)	0.0359 (2.0596°)	0.0595 (3.4093°)
1000 fpm Climb	0.0612 (3.5060°)	0.0659 (3.7761°)	0.0878 (5.0327°)
1400 fpm Climb	0.0961 (5.5046°)	0.0981 (5.6216°)	0.1162 (6.6570°)

Table 20. Group 5 Aircraft B, Climbing Spiral, Pitch Attitude Change Values (rad)

$\Delta\theta$	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
250 fpm Climb	0.0142 (0.8142°)	0.0140 (0.8025°)	0.0136 (0.7772°)
500 fpm Climb	0.0286 (1.6412°)	0.0277 (1.5845°)	0.0274 (1.5671°)
800 fpm Climb	0.0461 (2.6430°)	0.0451 (2.5865°)	0.0440 (2.5182°)

Table 21. Group 4 Aircraft, Climbing Spiral, Pitch Attitude Change Values (rad)

$\Delta\theta$	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
100 fpm Climb	0.0096 (0.5505°)	0.0107 (0.6142°)	0.0122 (0.6984°)
250 fpm Climb	0.0232 (1.3306°)	0.0244 (1.3980°)	0.0259 (1.4822°)
500 fpm Climb	0.0657 (3.7671°)	0.0646 (3.7007°)	0.0614 (3.5158°)

As the longitudinal control input, climb rate, increases, the pitch attitude change increases for all three aircraft. The explanation for this is found in simple aeronautical concepts. As the longitudinal control input increases, more lift must be produced. In order to achieve more lift, the angle of the angle of attack, α , must be increased.

The angle of attack change has a direct relationship to the pitch attitude change, $\Delta\theta = \Delta\alpha + \Delta\gamma$, where γ is the flight path angle.[57] As the longitudinal control input increases, the flight path angle increases and, as more lift is required, the angle of attack also increases. Thus providing the explanation for the consistent increase in pitch attitude change with increasing pitch control input for all three aircraft.

As the lateral-directional control input increases at a constant longitudinal control input, Group 5 Aircraft A and Group 4 Aircraft have similar tendencies. For both of these aircraft, as the lateral-directional control input increases, the pitch attitude change increases. This explanation, once again, lies in simple aeronautical and geometric concepts. As an aircraft banks, the lift vector remains perpendicular to the wing and the portion of lift used to keep the aircraft at a constant climb rate must be increased by a factor of $\frac{1}{\cos\phi} - 1$. In order to maintain a given climb rate, the lift vector must be increased to compensate for this reduction due to the aircraft bank angle. To increase the lift, the angle of attack must be increased. If the flight path angle, γ , remains constant, the relationship between angle of attack and pitch attitude is: $\Delta\theta = \Delta\alpha$. Since the longitudinal control input remains constant, the flight path angle remains constant and, therefore, the pitch attitude must increase with increasing angle of attack.

To further explain this concept, keeping longitudinal control input constant, at the small lateral-directional control inputs ($\approx 5^\circ$ angle of bank), the lift vector must be increased by only 0.38% and at the moderate lateral-directional control inputs ($\approx 15^\circ$ angle of bank), must be increased by 3.5% to maintain the desired longitudinal control input. The increase in lift, and therefore pitch, necessary at these two lateral-directional control inputs is very small and any deviations in the pitch attitude values can be explained with noise. However, the last column is the large lateral-directional control input ($\approx 30^\circ$ angle of bank for Group 5 Aircraft A and $\approx 25^\circ$ angle of bank for

Group 5 Aircraft B and Group 4 Aircraft) which requires an increase of the lift vector by a factor of 13.4% and 9.4% respectively. This increase in lift is significantly larger, therefore, at the large lateral-directional control inputs, the angle of attack, and therefore the pitch attitude change, must be notably increased to maintain the given longitudinal control input.[58] This explains the large increase in pitch attitude change from moderate to large lateral-directional control inputs. There is one deviation to this. In Group 4 Aircraft, at a large longitudinal control input and increasing lateral-directional control inputs, a decrease in the pitch attitude is seen. At this large pitch input, Group 4 Aircraft is initially climbing at 500 *fpm*. This climb rate is outside of the sustainable maximum climb capability for this aircraft and, therefore, several parameters are unsustainable. The decrease in pitch attitude change is the aircraft's control system ensuring the aircraft does not stall.

For Group 5 Aircraft B, as the lateral-directional control input is increased with a constant longitudinal control input, the pitch attitude decreases. This decrease in pitch attitude change is quite small and can be considered within the bounds of acceptable noise for all lateral-directional control inputs. The differences among Group 5 Aircraft B and Group 5 Aircraft A and Group 4 Aircraft demonstrate there is no correlation between weight and pitch attitude change. These differences are only seen during a change in lateral-directional control input which leads to the investigation of radius of gyration in the longitudinal plane correlation. When this value is nondimensionalized with respect to aircraft wing span, Group 5 Aircraft B has a much larger value (0.1670) compared to Group 4 Aircraft (0.0845) and Group 5 Aircraft A (0.0800). The larger the value, the greater the resistance to rotation in the longitudinal plane. This can also explain the non-standard tendency for Group 4 Aircraft at the moderate to large lateral-directional control input and the large longitudinal control input.

4.1.1.2 Peak Pitch Rate.

The peak pitch rate, Q_{pk} , is a criterion worth investigating as it helps describe the aircraft's ability to perform a task with respect to time. It is also the numerator in the pitch quickness equation. The tendencies for this criterion are consistent among all three aircraft in the longitudinal plane. However, the aircraft differ in the lateral-directional plane so the data for all three aircraft as seen in Tables 22, 23, and 24. As

Table 22. Group 5 Aircraft A, Climbing Spiral, Peak Pitch Rate Values (rad/sec)

Q_{pk}	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
500 fpm Climb	0.0106	0.0139	0.0404
1000 fpm Climb	0.0219	0.0214	0.0469
1400 fpm Climb	0.0366	0.0342	0.0537

Table 23. Group 5 Aircraft B, Climbing Spiral, Peak Pitch Rate Values (rad/sec)

Q_{pk}	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
250 fpm Climb	0.0070	0.0087	0.0207
500 fpm Climb	0.0128	0.0140	0.0228
800 fpm Climb	0.0198	0.0211	0.0256

the longitudinal control increases, the peak pitch rate also increases. This is expected as the more pitch attitude required for a maneuver, the more time the aircraft has to increase its pitch rate. This tendency is consistent among all three aircraft.

As the turn radius gets smaller, or the lateral-directional control input increases, in general, the peak pitch rate also increases. In general, this tendency is consistent among all three aircraft. As described previously, an increase in roll command input

Table 24. Group 4 Aircraft, Climbing Spiral, Peak Pitch Rate Values (rad/sec)

Q_{pk}	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
100 fpm Climb	0.0050	0.0125	0.0343
250 fpm Climb	0.0106	0.0146	0.0358
500 fpm Climb	0.0200	0.0226	0.0408

means there will be an increase in pitch attitude change and, therefore, an increase in pitch rate. Recalling that Group 5 Aircraft B had approximately constant pitch attitude change explains the relatively small pitch rate increase compared to Group 4 Aircraft and Group 5 Aircraft A.

The exception to this tendency is small to moderate lateral-directional control input at the moderate to large longitudinal control input for Group 5 Aircraft A. At these inputs, the peak pitch rate decreases. Investigating why this change in tendency occurs leads to the realization that the peak pitch rate at these control inputs occurs at the end of the climbing spiral when the control inputs are being taken out. The peak pitch rates for the remaining control input for Group 5 Aircraft A always occur at the initiation of the control input. So, when there is a moderate to large longitudinal control input and small to moderate lateral-directional control input, a higher pitch rate is required to stop the climb and turn. This occurs in Group 5 Aircraft A because the radius of gyration in the lateral-directional plane nondimensionalized by the wing span is smallest in this aircraft. Thus, the pitch rate is easier to achieve with a smaller resistance to rotation and, therefore, is larger in magnitude.

The magnitude of the peak pitch rate is another interesting item as shown in Figure 48. The nearly linear increase of peak pitch rate to pitch attitude change is similar to what was shown in Figure 44 and is, therefore, consistent with what

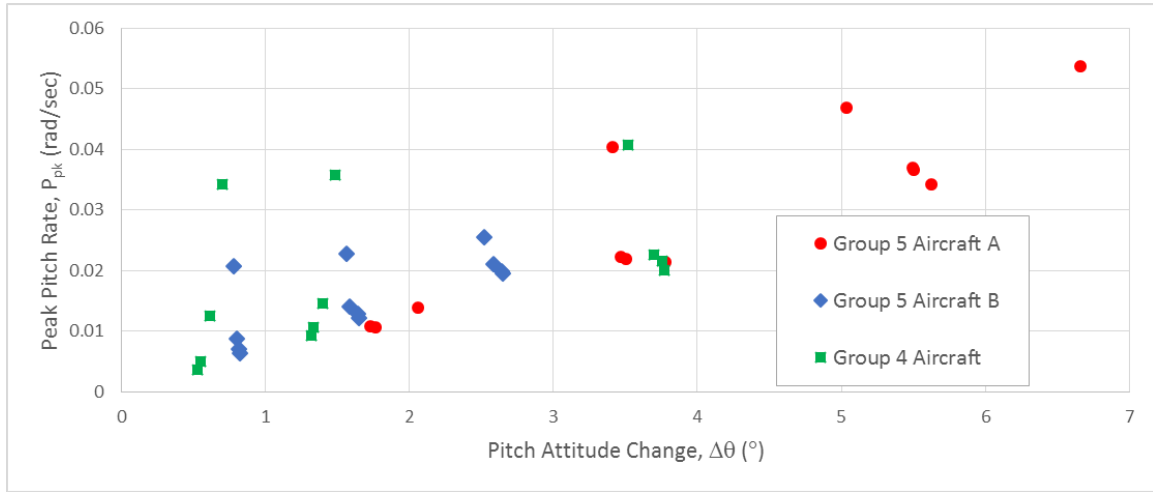


Figure 48. Climbing Spiral, Peak Pitch Rate Comparison

is expected for various control inputs from aircraft with control systems that give a similar responses to doublets. What is important to note are the outliers. Group 5 Aircraft A has the largest pitch attitude change. This is understandable as the large control input for this aircraft is a 1500 *fpm* climb while Group 5 Aircraft B has a 800 *fpm* climb and Group 4 Aircraft has a 500 *fpm* climb. The larger climb rate correlates to a steeper flight path and, therefore, a necessary larger pitch attitude change. This larger pitch attitude change necessitates, due to the linear increase in Figure 44, a larger peak pitch rate. The other standout data points from Figure 48 is Group 4 Aircraft having a large peak pitch rate at small pitch attitude change. Referring back to Table 18, the nondimensionalized radius of gyration in the longitudinal plane for Group 4 Aircraft is very similar to Group 5 Aircraft A and the peak pitch rates for these two aircraft at small longitudinal control inputs are similar. Group 5 Aircraft B has a larger nondimensional radius of gyration in the longitudinal plane, suggesting a resistance to rotation. This resistance is correlated in the peak pitch rates for the small control inputs. Group 5 Aircraft B has smaller peak pitch rates compared to the other two aircraft.

The peak pitch rate criterion in the non-precision non-aggressive climbing spiral maneuver is a valid criterion to demonstrate aircraft performance. Differences between peak pitch rates are seen between various longitudinal and lateral-directional control inputs. Furthermore, the magnitude of the peak pitch rate is directly linked to the nondimensionalized radius of gyration in the longitudinal plane.

4.1.1.3 Pitch Quickness.

The pitch quickness criterion, the ratio of the peak pitch rate, Q_{pk} , to the pitch attitude change, $\Delta\theta$, is a flying qualities criterion that has been used with success in ADS-33E-PRF. Since the tendencies found with this criterion are not consistent for the three aircraft, all three sets of data are shown in Tables 25, 26, and 27. Group

Table 25. Group 5 Aircraft A, Climbing Spiral, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
500 fpm Climb	0.3432	0.3862	0.6786
1000 fpm Climb	0.3580	0.3247	0.5341
1400 fpm Climb	0.3810	0.3487	0.4620

Table 26. Group 5 Aircraft B, Climbing Spiral, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
250 fpm Climb	0.4918	0.6241	1.5244
500 fpm Climb	0.4470	0.5079	0.8338
800 fpm Climb	0.4288	0.4673	0.5818

5 Aircraft B and Group 4 Aircraft have the same tendencies in both the longitudinal

Table 27. Group 4 Aircraft, Climbing Spiral, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
100 fpm Climb	0.5181	1.1641	2.8134
250 fpm Climb	0.4561	0.5981	1.3848
500 fpm Climb	0.3039	0.3504	0.6655

and lateral-directional planes. As the longitudinal control input increases, the pitch quickness values decrease. This decrease is due to the larger pitch attitude change increase compared to the smaller peak pitch rate increase. Then, as the lateral-directional control input increases, or the turn radius decreases, the pitch quickness values increase. This is the result of the larger increase in peak pitch rate versus the slight increase in pitch attitude change necessary to compensate for the reduction in lift caused by the lateral-directional control input.

Group 5 Aircraft A is not consistent with the other aircraft tendencies. As shown in Table 25, this aircraft has increasing pitch quickness at small lateral-directional control inputs with increasing longitudinal control inputs. There is also increasing pitch quickness at the moderate lateral-directional control input from moderate to large longitudinal control input. These changes in control inputs cause an increase in pitch quickness when the other two aircraft had decreases. This means, for Group 5 Aircraft A during the variations of this maneuver, the pitch attitude change increase is smaller than the peak pitch rate increase. This difference is due to the higher Group 5 Aircraft A climb rate. The climb rate is large enough that there is more time for the pitch rate to increase. Then, in the lateral-directional plane, there is decreasing pitch quickness in both the moderate and large longitudinal control inputs when changed from a small to moderate lateral-directional control input. This decrease in the pitch

quickness with the increasing longitudinal control input can be explained with the decrease noted in the peak pitch rate at these control inputs.

The relative magnitude of the pitch quickness criterion provides some insight and is seen in Figure 49. Group 5 Aircraft A has a very consistent pitch quickness value

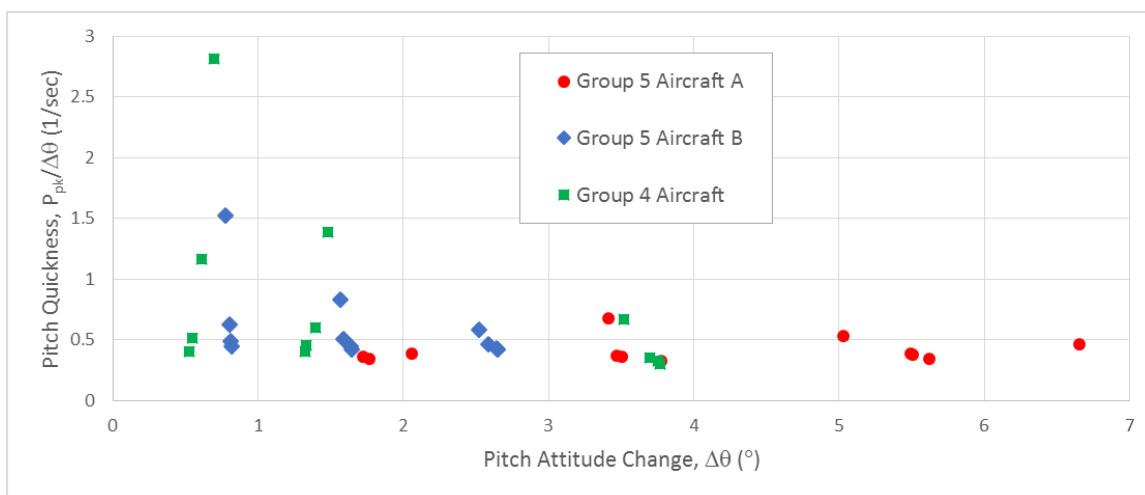


Figure 49. Climbing Spiral, Pitch Quickness Comparison

and only slight changes are seen with variations in control inputs. Group 5 Aircraft B has very consistent pitch quickness values as well, except for the one outlier at a small pitch attitude change. The magnitude of the pitch attitude change is less than one so the small increase of the peak pitch rate is amplified when divided by a value less than one. This also explains the outlier at small pitch attitude change for Group 4 Aircraft. Finally, the pitch quickness data points are widespread for Group 4 Aircraft. Group 5 Aircraft A pitch quickness values are widespread as well, but it is not as obvious because of the large pitch attitude changes at a constant longitudinal control input. The MIL-STD-1797 classification scheme for flying qualities separates aircraft based on weight and this distinction is not seen in this analysis. The magnitude of the pitch quickness criterion does not change with respect to weight. The pitch attitude change at a small longitudinal control input and large lateral-directional

control input is similar to the pitch attitude change at a moderate longitudinal control input and small lateral-directional control input. Both Group 4 Aircraft and Group 5 Aircraft A have a small nondimensionalized radius of gyration in the longitudinal plane correlating with less of a resistance to rotation and leading to a correlation of more widespread pitch quickness values. Group 5 Aircraft B pitch quickness values are more tightly clustered linked to a larger nondimensionalized radius of gyration.

The MIL-STD-1797 classification scheme for flying qualities separates aircraft based on weight and this distinction is not seen in this analysis. The magnitude of the pitch quickness criterion does not change with respect to an aircraft's weight. The results of this analysis indicate that the pitch quickness criterion has value in the non-precision non-aggressive climbing spiral maneuver along with the nondimensionalized radius of gyration in the longitudinal plane. The pitch quickness has a nearly consistent value among all three aircraft and any values beyond this can be explained.

4.1.1.4 Roll Attitude Change.

The roll attitude change, $\Delta\phi$, does not have any tendencies that are not expected and all are consistent among the three aircraft so only the data for Group 5 Aircraft A is shown in Table 28. This criterion does not change with respect to longitudinal

Table 28. Group 5 Aircraft A, Climbing Spiral, Roll Attitude Change Values (*rad*)

$\Delta\phi$	6.75 nm Turn Radius (4.95° AOB)	2.25 nm Turn Radius (14.57° AOB)	1.0 nm Turn Radius (30.3° AOB)
500 fpm Climb	0.0864 (4.948°)	0.2542 (14.565°)	0.5285 (30.281°)
1000 fpm Climb	0.0864 (4.951°)	0.2543 (14.571°)	0.5288 (30.298°)
1400 fpm Climb	0.0864 (4.952°)	0.2544 (14.575°)	0.5291 (30.313°)

nal control input and it increases with respect to an increase in lateral-directional

control input. The produced roll attitude change is approximately equal to the lateral-directional control input. For example, Group 5 Aircraft A at a moderate lateral-directional control input with a 2.25 *nm* turn radius has a 14.57° bank angle. The roll attitude change at this lateral-directional control input ranges from 14.565° to 14.575°, validating all three aircraft have very precise lateral-directional control.

4.1.1.5 Peak Roll Rate.

The peak roll rate, P_{pk} , has tendencies consistent in all three aircraft and is shown in Table 29 with Group 5 Aircraft A data. There is a slight increase in value as the

Table 29. Group 5 Aircraft A, Climbing Spiral, Peak Roll Rate Values (*rad/sec*)

P_{pk}	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
500 fpm Climb	0.0197	0.0580	0.1212
1000 fpm Climb	0.0202	0.0596	0.1241
1400 fpm Climb	0.0208	0.0610	0.1273

longitudinal control increases. This increase is explained by understanding that once an aircraft is rotating about an axis less force is required to increase the rotation than is required to initiate it. As expected, the peak roll rate also has an increase with lateral-directional control increase and tightening of the turn radius. There is more lateral-directional control input and, therefore, there is more time to increase the peak roll rate.

Furthermore, the magnitudes of the peak roll rate are consistent among the three aircraft with respect to lateral-directional control input. This is demonstrated in Figure 50. All three aircraft have approximately equal small and moderate lateral-directional control input. Group 5 Aircraft B and Group 4 Aircraft have the same bank angle values at the large lateral-directional control input, 25° bank angle, so it

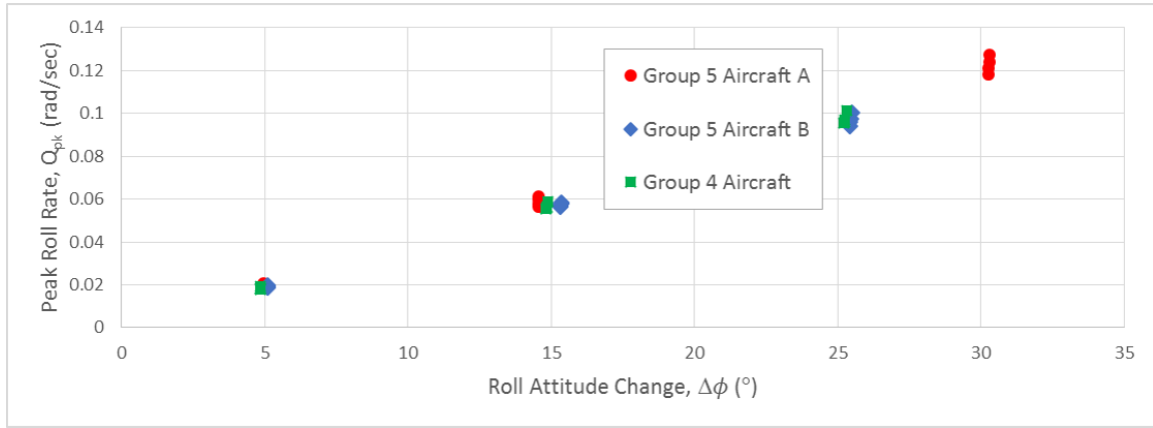


Figure 50. Climbing Spiral, Peak Roll Rate Comparison

is easy to compare the magnitudes of the peak roll rates. The values are consistent among the two aircraft for a given longitudinal control input. The larger Group 5 Aircraft A values are due to the larger lateral-directional control input of 30° bank angle. There is also a slight spread of peak roll rates for Group 5 Aircraft A. This can be explained by correlating the nondimensionalized radius of gyration in the lateral-directional plane. This value is 0.051 for Group 5 Aircraft A, 0.070 for Group 4 Aircraft, and 0.107 for Group 5 Aircraft B. The smaller this nondimensionalized radius of gyration, the less resistance to rotation there is, hence the larger spread of peak roll rates for the Group 5 Aircraft A.

The peak roll rate criterion is a valid aircraft performance indicator for the non-precision non-aggressive climbing spiral and has no correlation to aircraft weight. There was a link between peak roll rate and aircraft lateral-directional control input. The aircraft performance had a small correlation to the nondimensionalized radius of gyration in the lateral-directional plane.

4.1.1.6 Roll Quickness.

The roll quickness criterion is the ratio of the peak roll rate, P_{pk} , to the roll attitude change, $\Delta\phi$. The values for this criterion are shown for Group 5 Aircraft A in Table 30. Only these results are shown because the tendency is the same for all

Table 30. Group 5 Aircraft A, Climbing Spiral, Roll Quickness Values sec^{-1}

$\frac{P_{pk}}{\Delta\phi}$	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
500 fpm Climb	0.2277	0.2282	0.2294
1000 fpm Climb	0.2338	0.2342	0.2348
1400 fpm Climb	0.2404	0.2397	0.2406

three aircraft. As the longitudinal control input increases, the roll quickness values increase slightly. This is due to the increase in the numerator, the peak roll rate, and a minimal change in the denominator, the roll attitude change. Then, as the turn radius decreases, which correlates to an increase of lateral-directional control input, the roll quickness values change very slightly but the change too small to be significant.

Although the magnitude of the roll quickness criterion varies slightly from aircraft to aircraft, the difference is very small. This is seen in Figure 51. In fact, the standard deviation for all the roll quickness values is 0.0088, with an average value of 0.222 sec^{-1} . Furthermore, a slight increase in roll quickness does not correlate to an increase of aircraft weight. However, there is a correlation between the roll quickness criterion and the radius of gyration in the lateral-directional plane nondimensionalized by the wing span. The smaller this nondimensionalized value, the larger the roll quickness value since there is less of a resistance to rotation. This is validated by Group 5 Aircraft B having the smallest roll quickness value and the largest nondimensionalized

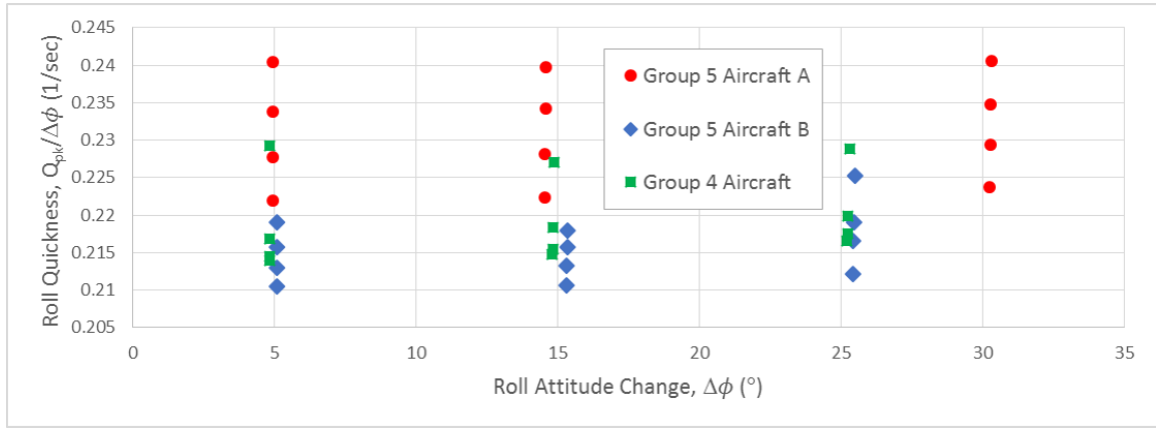


Figure 51. Climbing Spiral, Roll Quickness Comparison

radius of gyration in the lateral-directional plane, 0.1069. Group 4 Aircraft has roll quickness values between the values for Group 5 Aircraft B and Group 5 Aircraft A. This is validated with the middle value of the nondimensionalized radius of gyration, 0.0701. Finally, Group 5 Aircraft A has the largest roll quickness values corresponding with the smallest nondimensionalized value of 0.0514.

Roll quickness is a valid criterion for the non-precision non-aggressive climbing spiral maneuver. The flying qualities analysis shows no correlation to aircraft weight and has a definite limit for the aircraft in this maneuver. There is also a small correlation between the roll quickness values and the aircraft's specific nondimensionalized radius of gyration in the lateral-directional plane.

4.1.1.7 Bandwidth and Time Delay.

The pitch and roll bandwidth values were evaluated during the non-precision non-aggressive climbing spiral maneuver with moderate longitudinal and lateral-directional control inputs. The results are shown in Table 31. The same method used in Section 3.4.5 was used to calculate these results. Group 5 Aircraft A has a pitch bandwidth of 2.03 *rad/sec* which is 6.25 times as large as the pitch quickness

Table 31. Closed-Loop Bandwidth Comparison for Climbing Spiral Maneuver at Moderate Control Inputs

Aircraft	Pitch Bandwidth $\omega_{BW_{Pitch}} (rad/sec)$	Roll Bandwidth $\omega_{BW_{Roll}} (rad/sec)$
Group 5 Aircraft A	2.03	16.00
Group 5 Aircraft B	2.66	16.00
Group 4 Aircraft	4.75	14.80

value. Group 5 Aircraft B generates a pitch bandwidth value of 2.66 rad/sec which is 5.24 times as large as the pitch quickness value. Finally, Group 4 Aircraft results in a pitch bandwidth of 4.75 rad/sec which is 7.94 times as large as the pitch quickness value. The increasing value of pitch bandwidth corresponds with an increase in the pitch quickness values.

The roll bandwidth values are quite large in comparison to the pitch bandwidth values. Furthermore, the roll quickness values are significantly less than these calculated roll bandwidth values. This confirms the previous acknowledgement that these three aircraft are particularly agile and responsive in the roll axis. This is validated by the relatively smaller values of the nondimensionalized radius of gyration in the lateral-directional plane versus the longitudinal plane.

The bandwidth parameters make further sense by comparing the time delays found by reviewing the time history of the maneuver. The time delays in Table 32 were found by determining the time between respective control input and aircraft response in the corresponding plane. There is no apparent correlation to weight as the categories in MIL-STD-1797 use. The pitch time delays are 570% to 900% larger than the roll time delays. This is verified by reviewing the pitch and roll doublets used to design the control system. Furthermore, the pitch time delay correlates with the nondimensionalized radius of gyration in the longitudinal plane. The smaller the

Table 32. Closed-Loop Time Delay Comparison for Climbing Spiral Maneuver at Moderate Control Inputs

	Pitch Time Delay $\tau_{Pitch} \text{ (sec)}$	Roll Time Delay $\tau_{Roll} \text{ (sec)}$
Group 5 Aircraft A	0.45	0.05
Group 5 Aircraft B	0.68	0.09
Group 4 Aircraft	0.51	0.09

radius of gyration ratio the smaller the time delay. Group 5 Aircraft A has the smallest values followed by Group 4 Aircraft and then Group 5 Aircraft B.

There is a very short time delay between the lateral-directional control input and the aircraft's response which has been verified in the various roll criteria. The roll time delay for all three aircraft is less than 0.1 seconds and, therefore, the difference in this criterion seen among the three aircraft is not significant.

Bandwidth and time delay are valid criteria for the non-precision non-aggressive climbing spiral maneuver. Both have been used with success in current flying quality standards for both manned fixed-wing and manned rotary-wing aircraft. This research ensured the validity of these criteria to aid in understanding the aircraft's performance in this non-precision non-aggressive maneuver.

4.1.2 Non-Precision Aggressive Maneuver Results.

The non-precision aggressive maneuver chosen was the air-to-ground tracking and is discussed in Section 3.3.2. Each aircraft performed this maneuver fifteen different times at varying control inputs. The full analysis for each aircraft is contained in the appendices with specific focus on the coupled maneuvers in the following discussion.

4.1.2.1 Angle of Attack and Pitch Attitude Change.

The angle of attack, α , criterion was documented throughout each variation of this non-precision aggressive maneuver. Just as before, for all three aircraft, even at combined large longitudinal and lateral-directional control inputs, the largest angle of attack performed was not near the stall angle of attack, α_{stall} . Therefore, any unusual characteristics must be related to the airframe or possibly related to a thrust limitation.

The pitch attitude change criterion appears to have consistent tendencies through all three aircraft, so only Group 5 Aircraft A is shown in Table 33. With the increase of

Table 33. Group 5 Aircraft A, Air-to-Ground Tracking, Pitch Attitude Change Values (rad)

$\Delta\theta$	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
500 fpm Descent	0.0328 (1.8766°)	0.0328 (1.8819°)	0.0349 (1.9995°)
800 fpm Descent	0.0607 (3.4755°)	0.0609 (3.4917°)	0.0612 (3.5070°)
1400 fpm Descent	0.0878 (5.0322°)	0.0881 (5.0484°)	0.0884 (5.0670°)

longitudinal control input, there is a corresponding increase of pitch attitude change. This is consistent with the explanation in Section 4.1.1.1. With an increase of longitudinal control input, more lift is required; therefore, the angle of attack must increase and the pitch attitude increases an equal amount.

With an increase of lateral-directional control input, there is no significant increase or decrease of pitch attitude change seen in any of the three aircraft. Despite the reduction of lift associated with increased bank angle, the pitch attitude did not demonstrate any significant change with increased lateral-directional control input. This constant pitch attitude change despite increasing lateral-directional control input is due in part to the fact that the aircraft is descending. Even though the lift vector

is reduced during a turn, less lift is needed during a descent. Therefore, there is not significant change in the pitch attitude change with an increase in lateral-directional control input.

In general, Group 4 Aircraft has the smallest pitch attitude change followed closely by Group 5 Aircraft B and finally Group 5 Aircraft A. Table 34 demonstrates this tendency for the large longitudinal control input and varying lateral-directional control inputs. As stated previously, the nondimensionalized radius of gyration in the

Table 34. Air-to-Ground Tracking, Pitch Attitude Change Comparison at Large Longitudinal Control Input and Varying Lateral-Directional Control Inputs (*rad*)

$\Delta\theta$	Small Lateral-Directional Control Input	Moderate Lateral-Directional Control Input	Large Lateral-Directional Control Input
Group 5 Aircraft A	0.0878 (5.03°)	0.0881 (5.05°)	0.0884 (5.07°)
Group 5 Aircraft B	0.0757 (4.34°)	0.0757 (4.34°)	0.0757 (4.34°)
Group 4 Aircraft	0.0653 (3.74°)	0.0654 (3.75°)	0.0654 (3.75°)

longitudinal plane can demonstrate a resistance to rotation. Group 5 Aircraft A has the largest pitch attitude change correlating with the smallest nondimensionalized radius of gyration. Group 5 Aircraft B has the largest radius of gyration ratio value of 0.1670 leading to the assumption that it should have the smallest pitch attitude change; however, Group 4 Aircraft has smaller pitch attitude change values. So the relationship between the nondimensionalized radius of gyration do not directly relate to this criterion. The *aggressive* nature of this non-precision aggressive descent is able to overcome any resistance to rotation.

4.1.2.2 Peak Pitch Rate.

The peak pitch rate criterion for the air-to-ground tracking maneuver has some interesting characteristics. The three aircraft behave differently, so all three data

sets are shown in Tables 35, 36, and 37. For all three aircraft, as the longitudinal

Table 35. Group 5 Aircraft A, Air-to-Ground Tracking, Peak Pitch Rate Values (rad/sec)

Q_{pk}	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
500 fpm Descent	0.0105	0.0105	0.0364
800 fpm Descent	0.0212	0.0212	0.0350
1400 fpm Descent	0.0289	0.0296	0.0324

Table 36. Group 5 Aircraft B, Air-to-Ground Tracking, Peak Pitch Rate Values (rad/sec)

Q_{pk}	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
500 fpm Descent	0.0122	0.0122	0.0193
800 fpm Descent	0.0192	0.0192	0.0192
1400 fpm Descent	0.0326	0.0332	0.0332

control input increases so does the peak pitch rate. Similarly, as the lateral-directional control input increases, so does the peak pitch rate. Both of these tendencies were explained in Section 4.1.1.2; however, there are some exceptions. Group 5 Aircraft A's peak pitch rate decreases with increasing longitudinal control input. Referencing Section 3.3.2, during the air-to-ground tracking, the aircraft starts a descent and then performs a 90° turn to track a non-moving target on the ground. This turn always occurs in the middle of the descent. For Group 5 Aircraft A at large lateral-directional control input, the peak pitch rate occurs at the same time as the input of the lateral-directional control. For Group 4 Aircraft with moderate to large longitudinal control input and large lateral-directional control input, the peak pitch rate occurs at the removal of the lateral-directional control. At all other Group 5 Aircraft A and Group

Table 37. Group 4 Aircraft, Air-To-Ground Tracking, Peak Pitch Rate Values (rad/sec)

Q_{pk}	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
250 fpm Descent	0.0092	0.0141	0.0375
500 fpm Descent	0.0186	0.0186	0.0375
700 fpm Descent	0.0261	0.0261	0.0341

4 Aircraft control inputs, the peak pitch rate occurs at the initiation or termination of the descent. This explains why a deviation from the tendency is seen in this criterion. This unique tendency of decreasing peak pitch rate is explained by using the inertia of the aircraft during the lateral-directional control initiation or termination to assist in the descent of the aircraft and there is no need for an increase in the peak pitch rate. Group 5 Aircraft B does not have this correlation because of the higher value of the nondimensionalized radius of gyration in the longitudinal plane. This aircraft has a higher radius of gyration ratio and, therefore, has a higher resistance to rotation. This means the aircraft needs an increased peak pitch rate to ensure the proper *aggressive* descent is accomplished.

Another item to note is the fact that the peak pitch rate is almost constant for Group 5 Aircraft A and Group 5 Aircraft B when changing the lateral-directional control input from small to moderate. This goes back to the aeronautical discussion in Section 4.1.1.1. The necessary increase in lift to account for a 5° and 15° angle of back is minimal so the peak pitch rate should be constant; however, at the large lateral-directional control inputs, lift must be increased by a larger factor and, therefore, the peak pitch rate increases. Group 4 Aircraft demonstrates this tendency but only for moderate and large longitudinal control input. With small longitudinal control input, the peak pitch rate increases from small to moderate lateral-directional control input instead of remaining constant. This is due to the very small decent rate associated

with the small longitudinal control input for this aircraft. It is only 250 *fpm*. With such a small descent rate, the aircraft cannot use the descent rate to account for the change in the lift vector and the aircraft has to adjust the peak pitch rate. Finally, Group 5 Aircraft B has a constant peak pitch rate at moderate and large longitudinal control input not just at the small and moderate lateral-directional control input, but also the large lateral-directional control input. The reason for this is that the aircraft is resistant to rotation, correlated to the large nondimensionalized radius of gyration in the longitudinal plane. The excessive descent rates of moderate, 800 *fpm*, and large, 1400 *fpm*, longitudinal control inputs provide enough reduction in the lift vector as to not require a pitch attitude change.

Displaying all of the peak pitch rates together in Figure 52 provides some additional insight into the criterion. The nearly linear increase of peak pitch rate to pitch

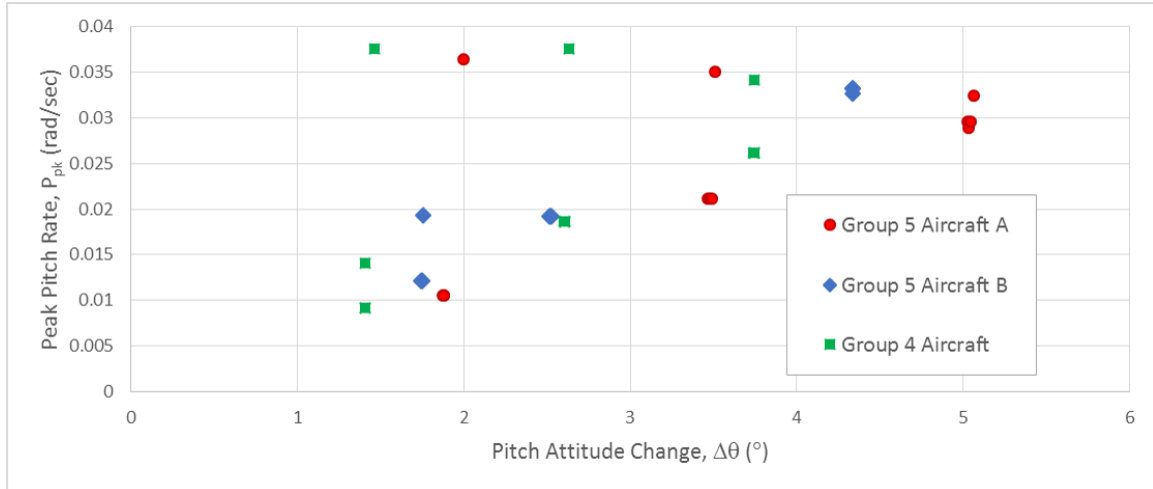


Figure 52. Air-To-Ground Tracking, Peak Pitch Rate Comparison

attitude change is the same as what was observed in Figure 48 for the previous maneuver. Group 5 Aircraft B has a larger nondimensionalized radius of gyration in the longitudinal plane and this corresponds with the lower peak pitch rate values. As the lateral-directional control input increases, and therefore the pitch attitude change, the

peak pitch rate increases linearly to the maximum value of 0.0332 rad/sec . However, for this non-precision aggressive maneuver, there appears to be a constant maximum value for Group 5 Aircraft A and Group 4 Aircraft without respect to longitudinal control input. Both of these aircraft have a smaller nondimensionalized radius of gyration in the longitudinal plane allowing for less resistance to rotation. Regardless, the maximum peak pitch rate value is the same for all three aircraft.

Peak pitch rate is valid criterion to use for flying qualities purposes. It provides insight into an aircraft's ability to perform the maneuver. Additionally, in this non-precision *aggressive* maneuver a maximum peak pitch rate for all three aircraft at large lateral-directional control inputs is demonstrated, without limitations on the maximum value due to longitudinal control inputs.

4.1.2.3 Pitch Quickness.

The pitch quickness criterion for the air-to-ground tracking maneuver varies depending on aircraft, longitudinal control input, and lateral-directional control input. Since there are no specific tendencies noted, all three aircraft pitch quickness data sets are shown. In Table 38 is the data for Group 5 Aircraft A. There are increas-

Table 38. Group 5 Aircraft A, Air-to-Ground Tracking, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
500 fpm Descent	0.3217	0.3208	1.0444
800 fpm Descent	0.3487	0.3471	0.5711
1400 fpm Descent	0.3295	0.3360	0.3660

ing and decreasing pitch quickness values throughout the various longitudinal and lateral-directional control inputs; however, each value makes sense when taking into

account the peak pitch rate and peak attitude changes as these are the numerator and denominator for the pitch quickness criterion. There is a small change in the pitch quickness at a given longitudinal control input when increasing from a small to a moderate lateral-directional control input. This goes back to the same tendency seen in the peak pitch rate for Group 5 Aircraft A. The large increase in pitch quickness from moderate to large lateral-directional control input is directly linked to the increase in peak pitch rate at these same locations. Finally, the pitch quickness decreases significantly at the large lateral-directional control input when increasing the longitudinal control input. This correlates with the decrease in peak pitch rate, numerator, and increase in pitch attitude change, denominator. Group 5 Aircraft A has non consistency in the pitch quickness data; however, the values at each location make sense.

Group 5 Aircraft B has pitch quickness values that vary for the various longitudinal and lateral-directional control inputs as well. The values are shown in Table 39. Once

Table 39. Group 5 Aircraft B, Air-To-Ground Tracking, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
500 fpm Descent	0.4003	0.3995	0.6306
800 fpm Descent	0.4368	0.4363	0.4357
1400 fpm Descent	0.4304	0.4385	0.4385

again, for this aircraft, there was minimal change in the peak pitch rate at a given longitudinal control input and increasing from small to moderate lateral-directional control input. Furthermore, for the given longitudinal control input, the pitch attitude change did not differ. This is validated by the nearly constant pitch quickness values for all longitudinal control inputs when increasing from small to moderate lateral-

directional control inputs. Group 5 Aircraft B was also unique because both the peak pitch rate and pitch attitude change were nearly constant for all lateral-directional control inputs at both moderate and large longitudinal control inputs. This is further validated by the nearly constant pitch quickness values at these locations. Finally, there is a small decrease in the pitch quickness value at large lateral-directional control input when increasing from small to moderate longitudinal control inputs. This is due to the nearly constant peak pitch rate in the numerator and the increase in the pitch attitude change in the denominator.

