

USAFTPS-TIM-19A-04



INVESTIGATING THE EFFECTS OF FORWARD INSTANTANEOUS CENTERS OF ROTATION ON AIRCRAFT HANDLING QUALITIES

(Project HASTA LA VISTA)

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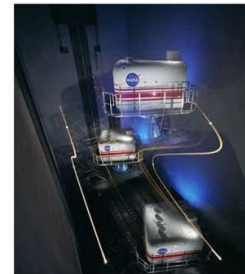
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This technical information memorandum (USAFTPS-TP-19A-04, *Investigating the Effects of Forward Instantaneous Centers of Rotation on Aircraft Handling Qualities*) was submitted under job order number MT19A400 by the Commandant, USAF Test Pilot School, Edwards Air Force Base, California 93524-6843.

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.					
1. REPORT DATE (DD-MM-YYYY) 21-11-2019		2. REPORT TYPE Final Technical Information Memorandum		3. DATES COVERED (From - Through) 06 Sep - 20 Sep 2019	
4. TITLE AND SUBTITLE Project HASTA LA VISTA Investigating the Effects of Forward Instantaneous Centers of Rotation on Aircraft Handling Qualities				5A. CONTRACT NUMBER N/A	
				5B. GRANT NUMBER N/A	
				5C. PROGRAM ELEMENT NUMBER N/A	
6. AUTHOR(S) Black, Allen, S, Captain, USAF Gaudin, Remi, F, Capitaine de corvette, Marine Nationale (France) Hamidani, Ali, M, Captain, USAF Horn, Cameron, R, Major, USAF McCafferty, Julian, P, Captain, USAF Schnurbusch, Jeremy, K, Captain, USAF				5D. PROJECT NUMBER MT19A400	
				5E. TASK NUMBER N/A	
				5F. WORK UNIT NUMBER N/A	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Test Center 412 th Test Wing USAF Test Pilot School Edwards AFB CA 93524-6485				8. PERFORMING ORGANIZATION REPORT NUMBER USAF TPS-TIM-19A-04	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) USAF TPS 1220 Wolfe Ave Edwards AFB, CA, 93524				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION A. Approved for public release. Distribution is unlimited.					
13. SUPPLEMENTARY NOTES SC: 012100 CA: 412th Test Wing Edwards AFB CA Print this document in COLOR .					
14. ABSTRACT This report documents results of the effects of forward instantaneous centers of rotation on up and away tasks such as simulated aerial refueling. Testing was requested by the 773TS, Edwards AFB, CA. The lead developmental test organization was the Air Force Test Center, Edwards AFB, California. The executing test organization was Class 19A of the USAF Test Pilot School, Edwards AFB. Testing was conducted from 06 September 2019 to 20 September 2019 and comprised of 16 sorties totaling 23.1 flight test hours and 31.6 hours in the NASA Vertical Motion Simulator (VMS) at Moffett Field, CA. The overall test objective was to investigate the effects of forward ICRs on aircraft handling qualities during tasks that included simulated aerial refueling, using in-flight, full-motion, and fixed-base simulators. All test objectives were met.					
15. SUBJECT TERMS Hasta La Vista, Instantaneous Centers of Rotation, ICR, Simulated Aerial Refueling, NF-16D VISTA, Full Motion Simulator, Vertical Motion Simulator, VMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report	18. NUMBER OF PAGES 75	19A. NAME OF RESPONSIBLE PERSON Mr. Joseph Duncan – 773 rd TS
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19B. TELEPHONE NUMBER (INCLUDE AREA CODE) 661-527-6627

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PREFACE

The test team would like to thank Mr. David Mitchell, founder of Mitchell Aerospace Research, Dr. M. Christopher Cotting, USAF Test Pilot School Master Instructor of Flying Qualities and the Calspan Team for their invaluable support and guidance.

Implementing the Variable stability In-flight Simulator Test Aircraft (VISTA) flight dynamics model on the Vertical Motion Simulator (VMS) was no small task. The authors wish to thank Dr. M. Christopher Cotting, USAF Test Pilot School Master Instructor of Flying Qualities, Ms. Marit Knapp, Research Engineer, US Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC), and Ms. Emily Lewis, Principal Simulation Engineer, SimLabs National Aeronautics and Space Administration (NASA) Ames Research Center, for their tremendous effort in verifying and validating the VMS and making Project Hasta La Vista possible.