Group 4 Aircraft also has varying pitch quickness values, as seen in Table 40; however, all are explained by reviewing the specific criterion in the numerator and denominator. The nearly constant pitch quickness values when increasing from small

Table 40. Group 4 Aircraft, Air-To-Ground Tracking, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
250 fpm Descent	0.3751	0.5764	1.4722
500 fpm Descent	0.4092	0.4095	0.8163
700 fpm Descent	0.3995	0.3994	0.5214

to moderate lateral-directional control input in the moderate and large longitudinal control input correlates directly to the same findings in the peak pitch rate. At the small longitudinal control input when increasing from small to moderate lateral-directional control input, there is an increase in the pitch quickness. This is linked directly to the increase in the peak pitch rate. Finally, at all longitudinal control inputs and a large lateral-directional control input, the pitch quickness values are decreasing. This is due to the either constant or slightly decreasing peak pitch rate at these conditions with a large pitch attitude change increase.

Throughout all three aircraft, there are no consistent tendencies in the pitch quickness values; however, all of the values make sense when you look at the peak pitch rate and pitch attitude change. However, it is still important to realize that the pitch quickness values are still similar for each aircraft at small and moderate lateral-directional control inputs, as seen in Figure 53. The few outliers in Figure 53 are

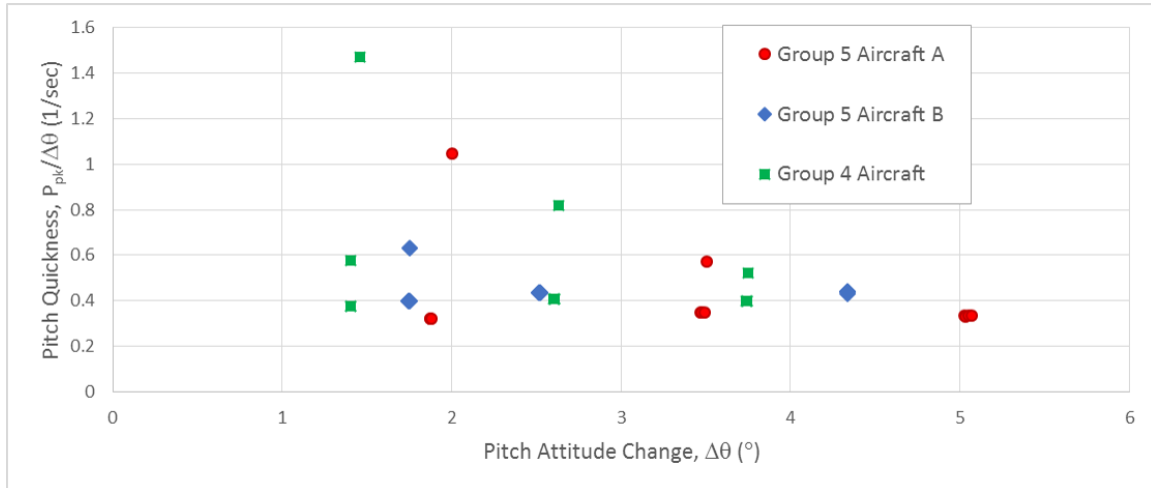


Figure 53. Air-To-Ground Tracking, Pitch Quickness Comparison

Group 4 Aircraft and Group 5 Aircraft A at small and moderate longitudinal control inputs and large lateral-directional control input. Both of these aircraft have smaller nondimensionalized radius of gyration in the longitudinal plane as compared to Group 5 Aircraft B. Smaller radius of gyration ratios equate to less resistance to rotation and, therefore, larger pitch quickness values.

Pitch quickness is valid flying qualities criterion as it can demonstrate some of the aircraft's ability to rotate in a plane. There is an average value for all three aircraft in this non-precision aggressive maneuver and the outliers help explain the unique characteristics of an aircraft.

4.1.2.4 Roll Attitude Change.

The roll attitude change for the air-to-ground tracking maneuver displays no change with an increase in longitudinal control input. However, there is an increase in the roll attitude change directly correlating to an increase in the lateral-directional control input. This is the same for all three aircraft and demonstrated in Table 41 with the data for Group 5 Aircraft A. In fact, the roll attitude change is approxi-

Table 41. Group 5 Aircraft A, Air-to-Ground Tracking, Roll Attitude Change Values (rad)

$\Delta\phi$	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
500 fpm Descent	0.0871 (4.990°)	0.2612 (14.969°)	0.5222 (29.922°)
800 fpm Descent	0.0871 (4.988°)	0.2611 (14.958°)	0.5224 (29.931°)
1400 fpm Descent	0.0870 (4.986°)	0.2612 (14.964°)	0.5222 (29.920°)

mately equal to the lateral-directional control input and, therefore, the input bank angle.

4.1.2.5 Peak Roll Rate.

The peak roll rate changes are consistent among all three aircraft, so only the data for Group 5 Aircraft A is shown in Table 42. The peak roll rate tends to remain con-

Table 42. Group 5 Aircraft A, Air-to-Ground Tracking, Peak Roll Rate Values (rad/sec)

P_{pk}	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
500 fpm Descent	0.0191	0.0561	0.1147
800 fpm Descent	0.0191	0.0563	0.1125
1400 fpm Descent	0.0186	0.0560	0.1121

stant when the longitudinal control input increases. There are some small increases and decreases, but nothing significant enough to warrant further investigation. Understandably, as the lateral-directional control input increases, so does the peak roll rate. The more lateral-directional control input used, the more time to increase the roll rate.

The magnitudes of the peak roll rates are displayed in Figure 54. There are

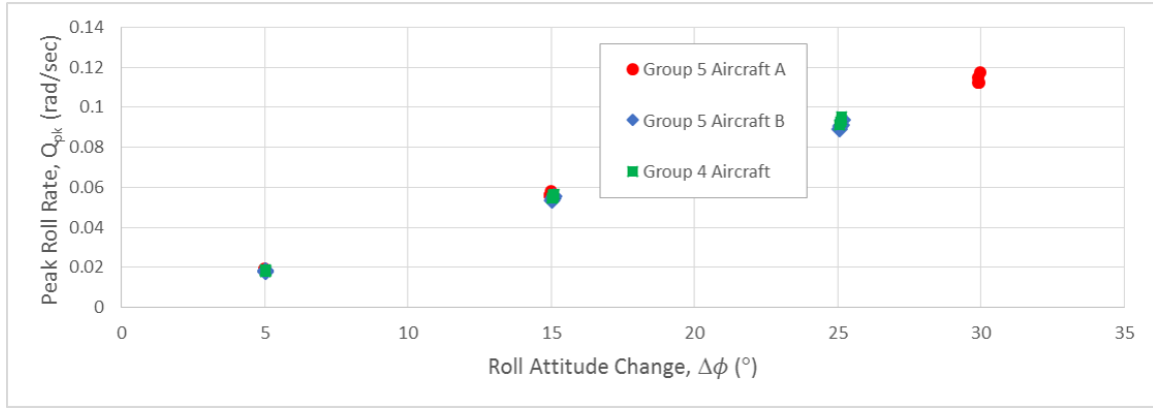


Figure 54. Air-To-Ground Tracking, Peak Roll Rate Comparison

small changes in the values; however, these changes are too small to cause further investigation. The constant peak roll rate values for the various aircraft are linked back to the similar responses to the roll doublets when creating the control systems. There is also an obvious linear increase in Figure 54 that correlates to what has been seen in the peak pitch rate for this maneuver and the peak rates in the previous maneuver. This linear increase also holds true for the different large lateral-directional control inputs for Group 5 Aircraft A.

The peak roll rate is a useful criterion for this non-precision aggressive maneuver that aids the aircraft designer and operator in determining the aircraft's performance capabilities. These three aircraft are very responsive in the lateral-directional plane, as indicated by the smaller nondimensionalized radius of gyration in the lateral-directional plane versus the longitudinal plane. The three aircraft compared in this

study have very responsive lateral-directional control systems, so little difference in roll parameters would be expected. Nonetheless, the peak roll rate criterion would have value if we were comparing aircraft with larger differences in lateral-directional performance.

4.1.2.6 Roll Quickness.

The air-to-ground tracking maneuver roll quickness criterion displays some interesting information about the aircraft. Since there is no consistency among aircraft, the data sets for all three aircraft are shown in Tables 43, 43, and 43. In general, as

Table 43. Group 5 Aircraft A, Air-to-Ground Tracking, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
500 fpm Descent	0.2193	0.2149	0.2196
800 fpm Descent	0.2188	0.2155	0.2154
1400 fpm Descent	0.2139	0.2145	0.2146

Table 44. Group 5 Aircraft B, Air-to-Ground Tracking, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
500 fpm Descent	0.2067	0.2076	0.2073
800 fpm Descent	0.2052	0.2064	0.2063
1400 fpm Descent	0.2082	0.2037	0.2041

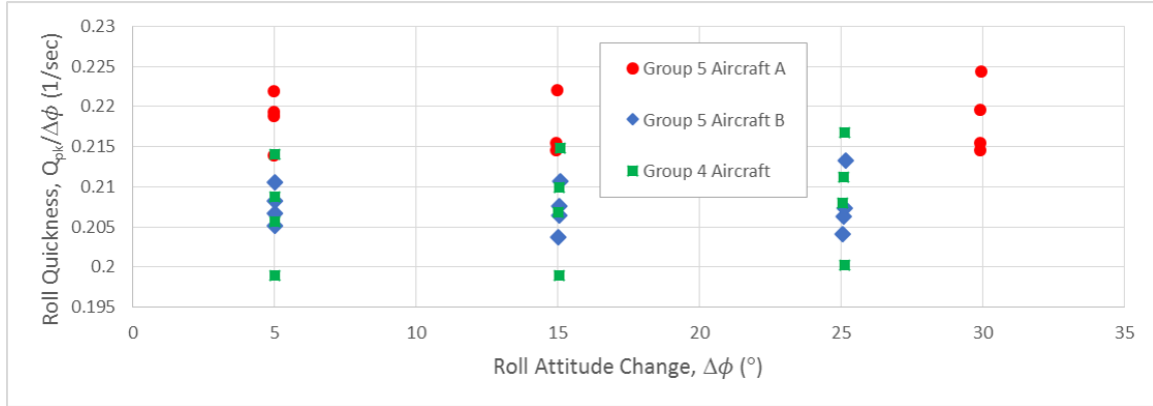
the longitudinal control input increases, the roll quickness values decrease. However, with each aircraft, there is always a situation where the roll quickness values will increase with increasing longitudinal control input. As the lateral-directional control

Table 45. Group 4 Aircraft, Air-To-Ground Tracking, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
250 fpm Descent	0.1990	0.1989	0.2002
500 fpm Descent	0.2088	0.2099	0.2112
700 fpm Descent	0.2056	0.2068	0.2080

input increases, in general, the roll quickness value increases; however, once again, there are always a few situations where this doesn't hold true for each aircraft. All of these variations are due in part to the variations found in the peak roll rate.

Despite these variations, it is important to realize that the standard deviations of the roll quickness values for Group 5 Aircraft A, Group 5 Aircraft B, and Group 4 Aircraft are 0.006, 0.003, and 0.006 respectively which demonstrates a tight tolerance on the roll quickness criterion. This tendency can also be seen in Figure 55.

**Figure 55. Air-To-Ground Tracking, Roll Quickness Comparison**

The roll quickness criterion demonstrates usefulness as a UAV flying qualities metric. Despite the weight and airframe differences in these three aircraft, there is still an obvious roll quickness limit for this non-precision aggressive maneuver.

4.1.2.7 Bandwidth and Time Delay.

The pitch and roll bandwidth values were evaluated for the respective moderate longitudinal and lateral-directional control inputs. The results are shown in Table 46. For Group 5 Aircraft A, the pitch quickness value for moderate longitudinal

Table 46. Closed-Loop Bandwidth Comparison for Air-To-Ground Tracking Maneuver at Moderate Control Inputs

Aircraft	Pitch Bandwidth $\omega_{BW_{Pitch}} (rad/sec)$	Roll Bandwidth $\omega_{BW_{Roll}} (rad/sec)$
Group 5 Aircraft A	1.97	16.30
Group 5 Aircraft B	2.85	13.70
Group 4 Aircraft	5.11	16.00

and lateral-directional control input is a factor of 6.12 times smaller than the pitch bandwidth of 1.97 rad/sec . Group 5 Aircraft B has a factor of 6.53 times the pitch quickness compared to a pitch bandwidth of 2.85 rad/sec . Finally Group 4 Aircraft pitch bandwidth of 5.11 rad/sec is 12.48 times as large as the pitch quickness. The roll bandwidth is significantly larger than any roll quickness criterion. It is important to note that Group 5 Aircraft B and Group 4 Aircraft did not have any speed deviations during the moderate longitudinal control input and moderate lateral-directional control input. However, during this non-precision aggressive maneuver, Group 5 Aircraft A had an airspeed increase of approximately 6 kts . This performance metric is validated by the, relatively speaking, small pitch bandwidth value seen in Group 5 Aircraft A.

The high roll bandwidth values demonstrate that all three aircraft are more maneuverable in the lateral-directional plane than the longitudinal plane. This is further validated by the correlation when the nondimensionalized radius of gyration values

having smaller magnitudes in the lateral-directional plane compared to the longitudinal plane.

The bandwidth parameters make further sense by comparing the time delays found during the air-to-ground tracking maneuver with moderate longitudinal and lateral-directional control inputs. The values of the time delays are seen in Table 47. The

Table 47. Closed-Loop Time Delay Comparison for Air-To-Ground Tracking Maneuver at Moderate Control Inputs

	Pitch Time Delay $\tau_{Pitch} \text{ (sec)}$	Roll Time Delay $\tau_{Roll} \text{ (sec)}$
Group 5 Aircraft A	0.40	0.1
Group 5 Aircraft B	0.42	0.1
Group 4 Aircraft	0.24	0.09

larger the pitch time delay, the smaller pitch bandwidth value. The smallest time delay, Group 4 Aircraft, has the largest of the pitch bandwidths and the greatest difference among the pitch bandwidth value and the pitch quickness value. The smaller roll time delays are logical since the roll quickness values are smaller, the aircraft responds quickly in the roll axis, and the roll bandwidth values are large.

Both the bandwidth and time delay criteria for the non-precision aggressive air-to-ground tracking maneuver provide insight into how the aircraft is performing the maneuver. Both criteria are commonly used in flying qualities analysis and this research further validates their usefulness.

4.1.3 Precision Non-Aggressive Maneuver Results.

The precision non-aggressive maneuver chosen was the precision offset landing discussed in Section 3.3.3. Each aircraft performed this maneuver approximately nineteen different times at varying control inputs. The lateral-directional control

input is varied through the small, moderate, and large control inputs; however, the longitudinal control input is either a constant 600 *fpm* descent or performing a level straight-in approach. There is also an additional variation in the distance offset from the runway. When reviewing the tables of data for this maneuver, there will be some cells left empty. Typically these cells are at small offsets and large lateral-directional control input. It is just not good judgement for an aircraft to perform a large lateral-directional control input when only 50 *ft* offset from the runway and sometimes it is not even feasible. As another reminder, roll quickness will not be discussed for this maneuver as it is not a valid criterion for reversal of control inputs, as discussed in Section 3.4.4. During the maneuver's correction to centerline, the aircraft performs a lateral-directional control input in one direction. Then, when about half way through the correction to centerline, the aircraft then performs the same amount of lateral-directional control input in the opposite direction. Then the aircraft centers itself on centerline with no lateral-directional control input. This demonstrates the reversal of control inputs that invalidates the roll quickness criterion. However, pitch quickness is still a valid criterion since during this maneuver a steady 600 *fpm* descent rate was flown.

4.1.3.1 Angle of Attack and Pitch Attitude Change.

The angle of attack, α , criterion was documented throughout each variation of this precision non-aggressive maneuver. For all three aircraft, even at the lateral-directional control input with smallest lateral offset from the runway, the largest angle of attack performed was not near the stall angle of attack, α_{stall} . Therefore, any unusual characteristics must be related to the airframe or possibly a thrust limitation.

The pitch attitude change for the precision offset landing is consistent throughout all the aircraft so just the data for Group 5 Aircraft A is shown in Table 48. As the

Table 48. Group 5 Aircraft A, Precision Offset Landing, Pitch Attitude Change Values (*rad*)

$\Delta\theta$	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.0770 (4.4140°)	0.0790 (4.5249°)	0.0814 (4.6628°)
150 ft Offset	0.0770 (4.4121°)	0.0793 (4.5432°)	
50 ft Offset	0.0769 (4.4087°)		

distance offset from centerline increases, there is no significant increase or decrease in the pitch attitude change. As the bank angle used to correct to centerline increases, the pitch attitude change increases slightly, but not of a significant value. There is little change throughout all the different longitudinal and lateral-directional control inputs to the pitch attitude change for all three aircraft. This is a logical result as all three aircraft are flying a constant 600 *fpm* descent down to the runway.

The magnitudes of the pitch attitude change are consistent throughout all variations of lateral-directional inputs and offset distances. An example of these magnitudes are shown in Table 49 for all three aircraft at a constant 300 *ft* offset distance from the runway centerline. Group 5 Aircraft B has the smallest values, followed by

Table 49. Precision Offset Landing, Pitch Attitude Change Values at 300 ft Offset (*rad*)

$\Delta\theta$	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
Group 5 Aircraft A	0.0770 (4.410°)	0.0790 (4.525°)	0.0814 (4.663°)
Group 5 Aircraft B	0.0471 (2.698°)	0.0473 (2.711°)	0.0519 (2.971°)
Group 4 Aircraft	0.0827 (4.740°)	0.0826 (4.735°)	0.0849 (4.863°)

Group 5 Aircraft A, and then Group 4 Aircraft. Group 5 Aircraft B has the largest

nondimensionalized radius of gyration in the longitudinal plane. It is logical that this aircraft is resistant to motion and has the smallest pitch attitude change values. Group 5 Aircraft A and Group 4 Aircraft are very close in pitch attitude change values and are also very close in value for the nondimensionalized radius of gyration in the longitudinal plane. Although the MIL-STD-1797 suggests weight as the primary delineating factor for classifying aircraft, the nondimensionalized radius of gyration has a stronger relationship to the pitch attitude change than does the aircraft weight.

4.1.3.2 Peak Pitch Rate.

For the peak pitch rate criterion during the precision offset landing task, there appears to be some consistency among all three aircraft. Since Group 5 Aircraft B and Group 4 Aircraft have an additional data point the data sets for all three aircraft are shown in Tables 50, 51, and 52. In general, the peak pitch rate is constant with

Table 50. Group 5 Aircraft A, Precision Offset Landing, Peak Pitch Rate Values (rad/sec)

Q_{pk}	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.0164	0.0164	0.0343
150 ft Offset	0.0164	0.0171	
50 ft Offset	0.0164		

respect to each aircraft, although there are slight variations for each aircraft. Group 5 Aircraft A has an increase in the peak pitch rate at the large lateral-directional control input at 300 ft offset and the moderate lateral-directional control input at the 150 ft offset. This aircraft has the smallest nondimensionalized radius of gyration in the longitudinal plane so it has the least resistance to rotation in that plane. In

Table 51. Group 5 Aircraft B, Precision Offset Landing, Peak Pitch Rate Values (rad/sec)

Q_{pk}	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.0170	0.0170	0.0240
150 ft Offset	0.0170	0.0170	0.0233
50 ft Offset	0.0170		

Table 52. Group 4 Aircraft, Precision Offset Landing, Peak Pitch Rate Values (rad/sec)

Q_{pk}	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.0260	0.0260	0.0607
150 ft Offset	0.0260	0.0260	0.0428
50 ft Offset	0.0260		

fact, the peak pitch rate increases by a factor of 2.1 when 300 ft offset and increasing from moderate to large lateral-directional control input. This ease of rotation in the longitudinal plane is further validated by the fact that there is also an increase in the peak pitch rate at 150 ft offset and moderate lateral-directional control input. Regardless, this increase in peak pitch rate during a constant descent is due to the loss of lift and the need to increase the angle of attack, and therefore the pitch attitude angle. Greater pitch attitude allows for more time for the pitch rate to increase.

For Group 5 Aircraft B an increase in the peak pitch rate is seen at the large lateral-directional control input for the 300 ft and 150 ft offset from centerline. This deviation at only the largest lateral-directional control input, speaks to the aircraft's resistance to rotation in the longitudinal plane. This is further validated with the

nondimensionalized radius of gyration in the longitudinal plane being the largest out of the three aircraft. Furthermore, the peak pitch rate only increases by a factor of 1.4. This is, understandably, less than what is seen in Group 5 Aircraft A.

Group 4 Aircraft has a nondimensionalized radius of gyration in the longitudinal plane that is between Group 5 Aircraft A and Group 5 Aircraft B. This value is further validated with the aircraft's performance. The increase of the peak pitch rate occurs again at the largest lateral-directional control input and at both the 300 *ft* and 150 *ft* offsets. The peak pitch rate at 300 *ft* offset increases by a factor of 2.3 when increasing from moderate to large lateral-directional control input. This value is greater than the increase seen in Group 5 Aircraft A and, initially, that is unexpected when referencing the nondimensionalized radius of gyration. However, referring back to Table 15, the large lateral-directional control input for Group 5 Aircraft A is 22° while Group 4 Aircraft is 25°. This additional lateral-directional control input allows for the larger increase of peak pitch rate.

Further understanding of the peak pitch rate can be seen by reviewing the magnitudes of this criterion as seen in Figure 56. Group 5 Aircraft B has smaller pitch

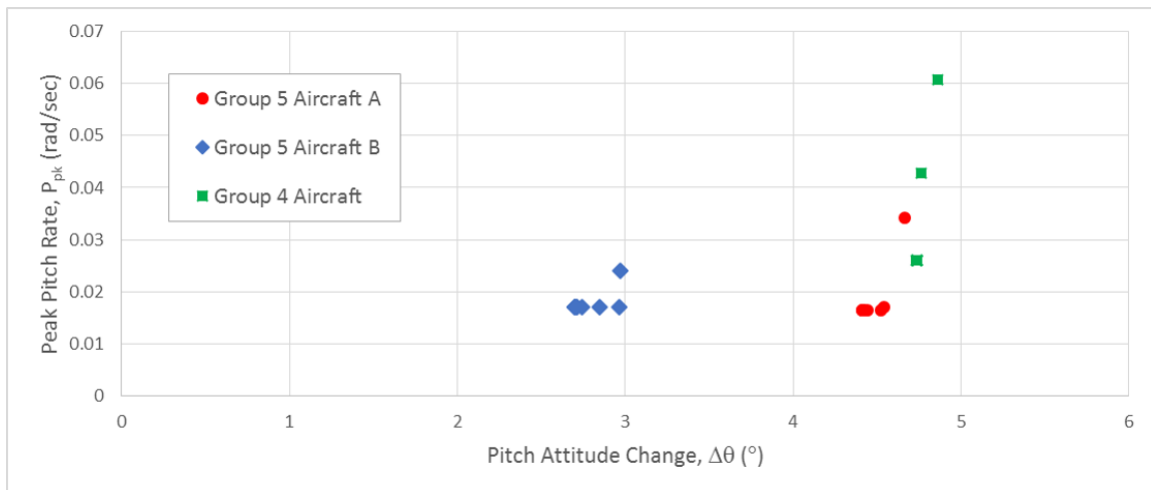


Figure 56. Precision Offset Landing, Peak Pitch Rate Comparison

attitude changes that relates back to the resistance to rotation demonstrated by the large nondimensionalized radius of gyration value. Group 5 Aircraft A and Group 4 Aircraft have similar nondimensionalized radius of gyration values and their pitch attitude change is similar; however, the expectation would be that Group 5 Aircraft A should have larger peak pitch rates. Reviewing the actual aircraft performance, although a 600 *fpm* descent was directed by the control system, Group 4 Aircraft did a better job of achieving the desired input. Group 5 Aircraft A did not ever achieve the 600 *fpm* descent, this accounts for the slightly lower peak pitch rates.

For this precision non-aggressive maneuver, the peak pitch rate is valid criterion to use for flying qualities purposes. It provides important insight into the aircraft's ability to perform this precision maneuver. The larger the value will indicate if an aircraft is achieving the desired pitch input. Applying a limit will ensure aircraft perform this precision non-aggressive maneuver properly.

4.1.3.3 Pitch Quickness.

The pitch quickness criterion has varying changes to the magnitude as the centerline offset distance increases and as the lateral-directional control input used to perform the offset increases. The full analysis is shown in Tables 53, 54, and 55.

Table 53. Group 5 Aircraft A, Precision Offset Landing, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.2129	0.2077	0.4212
150 ft Offset	0.2130	0.2159	
50 ft Offset	0.2132		

When using a small to moderate lateral-directional control input and increasing the

Table 54. Group 5 Aircraft B, Precision Offset Landing, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.3606	0.3589	0.4637
150 ft Offset	0.3606	0.3418	0.4501
50 ft Offset	0.3591		

Table 55. Group 4 Aircraft, Precision Offset Landing, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.3145	0.3148	0.7154
150 ft Offset	0.3145	0.3149	0.5155
50 ft Offset	0.3145		

offset distance, there is little to no change in the pitch quickness values. Any small decrease is linked directly to an increase of the pitch attitude change, the denominator in the pitch quickness equation. The pitch quickness values are mostly consistent except for the large lateral-directional control inputs. These variations in the pitch quickness values are directly linked back to the peak pitch rate values that were larger than what was seen at the smaller lateral-directional control inputs. Since the peak pitch rate is the numerator in the pitch quickness equation, an increase in this value leads to an increase in the pitch quickness value.

Furthermore, as seen in Figure 57, the values for the pitch quickness are similar in magnitude except for the outlying largest offset and large lateral-directional control input for Group 4 Aircraft. Referring back to Table 15, Group 4 Aircraft has the

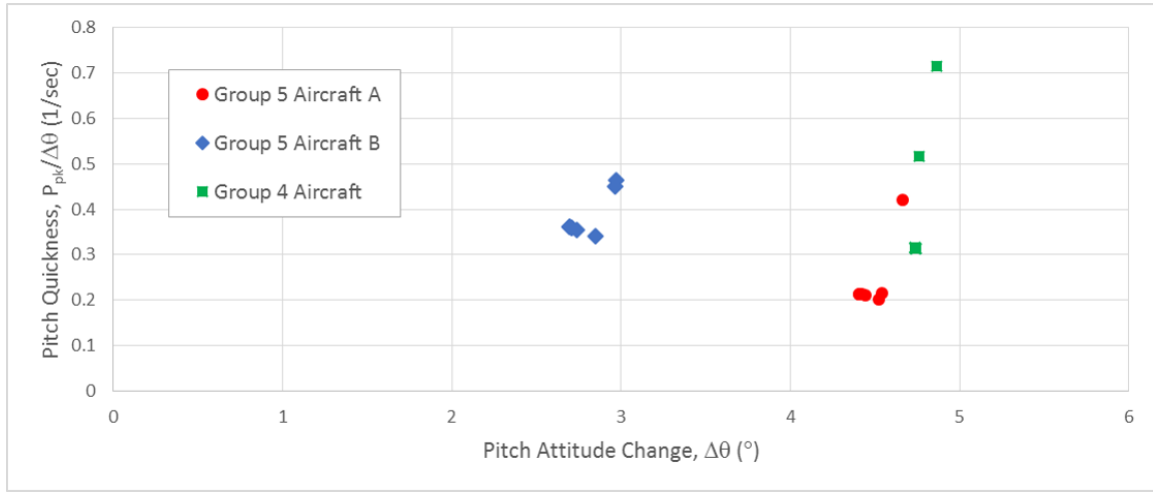


Figure 57. Precision Offset Landing, Pitch Quickness Comparison

largest bank angle at the large lateral-directional control input. This accounts for the pitch quickness outlier seen in Figure 57. The magnitudes of the pitch quickness criterion further validates that the MIL-STD-1797 weight classification scheme does not hold validity for these aircraft. Another item that has already been noted is further exemplified by Figure 57. Group 4 Aircraft B has a noticeably smaller pitch attitude change versus Group 4 Aircraft and Group 5 Aircraft A. The explanation for this was discussed in Section 4.1.3.1. Group 5 Aircraft B has the largest nondimensionalized radius of gyration in the longitudinal plane and, therefore, correlates with the largest resistance to motion and the smallest pitch attitude change.

The pitch quickness is a useful criterion for this precision non-aggressive maneuver ensuring the aircraft has the proper performance characteristics. The three aircraft demonstrate a relationship among the pitch quickness criterion and the nondimensionalized radius of gyration in the longitudinal plane. Realizing this relationship allows for limits to be noted in the pitch quickness criterion.

4.1.3.4 Roll Attitude Change.

The roll attitude change demonstrates some unique characteristics that might suggest some of the lateral-directional control inputs were too “aggressive” for this precision non-aggressive maneuver. As the offset increases, there is a slight increase in the roll attitude change. This is demonstrated in Tables 56, 57, and 58.

Table 56. Group 5 Aircraft A, Precision Offset Landing, Roll Attitude Change Values (*rad*)

$\Delta\phi$	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.1711 (9.804°)	0.5082 (29.118°)	0.7418 (42.503°)
150 ft Offset	0.1699 (9.735°)	0.5030 (28.818°)	
50 ft Offset	0.1677 (9.609°)		

Table 57. Group 5 Aircraft B, Precision Offset Landing, Roll Attitude Change Values (*rad*)

$\Delta\phi$	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.1708 (9.789°)	0.5020 (28.763°)	0.7446 (42.661°)
150 ft Offset	0.1690 (9.686°)	0.4961 (28.422°)	0.6629 (37.982°)
50 ft Offset	0.1648 (9.442°)		

Similarly, as the lateral-directional control input is increased, the roll attitude change increases as well. As expected, the roll attitude change is approximately twice the bank angle applied at the small and moderate lateral-directional control inputs. However, for the large lateral-directional control input, Group 5 Aircraft A and Group 5 Aircraft B do not reach this value. Both Group 5 Aircraft A and Group 5

Table 58. Group 4 Aircraft, Precision Offset Landing, Roll Attitude Change Values (*rad*)

$\Delta\phi$	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.1724 (9.878°)	0.5120 (29.337°)	1.0173 (58.288°)
150 ft Offset	0.1714 (9.822°)	0.5077 (29.088°)	0.8418 (48.230°)
50 ft Offset	0.1690 (9.026°)		

Aircraft B should reach approximately 44° roll attitude change since the large lateral-directional control input for both these aircraft is 22° as seen in Table 15. The actual value attained is 42° for Group 5 Aircraft A and 42° and 38° for Group 5 Aircraft B at 300 *ft* and 150 *ft* offset respectively. These values are less than what was expected leading to the conclusion that the large lateral-directional control input did not have enough time to reach its desired value before it had to reverse direction ensure the aircraft did not overshoot centerline.

Group 4 Aircraft, which has a nondimensionalized radius of gyration in the lateral-directional plane which indicates less of a resistance to rotation than Group 5 Aircraft B and it has more of a resistance to rotation than Group 5 Aircraft A. However, more bank angle, 25°, is used at the large lateral-directional control input compared to Group 5 Aircraft A. Therefore, when there is a large lateral-directional control input, a roll attitude change of 50° would be consistent with the tendency found in the small and moderate lateral-directional control inputs. However, as seen in Table 58, the roll attitude change attained at 300 *ft* offset was significantly larger, 58°. This aircraft has a tendency to favor rotation and is at the edge of its sustained performance capability.

Although roll attitude change is not a common flying qualities criterion, in the precision non-aggressive maneuver with these three hypothetical aircraft, several per-

formance capabilities were demonstrated. This is very useful information that can aid in flying qualities analysis.

4.1.3.5 Peak Roll Rate.

The peak roll rate criterion decreases as the distance offset from centerline increases. This tendency is consistent among all three aircraft so only one data set is shown in Table 59. For each control input, the peak roll rate occurs after the

Table 59. Group 5 Aircraft A, Precision Offset Landing, Peak Roll Rate Values, (rad/sec)

P_{pk}	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
300 ft Offset	0.0126	0.0645	0.1165
150 ft Offset	0.0171	0.0915	
50 ft Offset	0.0293		

lateral-directional reversal and when the aircraft is removing its lateral-directional control input to finish on centerline. The less offset from centerline the aircraft is, the quicker the return to neutral lateral-directional control is needed. Similarly, as the lateral-directional control input increases, so does the peak roll rate.

Among the different aircraft, the peak roll rate appears to be similar at the small and moderate lateral-directional control inputs for all the various distances offset from the runway. For example, in Table 60, it can be seen that with a 300 *ft* offset distance, the peak roll rate values are similar for all three aircraft. The difference in this criterion occurs when the large lateral-directional control is input. Group 5 Aircraft A attains a peak roll rate of 0.1165 *rad/sec*. Group 5 Aircraft B attains a peak roll rate of 0.1300 *rad/sec*. Finally, Group 4 Aircraft attains a peak roll rate of 0.1931 *rad/sec*.

Table 60. Precision Offset Landing, Peak Roll Rate Comparison with 300 ft Offset
(*rad/sec*)

	Small Lateral-Directional Control	Moderate Lateral-Directional Control
Group 5 Aircraft A	0.0126	0.0645
Group 5 Aircraft B	0.0136	0.0699
Group 4 Aircraft	0.0129	0.0651

All of the peak roll rates are seen in Figure 58. The nearly linear increase in

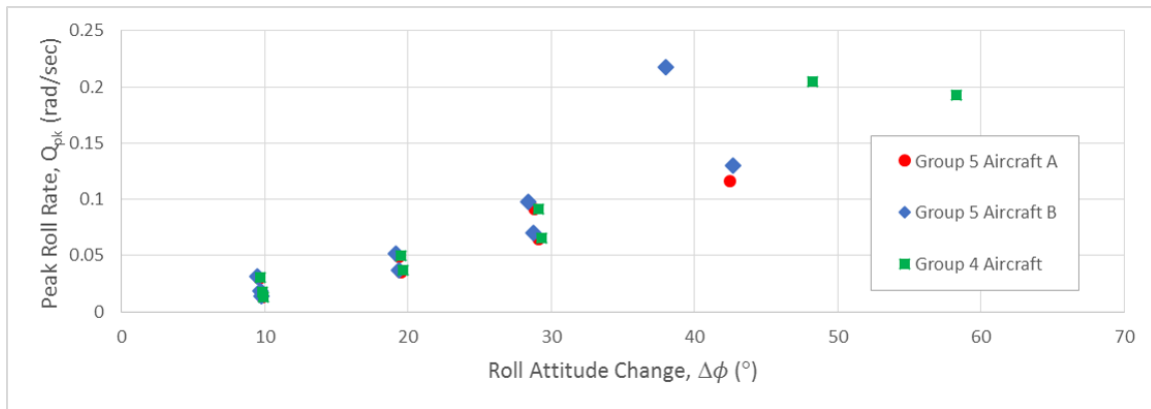


Figure 58. Precision Offset Landing, Peak Roll Rate Comparison

peak roll rate to roll attitude change is similar to what was seen in the previous two maneuvers. Group 5 Aircraft A is following the linear increase with no outliers. Group 4 Aircraft, while still in the nearly linear region, has two of the largest peak roll rates. This corresponds with the lower value of the nondimensionalized radius of gyration in the lateral-directional plane. It also is indicative of the larger bank angle at the large lateral-directional control input. Group 5 Aircraft B is resistant to rotation as it has the largest nondimensionalized radius of gyration in the lateral-directional plane, yet it has the largest peak roll rate. In order to understand this outlier data point, it is important to realize this is at 150 *ft* offset from runway centerline and is at the large

lateral-directional control input. For Group 5 Aircraft B, this equates to a 22° bank angle. Typically, it would be expected to see a roll attitude change of approximately 44° ; however, in this situation, only 38° is seen. Therefore, the aircraft is unable to attain the desired lateral-directional control input and the aircraft is performing at its maximum capability, explaining the large peak roll rate.

The peak roll rate is a valid flying qualities criterion for this precision non-aggressive maneuver. A nearly linear relationship is seen between peak roll rate and roll attitude change. Furthermore, weight is not related to this criterion; however, the nondimensionalized radius of gyration in the lateral-directional plane and the aircraft's performance capability play a large roll in the magnitude of this criterion.

4.1.3.6 Bandwidth and Time Delay.

The pitch and roll bandwidth values were evaluated for the respective moderate lateral-directional control inputs and a longitudinal control input of 600 *fpm* descent and the data is shown in Table 61. The pitch bandwidth values are compared with

Table 61. Closed-Loop Bandwidth Comparison for Precision Offset Landing Maneuver at Moderate Control Inputs

Aircraft	Pitch Bandwidth $\omega_{BW_{Pitch}} \text{ (rad/sec)}$	Roll Bandwidth $\omega_{BW_{Roll}} \text{ (rad/sec)}$
Group 5 Aircraft A	1.36	22.0
Group 5 Aircraft B	2.16	9.38
Group 4 Aircraft	3.60	18.20

the pitch quickness values. Group 5 Aircraft A has a greater pitch bandwidth than pitch quickness by a factor of 6.30. Group 5 Aircraft B has a similar factor of 6.32. Group 4 Aircraft has a significantly higher value of 11.40. This larger factor and larger pitch bandwidth is seen in all of the pitch criteria being larger for Group 4 Aircraft.

This aircraft has a smaller nondimensionalized radius of gyration in the longitudinal plane allowing a correlation to a quicker responses. Furthermore, Group 4 Aircraft has a longitudinal control input of 600 *fpm* descent and controls closely to this input; however, a 600 *fpm* descent rate is a significant descent rate for this aircraft as seen in the non-precision aggressive maneuver. The large pitch bandwidth values indicate Group 4 Aircraft's aggressive performance in this maneuver. Group 5 Aircraft A and Group 5 Aircraft B have similar descent profiles and, therefore, the pitch bandwidth values can be more closely correlated to the nondimensionalized radius of gyration in the longitudinal plane.

The roll bandwidth values are still very high suggesting the aircraft control systems are extremely responsive. Group 5 Aircraft B has a large roll bandwidth value but is still significantly less than the roll bandwidth value for Group 5 Aircraft A and Group 4 Aircraft. This lower value indicates the control system limited the aircraft's ability to attain the desired lateral-directional control input. Group 5 Aircraft B is still extremely responsive but it did not attain the desired input.

The bandwidth parameters make further sense by comparing the time delays found in Table 62. The quicker response and max sustained performance capabilities for

Table 62. Closed-Loop Time Delay Comparison for Precision Offset Landing Maneuver at Moderate Control Inputs

	Pitch Time Delay $\tau_{Pitch} \text{ (sec)}$	Roll Time Delay $\tau_{Roll} \text{ (sec)}$
Group 5 Aircraft A	0.6	0.1
Group 5 Aircraft B	0.6	0.1
Group 4 Aircraft	0.24	0.07

Group 4 Aircraft longitudinal control input is further validated by this time delay. It is less than Group 5 Aircraft A and Group 5 Aircraft B pitch time delays. It is

also closer in value to the roll time delays which helps validate this aircraft's quick responses. The pitch time delay for Group 5 Aircraft A and Group 5 Aircraft B are the same and this correlates with similar control systems with a modest and constant longitudinal control input of a 600 *fpm* descent rate.

The roll time delays are very small. This indicates the highly controlled and responsive nature of all three aircraft's lateral-directional control systems. It is further validated by the large roll bandwidth values.

As in the previous maneuvers, bandwidth and time delay are criteria that can be used to determine an aircraft's performance capabilities during this precision non-aggressive maneuver. Both criteria indicate if an aircraft is responsive to an input and can allow for insight into the aircraft's maximum performance abilities. Bandwidth and time delay have been used in current flying qualities standards and continue to show their usefulness in this research.

4.1.4 Precision Aggressive Maneuver Results.

The precision aggressive maneuver chosen was the pitch and roll discrete tracking discussed in Section 3.3.4. Each aircraft performed this maneuver fifteen different times at varying control inputs. The full analysis is noted in the appendices for each aircraft and the coupled analysis is the focus of the following discussion. As a reminder, pitch and roll quickness will not be discussed for this maneuver as they are not valid criteria for reversal of control inputs as discussed in Section 3.4.4.

4.1.4.1 Angle of Attack and Pitch Attitude Change.

The angle of attack, α , criterion was documented throughout each variation of this precision aggressive maneuver. Group 5 Aircraft A, even at combined large longitudinal and lateral-directional control inputs, the largest angle of attack performed was

not near the stall angle of attack, α_{stall} . Therefore, any unusual characteristics must be related to the airframe or possibly a thrust limitation. However, Group 5 Aircraft B attained an angle of attack just over 1.2° from the stall angle of attack during the coupled large longitudinal and lateral-directional control input. Most likely, any unusual characteristics should be related to the airframe or possibly a thrust limitation, but getting near a aerodynamic limit should cause further analysis. Finally, Group 4 Aircraft, during this precision aggressive maneuver, achieved an angle of attack within approximately 0.2° of the stall angle of attack. The Group 4 Aircraft analysis should take this aerodynamic limit into consideration when analyzing it.

The pitch attitude change criterion has some unique traits among the three aircraft. For all three aircraft, as the longitudinal control increases, so does the pitch attitude change, as seen in Table 63. This is logical, as a greater longitudinal control

Table 63. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Pitch Attitude Change Values (*rad*)

$\Delta\theta$	Small Lateral-Directional Control	Moderate Lateral-directional Control	Large Lateral-Directional Control
Small Longitudinal Control	0.0681 (3.9001°)	0.0671 (3.8441°)	0.0887 (5.0808°)
Moderate Longitudinal Control	0.1382 (7.9196°)	0.1312 (7.5188°)	0.1415 (8.1049°)
Large Longitudinal Control	0.2314 (13.2567°)	0.2144 (12.2817°)	0.2107 (12.0697°)

input will require more lift resulting in an increase in the angle of attack. This, in addition to the increase in flight path angle, results in a greater pitch attitude change. As the lateral-directional control input increases, each aircraft responds differently.

Referring to Table 63, Group 5 Aircraft A demonstrates a decrease in the pitch attitude change by increasing the lateral-directional control input from small to moderate for all longitudinal control inputs. This same decrease in pitch attitude change

is also seen only for the large longitudinal control input when increasing the lateral-directional control from moderate to large. Group 5 Aircraft B always increases its pitch attitude change as the lateral-directional control input increases, as seen in Table 64. Group 4 Aircraft is very similar except at the large longitudinal control where

Table 64. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Pitch Attitude Change Values (rad)

$\Delta\theta$	Small Lateral-Directional Control	Moderate Lateral-directional Control	Large Lateral-Directional Control
Small Longitudinal Control	0.0364 (2.0866°)	0.0399 (2.2877°)	0.0444 (2.5434°)
Moderate Longitudinal Control	0.0727 (4.1676°)	0.0740 (4.2412°)	0.0760 (4.3549°)
Large Longitudinal Control	0.1152 (6.6008°)	0.1164 (6.6685°)	0.1182 (6.7731°)

the pitch attitude change actually decreases slightly from moderate to large lateral-directional control input, as seen in Table 65. Despite the changes in pitch attitude

Table 65. Group 4 Aircraft, Pitch and Roll Discrete Tracking, Pitch Attitude Change Values (rad)

$\Delta\theta$	Small Lateral-Directional Control	Moderate Lateral-directional Control	Large Lateral-Directional Control
Small Longitudinal Control	0.0487 (2.7883°)	0.0490 (2.8069°)	0.0594 (3.4010°)
Moderate Longitudinal Control	0.0985 (5.6420°)	0.0986 (5.6497°)	0.0987 (5.6547°)
Large Longitudinal Control	0.1495 (8.5653°)	0.1495 (8.5644°)	0.1490 (8.5377°)

change, the largest decrease throughout all three aircraft is approximately 1° and the largest increase is just over 1° . These changes are so small they don't warrant further investigation.

4.1.4.2 Peak Pitch Rate.

Since pitch quickness is not a valid criteria due to the longitudinal control reversals used in this pitch and roll discrete tracking maneuver, the peak pitch rate will be a primary source of information used in this maneuver. The peak pitch rate has consistency among all three aircraft so the data for just one aircraft is shown in Table 66. As the longitudinal control input increases so does the peak pitch rate.

Table 66. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Peak Pitch Rate Values (rad/sec)

Q_{pk}	Small Lateral-Directional Control	Moderate Lateral-directional Control	Large Lateral-Directional Control
Small Longitudinal Control	0.0516	0.0618	0.0981
Moderate Longitudinal Control	0.1033	0.1169	0.1386
Large Longitudinal Control	0.1701	0.1826	0.2052

Similarly, as the lateral-directional control input increases, so does the peak pitch rate. As would be expected in this precision aggressive maneuver, the largest peak pitch rate is found when the largest longitudinal control and largest lateral-directional control are input and, once again, this is true for all three aircraft.

Figure 59 displays all three aircraft's peak pitch rate data points. As with the previous maneuvers, there is a nearly linear increase of peak pitch rate to pitch attitude change. The changes in the pitch attitude change have a correlation to the nondimensionalized radius of gyration in the longitudinal plane. As the nondimensionalized radius of gyration increases, the resistance to rotation increases. This is demonstrated by Group 5 Aircraft B having the largest nondimensionalized radius of gyration and the smallest pitch attitude changes. Meanwhile, Group 5 Aircraft A

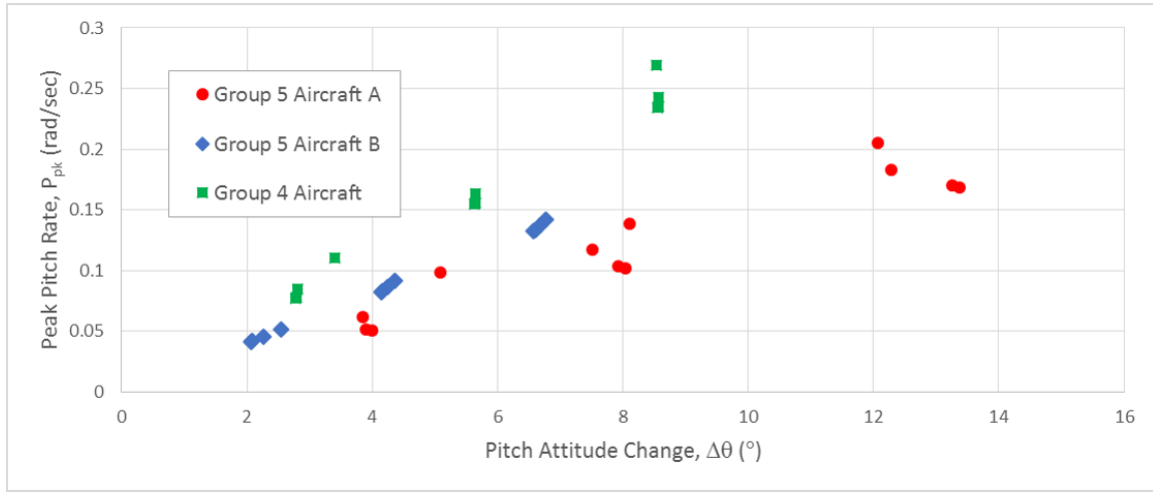


Figure 59. Pitch and Roll Discrete Tracking, Peak Pitch Rate Comparison

has the smallest nondimensionalized radius of gyration and it has the largest pitch attitude changes.

The peak pitch rate is always highest in Group 4 Aircraft, then Group 5 Aircraft B, and Group 5 Aircraft A always has the smallest peak pitch rate for the given longitudinal control input. This relationship demonstrates a stronger link to the aircraft's performance capabilities than the nondimensionalized radius of gyration. For example, at small longitudinal control inputs, all three aircraft have similar peak pitch rates. However, at large longitudinal control inputs, Group 4 Aircraft has a much larger peak pitch rate correlating with the given longitudinal control input max performing the aircraft.

The peak pitch rate is a flying qualities criterion that provides significant insight into these three aircraft's performance capabilities during this precision aggressive maneuver. No relationship the aircraft's gross weight, as suggested by MIL-STD-1797, was seen during this pitch and roll discrete tracking maneuver. Correlations can, however, be made to both the nondimensionalized radius of gyration in the longitudinal plane and also the aircraft's performance capabilities.

4.1.4.3 Roll Attitude Change.

The roll attitude change criterion tendencies are similar to previous maneuvers and are demonstrated in Table 67. Only one aircraft's set of data is shown since all

Table 67. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Roll Attitude Change Values (*rad*)

$\Delta\phi$	Small Lateral-Directional Control	Moderate Lateral-directional Control	Large Lateral-Directional Control
Small Longitudinal Control	0.2210 (12.665°)	0.6708 (38.435°)	1.1177 (64.040°)
Moderate Longitudinal Control	0.2214 (12.688°)	0.6723 (38.520°)	1.1208 (64.215°)
Large Longitudinal Control	0.2221 (12.724°)	0.6725 (38.533°)	1.1203 (64.188°)

three aircraft behave similarly. As the longitudinal control increases, so does the roll attitude change, although the increase is very small. In fact, it is so small that it is not worth further investigation. As the lateral-directional control input increases, the roll attitude change increases. This is understandable as the discrete roll tracking is also increasing in magnitude as the lateral-directional control input increases.

Group 5 Aircraft A has a maximum roll attitude change of 64.215°, followed by Group 4 Aircraft with a roll attitude change of 58.667° and finally Group 5 Aircraft B with 57.929°. Group 5 Aircraft A has a greater large lateral-directional control input of 30° while Group 5 Aircraft B and Group 4 Aircraft use 25° bank angle at large lateral-directional control input. This accounts for the large roll attitude change. However, it also correlates with the nondimensionalized radius of gyration in the lateral-directional plane. Group 5 Aircraft A has the smallest nondimensionalized radius of gyration in the lateral-directional plane and it has the largest roll attitude change. Group 4 Aircraft has the next largest nondimensionalized radius of gyration in the lateral-directional plane followed by Group 5 Aircraft B. This correlates with

Group 5 Aircraft B having the smallest roll attitude change followed closely by Group 4 Aircraft.

4.1.4.4 Peak Roll Rate.

The analysis seen in the peak roll rate for the precision aggressive maneuver mirrors the analysis seen in the peak pitch rate discussion. Once again, roll quickness will not be discussed as lateral-directional control reversals occur during this pitch and roll discrete tracking maneuver which invalidate the roll quickness calculations. The peak roll rates are similar through all three aircraft so only one data set is shown. As seen in Table 68, as the longitudinal control input increases, the peak roll rate, in general, increases. Any deviations to this tendency are not large enough to justify

Table 68. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Peak Roll Rate Values (rad/sec)

P_{pk}	Small Lateral-Directional Control	Moderate Lateral-directional Control	Large Lateral-Directional Control
Small Longitudinal Control	0.5630	1.6495	2.2401
Moderate Longitudinal Control	0.5633	1.6470	2.2420
Large Longitudinal Control	0.5739	1.6559	2.2439

further investigation. As the lateral-directional control input increases, so does the peak roll rate.

The largest peak roll rate values are always found with the largest longitudinal and lateral-directional control inputs as seen in Figure 60. Once again, there is a nearly linear correlation between the peak roll rate and roll attitude change. For this criterion, Group 5 Aircraft A has the largest roll rate ($2.2439 rad/sec$) followed by Group 4 Aircraft ($1.5653 rad/sec$), and then Group 5 Aircraft B ($1.3644 rad/sec$).

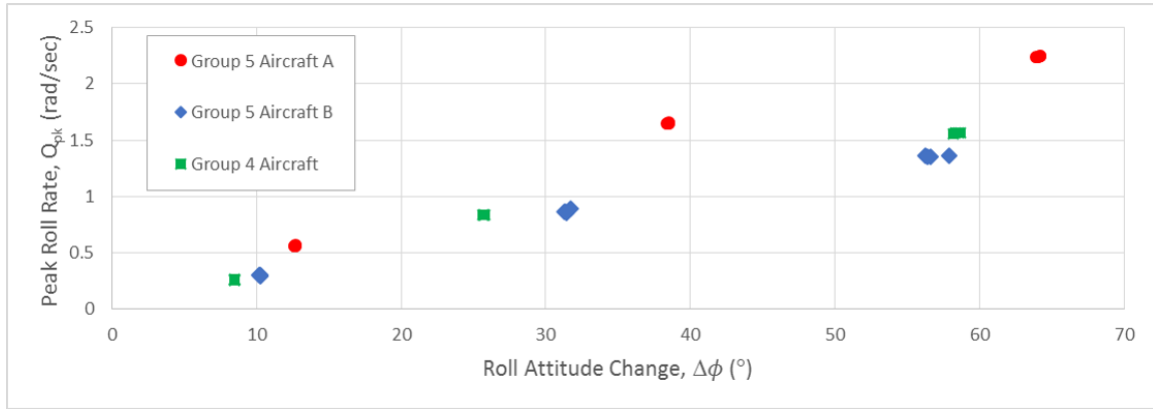


Figure 60. Pitch and Roll Discrete Tracking, Peak Roll Rate Comparison

This order of peak roll rate correlates directly with the nondimensionalized radius of gyration in the lateral-directional plane and not weight, as suggested by the MIL-STD-1797 aircraft classification scheme. Group 5 Aircraft A has a nondimensionalized radius of gyration of 0.0514, next is Group 4 Aircraft with 0.0701 and finally Group 5 Aircraft B with 0.1069. This order matches up perfectly with the changing magnitude of the peak roll rates.

The peak roll rate is a criterion that was used in this precision aggressive maneuver with success. It validates the aircraft's performance characteristics and demonstrates the aircraft's capabilities. Furthermore, there is a direct link between the peak roll rate and the nondimensionalized radius of gyration in the lateral-directional plane leading the analysis for this pitch and roll discrete tracking maneuver to focus on this relationship versus weight.

4.1.4.5 Bandwidth and Time Delay.

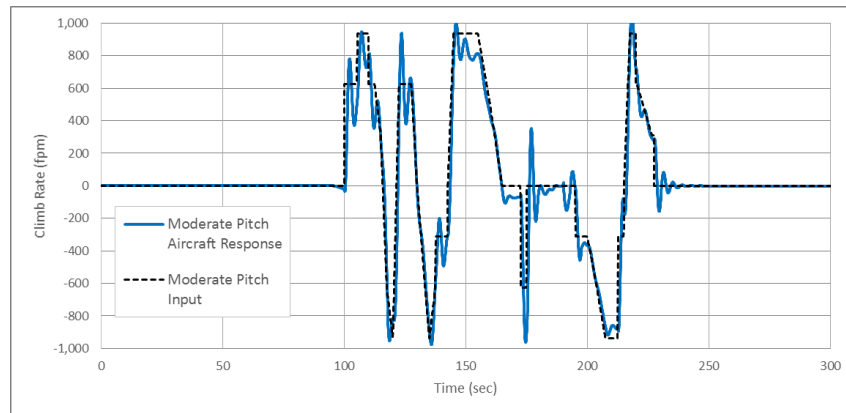
The pitch and roll bandwidth values were evaluated for the respective moderate longitudinal and lateral-directional control inputs and the data is shown in Table 69. Although a comparison of these values cannot be made to the quickness criteria, the values are still an important criteria to capture for flying qualities research. The

Table 69. Closed-Loop Bandwidth Comparison for Pitch and Roll Discrete Tracking Maneuver at Moderate Control Inputs

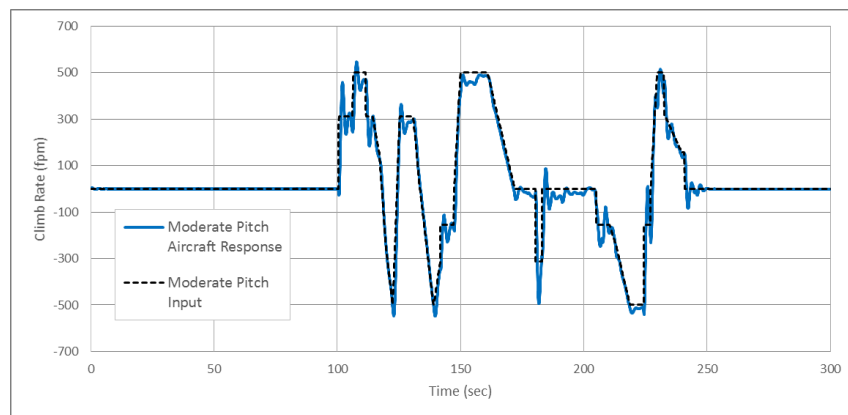
Aircraft	Pitch Bandwidth $\omega_{BW_{Pitch}} (rad/sec)$	Roll Bandwidth $\omega_{BW_{Roll}} (rad/sec)$
Group 5 Aircraft A	1.99	16.60
Group 5 Aircraft B	2.63	7.68
Group 4 Aircraft	5.04	18.10

largest pitch bandwidth is associated with Group 4 Aircraft. This demonstrates the ability of this aircraft to respond quickly and precisely to a given input during this maneuver. All three of the aircraft have pitch bandwidth values that initially appear to have a relationship to aircraft weight; however, the roll bandwidth values do not correlate with aircraft weight. Reviewing the pitch bandwidth again reveals that this criterion is demonstrating how well the aircraft is performing the maneuver. This is demonstrated in Figure 61. Group 4 Aircraft does the best job of tracking the input, followed by Group 5 Aircraft B and then Group 5 Aircraft A. All three aircraft perform the maneuver well, but Group 4 Aircraft tracks the input with smaller error compared to the other two aircraft and this results in a larger pitch bandwidth value.

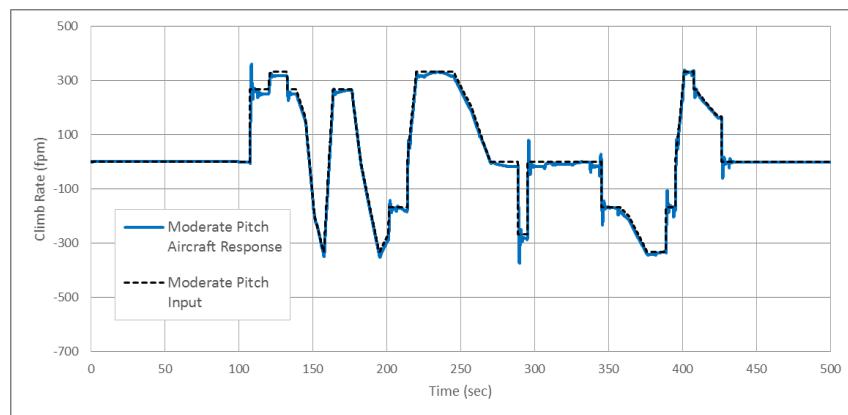
The high roll bandwidth values explain the tight tolerances for all the aircraft in the roll tracking maneuver. Group 5 Aircraft B has a large roll bandwidth value but is still significantly less than the roll bandwidth value for Group 5 Aircraft A and Group 4 Aircraft. This lower value indicates the control system does not track the discrete roll input as well as the other two aircraft. This is seen by looking at the time history of the maneuver; however, it is difficult to see in the roll tracking plots. It is difficult to see because, despite having a lower bandwidth than the other two aircraft, Group 5 Aircraft B is still extremely responsive and tracks the input closely.



(a) Group 5 Aircraft A, Precision Aggressive Pitch Tracking



(b) Group 5 Aircraft B, Precision Aggressive Pitch Tracking



(c) Group 4 Aircraft, Precision Aggressive Pitch Tracking

Figure 61. Precision Aggressive Pitch Tracking Comparison

The bandwidth parameters make further sense by comparing the time delays found in Table 70. The time delays verify what was found in the bandwidth discussion.

Table 70. Closed-Loop Time Delay Comparison for Pitch and Roll Discrete Tracking Maneuver at Moderate Control Inputs

	Pitch Time Delay $\tau_{Pitch} \text{ (sec)}$	Roll Time Delay $\tau_{Roll} \text{ (sec)}$
Group 5 Aircraft A	0.6	0.1
Group 5 Aircraft B	0.4	0.1
Group 4 Aircraft	0.22	0.12

Group 4 Aircraft has the smallest time delay and this correlates with the most responsive pitch tracking. The roll time delays are very small which corresponds to the large roll bandwidths.

Yet again, both the bandwidth and time delay criteria are valid sources to analyze the performance abilities of the aircraft during this discrete pitch and roll tracking maneuver. It does not appear either of the criteria correlate to aircraft weight and a direct correlation is seen as to the error the aircraft has when trying to track this precision aggressive maneuver.

4.2 Maneuver Comparisons on Common Aircraft

The first portion of these results focused on the comparison of criteria made when keeping the maneuver constant and analyzing the results when varying the aircraft. This analysis led to determining the validity, benefits, and difficulties of using the various criteria. Now this discussion will switch the focus. The aircraft will be kept constant while varying the four maneuvers. A similar analysis of the various criteria and the corresponding strengths and weaknesses will be performed.

4.2.1 Maneuver Comparisons on Group 5 Aircraft A.

When reviewing the results of the four maneuvers, referencing solely Group 5 Aircraft A, some additional characteristics come to light. Figure 62 displays the pitch attitude change versus peak pitch rate for the various maneuvers. As discussed

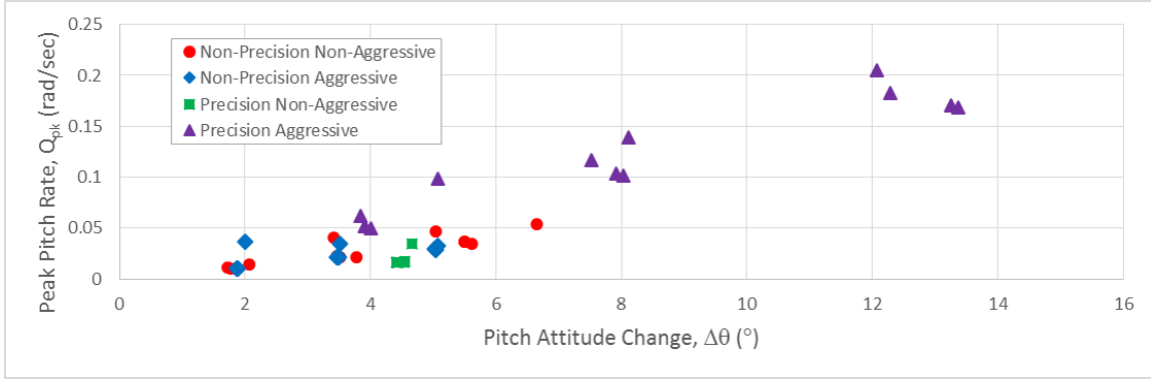


Figure 62. Group 5 Aircraft A, Peak Pitch Rate Comparisons

in the previous sections, there is a nearly linear relationship between the pitch attitude change and the peak pitch rate. The most notable characteristic is the larger peak pitch rate values for the precision aggressive maneuver when compared to the other three maneuvers. These large values are why the pitch quickness criterion is not used to analyze the precision aggressive maneuver, as discussed in Section 3.4.4. There is also a wide spread range of the pitch attitude change with this maneuver. The larger pitch attitude change is expected as there are longitudinal control reversals in the pitch and roll discrete tracking maneuver leading to a pitch attitude change values that are approximately double that of the other maneuvers. The slope of the nearly linear relationship between pitch attitude change and peak pitch rate is 0.791 sec^{-1} for the precision aggressive maneuver and 0.370 sec^{-1} for the non-precision non-aggressive and non-precision aggressive maneuvers. The precision aggressive maneuver has a slope that is 2.14 times as large as the slope of the non-precision non-aggressive and non-precision aggressive maneuvers. The precision non-aggressive maneuver was

not included in this slope analysis since there is not enough variation in the pitch attitude change values; however, the few precision non-aggressive data points did fall in line with the average slope of the non-precision maneuvers. The non-precision non-aggressive and non-precision aggressive slope value is of interest since the slope found in Figure 62 is simply the average value of the pitch quickness criterion for the maneuvers.

The data points for the non-precision non-aggressive and non-precision aggressive maneuvers demonstrate a nearly linear relationship between the two criteria; however, there appears to be two outlier data points. The non-precision non-aggressive maneuver has one data point that corresponds with the linear nature, but has a larger pitch attitude change value than the rest of the data points. This was explained in Section 3.3.1 and is due to the large pitch attitude change required for the large longitudinal control input of a 1500 *fpm* climb. The other data point outlier is in the non-precision aggressive maneuver at a small pitch attitude change but an unusually high peak pitch rate. As described in Section 3.3.2, this data point has a large peak pitch rate due to the larger nondimensionalized radius of gyration in the longitudinal plane allowing for less resistance to rotation.

The comparison of the pitch quickness values between maneuvers is shown in Figure 63. The black dotted line depicts 0.370 sec^{-1} , the average slope found for the non-precision non-aggressive and non-precision aggressive maneuvers in Figure 62. With a nearly linear relationship between the pitch attitude change and the peak pitch rate, most of the data points fall near the slope line but there are some deviations that warrant further investigation.

There are two non-precision aggressive data points at approximately 2° and 3.5° pitch attitude change that lie well above the slope line. As previously described, this is correlated to the small value of the nondimensionalized radius of gyration in the

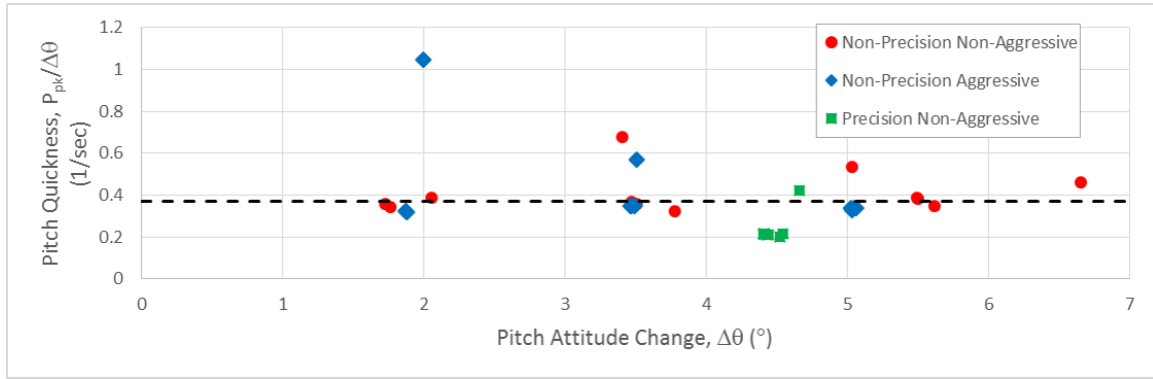


Figure 63. Group 5 Aircraft A, Pitch Quickness Comparisons

longitudinal plane allowing for less resistance to rotation. Another interesting item is that there are several non-precision non-aggressive data points above the black dotted slope line. This is explained by realizing the slope in Figure 62 is 0.430 sec^{-1} for the non-precision non-aggressive data points and 0.304 sec^{-1} for the non-precision aggressive data points resulting in an average slope of 0.370 sec^{-1} . The larger slope value explains the reason for several non-precision non-aggressive data points falling above the black dotted average slope line depicted in Figure 63.

Figure 64 displays the roll attitude change versus the peak roll rate and a nearly linear relationship is seen once again. As expected, there are similarities between

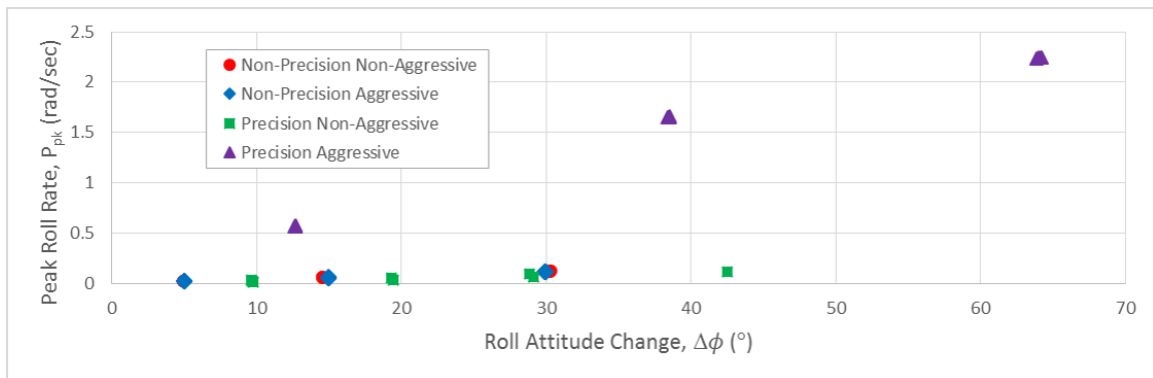


Figure 64. Group 5 Aircraft A, Peak Roll Rate Comparisons

the longitudinal plane, Figure 62, and the lateral-directional plane, Figure 64. The

precision aggressive maneuver demonstrates a wide range of pitch attitude changes over a wide range of peak pitch rates. The remaining three maneuvers are very close in magnitude to each other. As with the pitch analysis, the large roll attitude change and peak roll rates in the pitch and roll discrete tracking maneuver are due to the lateral-directional reversals. The slope of the nearly linear relationship between the roll attitude change and peak roll rate is 0.226 sec^{-1} for the non-precision non-aggressive maneuver and the non-precision aggressive maneuver. The slope for the precision aggressive maneuver is 1.868 sec^{-1} which is 8.25 times as large as the slope for the non-precision maneuvers. The slope analysis for the precision non-aggressive maneuver is calculated separately from the other maneuvers since there is a lateral-directional control reversal, similar to that seen in the precision aggressive maneuver. This slope is calculated to be 0.172 sec^{-1} . The expectation would be for this value to be larger than the slope found for the non-precision maneuvers, however, it is less. After further investigation, this unexpected result is due to a data point that was not included in this research. Group 5 Aircraft A was unable to perform the precision non-aggressive maneuver at a large lateral-directional control input of 25° angle of bank when offset only 150 ft from runway centerline. Looking at the tendencies for this maneuver, the peak roll rate at this specific control input condition would be expected to be much larger than the other peak roll rates documented. This large value would increase the slope to a value larger than that of the average slope calculated for the non-precision maneuvers. In the slope analysis for all four maneuvers, there is no outlying data points requiring further investigation.

The roll attitude change is plotted versus the roll quickness criterion in Figure 65. There is an obvious difference in the roll quickness magnitude for the non-precision non-aggressive and non-precision aggressive maneuvers. The non-precision non-aggressive values are always larger than the non-precision aggressive values. How-

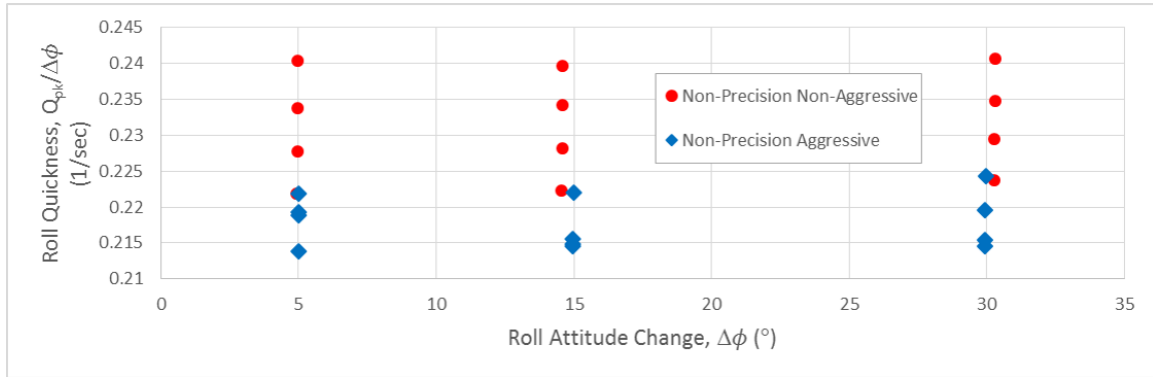


Figure 65. Group 5 Aircraft A, Roll Quickness Comparisons

ever, the magnitudes of these roll quickness values are similar and demonstrate the aircraft's ability to easily maneuver in the lateral directional plane. As a reminder, the roll quickness criterion is not used for the precision non-aggressive and precision aggressive maneuver analysis due to the lateral-directional control reversals performed.

The analysis of comparing maneuvers performed by Group 5 Aircraft A leads to some valuable results. All Group 5 Aircraft A maneuvers showed a nearly linear relationship between the pitch attitude change and peak pitch rate. This linear relationship can be explained by determining the slope generated by the data. The non-precision maneuvers have a slower slope magnitude than the precision aggressive maneuver. So a relationship between the magnitude of the slope and the level of precision and aggressiveness required can be drawn. A larger value is necessary for a precision aggressive maneuver compared to a non-precision maneuver with any level of aggressiveness. This conclusion is further validated with the pitch quickness analysis. Group 5 Aircraft A pitch quickness analysis also demonstrates for non-precision maneuvers, the pitch quickness criterion is typically slightly larger for a non-aggressive maneuver compared to an aggressive maneuver. Finally, it is necessary to review all the data as there are some data point outliers that can skew this analysis. Similar conclusions can be formed in the lateral directional plane. Once again, the

slope magnitude for the roll attitude change versus peak roll rate is larger for the precision aggressive maneuver than the non-precision maneuvers. This relationship is further validated by reviewing the roll quickness criterion. Once again, for non-precision maneuvers, the roll quickness criterion is slightly larger for a non-aggressive maneuver compared to an aggressive maneuver. Group 5 Aircraft A has a small nondimensionalized radius of gyration in the lateral directional plane, therefore, the aircraft has less of a resistance to rotation in the lateral directional plane leading to tightly constrained roll quickness values for the non-precision maneuvers.

4.2.2 Maneuver Comparisons on Group 5 Aircraft B.

Conclusions can be drawn analyzing the four maneuvers performed by Group 5 Aircraft B. First, it is important to remember Group 5 Aircraft B has the largest nondimensionalized radius of gyration in the longitudinal and lateral directional planes of all three aircraft. The larger this number, the more resistant the aircraft is to motion in each plane. This helps explain what is seen in Figure 66. As seen in

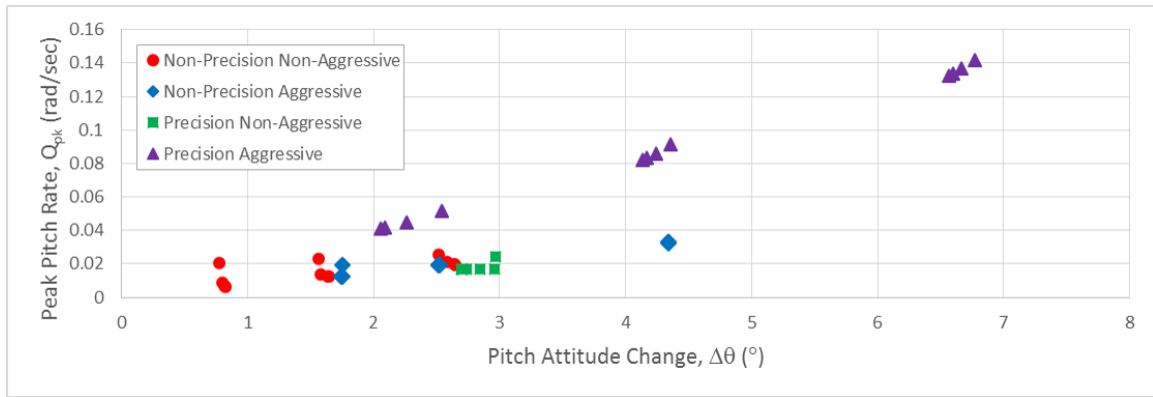


Figure 66. Group 5 Aircraft B, Peak Pitch Rate Comparisons

the previous aircraft, the precision aggressive maneuver stands out as having large pitch attitude changes and large peak pitch rates. The other three maneuvers have similar magnitudes of the peak pitch rate.

Once again, there is a nearly linear relationship between the pitch attitude change and the peak pitch rate. The slope of this relationship is 0.4097 sec^{-1} for the non-precision maneuvers. The precision aggressive maneuver has a slope of 1.1803 sec^{-1} which is 2.88 times as large as the slope for the non-precision maneuvers. The precision non-aggressive maneuver was not included in this analysis since there was not enough variation in the pitch attitude change to determine a relationship between the pitch attitude change and peak pitch rate. However, the data points do coincide with the average slope found for the non-precision maneuvers.

The average slope is consistent for the two non-precision maneuvers however, there are some data points that are worth reviewing. There are several non-precision non-aggressive peak pitch rates at all pitch attitude changes that appear slightly larger than expected with the linear relationship noted. These data points with larger peak pitch rates always occur at a larger lateral-directional control input without respect to the longitudinal control input. In order to perform the non-precision non-aggressive maneuver at a large lateral-directional control input of a 1.5 nm turn radius, approximately 25° angle of bank, Group 5 Aircraft B must increase its pitch rate to maintain the specified parameters of longitudinal control input, lateral-directional control input, and airspeed. The large peak pitch rate values demonstrate the aircraft is performing near an operational aircraft limit. The other data point outlier is the large pitch attitude change value for the non-precision aggressive maneuver. Once again, this outlier is due to Group 5 Aircraft B performing at an aircraft limit. The large longitudinal control input is quite large at 1400 *fpm* descent, the same as Group 5 Aircraft A, despite being a different aircraft with different performance capabilities.

Figure 67 demonstrates the pitch quickness criterion comparison. The black dotted line represents the average slope of 0.4097 sec^{-1} for the non-precision maneuvers. Upon initial review, the pitch quickness chart, it appears that the magnitudes are

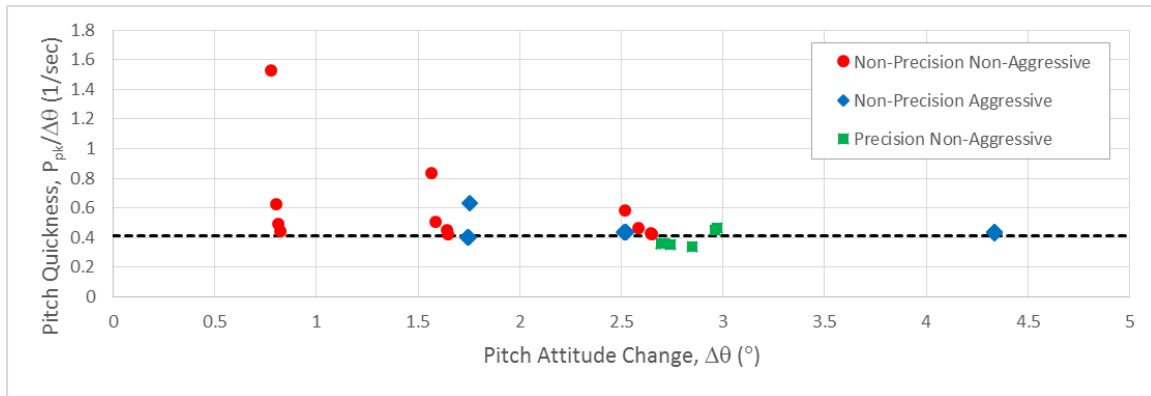


Figure 67. Group 5 Aircraft B, Pitch Quickness Comparisons

surprisingly large for the non-precision non-aggressive maneuver. However, one must remember that the pitch quickness is the ratio of the peak pitch rate to the pitch attitude change. Therefore, a large pitch quickness can be a result of a large peak pitch rate and/or a small pitch attitude change, as is the case for the non-precision non-aggressive maneuver. The large peak pitch rate was previously discussed. The small pitch attitude change is correlated to the large nondimensionalized radius of gyration in the longitudinal plane for Group 5 Aircraft B. The non-precision aggressive maneuver has most of the data points near the black dotted average slope line. The precision non-aggressive data points also are near the average slope line; however, there is only one pitch attitude change for this maneuver so it is difficult to draw any conclusions.

The comparison of the peak roll rates is seen in Figure 68 and the nearly linear relationship between roll attitude change and peak roll rate is seen again. The precision aggressive maneuver stands out from the remaining three maneuvers with larger roll attitude change and peak roll rate values. The non-precision non-aggressive and non-precision aggressive maneuvers have very similar peak roll rate values. It is difficult to distinguish between the data sets for the non-precision non-aggressive and non-precision aggressive maneuver. The values for the peak roll rate are so similar

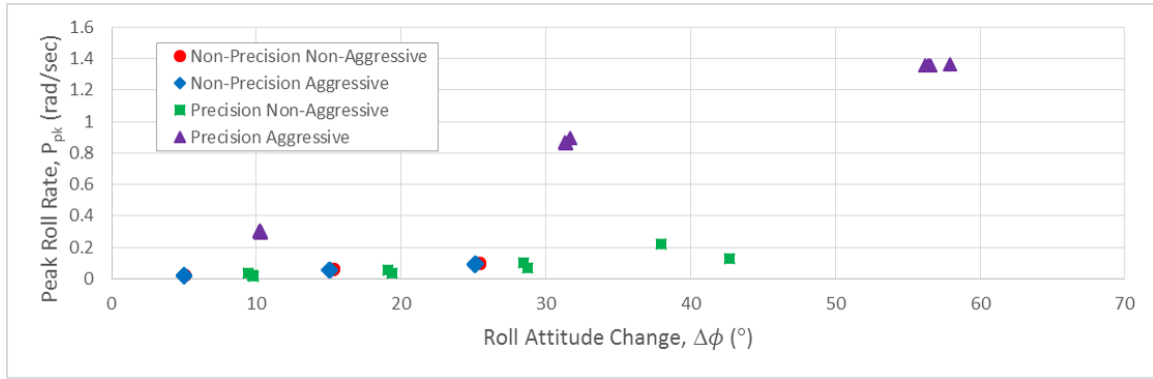


Figure 68. Group 5 Aircraft B, Peak Roll Rate Comparisons

due to the small value of the nondimensionalized radius of gyration in the lateral directional plane. However, the precision non-aggressive maneuver is unique due to the large roll attitude change and corresponding larger peak roll rate values compared to the non-precision maneuvers.

The average slope for the non precision maneuvers is 0.212 sec^{-1} and it is 1.295 sec^{-1} for the precision aggressive maneuver. This is 6.11 times as large as the slope for the non-precision maneuvers. The slope for the precision non-aggressive maneuver is 0.264 sec^{-1} . As expected, this is larger than the slope for the non-precision maneuvers and is due to the lateral-directional control reversal commanded in the precision non-aggressive maneuver.

Finally, Group 5 Aircraft B has a roll quickness analysis similar to Group 5 Aircraft A. This can be seen in Figure 69. The non-precision non-aggressive maneuver appears to consistently have a larger roll quickness values; however, the magnitude range for this criterion is very small and does not require further investigation.

Group 5 Aircraft B analysis of the maneuvers performed produces some valuable insight into the aircraft. As with Group 5 Aircraft A, demonstrated a nearly linear relationship between the pitch attitude change and peak pitch rate in the longitudinal plane. This relationship can be further defined by comparing the slope of this

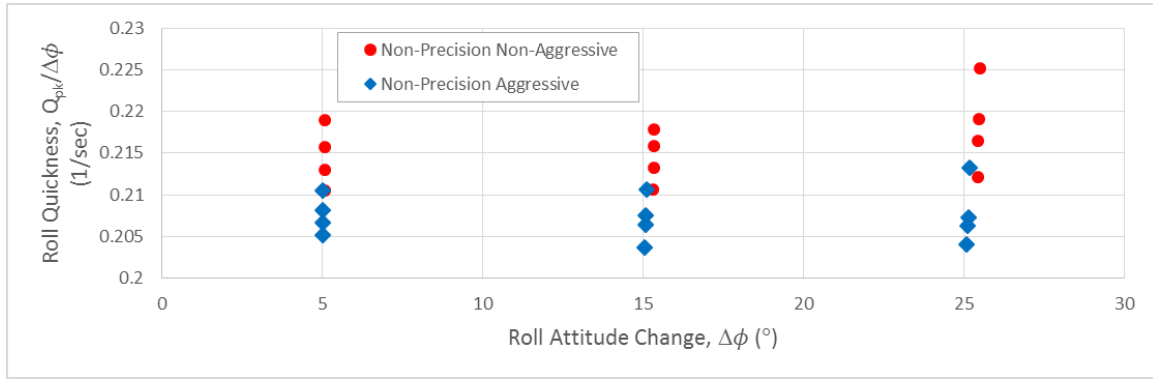


Figure 69. Group 5 Aircraft B, Roll Quickness Comparisons

relationship. The non-precision maneuvers, both non-aggressive and aggressive, have a significantly smaller average slope compared to the precision aggressive maneuver. This result is further verified by the pitch quickness analysis. Group 5 Aircraft B have a consistent pitch quickness value for non-precision maneuvers unless the aircraft is performing near its aircraft performance limit. If this is the case, then the pitch quickness values deviate from the constant value by increasing. Analysis of the lateral directional plane leads to similar conclusions. The slope found by comparing the relationship between the roll attitude change and peak roll rate is nearly constant for the non-precision maneuvers and it is also smaller compared to the precision aggressive maneuver. The roll quickness analysis validates this conclusion. Once again, Group 5 Aircraft B roll quickness analysis demonstrates for non-precision maneuvers, the roll quickness criterion is typically slightly larger for a non-aggressive maneuver compared to an aggressive maneuver.