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EXECUTIVE SUMMARY

This technical information memorandum (TIM) presents the results of Project Hasta La Vista, *Investigating the Effects of Forward Instantaneous Centers of Rotation on Aircraft Handling Qualities*. Testing was conducted by members of the United States Air Force (USAF) Test Pilot School (TPS) Class 19A, and the Calspan Corporation, as part of a student test management project (TMP). Testing was requested by the 773rd Test Squadron. The Lead Developmental Test Organization (LDTO) was the Air Force Test Center (AFTC), with the 412 Test Wing/USAF TPS, Edwards AFB, California, as the Executing Test Organization (ETO). Test sorties were conducted within the R-2508 complex under the Job Order Number (JON) MT19A400. The primary aircraft was the NF-16D Variable Stability In-flight Simulator Test Aircraft (VISTA), tail number 86-00048; an aircraft that was capable of approximating forward instantaneous centers of rotation (ICRs). In order to simulate aerial refueling, a T-38C Talon was used as a target aircraft. A total of 13.4 flight hours were flown across eight test sorties in the VISTA, and a total of 9.7 flight hours were flown across eight test sorties in the T-38C. Additionally, a total of 31.6 hours of fixed-base and full-motion simulator testing were conducted in the National Aeronautics and Space Administration (NASA) Ames Vertical Motion Simulator (VMS) at Moffett Federal Airfield in Mountain View, California. Flight testing took place from 6 – 20 September, 2019, and simulator testing took place from 16 – 19 September, 2019.

When a pilot commands a flight path change, the vehicle does not initially rotate about its center of gravity (CG), but rather, about a point known as the ICR. For traditional aircraft, this point is usually slightly aft of the cockpit such that the pilot perceives a positive normal acceleration when initiating the climb. However, in some aircraft with flying wing or delta wing geometries, like the Space Shuttle, the commanded upward deflection of the pitch control surface initially causes some loss of total lift and results in the aircraft sinking downward before climbing upward. Thus, the aircraft rotates about an ICR that is forward of the cockpit, creating confusing and non-standard acceleration cues for the pilot. This phenomenon poses a significant handling qualities challenge for the design of future flying wing or delta wing geometry aircraft.

Previous handling qualities research focused on the effects of forward ICRs during landing tasks. The general test objective (GTO) of this project was to investigate the effects of forward ICRs on aircraft handling qualities during tasks that included simulated aerial refueling, using in-flight, full-motion, and fixed-base simulators. The GTO was accomplished by completing the following specific test objectives (STOs):

1. Determine the implementation of forward ICRs on the NF-16D VISTA.
2. Determine longitudinal flying qualities of VISTA and VMS for selected ICRs.
3. Compare handling qualities of forward ICRs to previous research during the terminal phase of flight.
4. Demonstrate the effect of forward ICRs on handling qualities during pitch tracking tasks.
5. Investigate the effect of forward ICRs on handling qualities during simulated aerial refueling.
6. Compare the handling qualities of selected ICR configurations in the VISTA, and VMS with motion on and with motion off.

All objectives were met. Forward ICRs were successfully implemented on VISTA and short period dynamics were consistent for all configurations tested both in VISTA and in the VMS. Handling qualities evaluations were accomplished during offset landings and matched previous research. Handling qualities ratings and pilot comments collected during flight path tracking tasks such as formation station keeping and simulated aerial refueling conducted at 20,000 ft MSL and 300 KCAS showed that handling qualities degraded as ICRs moved forward; however it did not affect handling qualities during pitch tracking tasks conducted at the same flight conditions. The handling qualities ratings and pilot comments collected during the flight path tracking tasks conducted in the VMS both fixed-base and with motion on, simulated at the same conditions as in-flight testing, showed the same trends in handling qualities degradation with forward ICRs. The presence of the trend, even in fixed-base simulation points to the likelihood that the detriment to handling qualities was not a result of confusing pitch/g cues. Pilots overwhelmingly commented on a perceived time delay in flight path response across all three test platforms indicating that handling qualities were more closely tied to visual cues than proprioceptive cues. These results highlight the need for further investigation into the relationship between ICR location, delay in flight path response, and handling qualities.