4.2.3 Maneuver Comparisons on Group 4 Aircraft.

As with the other two aircraft, the maneuver analysis on Group 4 Aircraft demonstrates some relationships between the various maneuvers. The aircraft's pitch attitude change versus peak pitch rate is shown in Figure 70. This aircraft appears very

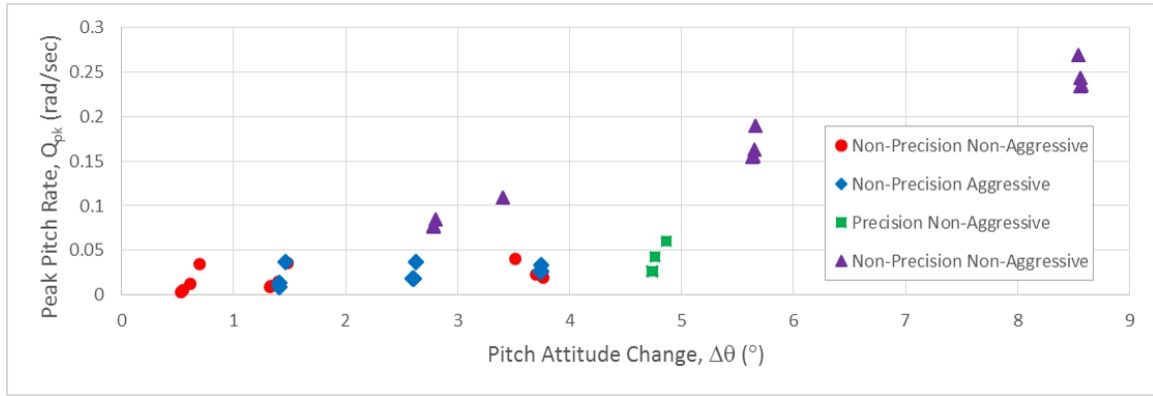


Figure 70. Group 4 Aircraft, Peak Pitch Rate Comparisons

maneuverable by the wide scattering of peak pitch rates. However, there is still a nearly linear relationship between the pitch attitude change and peak pitch rate. The precision aggressive maneuver, once again, has the largest pitch attitude change and peak pitch rate criteria values. The precision non-aggressive maneuver has a tight cluster of peak pitch rates due to the constant 600 *fpm* descent. The average slope for the non-precision maneuvers is 0.318 sec^{-1} . This is 5.14 times smaller than the 1.1629 sec^{-1} slope seen in the precision aggressive maneuver. There are not enough data points to perform this slope analysis on the precision non-aggressive maneuver, but it initially does appear to follow the same approximate slope of the non-precision maneuvers.

The nearly linear relationship for the non precision maneuvers demonstrated in Figure 70 has some data points that fall above the average slope line. This increase in peak pitch rate is explained by realizing, as with Group 5 Aircraft B non-precision aggressive maneuver, Group 4 Aircraft is operating near an aircraft performance limit.

Group 4 Aircraft pitch quickness criterion is displayed in Figure 71. The black dotted line represents the value of the average slope for the non-precision maneuvers. Most of the data points lie near this line; however, there are a few that warrant further investigation.

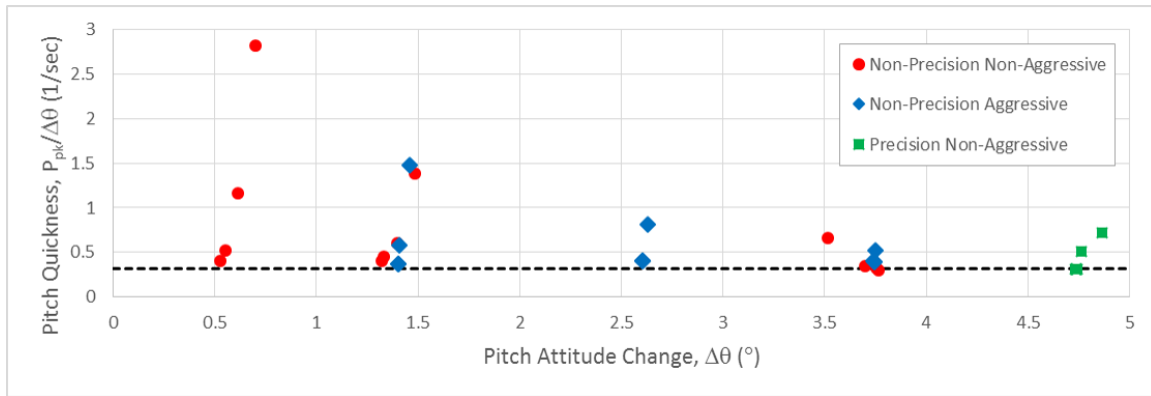


Figure 71. Group 4 Aircraft, Pitch Quickness Comparisons

As discussed with the previous aircraft, a large pitch quickness value is due to a large peak pitch rate and/or a small pitch attitude change. The large peak pitch rates already discussed are noted by some of the pitch quickness values that are above the dotted line at approximately 1.5° , 2.5° , and 3.5° pitch attitude change for both non-precision maneuvers. There is one non-precision non-aggressive data point at approximately 1.5° pitch attitude change that is particularly large. This is due to, not only a large peak pitch rate, but also a particularly small pitch attitude change.

As expected, the peak roll rate comparison is similar to what was seen in the previous two aircraft and is shown in Figure 72. The precision aggressive maneuver

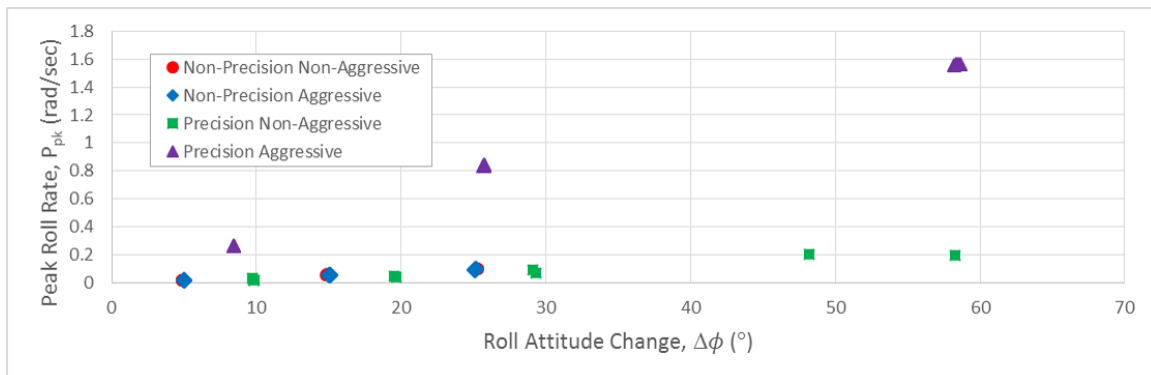


Figure 72. Group 4 Aircraft, Peak Roll Rate Comparisons

has very high peak roll rates and the remaining maneuvers have a very consistent

peak roll rate. There is very little difference between the non-precision non-aggressive and non-precision aggressive in terms of peak roll rate. The precision non-aggressive maneuver has large roll attitude changes due to the lateral-directional control reversals and the aircraft's ability to perform these reversals at a large lateral-directional control input of approximately 28° .

The nearly linear nature of the relationship between the roll attitude change and the peak roll rate is seen yet again. The non-precision maneuvers have a slope of 0.218 sec^{-1} . The precision aggressive maneuver has a slope of 1.461 sec^{-1} which is 6.71 times as large as the non-precision maneuvers. The precision non-aggressive maneuver has a slope of 0.229 sec^{-1} which is, as expected, larger than the slope for the non-precision maneuvers.

Finally, Group 4 Aircraft roll quickness criterion comparison is seen in Figure 73.

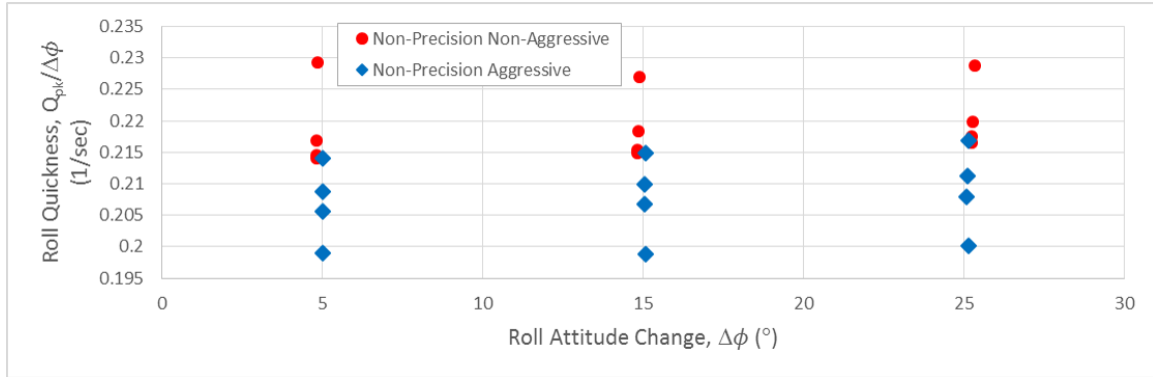


Figure 73. Group 4 Aircraft, Roll Quickness Comparisons

The same analysis seen in previous aircraft is seen here again. The non-precision non-aggressive maneuver has a higher roll quickness values compared to the non-precision aggressive maneuver; however, the magnitude of the values are very small and there is no need to further investigate this tendency.

Overall, the analysis of Group 4 Aircraft performing the four maneuvers provides similar results as the previous two aircraft. There is a nearly linear relationship be-

tween the pitch attitude change and the peak pitch rate. The slope of this relationship is smaller for both the non-precision non-aggressive and non-precision aggressive maneuvers. Meanwhile, the slope of the precision aggressive maneuver is significantly higher. There are some data points that fall slightly above this linear relationship that are primarily due to the aircraft operating near a performance limit. This is further validated by realizing Group 4 Aircraft has a consistent pitch quickness values for non-precision maneuvers. Similar results are demonstrated in the analysis of the lateral directional plane.

4.3 Evaluating the Maneuver

In current manned aircraft, both fixed-wing and rotary-wing, the pilot is used to determine how well an aircraft performs. This process has been refined to make it as predictable as possible with methods such as the Cooper-Harper Scale discussed in Section 2.2.1. Since there is no pilot in a UAV, this performance metric is not feasible and a new way of evaluating a UAV's performance must be found. The purpose of this research is not to recommend a specific method, but rather to suggest some options with corresponding strengths and weaknesses.

4.3.1 Airspeed Analysis.

During each maneuver, the airspeed was controlled to maintain the aircraft's initial starting airspeed. For Group 5 Aircraft A, that was 110 *kts* during the precision non-aggressive maneuver and 200 *kts* for all remaining maneuvers. For the Group 5 Aircraft B it was 150 *kts* and 220 *kts*, and for Group 4 Aircraft it was 95 *kts* and 120 *kts* respectively. As with manned aircraft, when an airspeed is controlled to a specific value, ideally, the aircraft will maintain that airspeed throughout any maneuver. If an aircraft is performing maneuvers either very aggressively or near an operating

limit, the airspeed controller might not have enough thrust capability or performance ability to maintain the desired airspeed. It is at the discretion of the operator if this airspeed deviation is acceptable. The airspeed deviation can then be used as a metric to measure of the aircraft's performance of a maneuver.

Flying straight and level or performing slight maneuvers should not cause an airspeed deviation if the airspeed controller is operating properly. Therefore, prior to each aircraft beginning a maneuver, each aircraft flew straight and level for 100 seconds prior to performing any maneuvers. With no airspeed deviations, the airspeed controller was proven valid. For each aircraft, each maneuver had various airspeed deviations and the tendencies were similar among the aircraft, therefore, only the data for one aircraft is included in this section. The full analysis for each aircraft is contained in the appendices.

The non-precision non-aggressive climbing spiral maneuver had some very minor airspeed deviations at the large longitudinal control input as seen in Table 71. This

Table 71. Group 5 Aircraft A, Climbing Spiral, Airspeed Deviations (*kts*)

<i>TAS</i>	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
500 fpm Climb	199.99 199.99	199.99 199.99	199.99 199.99
1000 fpm Climb	199.99 199.98	199.99 199.98	199.99 199.98
1400 fpm Climb	199.99 197.30	199.99 198.98	199.99 199.97

demonstrates that the aircraft was not thrust limited and had the ability to perform the maneuver with large longitudinal and lateral-directional control inputs without having to accept performance deviations.

During the non-precision aggressive maneuver, some airspeed deviations were observed, as seen in Table 72. During this maneuver the airspeed deviated up to 30 *kts* above the starting airspeed. Furthermore, there was a slight increase in airspeed

Table 72. Group 5 Aircraft A, Air-To-Ground Tracking, Airspeed Deviations (*kts*)

<i>TAS</i>	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
500 fpm	200	200	200
Descent	199.99	199.99	199.99
800 fpm	205.12	206.48	208.01
Descent	199.99	199.99	199.99
1400 fpm	227.98	228.66	229.35
Descent	199.99	199.99	199.99

as the lateral-directional control input increased but there was a significant increase in airspeed as the longitudinal control input increased. This indicates that the longitudinal control input was very aggressive, as the maneuver was defined that way. Without additional drag devices, this aircraft was unable to maintain the starting airspeed.

During the precision non-aggressive maneuver, some slight airspeed increases were observed. This is shown in Table 73. Up to 10 *kts* of airspeed increase was observed

Table 73. Group 5 Aircraft A, Precision Offset Landing, Airspeed Deviations (*kts*)

<i>TAS</i>	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft	119.75	120.26	120.74
Offset	110.00	110.00	110.00
150 ft	119.73	120.10	
Offset	110.00	110.00	
50 ft	119.70		
Offset	110.00		

during the approach. Since this increased was observed for all lateral-directional control inputs, the deviation could likely be linked to the constant descent rate of 600 *fpm*. Although there was a slight airspeed increase in the precision non-aggressive maneuver, it was not as significant as what was seen in the non-precision aggressive maneuver.

Finally, the airspeed information for the precision aggressive maneuver, the pitch and roll discrete tracking, is shown in Table 74. The airspeed deviations in this

Table 74. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Airspeed Deviations (*kts*)

<i>TAS</i>	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
500 fpm	200.00	200.08	200.16
Descent	199.98	199.97	199.95
800 fpm	200.18	200.16	200.43
Descent	199.98	199.97	199.95
1400 fpm	204.05	204.06	204.17
Descent	199.72	199.81	199.90

maneuver only showed up to 4 *kts* difference from the starting airspeed. This does not seem like a lot, especially when compared to the non-precision aggressive maneuver with 30 *kts* variation. However, it is important to note that the pitch and roll discrete tracking preformed longitudinal and lateral-directional control reversals during short time steps. In other words, there was no significant sustained climb or descent to demonstrate an airspeed deviation like what was seen in the non-precision aggressive maneuver. If the pitch and roll tracking was changed to allow for sustained control input prior to reversals, then airspeed deviations would most likely be similar to those seen in the non-precision aggressive maneuver.

Airspeed deviation observations are necessary to put any flying qualities criteria calculated into perspective and correlate it to aircraft safety and performance. Furthermore, for the four maneuvers performed, airspeed deviations do not show a correlation to the necessary precision level of a maneuver. However, they can provide insight into the aggressiveness of a maneuver and the aircraft's ability to successfully accomplish the mission.

4.3.2 Deviation From a Desired Maneuver Analysis.

Determining how far off from the desired maneuver is another method to determine how well an aircraft performs. Two possible methods are deviations from a desired end state and using a L^2 Norm. The deviations from a desired end state is a viable method to evaluate a maneuver if there is no requirement to follow a specific path. If the priority is to end at a given location and airspeed, then the end state is what must be analyzed, not how the aircraft got to that end state. The L^2 Norm is the summation of a strictly positive distance between the desired aircraft track and the actual aircraft track. Allowable tolerances must be decided upon by the operator or mission commander to ensure the aircraft can perform as needed.

Referring to the non-precision non-aggressive maneuver, the climbing spiral demonstrates a useful maneuver for the deviations from a desired end state requirement. Since this maneuver is non-precision and non-aggressive, the operator most likely has no specific need to ensure the aircraft follows a specified track during the climbing spiral. The desired outcome a specified altitude and heading are more important than deviations in airspeed and track are acceptable. During Group 5 Aircraft A's climbing spiral with moderate longitudinal and lateral-directional control inputs, the desire was to climb while performing a complete 360° turn. During the actual maneuver, the aircraft completed the climbing spiral at approximately 6.5° past a full turn. This is a concrete number that help define the aircraft's performance. The L^2 Norm was also analyzed during this non-precision non-aggressive maneuver and was found to be 10.6° . Although this value can be used to determine how closely the aircraft followed the expected flight path, this is a non-precision maneuver. If the L^2 Norm was found to be larger, as long as the desired end state was achieved within a specified error, then the aircraft performed the maneuver as needed.

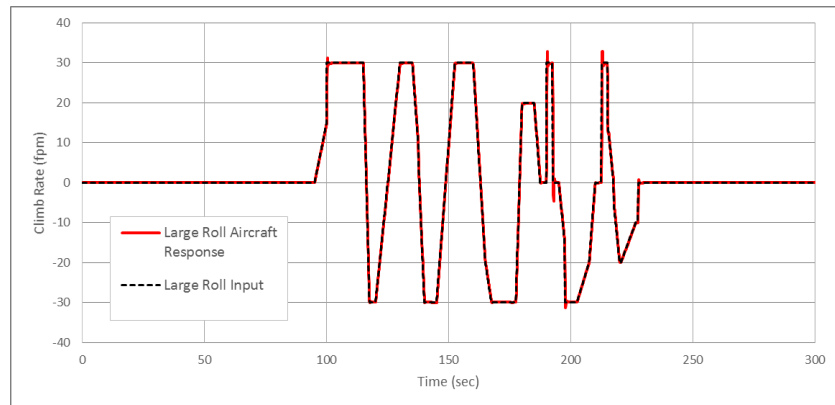
Another maneuver where this desired end state would be helpful is the non-precision aggressive air-to-ground tracking maneuver. Once again, the aircraft's mission during this maneuver is to ensure the aircraft is on track with the non moving target on the ground. During this maneuver, Group 5 Aircraft A desired a 4,000 *ft* descent and a 90° turn. During the moderate longitudinal and lateral-directional control inputs, this aircraft had an end state altitude deviation of 196 *ft* and a track deviation of 0.03°. This concrete measure of merit can aid in the analysis of an aircraft's performance. Once again, the L^2 Norm was calculated during this maneuver at moderate control inputs and the longitudinal control had a deviation of 3,360 *fpm* and the lateral-directional control had a deviation of 3.3°. As with the previous maneuver, this non-precision aggressive maneuver has a relatively small L^2 Norm, but this is not as crucial as being able to track the non-moving target on the ground. For this maneuver, the desired end state is more essential to a successful maneuver than following a specific flight path.

Using both a desired end state and a L^2 Norm are good methods for analyzing an aircraft's performance during a precision non-aggressive maneuver such as the precision offset landing. Landing an aircraft is a critical phase of flight and the desired end state of landing on centerline and continuing to track down centerline is vitally important not only to the maneuver but also to the aircraft's safety. During the large lateral-directional control input, the aircraft touched down on the runway with a heading deviation of 0.2° and 9 *ft* offset from centerline. This precision maneuver necessitated tight tolerances on the desired end state. Furthermore, during the critical landing phase, safety requires the aircraft to strictly follow the intended flight path, validating the L^2 Norm application. During the large lateral-directional control input of the precision offset landing, a L^2 Norm was performed on Group 5 Aircraft A. The pitch track had a deviation of 6,878 *fpm* and the roll track had a

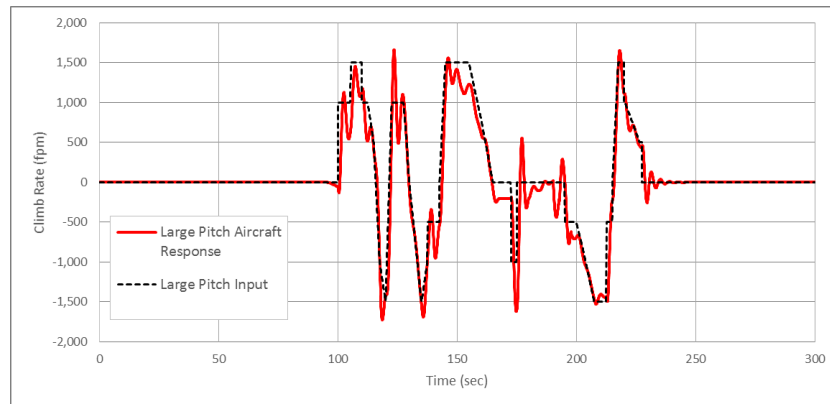
deviation of 13° . Understandably, the desire is to minimize this error as much as possible. During this precision non-aggressive maneuver, both maneuver evaluations demonstrated a beneficial application.

Finally, during the precision aggressive maneuver, the desired end state is not as critical as the L^2 Norm. Specifically, during the pitch and roll discrete tracking, the desired end state is unknown and has minimal impact as long as the aircraft and its sensors are able to track the desired path. Therefore, using the L^2 Norm method for this precision aggressive maneuver is ideal. Figure 74 displays the pitch and roll discrete tracking maneuver with large longitudinal and lateral-directional control inputs for Group 5 Aircraft A and the deviations from the desired tracking path and the aircraft's actual performance are seen. Referring to the time history exported from the j2 Universal Tool-Kit, an L^2 Norm was performed and the pitch deviation was found to be 11,408 *fpm* while the roll deviation was found to be 67° . Referring again to Figure 74, there are significantly more deviations in the pitch tracking than the roll tracking. If the UAV is tracking a target to eliminate it, this might not be acceptable. However, if the UAV is tracking a target to keep it in the aircraft's onboard sensor field of view, then these deviations might be acceptable. The operator must define the allowable error in a tracking maneuver; however, the L^2 Norm is a concrete method to providing information about an aircraft's ability to perform a maneuver.

Two valid maneuver evaluations were described and both hold viable methods for aircraft maneuver analysis. The desired end state was useful when analyzing both of the non-precision maneuvers and the precision non-aggressive maneuver. While this evaluation is helpful, the L^2 Norm analysis demonstrated important aircraft performance characteristics for the two precision maneuvers.



(a) Large Roll



(b) Large Pitch

Figure 74. Group 5 Aircraft A Pitch and Roll Discrete Tracking Performance Plots

4.3.3 Control Deflection Analysis.

Another method to help define how successful a UAV is in accomplishing a given maneuver is how much control deflection is used throughout the maneuver. An aircraft might be able to perform a maneuver with minimal error, but if the control surfaces are constantly moving and deflecting near their limit, then it might not be the ideal aircraft for that specific maneuver. During each maneuver performed in this research, the control surfaces deviations were documented. To help understand this performance metric, Group 5 Aircraft A ruddervator deviations are reviewed for each maneuver. In Table 75, the summation of the absolute values of the ruddervator movements are shown for Group 5 Aircraft A non-precision non-aggressive maneuver. As can be seen, for the climbing spiral, minimal ruddervator deflections

Table 75. Group 5 Aircraft A, Climbing Spiral, Sum of Ruddervator Deviations (*rad*)

	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
500 fpm Climb	0.0384 (2.1994°)	0.0680 (3.8980°)	0.1304 (7.4740°)
1000 fpm Climb	0.0710 (4.0677°)	0.0921 (5.2750°)	0.1468 (8.4096°)
1400 fpm Climb	0.1036 (5.9364°)	0.1240 (7.1064°)	0.1699 (9.7337°)

are observed. Switching to the non-precision aggressive maneuver, the ruddervator deflections can be seen in Table 76. The ruddervator deflections for this non-precision aggressive air-to-ground tracking maneuver are slightly higher than the non-precision non-aggressive climbing spiral maneuver. Adding a level of aggressiveness appears to require additional control deflections.

Next, the precision non-aggressive maneuver ruddervator deflection summations are seen in Table 77. Despite having a non-aggressive facet to this precision offset landing, the ruddervator deflections have greatly increased especially at large lateral-

Table 76. Group 5 Aircraft A, Air-to-Ground Tracking, Sum of Ruddervator Deviations (*rad*)

	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
500 fpm Climb	0.0486 (2.7856°)	0.0874 (5.0063°)	0.1484 (8.5014°)
1000 fpm Climb	0.0919 (5.2656°)	0.1284 (7.3592°)	0.1845 (10.5715°)
1400 fpm Climb	0.0912 (5.2277°)	0.1324 (7.5883°)	0.1831 (10.4889°)

Table 77. Group 5 Aircraft A, Precision Offset Landing, Ruddervator Deviations (*rad*)

	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft Offset	0.1318 (7.5529°)	0.3136 (17.9701°)	0.4998 (28.6388°)
150 ft Offset	0.1431 (8.2002°)	0.3834 (21.9690°)	
50 ft Offset	0.1737 (9.9497°)		

directional control inputs. The fact that this is a precision maneuver leads to the realization that it will also require the aircraft to follow a specific track and will have to make control deviations in order to remain within the required error tolerances for a desired flight path. Finally, the ruddervator deflection summaries for the precision aggressive pitch and roll discrete tracking maneuver are seen in Table 78. During

Table 78. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Sum of Ruddervator Deviations (*rad*)

	Small Lateral-Directional Control	Moderate Lateral-Directional Control	Large Lateral-Directional Control
Small Pitch Control	1.0228 (58.6006°)	1.8969 (108.6758°)	2.6945 (154.3812°)
Moderate Pitch Control	1.6322 (93.5184°)	2.4059 (137.8476°)	3.1457 (180.2351°)
Large Pitch Control	2.5460 (145.8724°)	3.1460 (180.2513°)	3.8185 (218.7860°)

the pitch and roll discrete tracking maneuver, the highest control deflection summations of all four maneuvers are observed. The desire to follow a specific constantly changing track in both the longitudinal and lateral-directional planes leads to a high workload for the UAV. This workload metric is highly valuable for UAV operations in determining their ability to perform a given maneuver.

Observing the UAV control deflections appears to demonstrate some usefulness in determining the aircraft's necessary workload to perform a given maneuver. The non-precision maneuvers constantly had a significantly smaller control deflection than the precision maneuvers. The level of aggressiveness appeared to affect the control deflection summations as well. with the non-precision maneuvers, increasing the level of aggressiveness increased the control deflections; however, with the precision maneuvers, there was a very large increase of control deflections when changing a maneuver from non-aggressive to aggressive. This control deflection summation is a valid source to determine how much these UAVs are working in order to perform a given maneuver.

4.4 Summary

This chapter has gone into detail describing the research accomplished. There were four maneuvers: the non-precision non-aggressive climbing spiral, the non-precision aggressive air-to-ground tracking, the precision non-aggressive precision offset landing, and the precision aggressive pitch and roll discrete tracking. These four maneuvers were executed by three different aircraft: Group 5 Aircraft A, Group 5 Aircraft B, and Group 4 Aircraft. For each maneuver, various flying qualities criteria were calculated, including: angle of attack, pitch attitude change, peak pitch rate, pitch quickness, roll attitude change, peak roll rate, roll quickness, bandwidth, and time

delay. Furthermore, for each maneuver varying amounts of longitudinal and lateral-directional control input were applied allowing for tendency analysis.

First, maneuvers were analyzed and correlations between the three aircraft were drawn for each criteria. Next the aircraft were analyzed and comparisons between maneuvers were drawn for each criteria. For both methods of analysis, the pitch and roll attitude change did not demonstrate significance; however, these criteria did aid in understanding the peak attitude rates and quickness values. In general, there is a nearly linear relationship between attitude change and peak attitude rate. This leads to a nearly constant quickness value. When values appear to deviate from this generality, typically there is an explanation that correlates to the aircraft's performance capability. Finally, there was a discussion about various methods to aid in defining a UAV's performance capabilities during a maneuver. Airspeed, end state and flight path deviations, and control workload were discussed as possible metrics

The UAVs have varying designs, weight, and missions. The above analysis validated the belief that weight is not a good classification scheme for these three UAVs despite being the current grouping method for current aircraft. Instead, there appears to be a high correlation to the radius of gyration nondimensionalized by the wing span and specific maneuver being performed.

V. Conclusions and Recommendations

UAVs have the potential to accomplish countless missions that manned aircraft either cannot accomplish or do not want to accomplish. This field has expanded exponentially even in the past few years. Despite this growth, there has been minimal research into criteria necessary for UAVs to accomplish their mission safely while still capturing the unique capability that unmanned aircraft have the potential to demonstrate.

5.1 Conclusions

The reasoning behind this research was to begin the discussion of unmanned aircraft flying qualities. Manned fixed-wing and rotary-wing aircraft have been refining their flying qualities research and requirements since the beginning of flight. It is important to leverage this knowledge but not let it bound UAV flying qualities research and recommendations. The focus of this research was to begin to create a process to be used during the UAV aircraft design and model validation method with the hopes of increasing the success rate of UAV operations.

5.1.1 Parameters and Analysis of Flying Qualities.

This research needed clearly defined parameters with which the problem scope would be bound. Aircraft type, level of automation, and mission tasks were defined and specific parameters were chosen. Three aircraft were defined that varied in size, weight, and performance capabilities, yet had some similar and some different operational missions. These aircraft also spanned various UAV categorizations from different sources in order to determine if a specific categorization was better suited for unmanned aircraft. The level of automation was observed assuming all inner and

outer control loops were closed. Finally, four maneuvers were chosen from each category of precision and aggressiveness levels. These four maneuvers, the non-precision non-aggressive climbing spiral, the non-precision aggressive air-to-ground tracking, the precision non-aggressive offset landing, and the precision aggressive pitch and roll discrete tracking were all clearly defined to allow for repeatability and comparison among the various aircraft. By carefully choosing the aircraft, automation level, and maneuvers, this research had the ability encompass a large field of variables and show applicability outside of the chosen parameters. With the research bounded, current flying qualities standards, in particular the MIL-STD-1797A and ADS-33E-PRF, were used as a reference to determine how best to analyze the aircraft performance. The focus was on nine different criteria: angle of attack, pitch attitude change, peak pitch rate, pitch quickness, roll attitude change, peak roll rate, roll quickness, bandwidth, and time delay.

The angle of attack criterion was investigated to help in understanding where the aircraft was in terms of a performance limit. This criteria aided in the understanding of how the aircraft is maneuvering. It also allowed for investigating how close the aircraft was to its aerodynamic performance limit. If it was close to the stall angle of attack, any degradations to the aircraft's performance can possibly be explained by the aerodynamic limit. Conversely, if there is a reduction in the aircraft's performance but the angle of attack is not near stall, the results can be related to a thrust performance limit.

The pitch attitude change was analyzed as a potential flying qualities criterion for unmanned aircraft. While this criterion demonstrated usefulness in understanding the specific aircraft characteristics it was not found to directly relate to a specific maneuver or aircraft gross weight. There was, however, a correlation between the magnitude of the pitch attitude change and the nondimensionalized radius of gyration

in the longitudinal plane. Furthermore, the pitch attitude change was more closely related to the longitudinal control input, not necessarily the level of precision and aggressiveness required to perform a given maneuver. However, this criterion did allow for a better understanding of, not only the peak pitch rate criterion, but also the pitch quickness criterion. So, although the pitch attitude change does not appear to directly affect flying quality analysis, it is a significant criterion in fully understanding other pertinent flying qualities characteristics.

The peak pitch rate criterion was found to strongly correlate to the nondimensionalized radius of gyration in the longitudinal plane for the both non-precision maneuvers. For both the aggressive maneuvers, the peak pitch rate was found in all three aircraft to have the largest magnitude at the large longitudinal control inputs. This leads to the conclusion that the peak pitch rate criterion is a valuable flying qualities criterion, particularly in determining the level of aggressiveness required for a given maneuver.

The pitch quickness criterion in this research demonstrated some differences between the various maneuvers that are valuable to note. During the non-precision non-aggressive maneuver, nearly constant pitch quickness values were seen. There were some data points that deviated from this nearly constant value; however, those data points were explained by realizing the aircraft was performing near an operational limit. During the non-precision aggressive maneuver, the pitch quickness criterion had a wider range than what was observed during the non-precision non-aggressive maneuver. The pitch quickness criterion demonstrated some usefulness during the precision non-aggressive maneuver. With the precision required during this maneuver, the pitch quickness value was affected by a correlation to the nondimensionalized radius of gyration in the longitudinal plane. Although this criterion was not a valid form of analysis for the precision aggressive maneuver due to the

pitch attitude reversals, it demonstrated usefulness in analyzing the remaining three maneuvers.

The roll attitude change criterion had little variation among maneuvers; however, it was directly linked to the amount of lateral-directional control input, particularly for the non-precision maneuvers and the precision non-aggressive maneuver. During the precision aggressive maneuver, the aircraft demonstrated the level of precision and aggressiveness required by performing a roll attitude change slight greater than what was desired. Therefore, this criterion is a benefit in determining the actual aircraft performance. Furthermore, while this criterion did not demonstrate the capability to define the aircraft's ability to perform a maneuver, it did help in understanding the other lateral directional criteria of peak roll rate and roll quickness.

The peak roll rate criterion had no relationship to aircraft weight; however, there was a correlation in the non-precision non-aggressive maneuver between the peak roll rate and the aircraft lateral-directional control input and, therefore, the aircraft performance characteristics. This relationship was also observed in the non-precision aggressive maneuver and precision non-aggressive maneuver. Additionally, in the precision aggressive maneuver, there appear to be a correlation between the peak roll rate and the nondimensionalized radius of gyration in the lateral directional plane.

Roll quickness demonstrated a nearly constant value for all three aircraft for each of the two non-precision maneuvers. This was due, in part, to the highly responsive lateral directional control system used for all three aircraft. There was a correlation between the roll quickness magnitudes and the nondimensionalized radius of gyration in the lateral directional plane; however, the criterion magnitudes were so close in value it is hard to determine if this relationship was related to the nondimensionalized radius of gyration or more a factor of the tightly constrained lateral-directional control system. The roll quickness criterion was only evaluated in two of the maneuvers as

there was a lateral-directional control reversal in the precision non-aggressive and precision aggressive maneuvers which would lead to inaccurate roll quickness values.

Bandwidth and time delay are criterion that are both used in current manned fixed-wing and manned rotary-wing flying quality standards. As expected with already proven and validated analysis, this research also found both bandwidth and time delay were useful in determining the unmanned aircraft's performance capabilities and its ability to accurately perform the given maneuver as desired.

Overall, all of the criteria analyzed in this research provided insight into each respective aircraft's ability to accomplish a given maneuver. The angle of attack analysis provided insight into the aerodynamic or thrust limitations of the aircraft's performance. The peak attitude rates can provide insight into the level of aggressiveness the aircraft can handle. The quickness criterion is not widely used for fixed-wing flying qualities research; however, it is a frequency measure that can lead to understanding the aircraft's internal ability to perform a maneuver. The benefit of the quickness criteria is the ability to combine the analysis of two other criteria, attitude change and peak attitude rate. The fact that bandwidth and time delay are a valid and common source of flying qualities analysis also leads to the belief that these are two criteria that will be beneficial to the unmanned aircraft flying qualities research.

5.1.2 Proposed Flying Qualities Framework.

This research proposed a UAV flying qualities structure that focused more on mission task than aircraft gross weight. Current manned fixed-wing flying qualities standards use weight as a primary aircraft categorization; however, unmanned aircraft have a wide range of aircraft weight, yet each of these aircraft must perform similar maneuvers. Similar understanding is what led manned rotary-winged researchers to develop the mission task element approach. Flying qualities criteria was defined by a

required task versus the aircraft's weight. This research proposed a similar framework. Through the j2 Universal Tool-Kit design of three unmanned aircraft with different weights, this approach was tested. The j2 Universal Tool-Kit allowed for all three aircraft to perform the same maneuvers in a similar manner. This allowed not only the variation of control inputs for each aircraft, but also a comparison of the three different aircraft's performance of the same maneuver.

Through this research, two primary aircraft categorizations demonstrated potential for future classifications in an unmanned aircraft standard: maneuvers and nondimensionalized radius of gyration. When analyzing a given maneuver and varying the aircraft, the nondimensionalized radius of gyration provided insight into the varying magnitudes of various criteria. However, when analyzing a given aircraft and varying the maneuver, the maneuver provided insight and correlations into the varying magnitudes of the various criteria. With the accomplished research, it is difficult to determine which categorization provides more insight into a given aircraft's flying quality characteristics. However, there are some benefits of using a mission oriented approach that are not seen if focusing on the correlations of the nondimensionalized radius of gyration.

First off, by focusing on a specific maneuver, the aircraft designer can create a more specialized aircraft. Without bounding the design to criteria based primarily on the nondimensionalized radius of gyration, the design of the aircraft potentially has unique characteristics allowing for expanded maneuver capabilities. Secondly, by categorizing flying qualities according to a maneuver, the aircraft can focus more on performance and safety. Finally, a mission centered approach will allow the customer a better understanding of what mission and respective maneuvers a given aircraft is capable of performing. This allows the customer to place emphasis on their needs, ensuring the aircraft will perform as desired. With current manned fixed-wing flying

qualities, the primary categorization is weight and maneuverability level, then there are additional categories. From this unmanned aircraft research, the nondimensionalized radius of gyration provided insight into flying qualities criteria. Therefore, if needed, this can be an additional layer of categorizations to further refine the given unmanned aircraft flying qualities requirements.

The four maneuver categories used in this research provide a well-rounded review of possible maneuvers and how various flying qualities criteria change with respect to these maneuvers. Varying the amounts of precision requires varying performance standards and allowable overshoots. This flexibility is a necessity to all aircraft since, at a minimum, precision maneuvering is required for the landing phase of flight. Similarly, varying the amounts of aggressiveness requires varying amounts of performance characteristics. These characteristics are required only for aircraft which need to perform these types of maneuvers. The four maneuver categories span all potential unmanned aircraft tasks and allow for flying qualities criteria to be refined for a given maneuver. By using this innovative mission orientated approach, unmanned aircraft will have the ability to have unique designs that can leverage their unique capabilities, while still ensure performance and safety standards are met.

5.1.3 Application of Flying Qualities Framework.

By focusing on the criteria and using the varying parameters, this research validated the proposed UAV flying qualities framework focusing on mission tasks. Correlations and tendencies were noted for each maneuver and respective aircraft; however, several times, by varying the longitudinal and lateral-directional control inputs, data points appeared to deviate from these expectations. Quite often, these outlying data points were explained by reviewing other criteria, such as a particularly small attitude change, or by realizing the aircraft was performing the maneuver at or near an

aircraft aerodynamic or thrust performance limit. This research also demonstrated a need to consider various causes for criteria not adhering to what was the expected result.

Furthermore, this research provided possible methods for evaluating a UAV's ability to perform a maneuver and gain insight into how much workload is required of the aircraft. One method was to analyze airspeed deviations. This allowed for insight into the aircraft's performance, aggressiveness level, and safety if and when operating near an aircraft limit. Two methods were discussed for deviations from a desired maneuver. Ensuring a specified end state is important for all maneuvers, however, the L^2 Norm was beneficial when analyzing aircraft performance characteristics during precision maneuvers. Finally, control deflection analysis demonstrated an understanding of the aircraft's necessary workload to perform a given maneuver. A higher workload is not necessarily a negative characteristic, it is just a data point that needs to be incorporated into the design of the aircraft, understood by the manufacturer, and accepted by the operator.

5.2 Recommendations for Future Work

With this research being unique and some of the first in this field, there are several areas for future work. The exploration into UAV flying qualities has just begun. As this field of research expands, it will be necessary to incorporate industry and the DoD to ensure UAV operations and unique capabilities are not hindered, but aided, by this research. Only three aircraft were modeled in the j2 Universal Tool-Kit software. These three aircraft were modeled after actual UAVs; however, no flight test data was gathered to ensure comparability. Model parameters were chosen by looking at aircraft similar to what was being modeled and minimal bare airframe analysis was accomplished on the models. Future work should include more in-depth analysis of

the bare airframe. Actual UAV aircraft, either through flight test or modeling, need to be used to help validate this research, its findings, and expand upon it. Flight test can be expensive and time consuming, so software models from manufactures can be used, or the j2 Universal Tool-Kit has the ability to verify a model through comparison of flight test data. Once a model is verified, the same process used in this research can be completed. The additional models should include aircraft of various sizes, nondimensionalized radius of gyrations, automation levels, missions, and different methods of controlling the aircraft.

During this research, all analysis was accomplished with a given control system where all loops were closed throughout the entire maneuver and no changes in the specified gains. This simplified the research; however, the future work should include several variations with regards to the control system. Three specific areas of future research include adjusting the gains for a given maneuver, researching and analyzing different levels of automation, and investigating the effects of time delays on unmanned aircraft flying qualities. Current manned aircraft can change their gains within the control system when performing specific maneuvers such as landing or air refueling. Some unmanned aircraft may hold similar performance characteristics and this gain adjustment should be examined. In this research, the four levels of autonomy were consolidated into two control specific levels. One was when the unmanned aircraft had an operator in the loop and was being hand-flown. The other was when the aircraft was being controlled by the automation and defined control system with the loops closed. This second specific automation level was the focus of this research; however, the operator in the loop is an essential aspect of unmanned aircraft operations and should be further investigated. Similarly, as the automation levels are expanded, the research should also explore how time delays affect the unmanned aircraft flying qualities. Time delays are inherent in unmanned aircraft and vary

depending on several facets. The time delay can significantly affect the unmanned aircraft's operations and should be researched as this topic expands.

Another important area for future work is to incorporate other maneuvers. This will help validate the trends noted in this research. In particular another precision non-aggressive maneuver that has the same initial conditions as the other maneuvers. The varying initial conditions also demonstrates the need to test these maneuvers at the edges of the flight envelope, whereas this research performed three of the maneuvers in the middle of the flight envelope. Furthermore, maneuvers which did not perform longitudinal or lateral-directional control reversals would allow for the analysis of the pitch and roll quickness criteria, expanding the flying qualities research database.

The field of UAV flying qualities is extensive and has not been given the attention necessary for sustained flying operations. It is necessary to work with all players in the field of UAVs, from the FAA to manufacturers and designers to operators, both UAV hobby enthusiasts and operators who use UAVs to accomplish specific missions. The framework proposed was validated through the use of the defined parameters, aircraft, and maneuvers; however, there are several aspects which this research does not address. The hope is this research is the needed stepping stone and has started the discussion to demonstrate the need for a UAV flying qualities standard and has set up a successful paradigm for this future research.

Appendix A. Group 5 Aircraft A

1.1 Model Data

Table 79. Group 5 Aircraft A, Full Model Parameter Inputs

Parameter	Value
Wing Span, b	130.9 <i>ft</i>
Mean Chord, $\bar{c}$	5.05 <i>ft</i>
Planform Area, S	621.72 <i>ft</i> ²
Mass with Fuel, m	32,500 <i>lbs</i>
Moment of Inertia, I_x	1,471,282 <i>lbs</i> · <i>ft</i> ²
Moment of Inertia, I_y	3,559,554 <i>lbs</i> · <i>ft</i> ²
Moment of Inertia, I_z	4,888,454 <i>lbs</i> · <i>ft</i> ²
Aircraft Drag Coefficient, C_D	0.01
Aircraft Center of Gravity, CoG , (x, y, z)	(25.19, 0.0, 0.4) <i>ft</i>
Aircraft Neutral Point, NP (x, y, z)	(23.8, 0.0, 0.0) <i>ft</i>
Fuel Mass	14,500 <i>lbs</i>
Engine Location, (x, y, z)	(24.53, 0, -3.609) <i>ft</i>
Aspect Ratio, AR	27.56
Wing Sweep,	4.115°
Wing Leading Edge Location, x	20.54 <i>ft</i>
Wing Neutral Point, NP_w	22.44 <i>ft</i>
R/L Wing Strip Location, (x)	0.0 <i>ft</i> to 65.45 <i>ft</i>
Number of R/L Wing Strips	10
Wing Airfoil Shape	LRN 1015
R/L Aileron Location, (y)	11.66 <i>ft</i> to 49.69 <i>ft</i>
Number of R/L Aileron Strips	10
Tail Airfoil Shape	NACA 0008

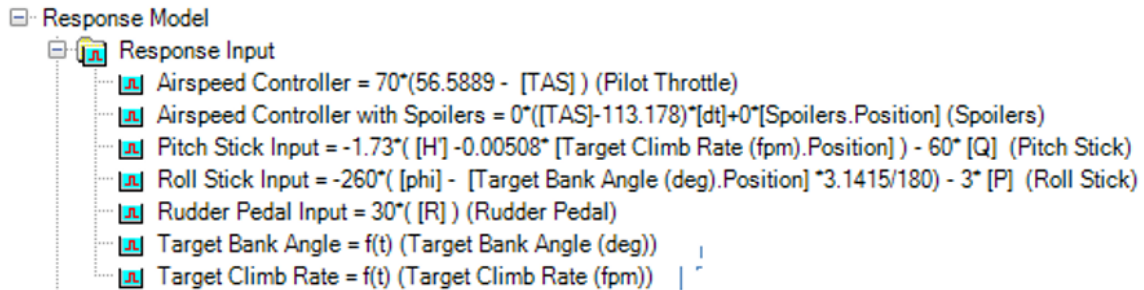
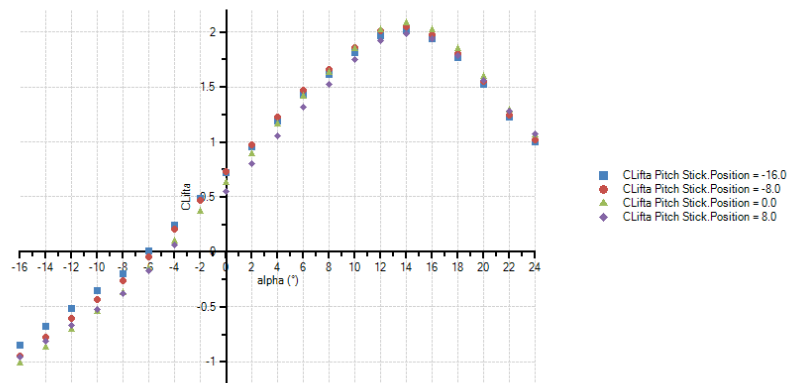
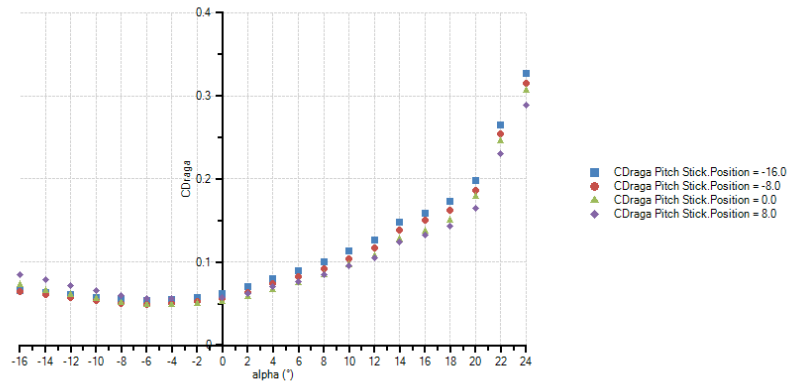


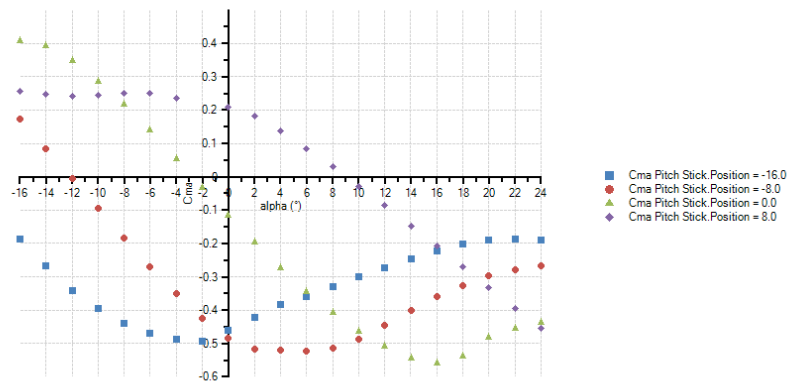
Figure 75. Group 5 Aircraft A Control System



(a) Lift Curve

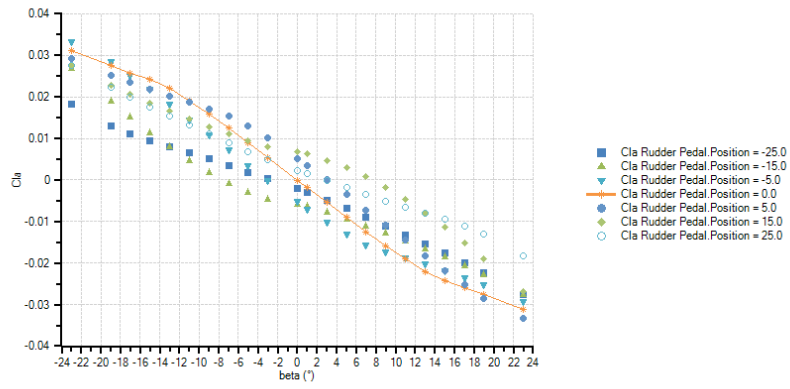


(b) Drag Curve

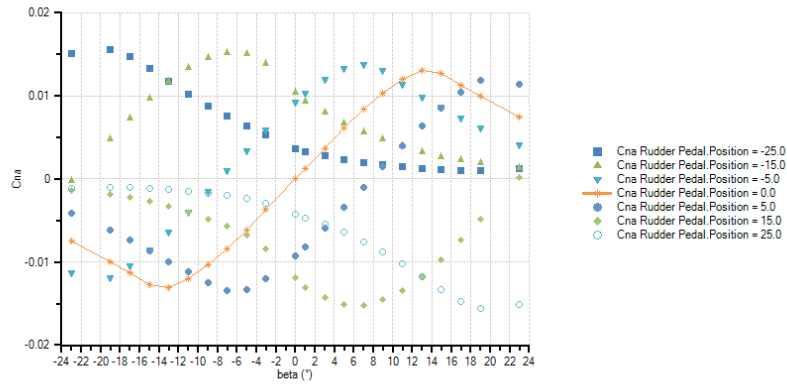


(c) Moment Curve

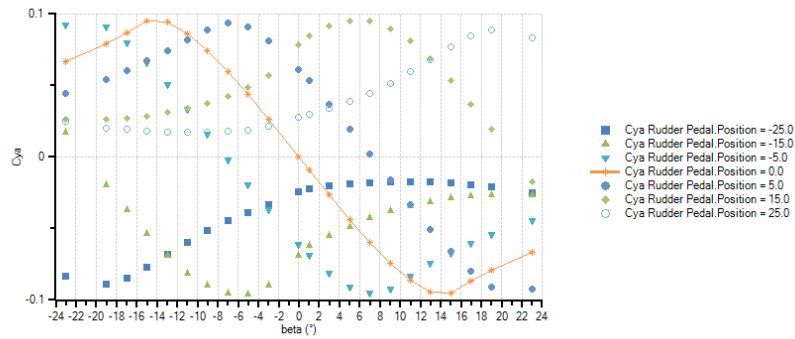
Figure 76. Group 5 Aircraft A Lift, Drag, and Moment Curves



(a) $C_{l_{\alpha}}$ Curve



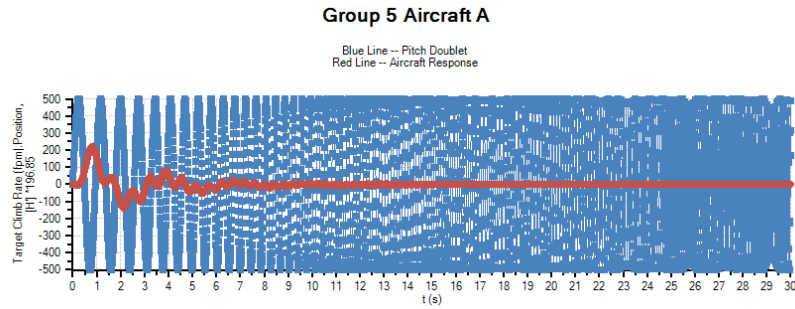
(b) $C_{n_{\alpha}}$ Curve



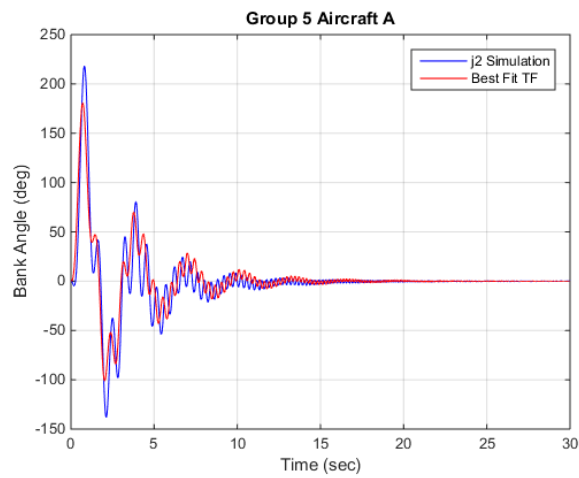
(c) $C_{y_{\alpha}}$ Curve

Figure 77. Group 5 Aircraft A Beta Derivative Curves

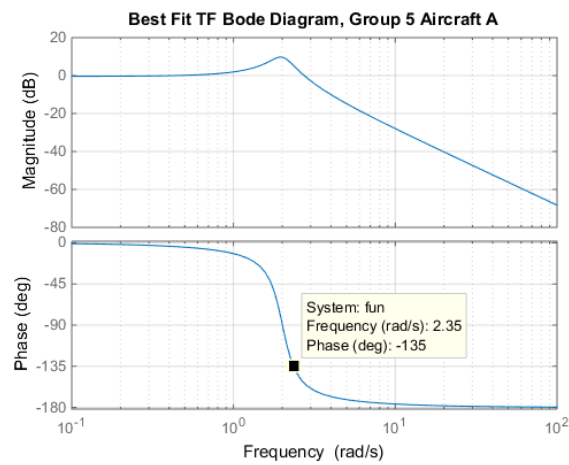
1.2 Bandwidth and Time Delay



(a) Frequency Sweep with Model Response

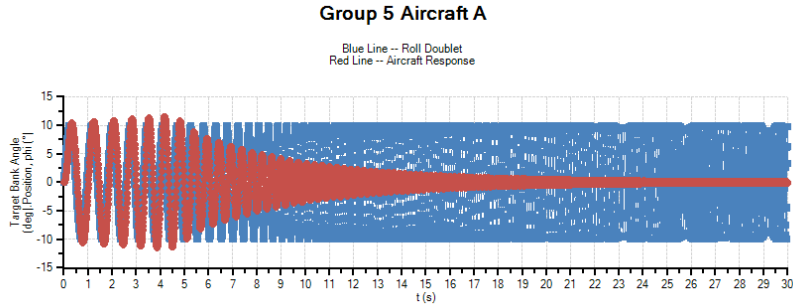


(b) Model Response and Best Fit Transfer Function

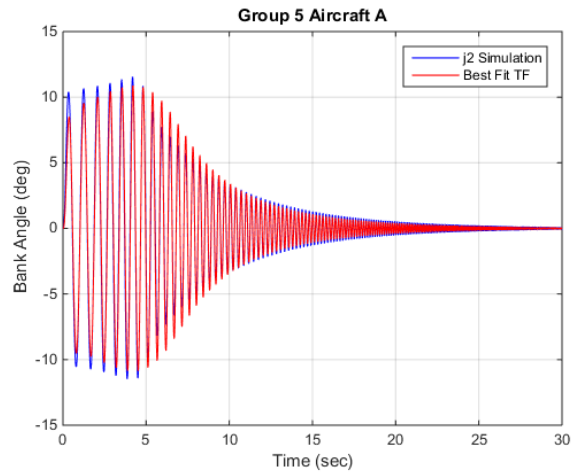


(c) Best Fit Transfer Function Bode Plot

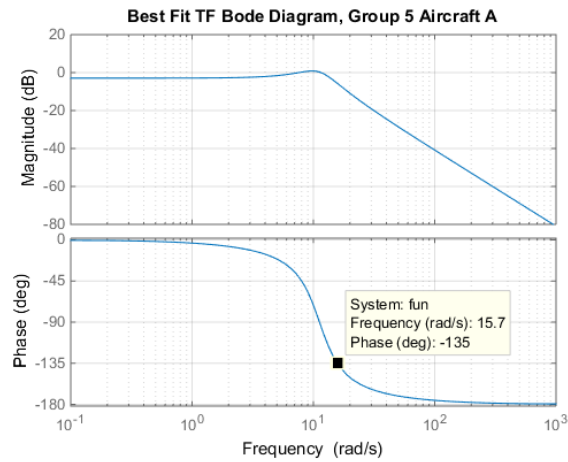
Figure 78. Group 5 Aircraft A Pitch Bandwidth Analysis Plots



(a) Frequency Sweep with Model Response



(b) Model Response and Best Fit Transfer Function



(c) Best Fit Transfer Function Bode Plot

Figure 79. Group 5 Aircraft A Roll Bandwidth Analysis Plots

Table 80. Closed-Loop Bandwidth for Group 5 Aircraft A at Moderate Control Inputs

	Pitch Bandwidth $\omega_{BW_{Pitch}} (rad/sec)$	Roll Bandwidth $\omega_{BW_{Roll}} (rad/sec)$
Frequency Sweep	2.35	15.70
Non-Precision Non-Aggressive	2.03	16.00
Non-Precision Aggressive	1.97	16.30
Precision Non-Aggressive	1.36	22.00
Precision Aggressive	1.99	16.60

Table 81. Closed-Loop Time Delay for Group 5 Aircraft A at Moderate Control Inputs

	Pitch Time Delay $\tau_{Pitch} (sec)$	Roll Time Delay $\tau_{Roll} (sec)$
Frequency Sweep	0.26	0.01
Non-Precision Non-Aggressive	0.45	0.05
Non-Precision Aggressive	0.40	0.1
Precision Non-Aggressive	0.6	0.1
Precision Aggressive	0.6	0.1

1.3 Non-Precision Non-Aggressive Maneuver Data

Table 82. Group 5 Aircraft A, Climbing Spiral, Pitch Attitude Change Values (*rad*)

$\Delta\theta$	No Turn	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
0 fpm Climb		0.0010 (0.0588°)	0.0087 (0.4958°)	0.0355 (2.0327°)
500 fpm Climb	0.0301 (1.7265°)	0.0308 (1.7631°)	0.0359 (2.0596°)	0.0595 (3.4093°)
1000 fpm Climb	0.0606 (3.4700°)	0.0612 (3.5060°)	0.0659 (3.7761°)	0.0878 (5.0327°)
1400 fpm Climb	0.0959 (5.4933°)	0.0961 (5.5046°)	0.0981 (5.6216°)	0.1162 (6.6570°)

Table 83. Group 5 Aircraft A, Climbing Spiral, Peak Pitch Rate Values (*rad/sec*)

Q_{pk}	No Turn	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
0 fpm Climb		0.0010	0.0084	0.0376
500 fpm Climb	0.0108	0.0106	0.0139	0.0404
1000 fpm Climb	0.0222	0.0219	0.0214	0.0469
1400 fpm Climb	0.0369	0.0366	0.0342	0.0537

Table 84. Group 5 Aircraft A, Climbing Spiral, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	No Turn	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
0 fpm Climb		0.9422	0.8688	1.0584
500 fpm Climb	0.3583	0.3432	0.3862	0.6786
1000 fpm Climb	0.3665	0.3580	0.3247	0.5341
1400 fpm Climb	0.3853	0.3810	0.3487	0.4620

Table 85. Group 5 Aircraft A, Climbing Spiral, Roll Attitude Change Values (rad)

$\Delta\phi$	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
0 fpm Climb	0.0863 (4.946°)	0.2541 (14.557°)	0.5282 (30.264°)
500 fpm Climb	0.0864 (4.948°)	0.2542 (14.565°)	0.5285 (30.281°)
1000 fpm Climb	0.0864 (4.951°)	0.2543 (14.571°)	0.5288 (30.298°)
1400 fpm Climb	0.0864 (4.952°)	0.2544 (14.575°)	0.5291 (30.313°)

Table 86. Group 5 Aircraft A, Climbing Spiral, Peak Roll Rate Values (rad/sec)

P_{pk}	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
0 fpm Climb	0.0192	0.0565	0.1182
500 fpm Climb	0.0197	0.0580	0.1212
1000 fpm Climb	0.0202	0.0596	0.1241
1400 fpm Climb	0.0208	0.0610	0.1273

Table 87. Group 5 Aircraft A, Climbing Spiral, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
0 fpm Climb	0.2219	0.2223	0.2238
500 fpm Climb	0.2277	0.2282	0.2294
1000 fpm Climb	0.2338	0.2342	0.2348
1400 fpm Climb	0.2404	0.2397	0.2406

Table 88. Group 5 Aircraft A, Climbing Spiral, Airspeed Deviations (kts)

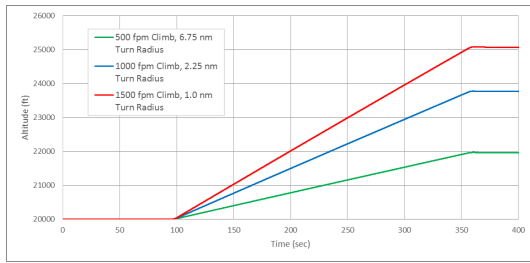
TAS	No Turn	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
0 fpm Climb	199.99 199.99	199.99 199.99	199.99 199.99	199.99 199.99
500 fpm Climb	199.99 199.98	199.99 199.99	199.99 199.99	199.99 199.99
1000 fpm Climb	199.99 199.98	199.99 199.98	199.99 199.98	199.99 199.98
1400 fpm Climb	199.99 197.02	199.99 197.30	199.99 198.98	199.99 199.97

Table 89. Group 5 Aircraft A, Climbing Spiral, Sum of Aileron Deviations (rad)

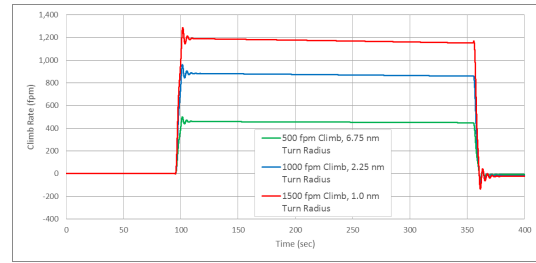
	No Turn	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
0 fpm Climb		0.0183 (1.0508°)	0.0540 (3.0914°)	0.1113 (6.3771°)
500 fpm Climb	0.0 (0.0°)	0.0188 (1.0752°)	0.0500 (3.1508°)	0.1132 (6.4870°)
1000 fpm Climb	0.0 (0.0°)	0.192 (1.1028°)	0.0564 (3.2291°)	0.1156 (6.6211°)
1400 fpm Climb	0.0 (0.0°)	0.0199 (1.1407°)	0.0584 (3.3471°)	0.1187 (6.8035°)

Table 90. Group 5 Aircraft A, Climbing Spiral, Sum of Ruddervator Deviations (*rad*)

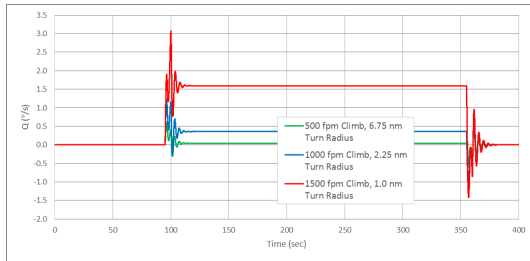
	No Turn	6.75 nm Turn Radius	2.25 nm Turn Radius	1.0 nm Turn Radius
0 fpm Climb		0.0189 (1.0829°)	0.0571 (3.2723°)	0.1243 (7.1191°)
500 fpm Climb	0.0319 (1.8266°)	0.0384 (2.1994°)	0.0680 (3.8980°)	0.1304 (7.4740°)
1000 fpm Climb	0.0676 (3.8758°)	0.0710 (4.0677°)	0.0921 (5.2750°)	0.1468 (8.4096°)
1400 fpm Climb	0.1091 (6.2522°)	0.1036 (5.9364°)	0.1240 (7.1064°)	0.1699 (9.7337°)



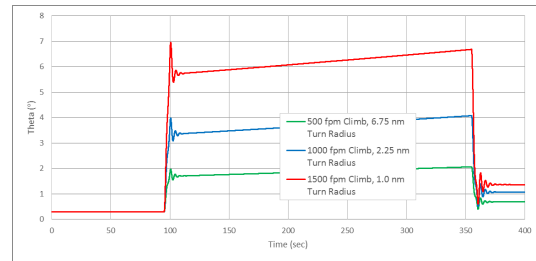
(a) Altitude



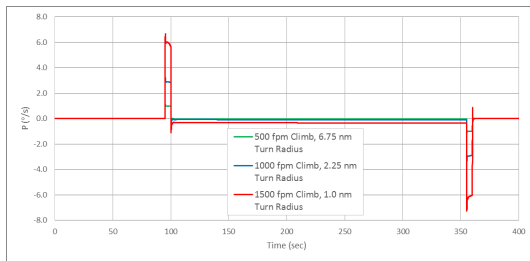
(b) Climb Rate



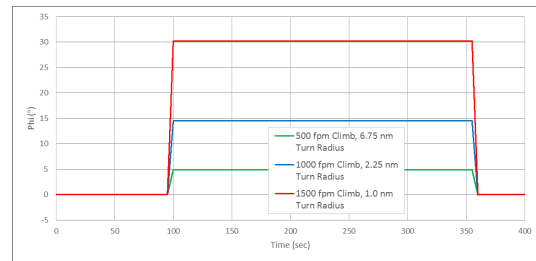
(c) Pitch Rate



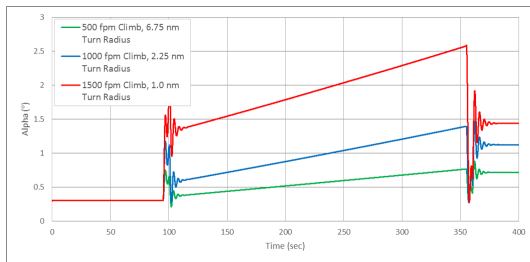
(d) Pitch Attitude



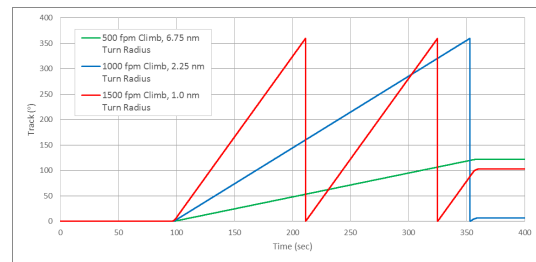
(e) Roll Rate



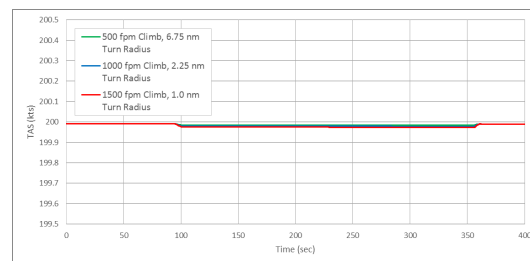
(f) Roll Attitude



(g) Angle of Attack



(h) Heading



(i) Airspeed

Figure 80. Group 5 Aircraft A Non-Precision Non-Aggressive, Spiral Climb, Performance Plots

1.4 Non-Precision Aggressive Maneuver Data

Table 91. Group 5 Aircraft A, Air-to-Ground Tracking, Pitch Attitude Change Values (rad)

$\Delta\theta$	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
0 fpm Descent		0.0010 (0.0587°)	0.0087 (0.4960°)	0.0326 (1.8702°)
500 fpm Descent	0.0327 (1.8739°)	0.0328 (1.8766°)	0.0328 (1.8819°)	0.0349 (1.9995°)
800 fpm Descent	0.0605 (3.4666°)	0.0607 (3.4755°)	0.0609 (3.4917°)	0.0612 (3.5070°)
1400 fpm Descent	0.0877 (5.0255°)	0.0878 (5.0322°)	0.0881 (5.0484°)	0.0884 (5.0670°)

Table 92. Group 5 Aircraft A, Air-to-Ground Tracking, Peak Pitch Rate Values (rad/sec)

Q_{pk}	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
0 fpm Descent		0.0010	0.0089	0.0368
500 fpm Descent	0.0105	0.0105	0.0105	0.0364
800 fpm Descent	0.0212	0.0212	0.0212	0.0350
1400 fpm Descent	0.0296	0.0289	0.0296	0.0324

Table 93. Group 5 Aircraft A, Air-to-Ground Tracking, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
0 fpm Descent		0.9608	1.0276	1.1262
500 fpm Descent	0.3222	0.3217	0.3208	1.0444
800 fpm Descent	0.3496	0.3487	0.3471	0.5711
1400 fpm Descent	0.3375	0.3295	0.3360	0.3660

Table 94. Group 5 Aircraft A, Air-to-Ground Tracking, Roll Attitude Change Values (rad)

$\Delta\phi$	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
0 fpm Descent	0.0872 (4.994°)	0.2616 (14.987°)	0.5231 (29.969°)
500 fpm Descent	0.0871 (4.990°)	0.2612 (14.969°)	0.5222 (29.922°)
800 fpm Descent	0.0871 (4.988°)	0.2611 (14.958°)	0.5224 (29.931°)
1400 fpm Descent	0.0870 (4.986°)	0.2612 (14.964°)	0.5222 (29.920°)

Table 95. Group 5 Aircraft A, Air-to-Ground Tracking, Peak Roll Rate Values (rad/sec)

P_{pk}	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
0 fpm Descent	0.0193	0.0581	0.1173
500 fpm Descent	0.0191	0.0561	0.1147
800 fpm Descent	0.0191	0.0563	0.1125
1400 fpm Descent	0.0186	0.0560	0.1121

Table 96. Group 5 Aircraft A, Air-to-Ground Tracking, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	5° Angle of Bank Turn	15° Angle of Bank Turn	30° Angle of Bank Turn
0 fpm Descent	0.2219	0.2220	0.2243
500 fpm Descent	0.2193	0.2149	0.2196
800 fpm Descent	0.2188	0.2155	0.2154
1400 fpm Descent	0.2139	0.2145	0.2146

Table 97. Group 5 Aircraft A, Air-To-Ground Tracking, Airspeed Deviations (kts)

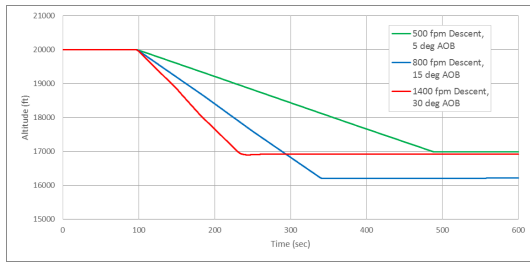
TAS	No Angle of Bank	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
0 fpm Descent	200 199.99	200 199.99	200 199.99	200 199.99
500 fpm Descent	200 199.99	200 199.99	200 199.99	200 199.99
800 fpm Descent	204.9 199.99	205.12 199.99	206.48 199.99	208.01 199.99
1400 fpm Descent	227.8 199.99	227.98 199.99	228.66 199.99	229.35 199.99

Table 98. Group 5 Aircraft A, Air-To-Ground Tracking, Sum of Aileron Deviations (rad)

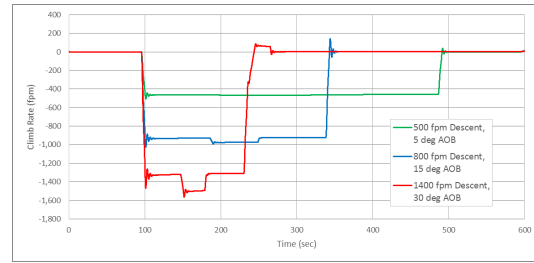
	No Angle of Bank	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
0 fpm Climb		0.0176 (1.0059°)	0.0530 (3.0386°)	0.1061 (6.0800°)
500 fpm Climb	0.0 (0.0°)	0.0178 (1.0179°)	0.0529 (3.0307°)	0.1057 (6.0551°)
1000 fpm Climb	0.0 (0.0°)	0.0174 (0.9994°)	0.0514 (2.9468°)	0.1020 (5.8450°)
1400 fpm Climb	0.0 (0.0°)	0.0091 (0.5236°)	0.0478 (2.7363°)	0.0935 (5.3577°)

Table 99. Group 5 Aircraft A, Air-to-Ground Tracking, Sum of Ruddervator Deviations
(*rad*)

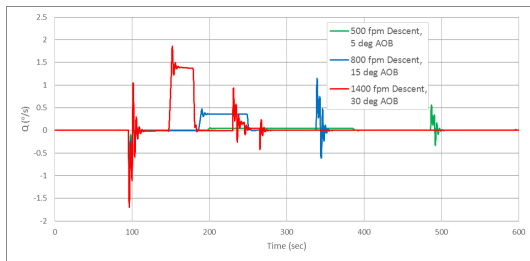
	No Angle of Bank	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
0 fpm Climb		0.0191 (1.0928°)	0.0588 (3.3690°)	0.1235 (7.0736°)
500 fpm Climb	0.0295 (1.6888°)	0.0486 (2.7856°)	0.0874 (5.0063°)	0.1484 (8.5014°)
1000 fpm Climb	0.0740 (4.2410°)	0.0919 (5.2656°)	0.1284 (7.3592°)	0.1845 (10.5715°)
1400 fpm Climb	0.0830 (4.7583°)	0.0912 (5.2277°)	0.1324 (7.5883°)	0.1831 (10.4889°)



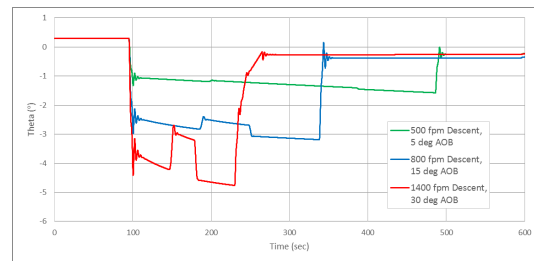
(a) Altitude



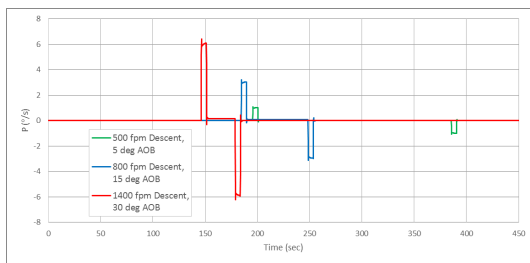
(b) Climb Rate



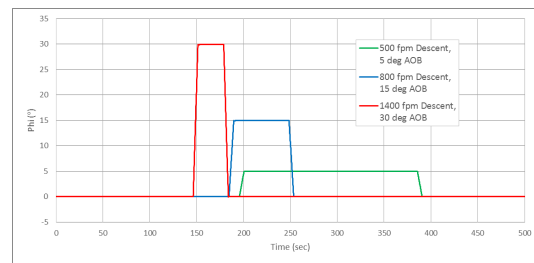
(c) Pitch Rate



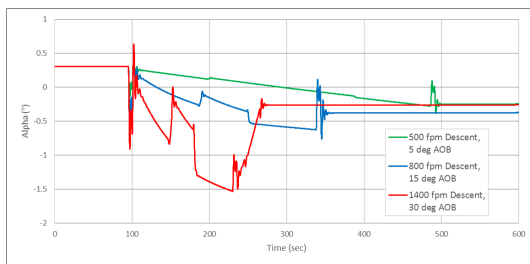
(d) Pitch Attitude



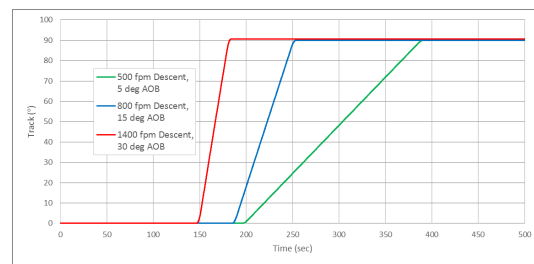
(e) Roll Rate



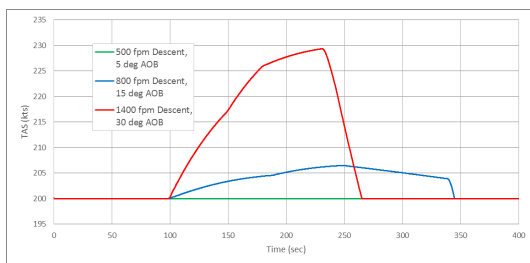
(f) Roll Attitude



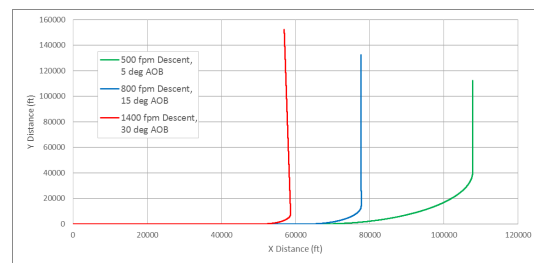
(g) Angle of Attack



(h) Heading



(i) Airspeed



(j) Ground Track

Figure 81. Group 5 Aircraft A Non-Precision Aggressive, Air-To-Ground Tracking, Performance Plots

1.5 Precision Non-Aggressive Maneuver Data

Table 100. Group 5 Aircraft A, Precision Offset Landing, Pitch Attitude Change Values (*rad*)

$\Delta\theta$	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft Offset	0.0770 (4.4140°)	0.0790 (4.5249°)	0.0814 (4.6628°)
150 ft Offset	0.0770 (4.4121°)	0.0793 (4.5432°)	
50 ft Offset	0.0769 (4.4087°)		

Table 101. Group 5 Aircraft A, Precision Offset Landing, Peak Pitch Rate Values (*rad/sec*)

Q_{pk}	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft Offset	0.0164	0.0164	0.0343
150 ft Offset	0.0164	0.0171	
50 ft Offset	0.0164		

Table 102. Group 5 Aircraft A, Precision Offset Landing, Pitch Quickness Values
(sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft Offset	0.2129	0.2077	0.4212
150 ft Offset	0.2130	0.2159	
50 ft Offset	0.2132		

Table 103. Group 5 Aircraft A, Precision Offset Landing, Roll Attitude Change Values
(rad)

$\Delta\phi$	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft Offset	0.1711 (9.804°)	0.5082 (29.118°)	0.7418 (42.503°)
150 ft Offset	0.1699 (9.735°)	0.5030 (28.818°)	
50 ft Offset	0.1677 (9.609°)		

Table 104. Group 5 Aircraft A, Precision Offset Landing, Peak Roll Rate Values
(rad/sec)

P_{pk}	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft Offset	0.0126	0.0645	0.1165
150 ft Offset	0.0171	0.0915	
150 ft Offset	0.0293		

Table 105. Group 5 Aircraft A, Precision Offset Landing, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft Offset	0.0736	0.1269	0.1570
150 ft Offset	0.1008	0.1820	
150 ft Offset	0.1747		

Table 106. Group 5 Aircraft A, Precision Offset Landing, Airspeed Deviations (kts)

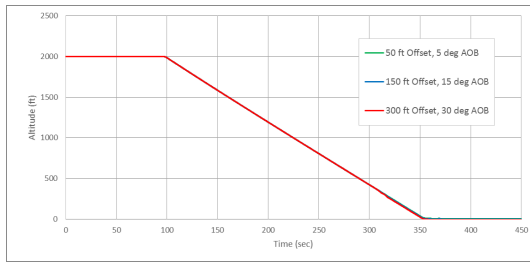
TAS	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft Offset	119.75 110.00	120.26 110.00	120.74 110.00
150 ft Offset	119.73 110.00	120.10 110.00	
50 ft Offset	119.70 110.00		

Table 107. Group 5 Aircraft A, Precision Offset Landing, Aileron Deviations (rad)

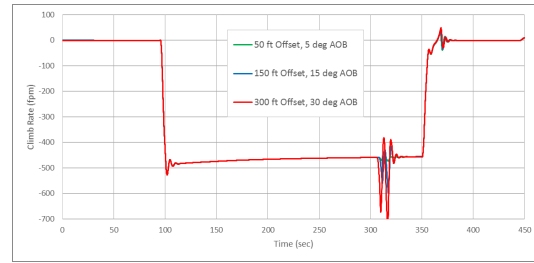
	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft Offset	0.0294 (1.6834°)	0.1431 (8.2000°)	0.2595 (14.8666°)
150 ft Offset	0.0391 (2.2410°)	0.2013 (11.5342°)	
50 ft Offset	0.0654 (3.7443°)		

Table 108. Group 5 Aircraft A, Precision Offset Landing, Ruddervator Deviations (rad)

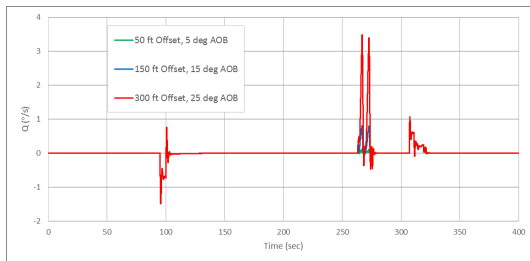
	5° Angle of Bank	15° Angle of Bank	30° Angle of Bank
300 ft Offset	0.1318 (7.5529°)	0.3136 (17.9701°)	0.4998 (28.6388°)
150 ft Offset	0.1431 (8.2002°)	0.3834 (21.9690°)	
50 ft Offset	0.1737 (9.9497°)		



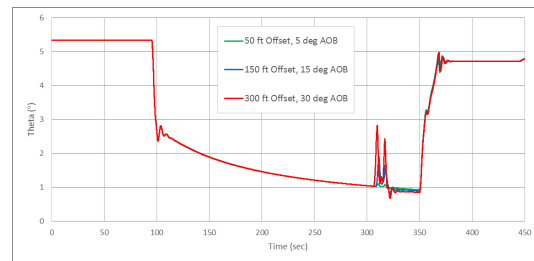
(a) Altitude



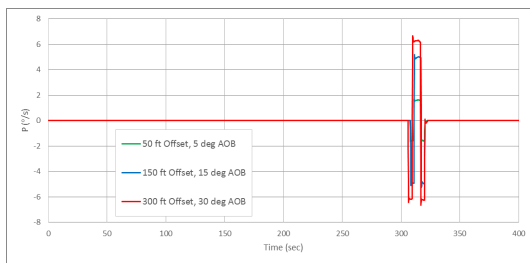
(b) Climb Rate



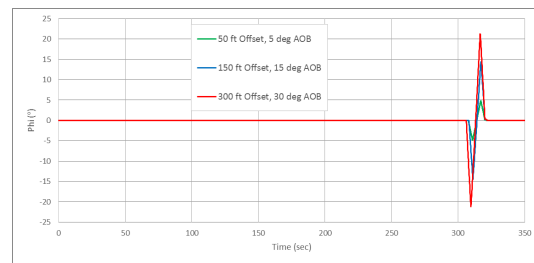
(c) Pitch Rate



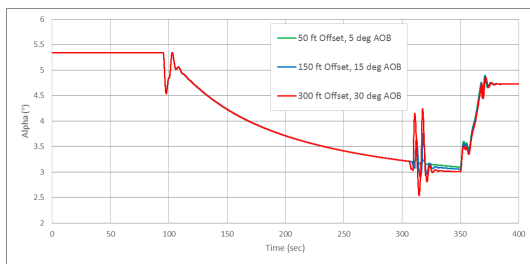
(d) Pitch Attitude



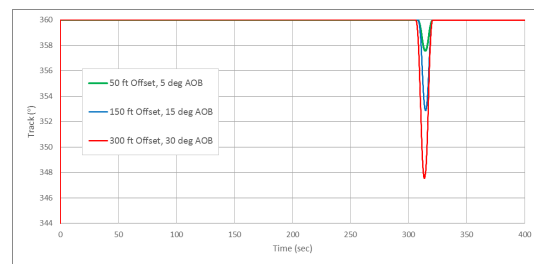
(e) Roll Rate



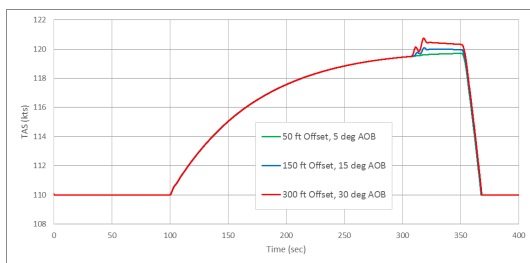
(f) Roll Attitude



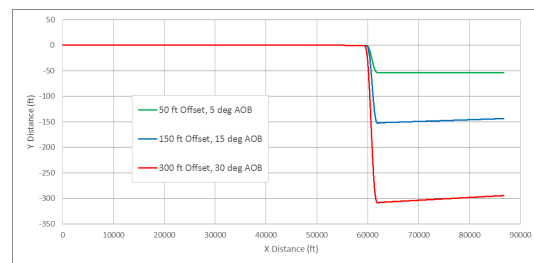
(g) Angle of Attack



(h) Heading



(i) Airspeed



(j) Ground Track

Figure 82. Group 5 Aircraft A Precision Non-Aggressive, Precision Offset Landing, Performance Plots

1.6 Precision Aggressive Maneuver Data

Table 109. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Pitch Attitude Change Values (rad)

$\Delta\theta$	No Lat-Dir Input	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input		0.0029 (0.1674°)	0.0267 (1.5287°)	0.0814 (4.6659°)
Small Longitudinal Input	0.0698 (4.0016°)	0.0681 (3.9001°)	0.0671 (3.8441°)	0.0887 (5.0808°)
Moderate Longitudinal Input	0.1403 (8.0376°)	0.1382 (7.9196°)	0.1312 (7.5188°)	0.1415 (8.1049°)
Large Longitudinal Input	0.2335 (13.3758°)	0.2314 (13.2567°)	0.2144 (12.2817°)	0.2107 (12.0697°)

Table 110. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Peak Pitch Rate Values (rad/sec)

Q_{pk}	No Lat-Dir Input	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input		0.0032	0.0316	0.1166
Small Longitudinal Input	0.0503	0.0516	0.0618	0.0981
Moderate Longitudinal Input	0.1017	0.1033	0.1169	0.1386
Large Longitudinal Input	0.1684	0.1701	0.1826	0.2052

Table 111. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	No Lat-Dir Input	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input		1.0989	1.1830	1.4313
Small Longitudinal Input	0.7207	0.7577	0.9206	1.1065
Moderate Longitudinal Input	0.7248	0.7476	0.8908	0.9795
Large Longitudinal Input	0.7213	0.7353	0.8518	0.9747

Table 112. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Roll Attitude Change Values (rad)

$\Delta\phi$	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input	0.2206 (12.642°)	0.6695 (38.362°)	1.1151 (63.891°)
Small Longitudinal Input	0.2210 (12.665°)	0.6708 (38.435°)	1.1177 (64.040°)
Moderate Longitudinal Input	0.2214 (12.688°)	0.6723 (38.520°)	1.1208 (64.215°)
Large Longitudinal Input	0.2221 (12.724°)	0.6725 (38.533°)	1.1203 (64.188°)

Table 113. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Peak Roll Rate Values (rad/sec)

P_{pk}	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input	0.5641	1.6520	2.2379
Small Longitudinal Input	0.5630	1.6495	2.2401
Moderate Longitudinal Input	0.5633	1.6470	2.2420
Large Longitudinal Input	0.5739	1.6559	2.2439

Table 114. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input	2.5565	2.4674	2.0069
Small Longitudinal Input	2.5471	2.4590	2.0041
Moderate Longitudinal Input	2.5440	2.4498	2.0004
Large Longitudinal Input	2.5841	2.4623	2.0030

Table 115. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Airspeed Deviations (*kts*)

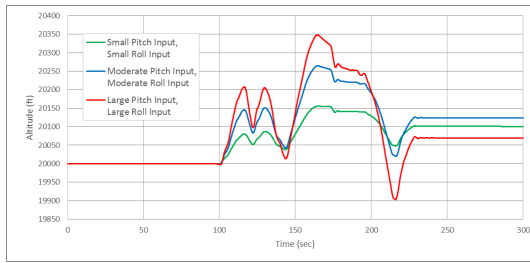
<i>TAS</i>	No Lat-Dir Input	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input	200 199.99	199.99 199.99	200.05 199.97	200.11 199.96
Small Longitudinal Input	200.00 199.98	200.00 199.98	200.08 199.97	200.16 199.95
Moderate Longitudinal Input	200.19 199.98	200.18 199.98	200.16 199.97	200.43 199.95
Large Longitudinal Input	204.07 199.72	204.05 199.72	204.06 199.81	204.17 199.90

Table 116. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Sum of Aileron Deviations (*rad*)

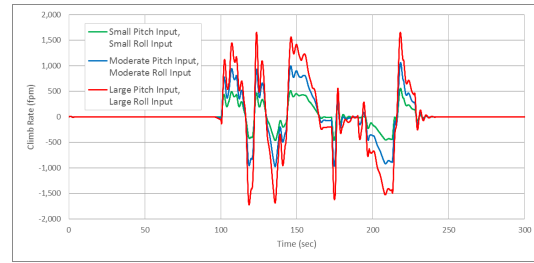
	No Lat-Dir Input	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input		1.8842 (107.9556°)	5.2427 (300.3837°)	7.2914 (417.7646°)
Small Longitudinal Input	0.0 (0.0°)	1.8905 (108.3162°)	5.2579 (301.2533°)	7.3125 (418.9726°)
Moderate Longitudinal Input	0.0 (0.0°)	1.8967 (108.6743°)	5.2775 (302.3794°)	7.3505 (421.1505°)
Large Longitudinal Input	0.0 (0.0°)	1.9019 (108.9704°)	5.2962 (303.4521°)	7.4243 (425.3825°)

Table 117. Group 5 Aircraft A, Pitch and Roll Discrete Tracking, Sum of Ruddervator Deviations (*rad*)

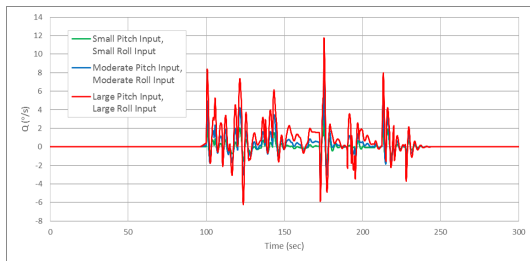
	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control		0.5039 (28.8727°)	1.5031 (86.1239°)	2.3743 (136.0394°)
Small Longitudinal Control	0.7123 (40.8144°)	1.0228 (58.6006°)	1.8969 (108.6758°)	2.6945 (154.3812°)
Moderate Longitudinal Control	1.3994 (80.1820°)	1.6322 (93.5184°)	2.4059 (137.8476°)	3.1457 (180.2351°)
Large Longitudinal Control	2.3719 (135.9027°)	2.5460 (145.8724°)	3.1460 (180.2513°)	3.8185 (218.7860°)



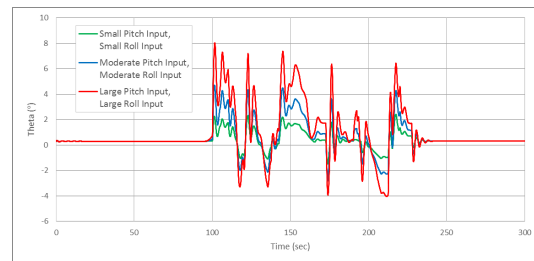
(a) Altitude



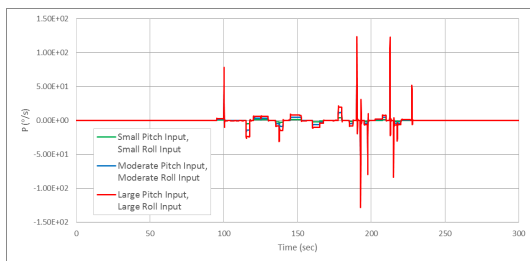
(b) Climb Rate



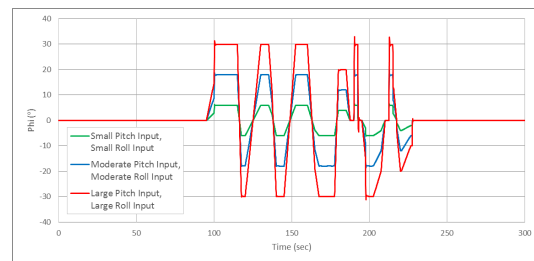
(c) Pitch Rate



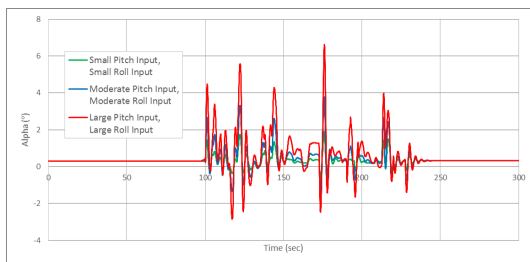
(d) Pitch Attitude



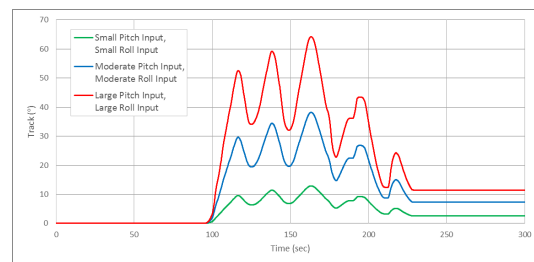
(e) Roll Rate



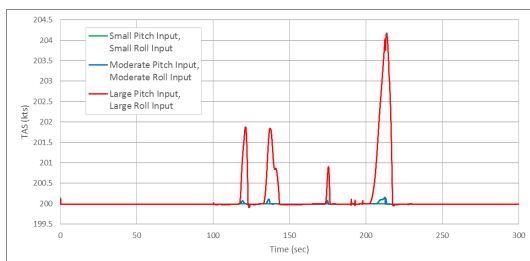
(f) Roll Attitude



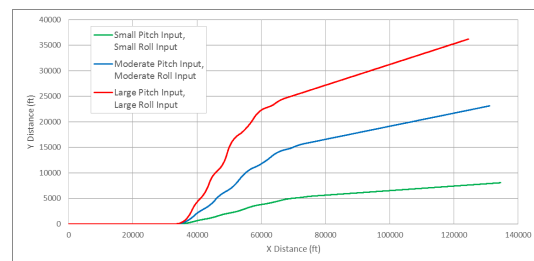
(g) Angle of Attack



(h) Heading

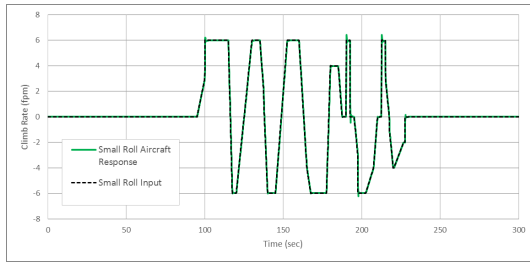


(i) Airspeed

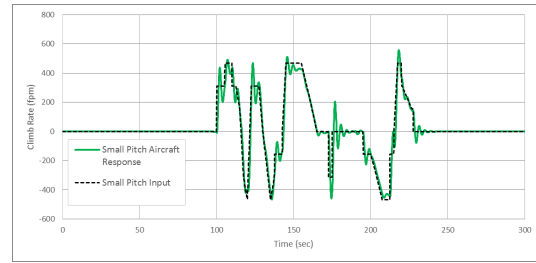


(j) Ground Track

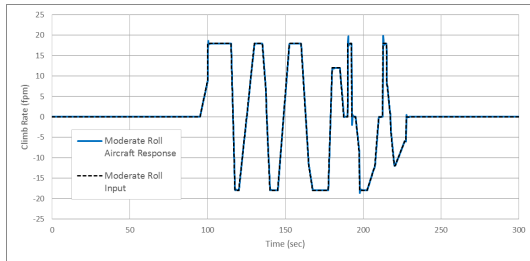
Figure 83. Group 5 Aircraft A Precision Aggressive, Pitch and Roll Discrete Tracking, Performance Plots



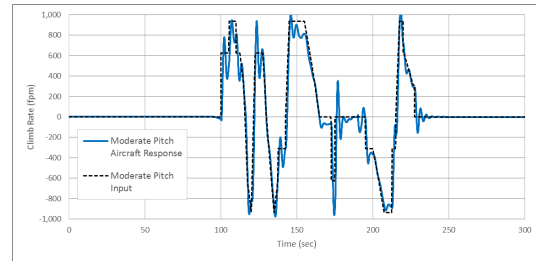
(a) Small Lateral-Directional



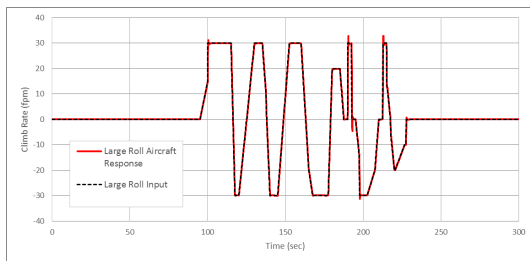
(b) Small Longitudinal



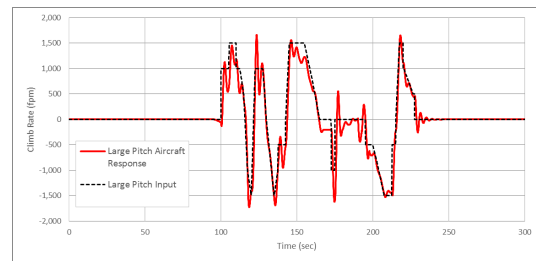
(c) Moderate Lateral-Directional



(d) Moderate Longitudinal



(e) Large Lateral-Directional



(f) Large Longitudinal

Figure 84. Group 5 Aircraft A Precision Aggressive Performance Plots

Appendix B. Group 5 Aircraft B

2.1 Model Data

Table 118. Group 5 Aircraft B, Full Model Parameter Inputs

Parameter	Value
Wing Span, b	66.0 <i>ft</i>
Mean Chord, $\bar{c}$	3.88 <i>ft</i>
Planform Area, S	256.0 <i>ft</i> ²
Mass with Fuel, m	10,500 <i>lbs</i>
Moment of Inertia, I_x	522,353 <i>lbs</i> · <i>ft</i> ²
Moment of Inertia, I_y	1,275,578 <i>lbs</i> · <i>ft</i> ²
Moment of Inertia, I_z	1,752,250 <i>lbs</i> · <i>ft</i> ²
Aircraft Drag Coefficient, C_D	0.01
Aircraft Center of Gravity, CoG , (x, y, z)	(17.0, 0.0, 0.0) <i>ft</i>
Aircraft Neutral Point, NP (x, y, z)	(17.7, 0.0, 0.0) <i>ft</i>
Fuel Mass	3000 <i>lbs</i>
Engine Location, (x, y, z)	(25, 0, 3) <i>ft</i>
Aspect Ratio, AR	17.0
Wing Sweep,	2.223°
Wing Leading Edge Location, x	15.9 <i>ft</i>
Wing Neutral Point, NP_w	17.131 <i>ft</i>
R/L Wing Strip Location, x	1.989 <i>ft</i> to 33.0 <i>ft</i>
Number of R/L Wing Strips	10
Wing Airfoil Shape	NACA 63-215
R/L Aileron Location, y	1.989 <i>ft</i> to 33.0 <i>ft</i>
Number of R/L Aileron Strips	10
Tail Airfoil Shape	NACA 0006

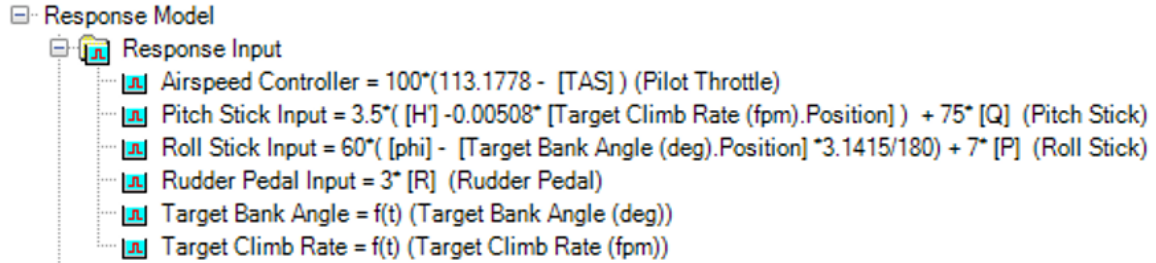
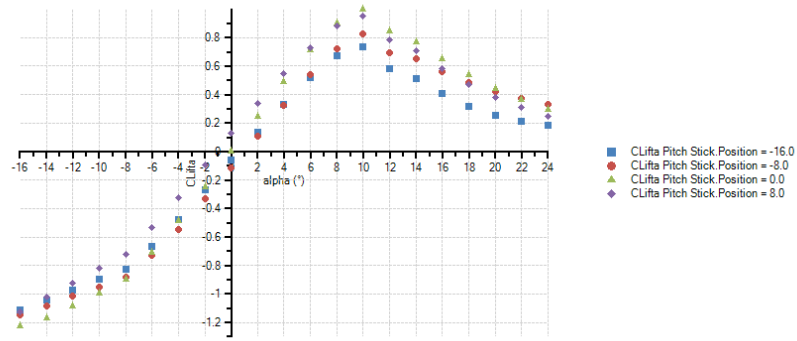
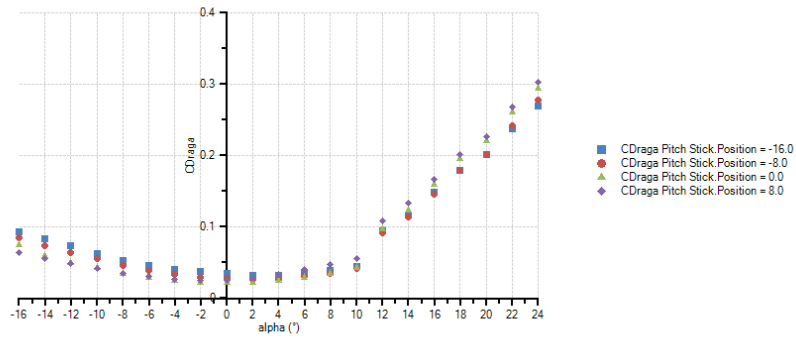


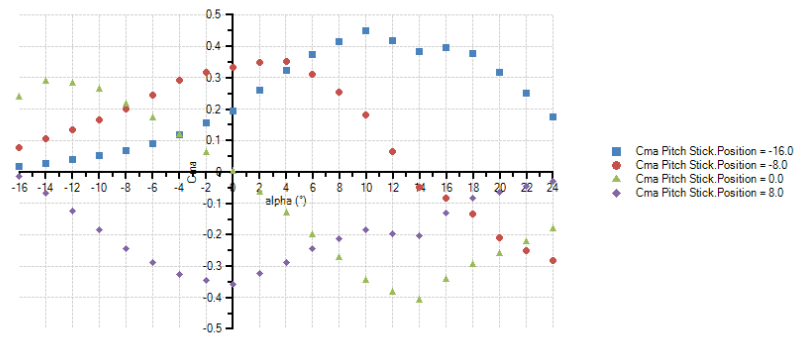
Figure 85. Group 5 Aircraft B Control System



(a) Lift Curve

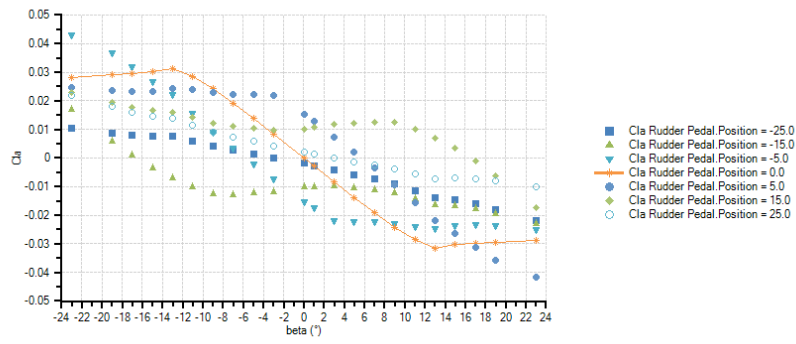


(b) Drag Curve

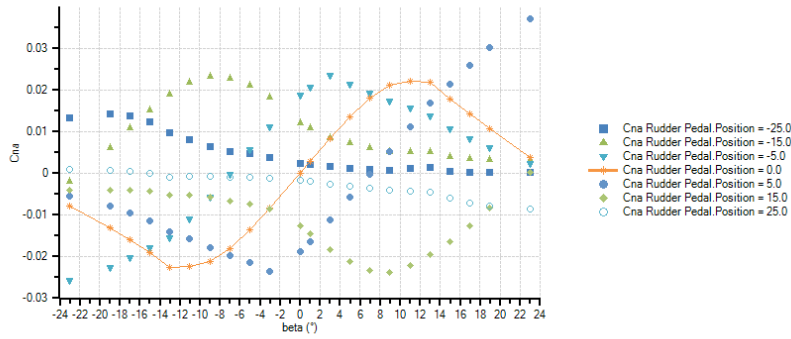


(c) Moment Curve

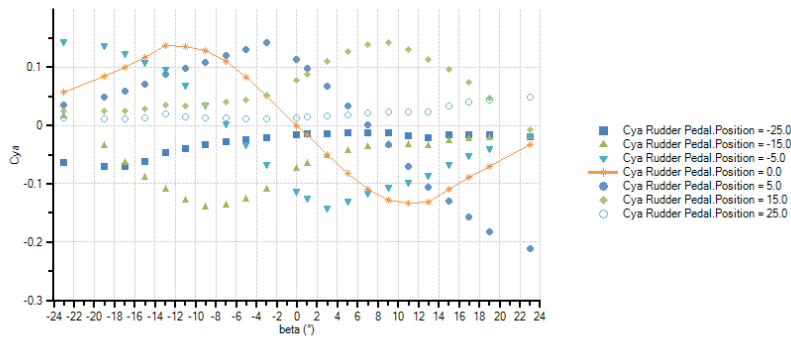
Figure 86. Group 5 Aircraft B Lift, Drag, and Moment Curves



(a) $C_{l_{\alpha}}$ Curve



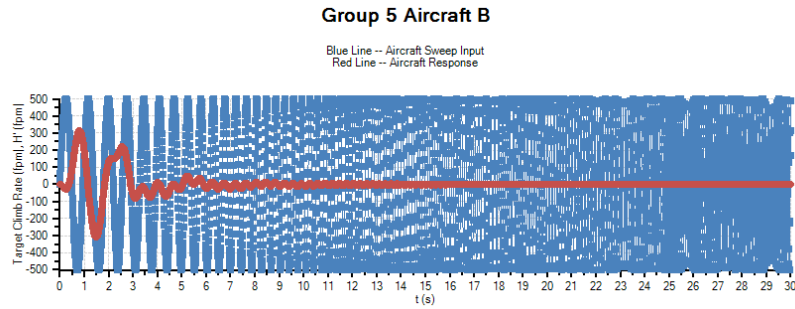
(b) $C_{n_{\alpha}}$ Curve



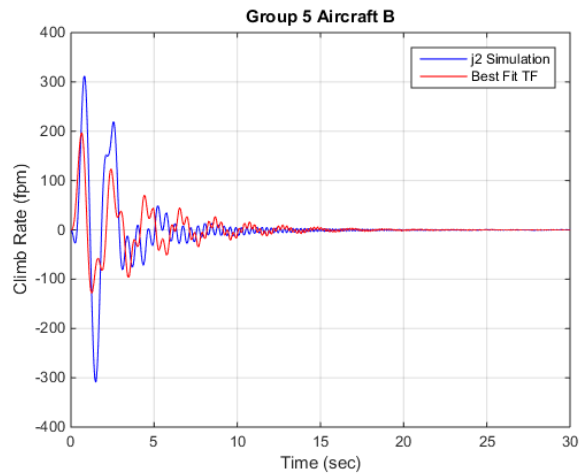
(c) $C_{y_{\alpha}}$ Curve

Figure 87. Group 5 Aircraft B Beta Derivative Curves

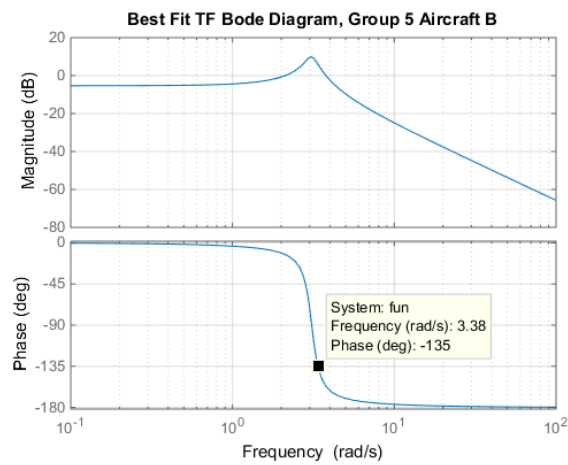
2.2 Bandwidth and Time Delay



(a) Frequency Sweep with Model Response

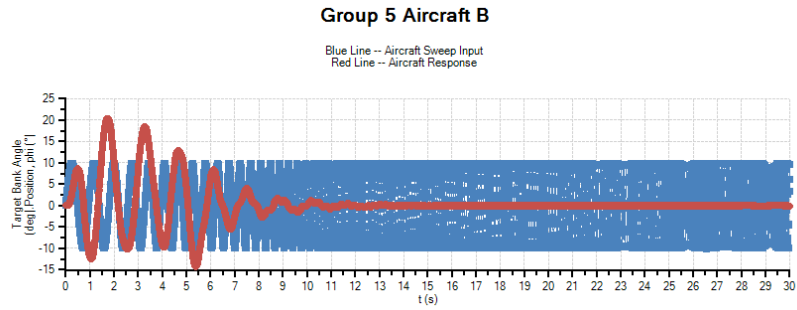


(b) Model Response and Best Fit Transfer Function

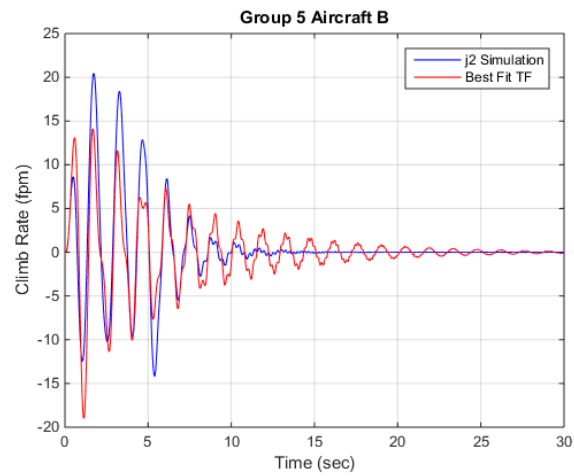


(c) Best Fit Transfer Function Bode Plot

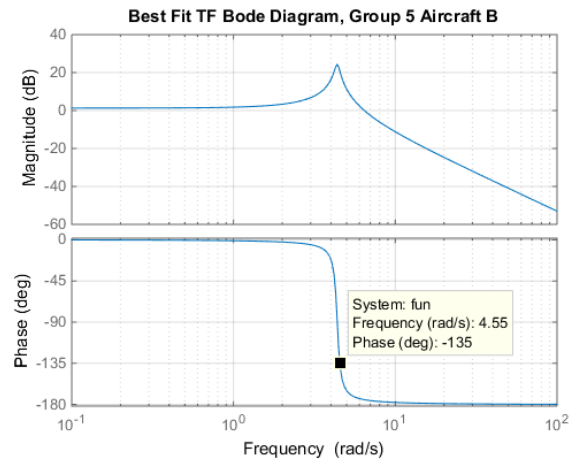
Figure 88. Group 5 Aircraft B Pitch Bandwidth Analysis Plots



(a) Frequency Sweep with Model Response



(b) Model Response and Best Fit Transfer Function



(c) Best Fit Transfer Function Bode Plot

Figure 89. Group 5 Aircraft B Roll Bandwidth Analysis Plots

Table 119. Closed-Loop Bandwidth for Group 5 Aircraft B at Moderate Control Inputs

	Pitch Bandwidth $\omega_{BW_{Pitch}} (rad/sec)$	Roll Bandwidth $\omega_{BW_{Roll}} (rad/sec)$
Frequency Sweep	3.38	4.55
Non-Precision Non-Aggressive	2.66	16.00
Non-Precision Aggressive	2.85	13.70
Precision Non-Aggressive	2.16	9.38
Precision Aggressive	2.63	7.68

Table 120. Closed-Loop Time Delay for Group 5 Aircraft B at Moderate Control Inputs

	Pitch Time Delay $\tau_{Pitch} (sec)$	Roll Time Delay $\tau_{Roll} (sec)$
Frequency Sweep	0.36	0.05
Non-Precision Non-Aggressive	0.68	0.09
Non-Precision Aggressive	0.42	0.1
Precision Non-Aggressive	0.6	0.1
Precision Aggressive	0.4	0.1

2.3 Non-Precision Non-Aggressive Maneuver Data

Table 121. Group 5 Aircraft B, Climbing Spiral, Pitch Attitude Change Values (*rad*)

$\Delta\theta$	No Turn	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
0 fpm Climb		0.0008 (0.0455°)	0.0029 (0.1690°)	0.0062 (0.3559°)
250 fpm Climb	0.0143 (0.8210°)	0.0142 (0.8142°)	0.0140 (0.8025°)	0.0136 (0.7772°)
500 fpm Climb	0.0288 (1.6480°)	0.0286 (1.6412°)	0.0277 (1.5845°)	0.0274 (1.5671°)
800 fpm Climb	0.0462 (2.6498°)	0.0461 (2.6430°)	0.0451 (2.5865°)	0.0440 (2.5182°)

Table 122. Group 5 Aircraft B, Climbing Spiral, Peak Pitch Rate Values (*rad/sec*)

Q_{pk}	No Turn	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
0 fpm Climb		0.0018	0.0081	0.0202
250 fpm Climb	0.0064	0.0070	0.0087	0.0207
500 fpm Climb	0.0122	0.0128	0.0140	0.0228
800 fpm Climb	0.0195	0.0198	0.0211	0.0256

Table 123. Group 5 Aircraft B, Climbing Spiral, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	No Turn	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
0 fpm Climb		2.2515	2.7564	3.2559
250 fpm Climb	0.444	0.4918	0.6241	1.5244
500 fpm Climb	0.4242	0.4470	0.5079	0.8338
800 fpm Climb	0.4223	0.4288	0.4673	0.5818

Table 124. Group 5 Aircraft B, Climbing Spiral, Roll Attitude Change Values (rad)

$\Delta\phi$	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
0 fpm Climb	0.0887 (5.081°)	0.2673 (15.317°)	0.4437 (25.424°)
250 fpm Climb	0.0887 (5.084°)	0.2675 (15.327°)	0.4440 (25.442°)
500 fpm Climb	0.0888 (5.088°)	0.2677 (15.338°)	0.444 (25.461°)
800 fpm Climb	0.0889 (5.096°)	0.2679 (15.351°)	0.4448 (25.485°)

Table 125. Group 5 Aircraft B, Climbing Spiral, Peak Roll Rate Values (rad/sec)

P_{pk}	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
0 fpm Climb	0.0187	0.0563	0.0941
250 fpm Climb	0.0189	0.0570	0.0961
500 fpm Climb	0.0192	0.0578	0.0974
800 fpm Climb	0.0195	0.0584	0.1002

Table 126. Group 5 Aircraft B, Climbing Spiral, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
0 fpm Climb	0.2105	0.2106	0.2121
250 fpm Climb	0.2130	0.2132	0.2165
500 fpm Climb	0.2157	0.2158	0.2191
800 fpm Climb	0.2190	0.2179	0.2252

Table 127. Group 5 Aircraft B, Climbing Spiral, Airspeed Deviations (kts)

TAS	No Turn	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
0 fpm Climb	220.01 219.99	220.01 219.99	220.01 219.99	220.01 219.99
250 fpm Climb	220.01 219.98	220.01 219.99	220.01 219.99	220.01 219.99
500 fpm Climb	220.01 219.98	220.01 219.98	220.01 219.98	220.01 219.98
800 fpm Climb	220.01 219.95	220.01 219.94	220.01 219.96	220.01 219.99

Table 128. Group 5 Aircraft B, Climbing Spiral, Sum of Aileron Deviations (rad)

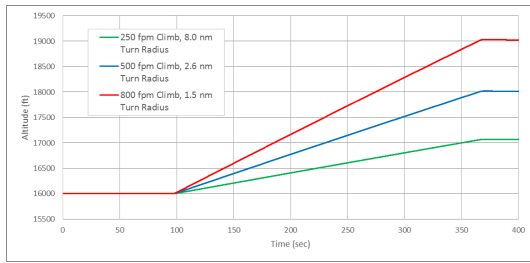
	No Turn	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
0 fpm Climb		0.0087 (0.499°)	0.0267 (1.530°)	0.0458 (2.627°)
250 fpm Climb	0.0 (0.0°)	0.0090 (0.517°)	0.0277 (1.588°)	0.0478 (2.742°)
500 fpm Climb	0.0 (0.0°)	0.0094 (0.538°)	0.0289 (1.655°)	0.0496 (2.841°)
800 fpm Climb	0.0 (0.0°)	0.0099 (0.568°)	0.0295 (1.688°)	0.0519 (2.971°)

Table 129. Group 5 Aircraft B, Climbing Spiral, Sum of Elevator Deviations (*rad*)

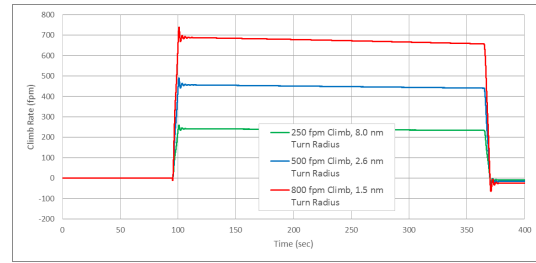
	No Turn	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
0 fpm Climb		0.0077 (0.440°)	0.0938 (5.377°)	0.2726 (15.620°)
500 fpm Climb	0.0071 (0.417°)	0.0071 (0.417°)	0.0937 (5.371°)	0.2743 (15.718°)
1000 fpm Climb	0.0069 (0.394°)	0.0069 (0.394°)	0.0936 (5.364°)	0.2695 (15.438°)
1400 fpm Climb	0.0062 (0.353°)	0.0062 (0.353°)	0.0918 (5.261°)	0.2360 (13.521°)

Table 130. Group 5 Aircraft B, Climbing Spiral, Sum of Rudder Deviations (*rad*)

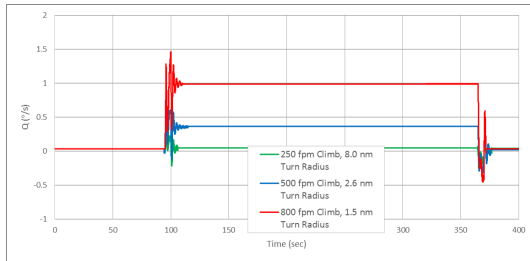
	No Turn	8.0 nm Turn Radius	2.6 nm Turn Radius	1.5 nm Turn Radius
0 fpm Climb		0.0020 (0.115°)	0.0061 (0.351°)	0.0104 (0.596°)
500 fpm Climb	0.0 (0.0°)	0.0021 (0.120°)	0.0064 (0.366°)	0.0108 (0.621°)
1000 fpm Climb	0.0 (0.0°)	0.0022 (0.125°)	0.0067 (0.383°)	0.0113 (0.649°)
1400 fpm Climb	0.0 (0.0°)	0.0023 (0.132°)	0.0070 (0.401°)	0.0120 (0.687°)



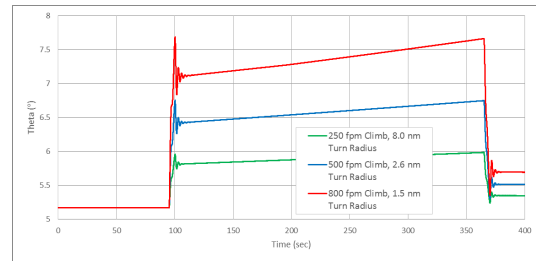
(a) Altitude



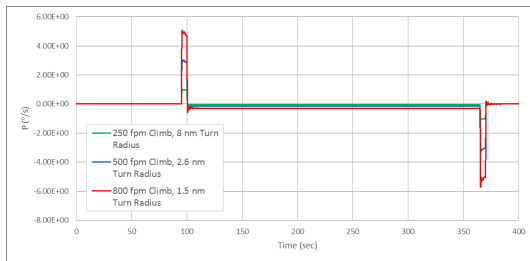
(b) Climb Rate



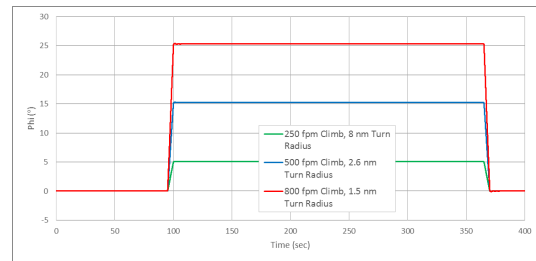
(c) Pitch Rate



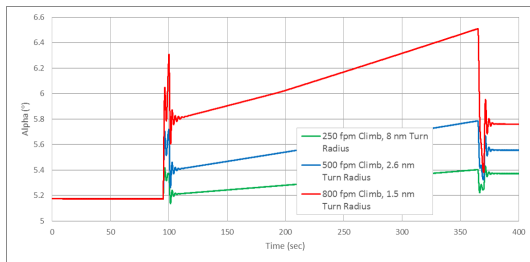
(d) Pitch Attitude



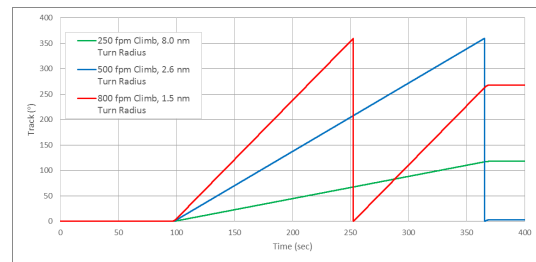
(e) Roll Rate



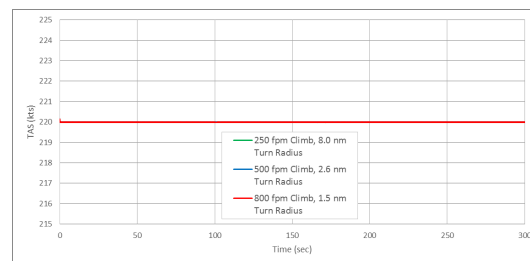
(f) Roll Attitude



(g) Angle of Attack



(h) Heading



(i) Airspeed

Figure 90. Group 5 Aircraft B Non-Precision Non-Aggressive, Spiral Climb, Performance Plots

2.4 Non-Precision Aggressive Maneuver Data

Table 131. Group 5 Aircraft B, Air-to-Ground Tracking, Pitch Attitude Change Values (rad)

$\Delta\theta$	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent		0.0008 (0.0450°)	0.0029 (0.1657°)	0.0063 (0.3629°)
500 fpm Descent	0.0304 (1.7438°)	0.0305 (1.7456°)	0.0305 (1.7491°)	0.0306 (1.7523°)
800 fpm Descent	0.0439 (2.5152°)	0.0439 (2.5171°)	0.0440 (2.5205°)	0.0440 (2.5238°)
1400 fpm Descent	0.0757 (4.3366°)	0.0757 (4.3370°)	0.0757 (4.3366°)	0.0757 (4.3366°)

Table 132. Group 5 Aircraft B, Air-to-Ground Tracking, Peak Pitch Rate Values (rad/sec)

Q_{pk}	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent		0.0018	0.0080	0.0200
500 fpm Descent	0.0122	0.0122	0.0122	0.0193
800 fpm Descent	0.0192	0.0192	0.0192	0.0192
1400 fpm Descent	0.0332	0.0326	0.0332	0.0332

Table 133. Group 5 Aircraft B, Air-to-Ground Tracking, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent		2.2535	2.7515	3.1595
500 fpm Descent	0.4007	0.4003	0.3995	0.6306
800 fpm Descent	0.4372	0.4368	0.4363	0.4357
1400 fpm Descent	0.4385	0.4304	0.4385	0.4385

Table 134. Group 5 Aircraft B, Air-to-Ground Tracking, Roll Attitude Change Values (rad)

$\Delta\phi$	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent	0.0878 (5.031°)	0.2635 (15.096°)	0.4394 (25.175°)
500 fpm Descent	0.0877 (5.023°)	0.2630 (15.069°)	0.4385 (25.126°)
800 fpm Descent	0.0876 (5.021°)	0.2629 (15.064°)	0.4384 (25.116°)
1400 fpm Descent	0.0875 (5.014°)	0.2625 (15.040°)	0.4375 (25.068°)

Table 135. Group 5 Aircraft B, Air-to-Ground Tracking, Peak Roll Rate Values (rad/sec)

P_{pk}	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent	0.0185	0.0555	0.0937
500 fpm Descent	0.0181	0.0546	0.0909
800 fpm Descent	0.0180	0.0543	0.0905
1400 fpm Descent	0.0182	0.0535	0.0893

Table 136. Group 5 Aircraft B, Air-to-Ground Tracking, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent	0.2105	0.2107	0.2133
500 fpm Descent	0.2067	0.2076	0.2073
800 fpm Descent	0.2052	0.2064	0.2063
1400 fpm Descent	0.2082	0.2037	0.2041

Table 137. Group 5 Aircraft B, Air-To-Ground Tracking, Airspeed Deviations (kts)

TAS	No Angle of Bank	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
0 fpm Descent	220.01 219.99	220.01 219.99	220.01 219.99	220.01 219.99
500 fpm Descent	220.02 219.99	220.02 219.99	220.02 219.99	220.02 219.99
800 fpm Descent	220.02 219.99	220.02 219.99	220.02 219.99	220.02 219.99
1400 fpm Descent	228.57 219.99	228.64 219.99	228.92 219.99	229.14 219.99

Table 138. Group 5 Aircraft B, Air-To-Ground Tracking, Sum of Aileron Deviations (rad)

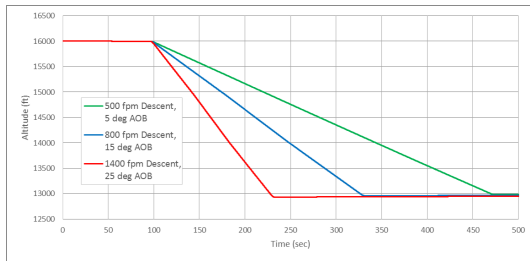
	No Angle of Bank	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
0 fpm Climb		0.0086 (0.491°)	0.0258 (1.480°)	0.0448 (2.569°)
500 fpm Climb	0.0 (0.0°)	0.0076 (0.438°)	0.0230 (1.319°)	0.0400 (2.291°)
1000 fpm Climb	0.0 (0.0°)	0.0076 (0.435°)	0.0229 (1.313°)	0.0398 (2.283°)
1400 fpm Climb	0.0 (0.0°)	0.0036 (0.206°)	0.02004 (1.168°)	0.0346 (1.984°)

Table 139. Group 5 Aircraft B, Air-to-Ground Tracking, Sum of Elevator Deviations
(*rad*)

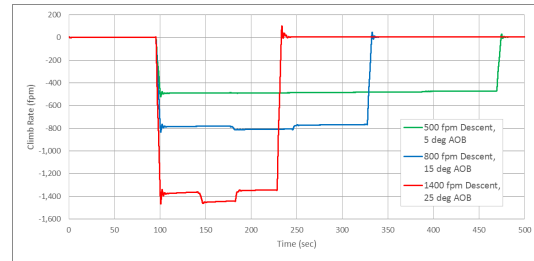
	No Angle of Bank	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
0 fpm Climb		0.0044 (0.2504°)	0.0129 (0.7391°)	0.0193 (1.1081°)
500 fpm Climb	0.8385 (1.6888°)	0.0486 (2.7856°)	0.0874 (5.0063°)	0.1484 (8.5014°)
1000 fpm Climb	0.0740 (4.2410°)	0.0919 (5.2656°)	0.1284 (7.3592°)	0.1845 (10.5715°)
1400 fpm Climb	0.0830 (4.7583°)	0.0912 (5.2277°)	0.1324 (7.5883°)	0.1831 (10.4889°)

Table 140. Group 5 Aircraft B, Air-to-Ground Tracking, Sum of Rudder Deviations
(*rad*)

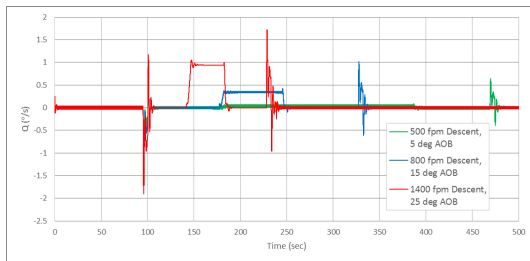
	No Angle of Bank	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
0 fpm Climb		0.0020 (0.114°)	0.0061 (0.347°)	0.0104 (0.597°)
500 fpm Climb	0.0 (0.0°)	0.0018 (0.102°)	0.0054 (0.308°)	0.0093 (0.531°)
1000 fpm Climb	0.0 (0.0°)	0.0018 (0.102°)	0.0053 (0.307°)	0.0092 (0.529°)
1400 fpm Climb	0.0 (0.0°)	0.0008 (0.048°)	0.0047 (0.267°)	0.0078 (0.447°)



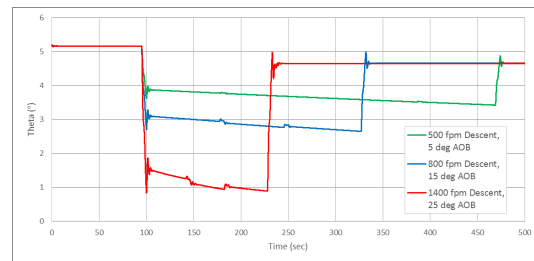
(a) Altitude



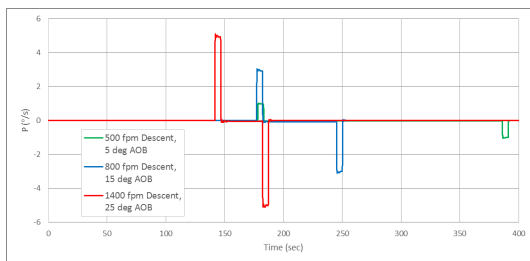
(b) Climb Rate



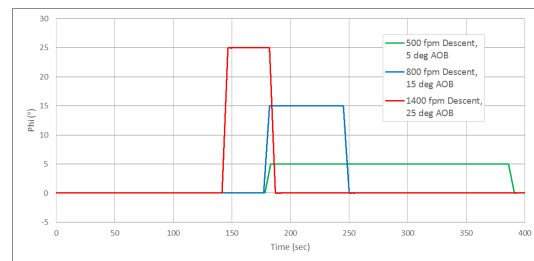
(c) Pitch Rate



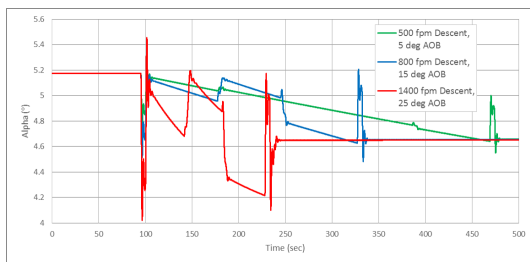
(d) Pitch Attitude



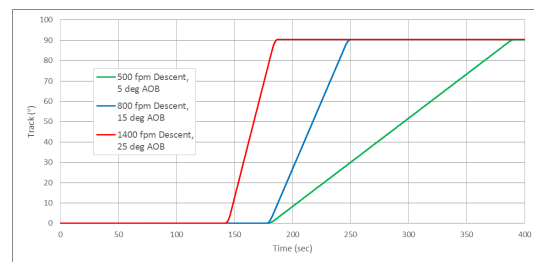
(e) Roll Rate



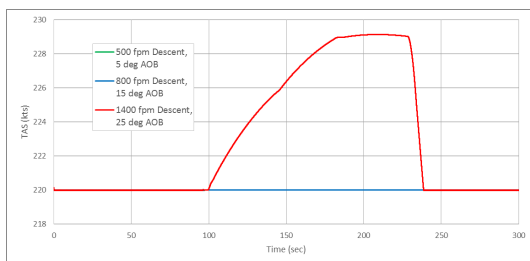
(f) Roll Attitude



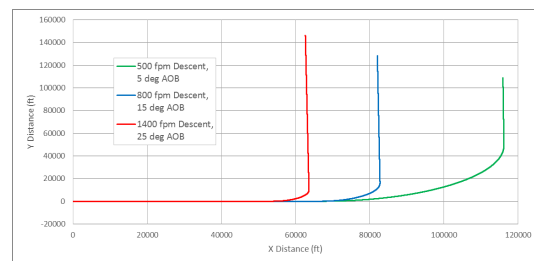
(g) Angle of Attack



(h) Heading



(i) Airspeed



(j) Ground Track

Figure 91. Group 5 Aircraft B Non-Precision Aggressive Performance Plots

2.5 Precision Non-Aggressive Maneuver Data

Table 141. Group 5 Aircraft B, Precision Offset Landing, Pitch Attitude Change Values (rad)

$\Delta\theta$	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0470 (206979°)	0.0473 (2.7111°)	0.0519 (2.9710°)
150 ft Offset	0.0471 (2.6979°)	0.0497 (2.8466°)	0.0517
50 ft Offset	0.0473 (2.7091°)		

Table 142. Group 5 Aircraft B, Precision Offset Landing, Peak Pitch Rate Values (rad/sec)

Q_{pk}	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0233	0.0170	0.0240
150 ft Offset	0.0170	0.0170	0.0170
50 ft Offset	0.0170		

Table 143. Group 5 Aircraft B, Precision Offset Landing, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.3606	0.3589	0.4637
150 ft Offset	0.3606	0.3418	0.4501
50 ft Offset	0.3591		

Table 144. Group 5 Aircraft B, Precision Offset Landing, Roll Attitude Change Values (rad)

$\Delta\phi$	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.1708 (9.789°)	0.5020 (28.763°)	0.7446 (42.661°)
150 ft Offset	0.1690 (9.686°)	0.4961 (28.422°)	0.6629 (37.982°)
50 ft Offset	0.1648 (9.442°)		

Table 145. Group 5 Aircraft B, Precision Offset Landing, Peak Roll Rate Values (rad/sec)

P_{pk}	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0136	0.1699	0.1300
150 ft Offset	0.0186	0.0977	0.2174
50 ft Offset	0.0314		

Table 146. Group 5 Aircraft B, Precision Offset Landing, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0793	0.1393	0.1747
150 ft Offset	0.1101	0.1970	0.3280
150 ft Offset	0.1906		

Table 147. Group 5 Aircraft B, Precision Offset Landing, Airspeed Deviations (kts)

TAS	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	150.01 150.00	150.01 150.00	150.01 150.00
150 ft Offset	150.01 150.00	150.01 150.00	150.01 150.00
50 ft Offset	150.01 150.00		

Table 148. Group 5 Aircraft B, Precision Offset Landing, Aileron Deviations (rad)

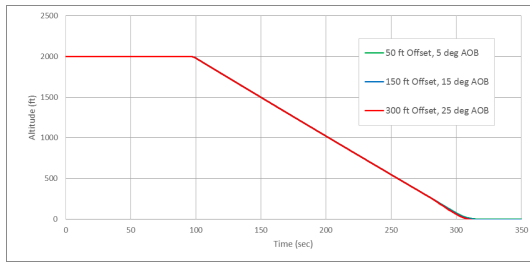
	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0173 (0.992°)	0.0882 (5.055°)	0.1640 (9.398°)
150 ft Offset	0.0246 (1.407°)	0.1210 (6.930°)	0.2030 (11.629°)
50 ft Offset	0.0387 (2.215°)		

Table 149. Group 5 Aircraft B, Precision Offset Landing, Elevator Deviations (rad)

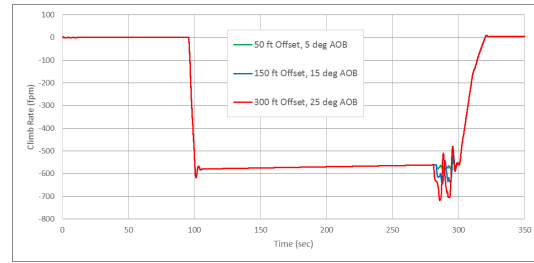
	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0463 (2.655°)	0.0811 (4.646°)	0.1322 (7.577°)
150 ft Offset	0.0486 (2.783°)	0.0906 (5.194°)	0.1278 (7.320°)
50 ft Offset	0.0530 (3.036°)		

Table 150. Group 5 Aircraft B, Precision Offset Landing, Rudder Deviations (*rad*)

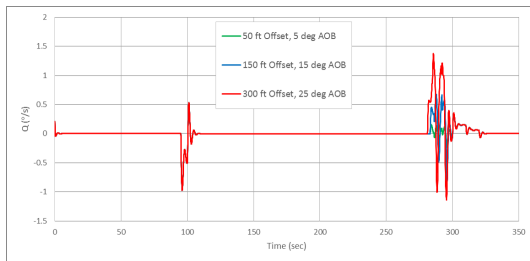
	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0040 (0.229°)	0.0159 (0.911°)	0.0221 (1.265°)
150 ft Offset	0.0051 (0.290°)	0.0205 (1.174°)	0.0275 (1.577°)
50 ft Offset	0.0061 (0.351°)		



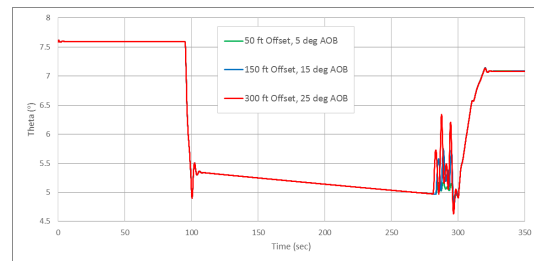
(a) Altitude



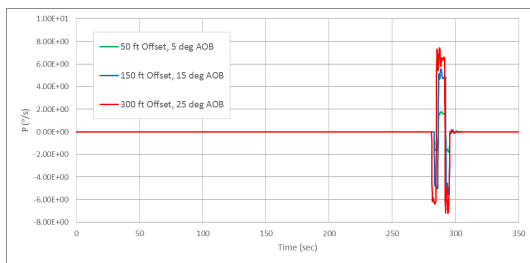
(b) Climb Rate



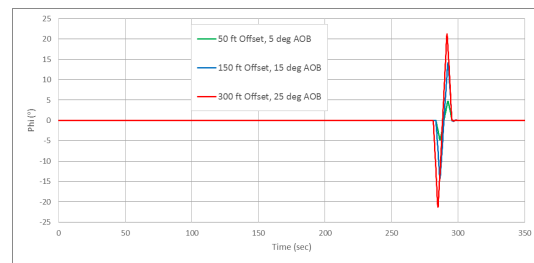
(c) Pitch Rate



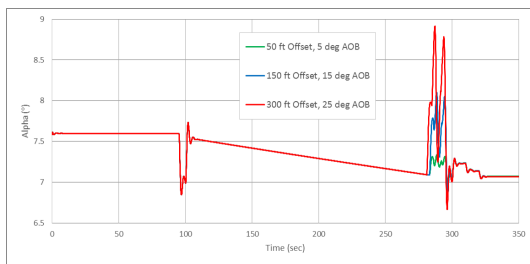
(d) Pitch Attitude



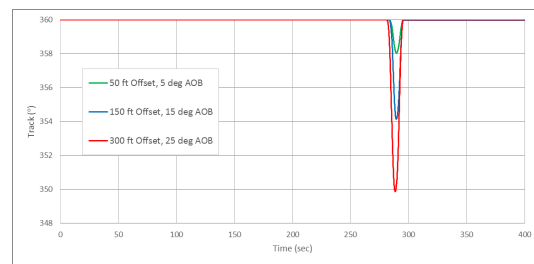
(e) Roll Rate



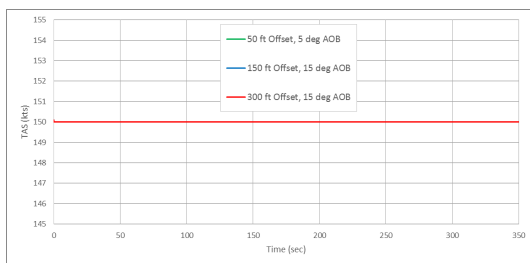
(f) Roll Attitude



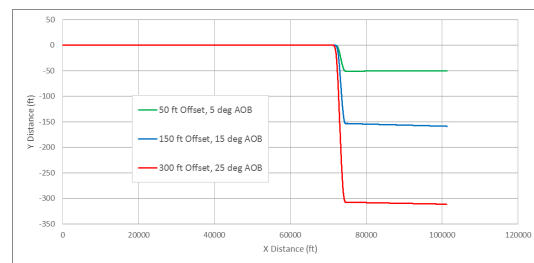
(g) Angle of Attack



(h) Heading



(i) Airspeed



(j) Ground Track

Figure 92. Group 5 Aircraft B Precision Non-Aggressive Performance Plots

2.6 Precision Aggressive Maneuver Data

Table 151. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Pitch Attitude Change Values (rad)

$\Delta\theta$	No Lat-Dir Input	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input		0.0045 (0.2574°)	0.0145 (0.8300°)	0.0344 (1.9737°)
Small Longitudinal Input	0.0359 (2.0590°)	0.0364 (2.0866°)	0.0399 (2.2877°)	0.0444 (2.5434°)
Moderate Longitudinal Input	0.0722 (4.1381°)	0.0727 (4.1676°)	0.0740 (4.2412°)	0.0760 (4.3549°)
Large Longitudinal Input	0.1146 (6.5668°)	0.1152 (6.6008°)	0.1164 (6.6685°)	0.1182 (6.7731°)

Table 152. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Peak Pitch Rate Values (rad/sec)

Q_{pk}	No Lat-Dir Input	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input		0.0076	0.0176	0.0477
Small Longitudinal Input	0.0410	0.0419	0.0450	0.0517
Moderate Longitudinal Input	0.0824	0.0833	0.0864	0.0916
Large Longitudinal Input	0.1327	0.1336	0.1368	0.1420

Table 153. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	No Lat-Dir Input	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input		1.6895	1.2162	1.3838
Small Longitudinal Input	1.1415	1.1503	1.1268	1.1654
Moderate Longitudinal Input	1.1411	1.1449	1.1666	1.2053
Large Longitudinal Input	1.1574	1.1594	1.1750	1.2012

Table 154. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Roll Attitude Change Values (rad)

$\Delta\phi$	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input	0.1785 (10.228°)	0.5461 (31.289°)	0.9814 (56.228°)
Small Longitudinal Input	0.1786 (10.235°)	0.5473 (31.360°)	0.9848 (56.424°)
Moderate Longitudinal Input	0.1791 (10.260°)	0.5485 (31.424°)	0.9878 (56.598°)
Large Longitudinal Input	0.1797 (10.296°)	0.5533 (31.703°)	1.0111 (57.929°)

Table 155. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Peak Roll Rate Values (rad/sec)

P_{pk}	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input	0.3039	0.8663	1.3610
Small Longitudinal Input	0.3016	0.86185	1.3577
Moderate Longitudinal Input	0.3012	0.8603	1.3561
Large Longitudinal Input	0.2951	0.8938	1.3644

Table 156. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	Small Lat-Dir Input	Moderate Lat-Dir Input	Large Lat-Dir Input
No Longitudinal Input	1.7026	1.5863	1.3869
Small Longitudinal Input	1.6884	1.5745	1.3787
Moderate Longitudinal Input	1.6819	1.5685	1.3729
Large Longitudinal Input	1.6423	1.6154	1.3494

Table 157. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Airspeed Deviations (*kts*)

<i>TAS</i>	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control	220.01 219.99	220.01 219.99	220.00 219.99	220.01 219.99
Small Longitudinal Control	220.02 219.99	220.02 219.99	220.02 219.99	220.02 219.99
Moderate Longitudinal Control	220.02 219.99	220.02 219.99	220.02 219.99	220.02 219.96
Large Longitudinal Control	220.01 219.86	220.01 219.86	220.00 219.87	220.01 219.79

Table 158. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Sum of Aileron Deviations (*rad*)

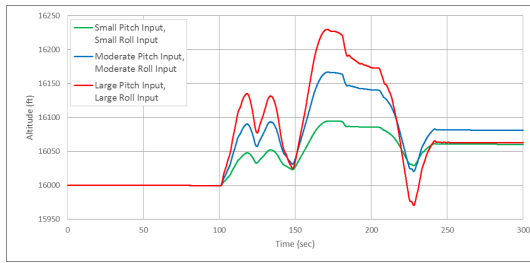
	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control		0.4431 (25.389°)	1.2147 (69.600°)	2.2897 (131.190°)
Small Longitudinal Control	0.0 (0.0°)	0.4487 (25.708°)	1.2304 (70.498°)	2.3266 (133.303°)
Moderate Longitudinal Control	0.0 (0.0°)	0.4545 (26.039°)	1.2545 (71.877°)	2.3748 (136.068°)
Large Longitudinal Control	0.0 (0.0°)	0.4573 (26.201°)	1.3235 (75.831°)	2.3974 (137.362°)

Table 159. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Sum of Elevator Deviations (*rad*)

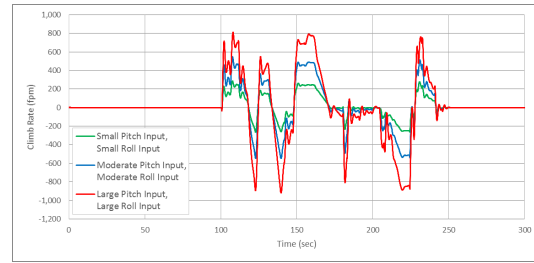
	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control		0.023 (1.290°)	0.079 (4.542°)	0.214 (12.257°)
Small Longitudinal Control	0.361 (20.704°)	0.385 (22.051°)	0.434 (24.858°)	0.563 (32.240°)
Moderate Longitudinal Control	0.731 (41.888°)	0.761 (43.587°)	0.805 (46.109°)	0.937 (53.680°)
Large Longitudinal Control	1.531 (87.741°)	1.576 (90.292°)	1.651 (94.579°)	1.812 (103.819°)

Table 160. Group 5 Aircraft B, Pitch and Roll Discrete Tracking, Sum of Rudder Deviations (*rad*)

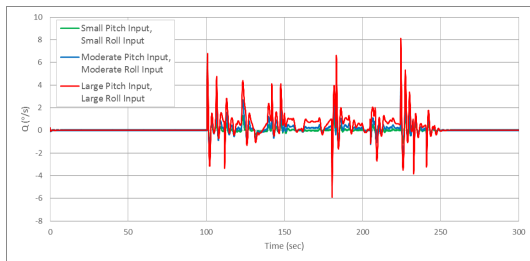
	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control		0.0274 (1.572°)	0.0799 (4.578°)	0.1370 (7.848°)
Small Longitudinal Control	0.0 (0.0°)	0.0287 (1.647°)	0.0834 (4.778°)	0.1431 (8.202°)
Moderate Longitudinal Control	0.0 (0.0°)	0.0302 (1.732°)	0.0886 (5.077°)	0.1527 (8.751°)
Large Longitudinal Control	0.0 (0.0°)	0.0326 (1.866°)	0.0957 (5.485°)	0.1665 (9.542°)



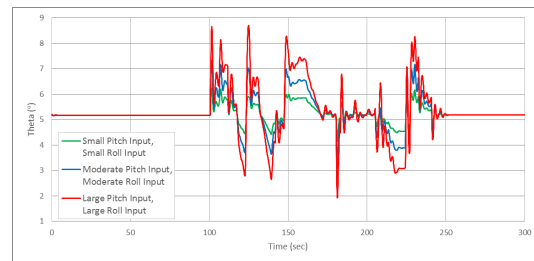
(a) Altitude



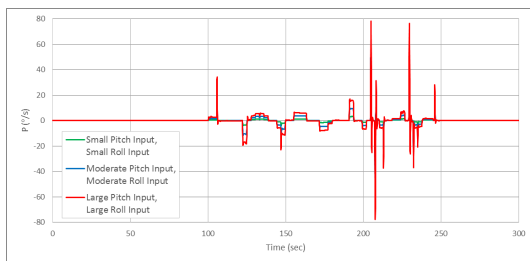
(b) Climb Rate



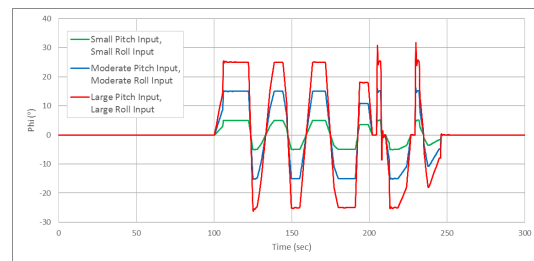
(c) Pitch Rate



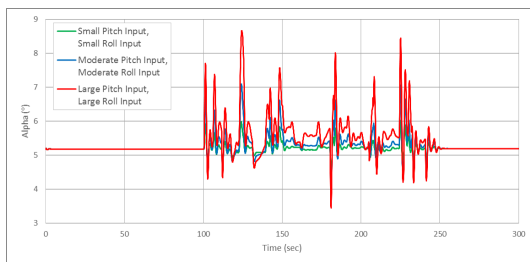
(d) Pitch Attitude



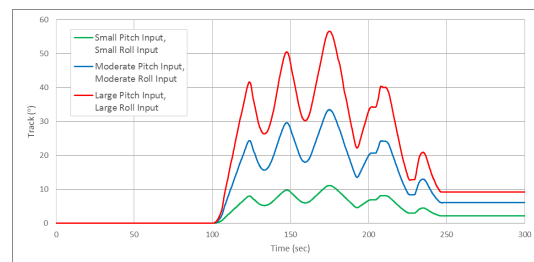
(e) Roll Rate



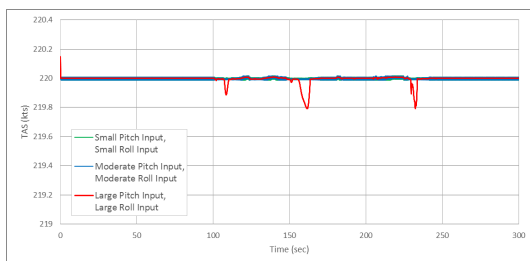
(f) Roll Attitude



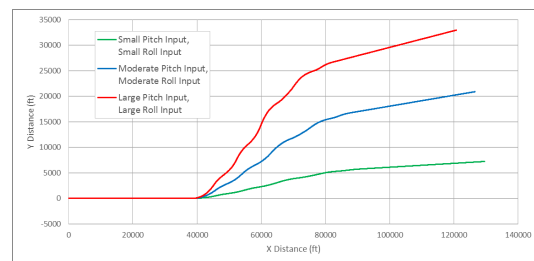
(g) Angle of Attack



(h) Heading

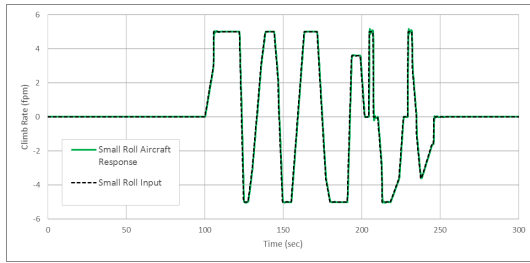


(i) Airspeed

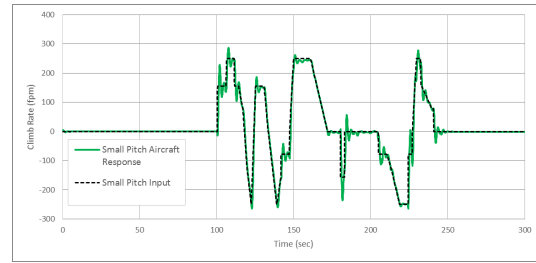


(j) Ground Track

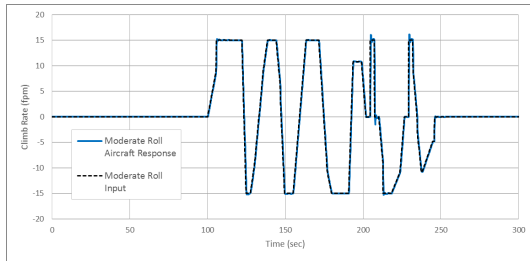
Figure 93. Group 5 Aircraft B Precision Aggressive Performance Plots



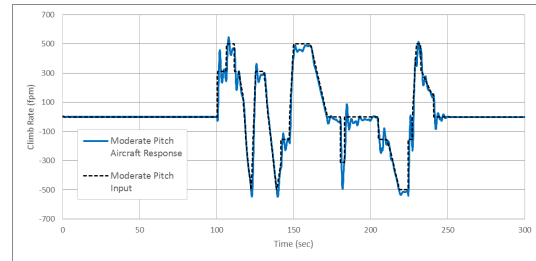
(a) Small Lateral-Directional



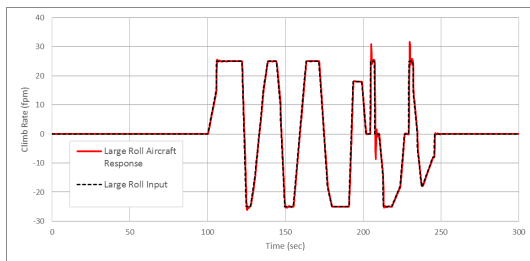
(b) Small Longitudinal



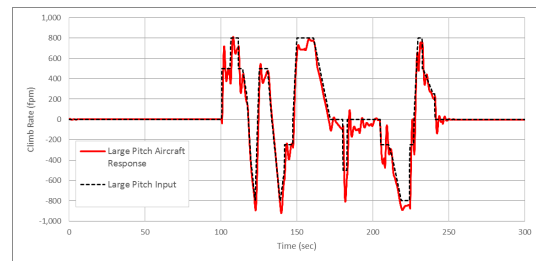
(c) Moderate Lateral-Directional



(d) Moderate Longitudinal



(e) Large Lateral-Directional



(f) Large Longitudinal

Figure 94. Group 5 Aircraft B Precision Aggressive Target Performance Plots

Appendix C. Group 4 Aircraft

3.1 Model Data

Table 161. Group 4 Aircraft, Full Model Parameter Inputs

Parameter	Value
Wing Span, b	55.25 ft
Mean Chord, $\bar{c}$	2.46 ft
Planform Area, S	128.84 ft^2
Mass with Fuel, m	2,250 lbs
Moment of Inertia, I_x	33,721 $lbs \cdot ft^2$
Moment of Inertia, I_y	49,074 $lbs \cdot ft^2$
Moment of Inertia, I_z	66,113 $lbs \cdot ft^2$
Aircraft Drag Coefficient, C_D	0.01
Aircraft Center of Gravity, CoG , (x, y, z)	(12.5, 0.0, 0.0) ft
Aircraft Neutral Point, NP (x, y, z)	(13.5, 0.0, 0.0) ft
Fuel Mass	550 lbs
Engine Location, (x, y, z)	(21.24, 0, -0.735) ft
Aspect Ratio, AR	23.69
Wing Sweep,	2.223°
Wing Leading Edge Location, x	12.3 ft
Wing Neutral Point, NP_w	13.3 ft
R/L Wing Strip Location, x	0.0 ft to 27.63 ft
Number of R/L Wing Strips	10
Wing Airfoil Shape	NACA 63-215
R/L Aileron Location, y	0.318 ft to 27.63 ft
Number of R/L Aileron Strips	10
Tail Airfoil Shape	NACA 0006

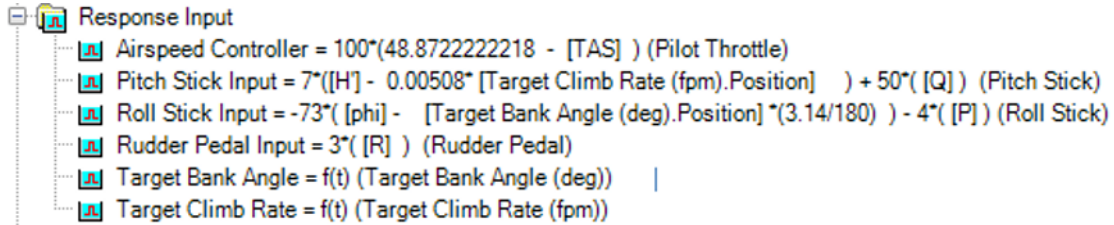
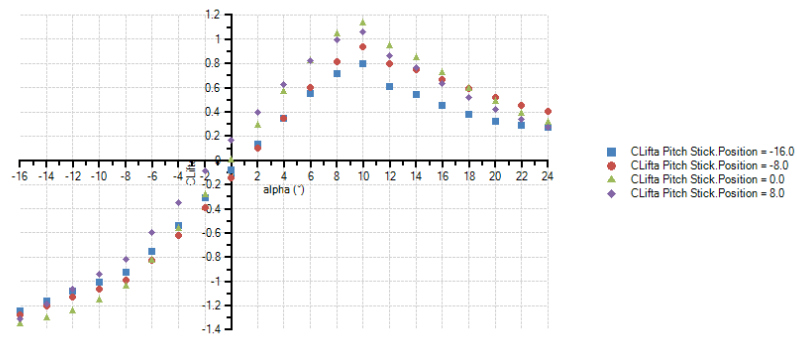
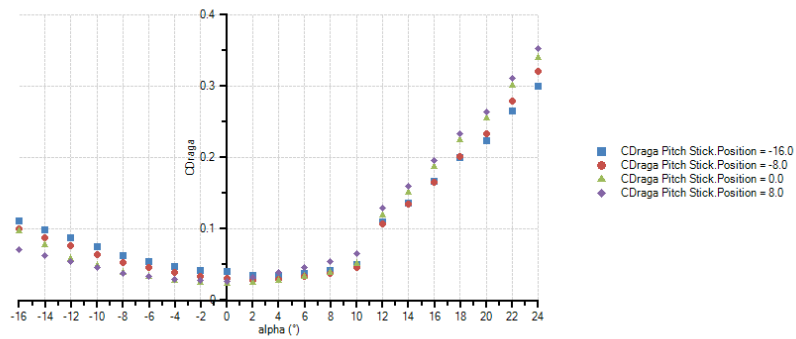


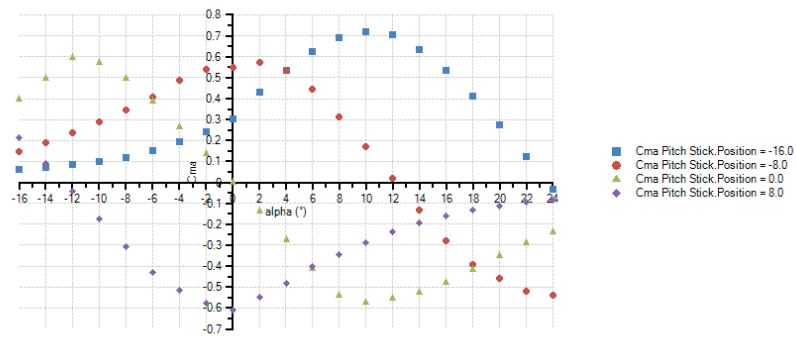
Figure 95. Group 4 Aircraft Control System



(a) Lift Curve

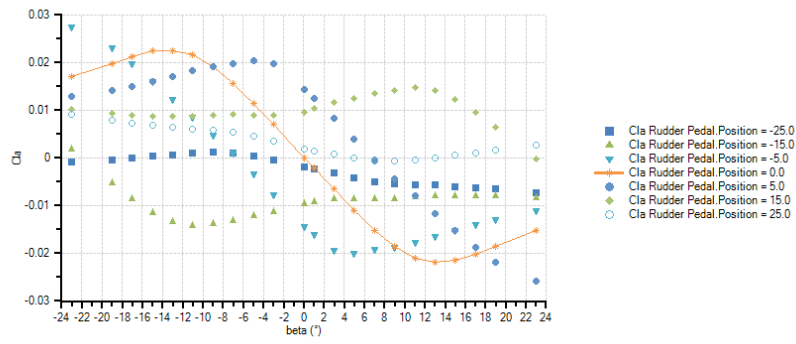


(b) Drag Curve

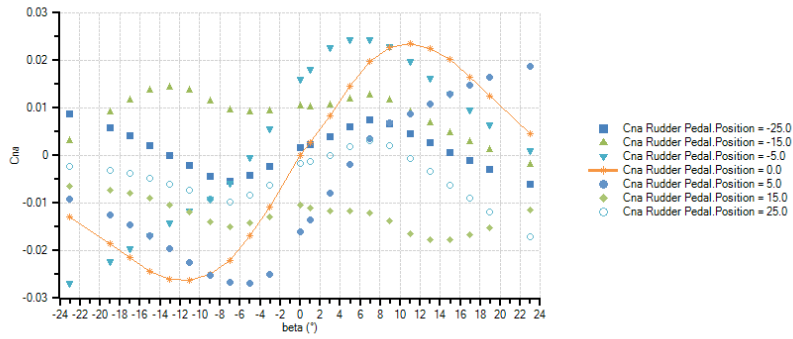


(c) Moment Curve

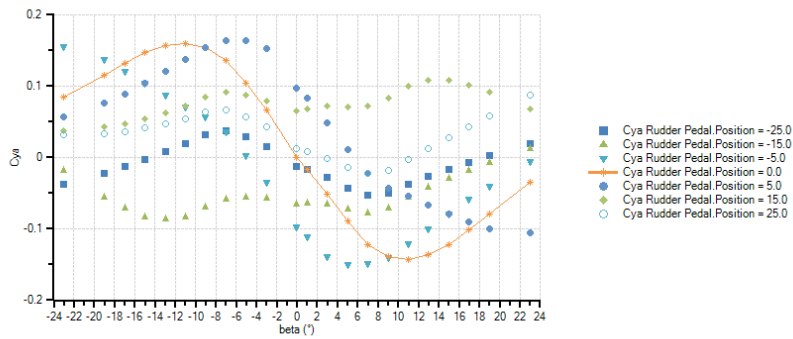
Figure 96. Group 4 Aircraft Lift, Drag, and Moment Curves



(a) $C_{l_{\alpha}}$ Curve



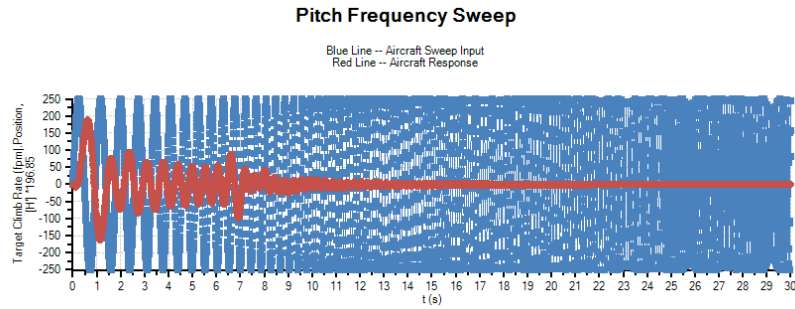
(b) $C_{n_{\alpha}}$ Curve



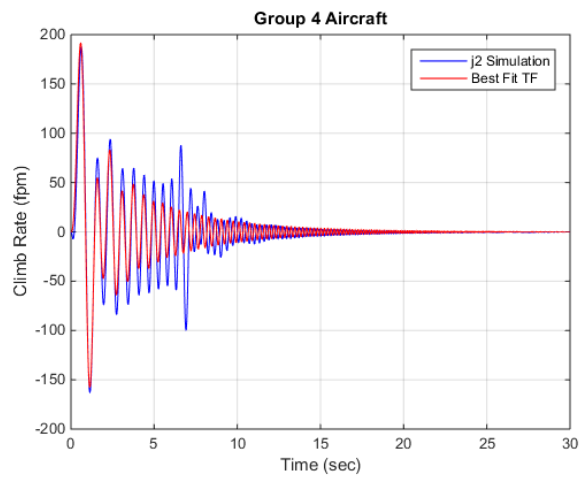
(c) $C_{y_{\alpha}}$ Curve

Figure 97. Group 4 Aircraft Beta Derivative Curves

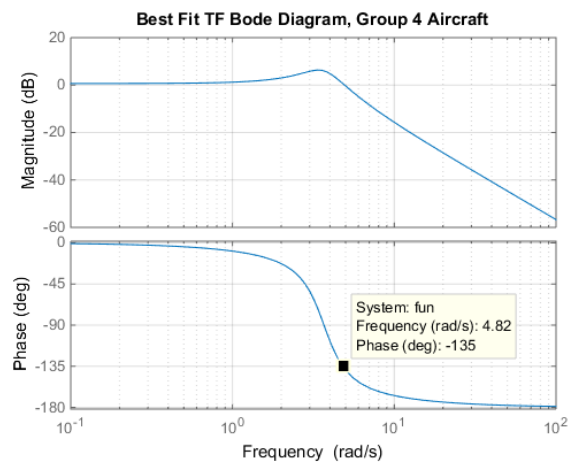
3.2 Bandwidth and Time Delay



(a) Frequency Sweep with Model Response

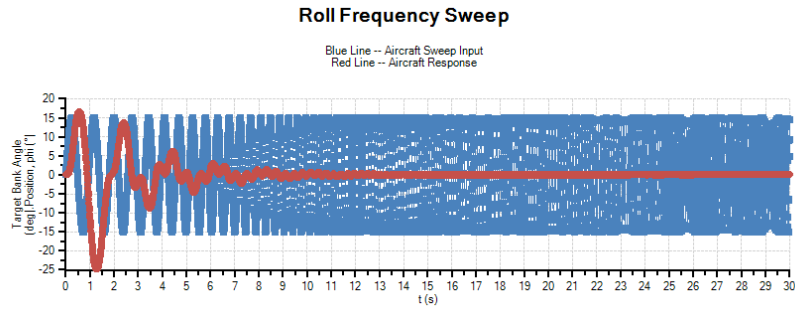


(b) Model Response and Best Fit Transfer Function

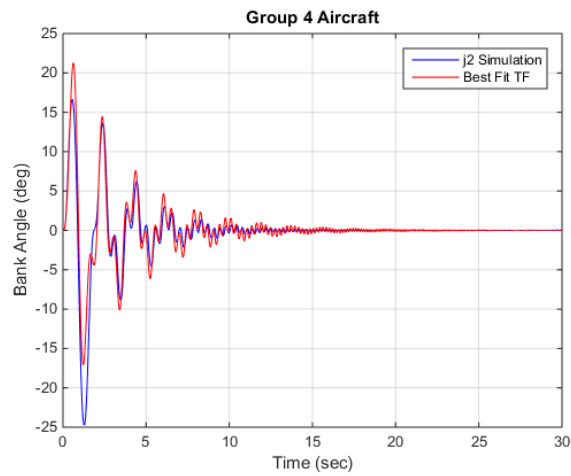


(c) Best Fit Transfer Function Bode Plot

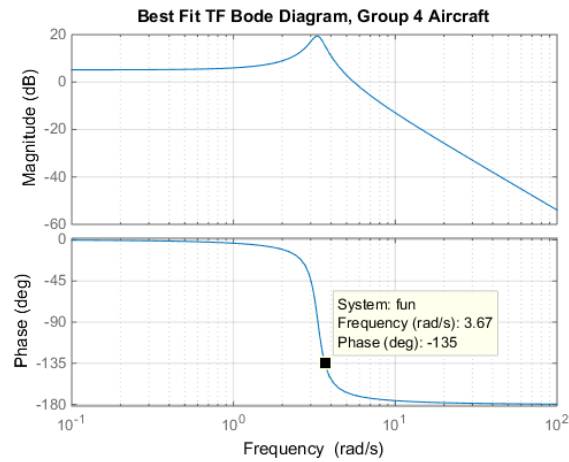
Figure 98. Group 4 Aircraft Pitch Bandwidth Analysis Plots



(a) Frequency Sweep with Model Response



(b) Model Response and Best Fit Transfer Function



(c) Best Fit Transfer Function Bode Plot

Figure 99. Group 4 Aircraft Roll Bandwidth Analysis Plots

Table 162. Closed-Loop Bandwidth for Group 4 Aircraft at Moderate Control Inputs

	Pitch Bandwidth $\omega_{BW_{Pitch}} \text{ (rad/sec)}$	Roll Bandwidth $\omega_{BW_{Roll}} \text{ (rad/sec)}$
Frequency Sweep	4.82	3.67
Non-Precision Non-Aggressive	4.75	14.80
Non-Precision Aggressive	5.11	16.00
Precision Non-Aggressive	3.60	18.20
Precision Aggressive	5.04	18.10

Table 163. Closed-Loop Time Delay for Group 4 Aircraft at Moderate Control Inputs

	Pitch Time Delay $\tau_{Pitch} \text{ (sec)}$	Roll Time Delay $\tau_{Roll} \text{ (sec)}$
Frequency Sweep	0.2	0.07
Non-Precision Non-Aggressive	0.51	0.09
Non-Precision Aggressive	0.24	0.09
Precision Non-Aggressive	0.24	0.07
Precision Aggressive	0.22	0.12

3.3 Non-Precision Non-Aggressive Maneuver Data

Table 164. Group 4 Aircraft, Climbing Spiral, Pitch Attitude Change Values (*rad*)

$\Delta\theta$	No Turn	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
0 fpm Climb		0.0010 (0.0547°)	0.0034 (0.1935°)	0.0074 (0.4231°)
100 fpm Climb	0.0092 (0.5285°)	0.0096 (0.5505°)	0.0107 (0.6142°)	0.0122 (0.6984°)
250 fpm Climb	0.0231 (1.3217°)	0.0232 (1.3306°)	0.0244 (1.3980°)	0.0259 (1.4822°)
500 fpm Climb	0.0655 (3.7542°)	0.0657 (3.7671°)	0.0646 (3.7007°)	0.0614 (3.5158°)

Table 165. Group 4 Aircraft, Climbing Spiral, Peak Pitch Rate Values (*rad/sec*)

Q_{pk}	No Turn	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
0 fpm Climb		0.0023	0.0141	0.0383
100 fpm Climb	0.0037	0.0050	0.0125	0.0343
250 fpm Climb	0.0093	0.0106	0.0146	0.0358
500 fpm Climb	0.0216	0.0200	0.0226	0.0408

Table 166. Group 4 Aircraft, Climbing Spiral, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	No Turn	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
0 fpm Climb		2.4190	4.1644	5.1925
100 fpm Climb	0.4010	0.5181	1.1641	2.8134
250 fpm Climb	0.4027	0.4561	0.5981	1.3848
500 fpm Climb	0.3297	0.3039	0.3504	0.6655

Table 167. Group 4 Aircraft, Climbing Spiral, Roll Attitude Change Values (rad)

$\Delta\phi$	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
0 fpm Climb	0.0843 (4.827°)	0.2588 (14.82°)	0.4402 (25.223°)
100 fpm Climb	0.0843 (4.829°)	0.2589 (14.832°)	0.4404 (25.233°)
250 fpm Climb	0.0843 (4.831°)	0.2590 (14.839°)	0.4407 (25.250°)
500 fpm Climb	0.0845 (4.844°)	0.2597 (14.887°)	0.4421 (25.331°)

Table 168. Group 4 Aircraft, Climbing Spiral, Peak Roll Rate Values (rad/sec)

P_{pk}	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
0 fpm Climb	0.0180	0.0556	0.0953
100 fpm Climb	0.0181	0.0557	0.0958
250 fpm Climb	0.0183	0.0566	0.0969
500 fpm Climb	0.0194	0.0590	0.1012

Table 169. Group 4 Aircraft, Climbing Spiral, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
0 fpm Climb	0.2140	0.2148	0.2166
100 fpm Climb	0.2145	0.2154	0.2176
250 fpm Climb	0.2168	0.2184	0.2199
500 fpm Climb	0.2293	0.2270	0.2288

Table 170. Group 4 Aircraft, Climbing Spiral, Airspeed Deviations (kts)

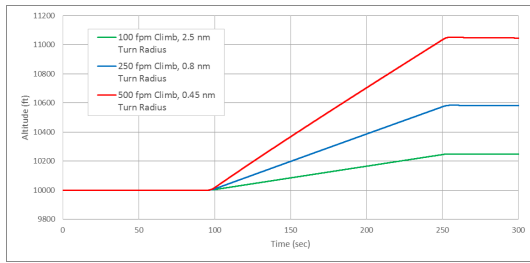
TAS	No Turn	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
0 fpm Climb	119.99 119.99	119.99 119.99	119.99 119.99	119.99 119.99
500 fpm Climb	119.99 119.99	119.99 119.99	119.99 119.99	119.99 119.99
1000 fpm Climb	119.99 119.98	119.99 119.98	119.99 119.98	119.99 119.98
1400 fpm Climb	119.99 110.68	119.99 110.65	119.99 110.65	119.99 112.15

Table 171. Group 4 Aircraft, Climbing Spiral, Sum of Aileron Deviations (rad)

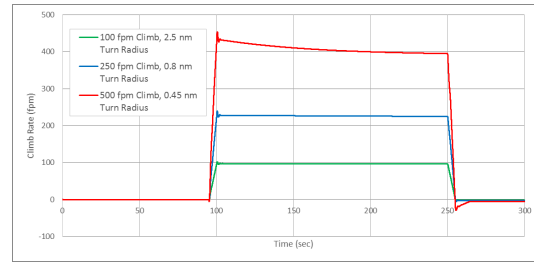
	No Turn	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
0 fpm Climb		0.0089 (0.512°)	0.0273 (1.567°)	0.0459 (2.627°)
100 fpm Climb	0.0 (0.0°)	0.0090 (0.518°)	0.0276 (1.582°)	0.0461 (2.641°)
250 fpm Climb	0.0 (0.0°)	0.0092 (0.528°)	0.0279 (1.596°)	0.0466 (2.667°)
500 fpm Climb	0.0 (0.0°)	0.0110 (0.630°)	0.0325 (1.862°)	0.0569 (3.262°)

Table 172. Group 4 Aircraft, Climbing Spiral, Sum of Elevator Deviations (*rad*)

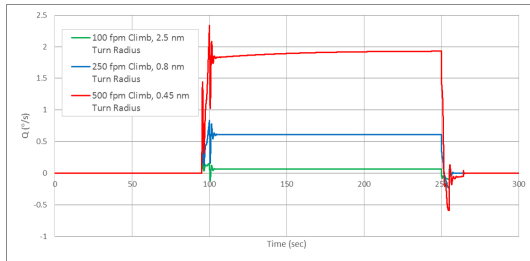
	No Turn	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
0 fpm Climb		0.0052 (0.298°)	0.0198 (1.133°)	0.0446 (2.553°)
100 fpm Climb	0.0086 (0.494°)	0.0098 (0.561°)	0.0221 (1.266°)	0.0447 (2.564°)
250 fpm Climb	0.0216 (1.235°)	0.0221 (1.267°)	0.0298 (1.710°)	0.0507 (2.903°)
500 fpm Climb	0.0805 (4.611°)	0.0807 (4.622°)	0.0858 (4.918°)	0.1018 (5.834°)



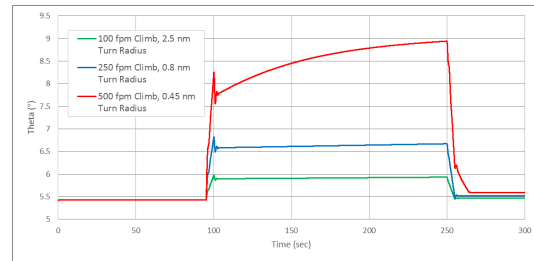
(a) Altitude



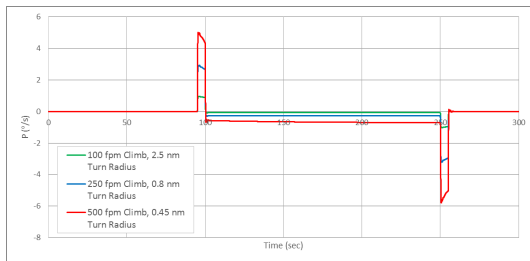
(b) Climb Rate



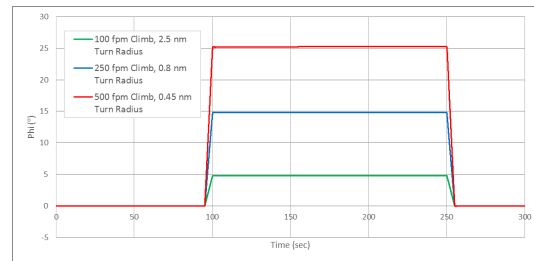
(c) Pitch Rate



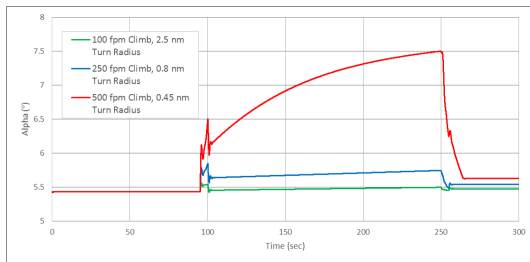
(d) Pitch Attitude



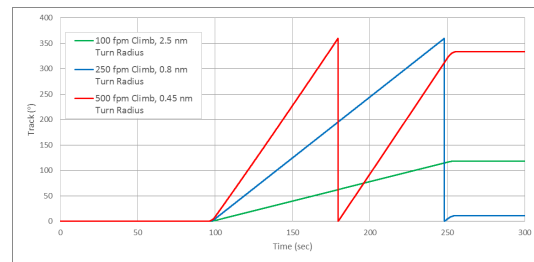
(e) Roll Rate



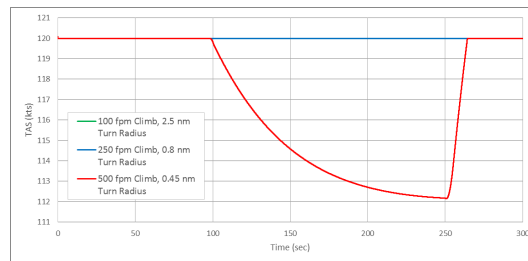
(f) Roll Attitude



(g) Angle of Attack



(h) Heading



(i) Airspeed

Figure 100. Group 4 Aircraft Non-Precision Non-Aggressive, Spiral Climb, Performance Plots

3.4 Non-Precision Aggressive Maneuver Data

Table 173. Group 4 Aircraft, Air-To-Ground Tracking, Pitch Attitude Change Values (*rad*)

$\Delta\theta$	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent		0.0010 (0.0571°)	0.0034 (0.1976°)	0.0079 (0.4511°)
250 fpm Descent	0.0245 (1.4043°)	0.0245 (1.4050°)	0.0245 (1.4063°)	0.0255 (1.4602°)
500 fpm Descent	0.0455 (2.6051°)	0.0455 (2.6044°)	0.0454 (2.6031°)	0.0459 (2.6322°)
700 fpm Descent	0.0652 (3.7384°)	0.0653 (3.7442°)	0.0654 (3.7450°)	0.0654 (3.7480°)

Table 174. Group 4 Aircraft, Air-To-Ground Tracking, Peak Pitch Rate Values (*rad/sec*)

Q_{pk}	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent		0.0025	0.0145	0.0382
250 fpm Descent	0.0092	0.0092	0.0141	0.0375
500 fpm Descent	0.0186	0.0186	0.0186	0.0375
700 fpm Descent	0.0261	0.0261	0.0261	0.0341

Table 175. Group 4 Aircraft, Air-To-Ground Tracking, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent		2.4575	4.2132	4.8496
250 fpm Descent	0.3753	0.3751	0.5764	1.4722
500 fpm Descent	0.4091	0.4092	0.4095	0.8163
700 fpm Descent	0.4001	0.3995	0.3994	0.5214

Table 176. Group 4 Aircraft, Air-To-Ground Tracking, Roll Attitude Change Values (rad)

$\Delta\phi$	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent	0.0878 (5.028°)	0.2633 (15.089°)	0.4390 (25.153°)
250 fpm Descent	0.0877 (5.022°)	0.2630 (15.069°)	0.4385 (25.126°)
500 fpm Descent	0.0876 (5.018°)	0.2628 (15.056°)	0.4381 (25.102°)
700 fpm Descent	0.0875 (5.013°)	0.2624 (15.034°)	0.4374 (25.060°)

Table 177. Group 4 Aircraft, Air-To-Ground Tracking, Peak Roll Rate Values (rad/sec)

P_{pk}	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent	0.0188	0.0566	0.0952
250 fpm Descent	0.0185	0.0558	0.0936
500 fpm Descent	0.0183	0.0552	0.0925
700 fpm Descent	0.0180	0.0543	0.0910

Table 178. Group 4 Aircraft, Air-To-Ground Tracking, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent	0.2140	0.2148	0.2168
250 fpm Descent	0.1990	0.1989	0.2002
500 fpm Descent	0.2088	0.2099	0.2112
700 fpm Descent	0.2056	0.2068	0.2080

Table 179. Group 4 Aircraft, Air-To-Ground Tracking, Airspeed Deviations (kts)

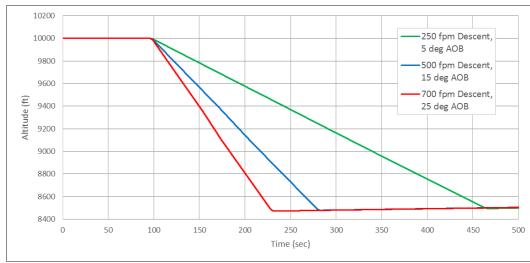
TAS	No Turn	2.5 nm Turn Radius	0.8 nm Turn Radius	0.45 nm Turn Radius
0 fpm Descent	119.99 119.99	119.99 119.99	119.99 119.99	119.99 119.99
250 fpm Descent	119.99 119.99	119.99 119.99	119.99 119.99	119.99 119.99
500 fpm Descent	120.00 119.99	120.00 119.99	120.00 119.99	120.00 119.99
700 fpm Descent	124.24 119.99	124.31 119.99	124.54 119.99	124.70 119.99

Table 180. Group 4 Aircraft, Air-To-Ground Tracking, Sum of Aileron Deviations (rad)

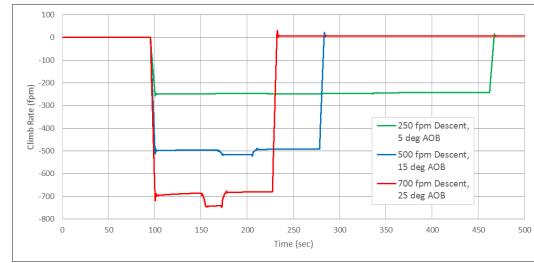
	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent		0.0093 (0.533°)	0.0278 (1.595°)	0.0459 (2.628°)
250 fpm Descent	0.0 (0.0°)	0.0088 (0.506°)	0.0266 (1.525°)	0.0440 (2.522°)
500 fpm Descent	0.0 (0.0°)	0.0088 (0.502°)	0.0264 (1.515°)	0.0437 (2.506°)
700 fpm Descent	0.0 (0.0°)	0.0081 (0.463°)	0.0229 (1.313°)	0.0396 (2.271°)

Table 181. Group 4 Aircraft, Air-To-Ground Tracking, Sum of Elevator Deviations
(*rad*)

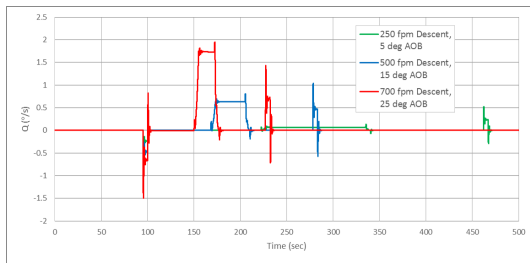
	No Turn	5° Angle of Bank Turn	15° Angle of Bank Turn	25° Angle of Bank Turn
0 fpm Descent		0.0054 (0.311°)	0.0202 (1.155°)	0.0440 (2.522°)
250 fpm Descent	0.0235 (1.344°)	0.0284 (1.628°)	0.0424 (2.430°)	0.0650 (3.725°)
500 fpm Descent	0.0418 (2.395°)	0.0466 (2.668°)	0.0607 (3.478°)	0.0833 (4.774°)
700 fpm Descent	0.0644 (3.688°)	0.0665 (3.812°)	0.0795 (4.556°)	0.0996 (5.707°)



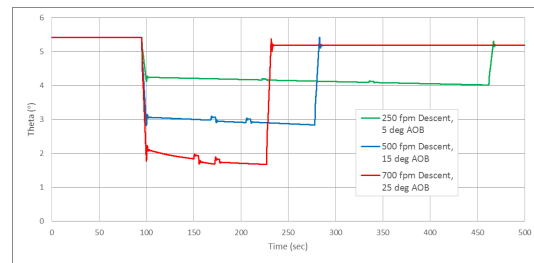
(a) Altitude



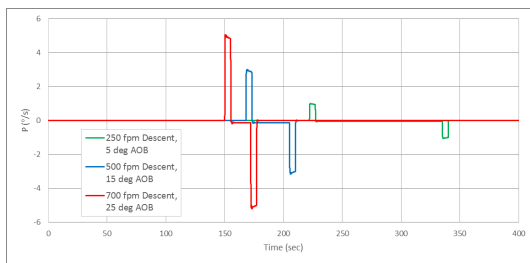
(b) Climb Rate



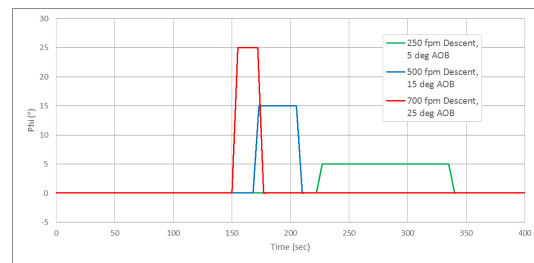
(c) Pitch Rate



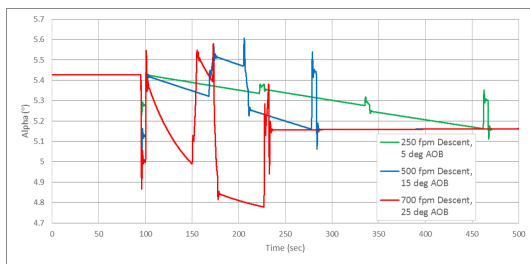
(d) Pitch Attitude



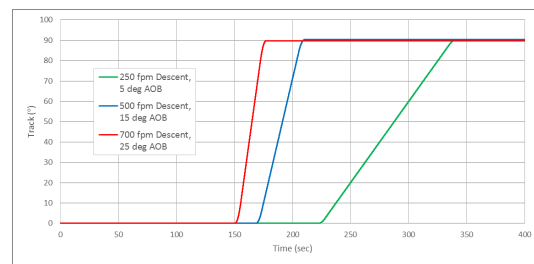
(e) Roll Rate



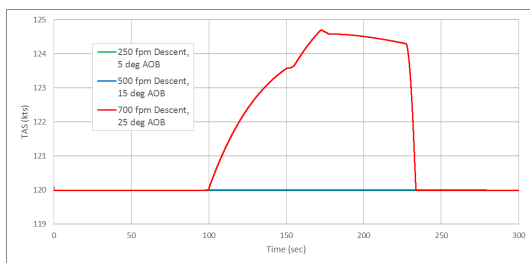
(f) Roll Attitude



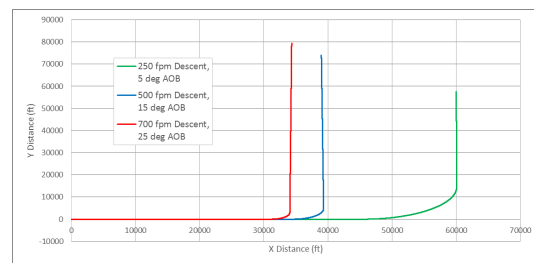
(g) Angle of Attack



(h) Heading



(i) Airspeed



(j) Ground Track

Figure 101. Group 4 Aircraft Non-Precision Aggressive, Air-To-Ground Tracking, Performance Plots

3.5 Precision Non-Aggressive Maneuver Data

Table 182. Group 4 Aircraft, Precision Offset Landing, Pitch Attitude Change Values (*rad*)

$\Delta\theta$	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0827 (4.7402°)	0.0826 (4.7347°)	0.0849 (4.8626°)
150 ft Offset	0.0827 (4.7397°)	0.0826 (4.7341°)	0.0831 (4.7611°)
50 ft Offset	0.0827 (4.7392°)		

Table 183. Group 4 Aircraft, Precision Offset Landing, Peak Pitch Rate Values (*rad/sec*)

Q_{pk}	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0260	0.0260	0.0607
150 ft Offset	0.0260	0.0260	0.0428
50 ft Offset	0.0260		

Table 184. Group 4 Aircraft, Precision Offset Landing, Pitch Quickness Values (sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.3145	0.3148	0.7154
150 ft Offset	0.3145	0.3149	0.5155
50 ft Offset	0.3145		

Table 185. Group 4 Aircraft, Precision Offset Landing, Roll Attitude Change Values (rad)

$\Delta\phi$	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.1724 (9.878°)	0.5120 (29.337°)	1.0173 (58.288°)
150 ft Offset	0.1714 (9.822°)	0.5077 (29.088°)	0.8418 (48.230°)
50 ft Offset	0.1690 (0.026°)		

Table 186. Group 4 Aircraft, Precision Offset Landing, Peak Roll Rate Values (rad/sec)

P_{pk}	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0129	0.0651	0.1931
150 ft Offset	0.0178	0.0914	0.2043
50 ft Offset	0.0303		

Table 187. Group 4 Aircraft, Precision Offset Landing, Roll Quickness Values (sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0750	0.1272	0.1898
150 ft Offset	0.1037	0.1800	0.2428
50 ft Offset	0.1793		

Table 188. Group 4 Aircraft, Precision Offset Landing, Airspeed Deviations (*kts*)

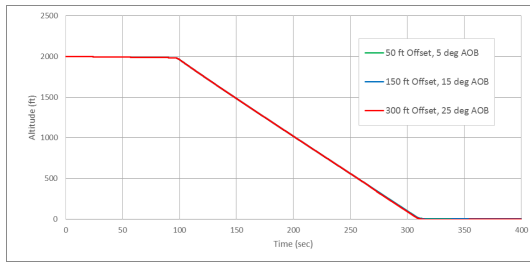
<i>TAS</i>	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	105.59 94.99	105.59 94.99	105.59 94.99
150 ft Offset	105.59 94.99	105.59 94.99	105.59 94.99
50 ft Offset	105.59 94.99		

Table 189. Group 4 Aircraft, Sum of Aileron Deviations (*rad*)

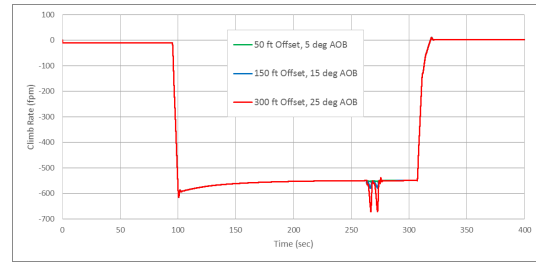
	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0098 (0.561°)	0.0495 (2.835°)	0.1442 (8.263°)
150 ft Offset	0.0136 (0.779°)	0.0670 (3.841°)	0.1417 (8.121°)
50 ft Offset	0.0230 (1.319°)		

Table 190. Group 4 Aircraft, Sum of Elevator Deviations (*rad*)

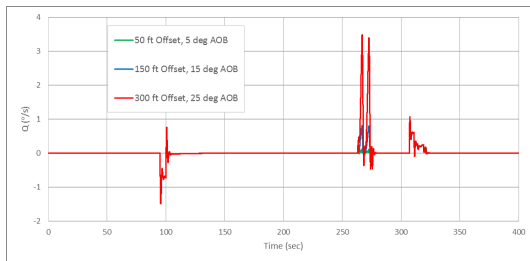
	5° Angle of Bank	15° Angle of Bank	25° Angle of Bank
300 ft Offset	0.0970 (5.558°)	0.1197 (6.857°)	0.1962 (11.243°)
150 ft Offset	0.0980 (5.617°)	0.1237 (7.086°)	0.1713 (9.817°)
50 ft Offset	0.1003 (5.746°)		



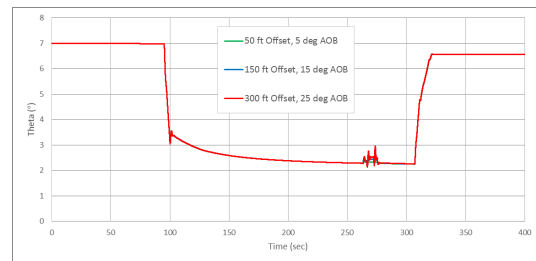
(a) Altitude



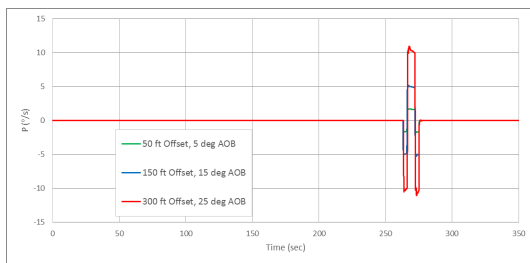
(b) Climb Rate



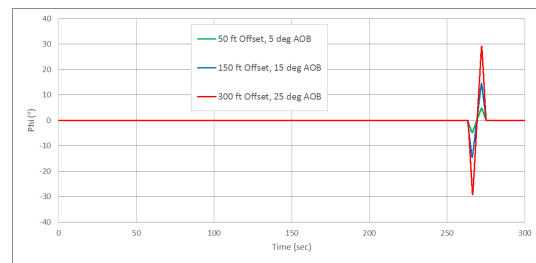
(c) Pitch Rate



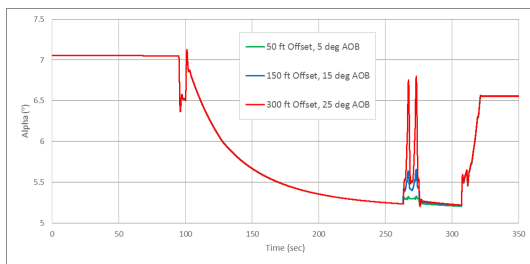
(d) Pitch Attitude



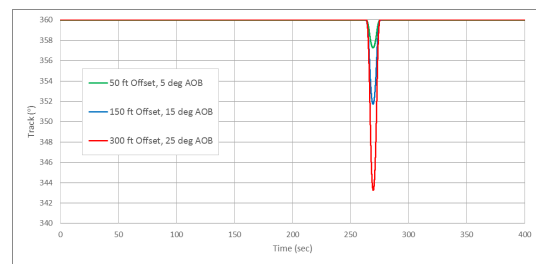
(e) Roll Rate



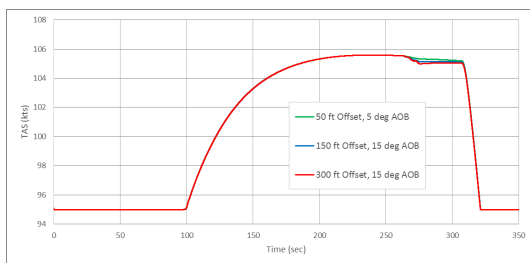
(f) Roll Attitude



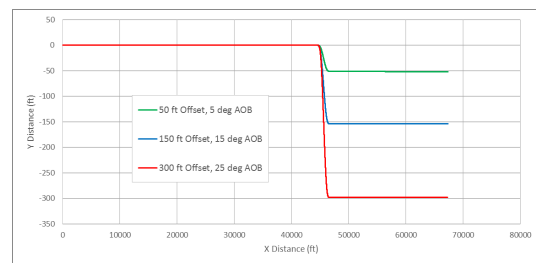
(g) Angle of Attack



(h) Heading



(i) Airspeed



(j) Ground Track

Figure 102. Group 4 Aircraft Precision Non-Aggressive, Precision Offset Landing, Performance Plots

3.6 Precision Aggressive Maneuver Data

Table 191. Group 4 Aircraft, Pitch and Roll Discrete Tracking, Pitch Attitude Change Values (*rad*)

$\Delta\theta$	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control		0.0051 (0.2930°)	0.0125 (0.7156°)	0.0417 (2.3911°)
Small Longitudinal Control	0.0485 (2.7811°)	0.0487 (2.7883°)	0.0490 (2.8069°)	0.0594 (3.4010°)
Moderate Longitudinal Control	0.0983 (5.6346°)	0.0985 (5.6420°)	0.0986 (5.6497°)	0.0987 (5.6547°)
Large Longitudinal Control	0.1493 (8.5565°)	0.1495 (8.5653°)	0.1495 (8.5644°)	0.1490 (8.5377°)

Table 192. Group 4 Aircraft, Pitch and Roll Discrete Tracking, Peak Pitch Rate Values
(rad/sec)

Q_{pk}	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control		0.0112	0.0246	0.0963
Small Longitudinal Control	0.0767	0.0775	0.0845	0.1099
Moderate Longitudinal Control	0.1547	0.1556	0.1632	0.1893
Large Longitudinal Control	0.2340	0.2351	0.2428	0.2693

Table 193. Group 4 Aircraft, Pitch and Roll Discrete Tracking, Pitch Quickness Values
(sec^{-1})

$\frac{Q_{pk}}{\Delta\theta}$	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control		2.1966	1.9728	2.3083
Small Longitudinal Control	1.5797	1.5917	1.7255	1.8521
Moderate Longitudinal Control	1.5727	1.5804	1.6548	1.9179
Large Longitudinal Control	1.5672	1.5723	1.6245	1.8072

Table 194. Group 4 Aircraft, Pitch and Roll Discrete Tracking, Roll Attitude Change Values (rad)

$\Delta\phi$	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control	0.1477 (8.462°)	0.4481 (25.674°)	1.0161 (58.221°)
Small Longitudinal Control	0.1477 (8.462°)	0.4486 (25.704°)	1.0187 (58.370°)
Moderate Longitudinal Control	0.1477 (8.463°)	0.4491 (25.734°)	1.0214 (58.523°)
Large Longitudinal Control	0.1477 (8.463°)	0.4497 (25.765°)	1.0239 (58.667°)

Table 195. Group 4 Aircraft, Pitch and Roll Discrete Tracking, Peak Roll Rate Values (rad/sec)

P_{pk}	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control	0.2619	0.8374	1.5598
Small Longitudinal Control	0.2617	0.8385	1.5616
Moderate Longitudinal Control	0.2614	0.8396	1.5636
Large Longitudinal Control	0.2611	0.8406	1.5653

Table 196. Group 4 Aircraft, Pitch and Roll Discrete Tracking, Roll Quickness Values
(sec^{-1})

$\frac{P_{pk}}{\Delta\phi}$	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control	1.7733	1.8688	1.5350
Small Longitudinal Control	1.7718	1.8692	1.5329
Moderate Longitudinal Control	1.7697	1.8694	1.5308
Large Longitudinal Control	1.7674	1.8694	1.5287

Table 197. Group 4 Aircraft, Pitch and Roll Discrete Tracking, Airspeed Deviations
(kts)

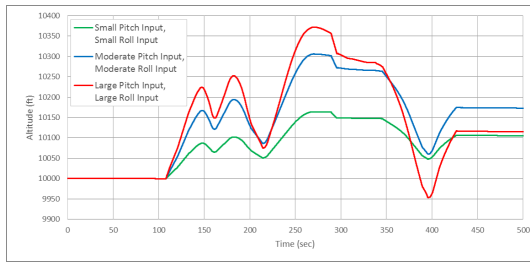
TAS	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control	119.99 119.99	119.99 119.99	119.99 119.99	119.99 119.99
Small Longitudinal Control	119.99 119.98	119.99 119.98	119.99 119.98	119.99 119.98
Moderate Longitudinal Control	120.00 119.98	120.00 119.98	120.00 119.97	120.00 119.97
Large Longitudinal Control	120.00 115.76	120.00 115.69	120.00 115.63	120.00 115.69

Table 198. Group 4 Aircraft, Pitch and Roll Discrete Tracking, Sum of Aileron Deviations (*rad*)

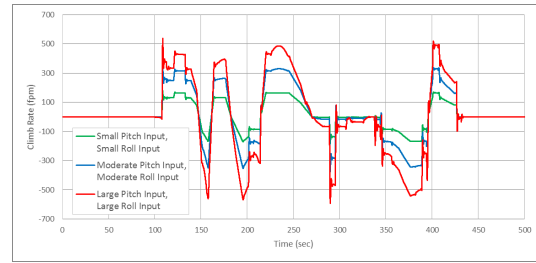
	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control		0.3116 (17.854°)	0.9377 (53.725°)	2.2978 (131.654°)
Small Longitudinal Control	0.0 (0.0°)	0.3140 (17.993°)	0.9463 (54.222°)	2.3308 (133.544°)
Moderate Longitudinal Control	0.0 (0.0°)	0.3169 (18.159°)	0.9556 (54.752°)	2.3727 (135.943°)
Large Longitudinal Control	0.0 (0.0°)	0.3204 (18.357°)	0.9674 (55.425°)	2.4335 (139.431°)

Table 199. Group 4 Aircraft, Pitch and Roll Discrete Tracking, Sum of Elevator Deviations (*rad*)

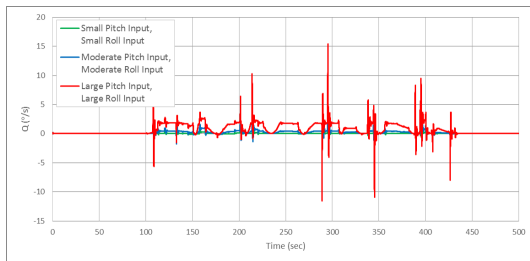
	No Lat-Dir Control	Small Lat-Dir Control	Moderate Lat-Dir Control	Large Lat-Dir Control
No Longitudinal Control		0.0757 (4.339°)	0.2021 (11.582°)	0.6431 (36.850°)
Small Longitudinal Control	0.3799 (21.765°)	0.4377 (25.080°)	0.5457 (31.267°)	0.9558 (54.763°)
Moderate Longitudinal Control	0.7627 (43.298°)	0.8197 (46.968°)	0.9263 (53.070°)	1.3257 (75.956°)
Large Longitudinal Control	1.1742 (67.279°)	1.2307 (70.513°)	1.3398 (76.766°)	1.7387 (99.619°)



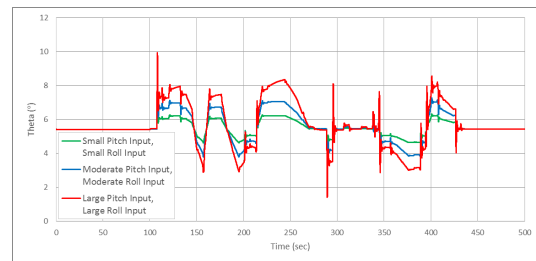
(a) Altitude



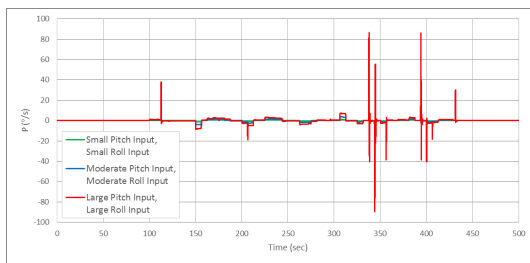
(b) Climb Rate



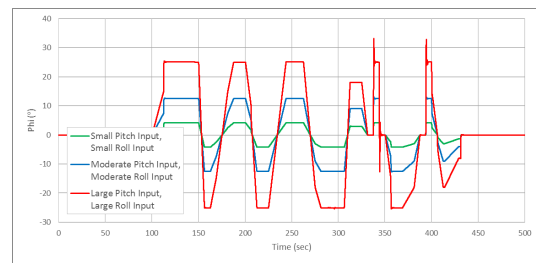
(c) Pitch Rate



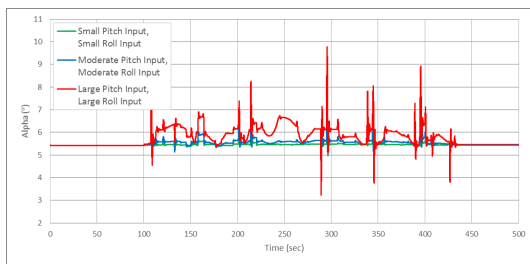
(d) Pitch Attitude



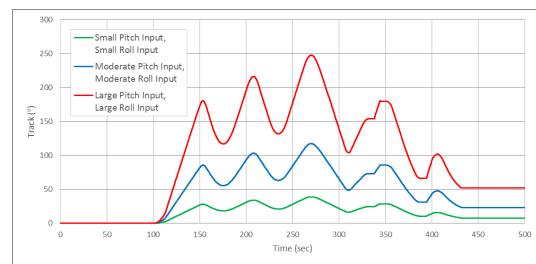
(e) Roll Rate



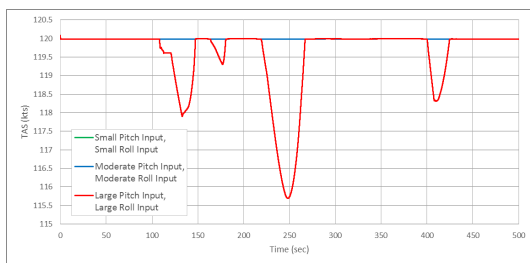
(f) Roll Attitude



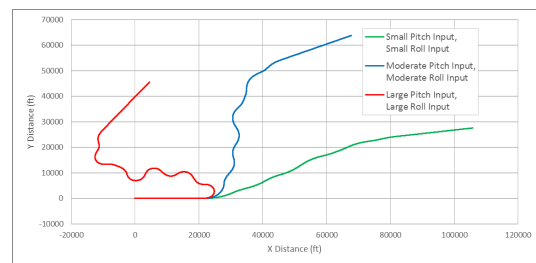
(g) Angle of Attack



(h) Heading

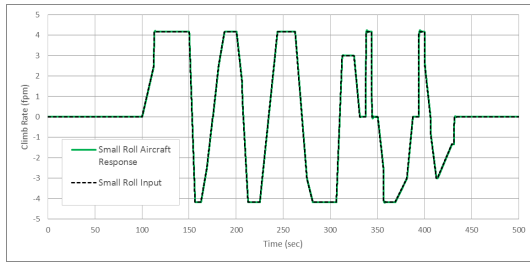


(i) Airspeed

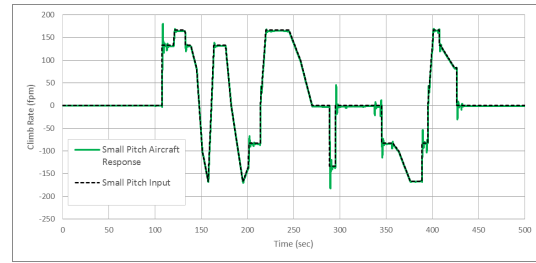


(j) Ground Track

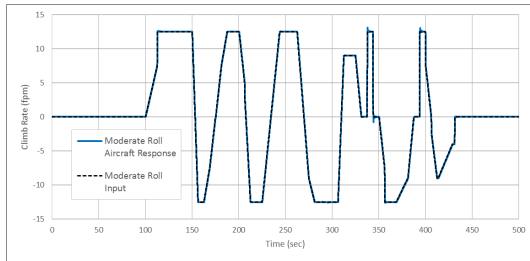
Figure 103. Group 4 Aircraft Precision Aggressive, Pitch and Roll Discrete Tracking, Performance Plots



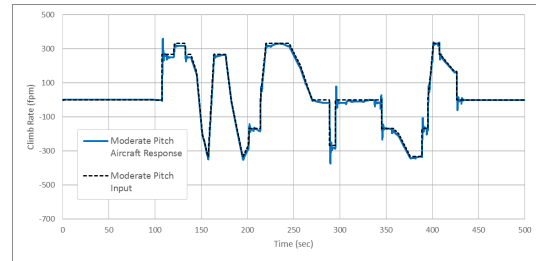
(a) Small Lateral-Directional



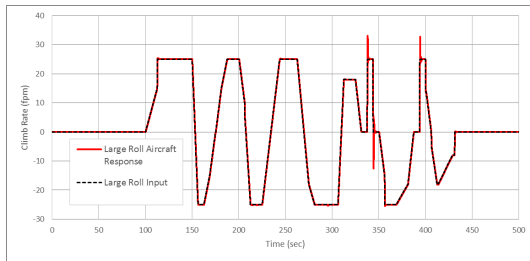
(b) Small Longitudinal



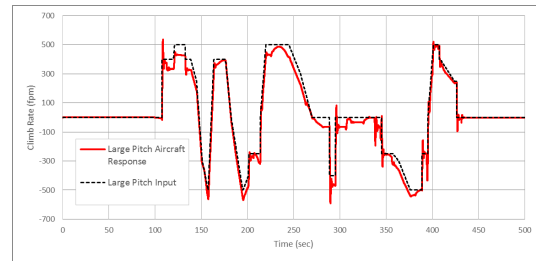
(c) Moderate Lateral-Directional



(d) Moderate Longitudinal



(e) Large Lateral-Directional



(f) Large Longitudinal

Figure 104. Group 4 Aircraft Precision Aggressive Target Performance Plots

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14. ABSTRACT The topic of aircraft flying qualities has been pursued since before the Wright Brothers'. As aircraft have advanced, the understanding of flying qualities has progressed; however, a new field of aviation has been uncovered. Unmanned aircraft have garnered an increasing amount of attention and are on the way to becoming a third major aircraft type next to manned fixed-wing and rotary-wing aircraft. The reason for the increased attention is unmanned aircraft have demonstrated operational usefulness and success in accomplishing missions that were too dull, dirty, or dangerous for manned aircraft. In spite of this, the design and development cycle for unmanned aircraft has not achieved the level of sophistication observed in manned aircraft, to include a lack of a flying qualities standard. This research begins the discussion of how this standard can be created to ensure the unique benefits of unmanned aircraft are upheld while still ensuring a necessary safety level. Focusing on specific tasks accomplished during missions will alleviate the complications that arise with the current delineation for manned fixed-wing aircraft according to weight, airspeed, and operational altitude. Three hypothetical models are created to test this proposed flying qualities framework. Various												
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