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INTRODUCTION

This technical information memorandum (TIM) presents the results of Project Hasta La Vista, Investigating the Effects of Forward Instantaneous Centers of Rotation on Aircraft Handling Qualities. Testing was conducted by members of the United States Air Force (USAF) Test Pilot School (TPS) Class 19A, and the Calspan Corporation, as part of a student test management project (TMP). Testing was requested by the 773rd Test Squadron. The Lead Developmental Test Organization (LDTO) was the Air Force Test Center (AFTC), with the 412 Test Wing/USAF TPS, Edwards AFB, California, as the Executing Test Organization (ETO). Test sorties were conducted within the R-2508 complex under the Job Order Number (JON) MT19A400. The primary aircraft was the NF-16D Variable Stability In-flight Simulator Test Aircraft (VISTA), tail number 86-00048; an aircraft that was capable of simulating forward instantaneous centers of rotation (ICRs). A T-38C Talon was used as a target aircraft to execute simulated aerial refueling tasks. A total of 13.4 flight hours were flown across eight test sorties in the VISTA, and a total of 9.7 flight hours were flown across eight test sorties in the T-38C. Additionally, a total of 31.6 hours of fixed-base and full-motion simulator testing were conducted in the National Aeronautics and Space Administration (NASA) Ames Vertical Motion Simulator (VMS) at Moffett Federal Airfield in Mountain View, California. Flight testing took place from 6 – 20 September, 2019, and simulator testing took place from 16 – 19 September, 2019.

BACKGROUND

When a pilot commands a flight path change, the vehicle does not initially rotate about its center of gravity (CG), but rather, about a point known as the ICR. This point is located on the X_{body} axis of the aircraft and remains on the original aircraft flight path at the very instant the aircraft begins to rotate. For traditional aircraft, this point is usually slightly aft of the cockpit such that the pilot perceives a positive normal acceleration when initiating a climb. However, in aircraft with flying wing or delta wing geometries, like the Space Shuttle, the commanded upward deflection of the pitch control surface initially causes some loss of total lift and results in the aircraft sinking downward before climbing upward. Thus, the aircraft rotates about an ICR that is forward of the cockpit, creating confusing and non-standard acceleration cues for the pilot (reference 4). This phenomenon is illustrated in figure 1.

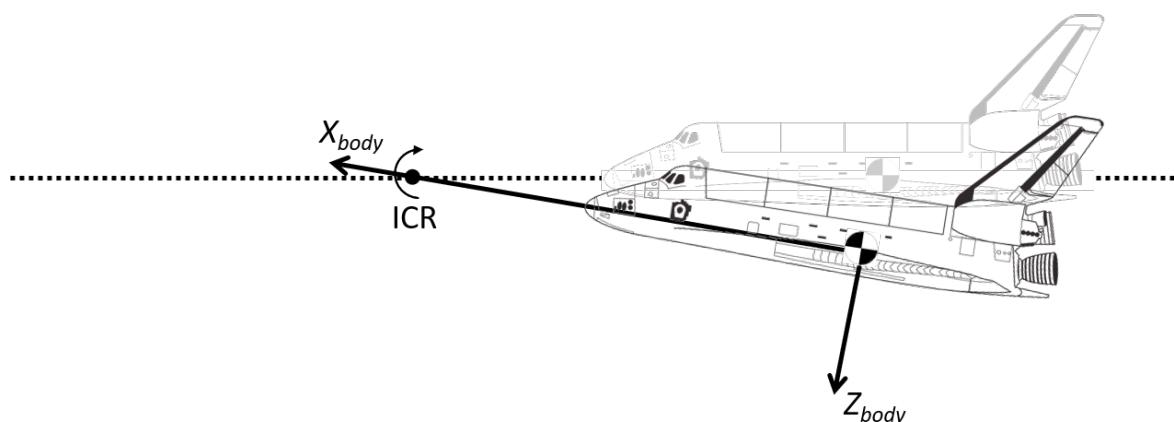


Figure 1 Initial Aircraft Sink due to Forward ICR

Several previous studies were conducted to investigate the handling qualities effects of forward aircraft

ICRs during landing tasks. Results from two of these studies were of particular interest to the test team. A 1982 NASA funded research project (reference 2) used the USAF/Calspan Total In-Flight Simulator (TIFS), a highly modified C-131, to artificially vary the location of the pilot station relative to the aircraft ICR. When the ICR was moved forward of the pilot station, pilots commented that the aircraft response became sluggish, or delayed, and that control deteriorated. In some cases, a pilot-induced oscillation (PIO) would occur, and precise descent rate control became poor or nearly impossible. In another study, which examined performance data from simulated landings in the NASA VMS, it was found that moving the aircraft ICR forward of the pilot station resulted in harder landings with touchdowns occurring shorter than the intended aim point (reference 2).

While there is overwhelming evidence that forward aircraft ICRs negatively affect handling qualities during landing, there were not any studies to determine the extent of this issue during up-and-away tasks, such as aerial refueling. Due to the potential for aircraft designs in the future to have an ICR forward of the pilot station this project was aimed at further examining forward ICR handling qualities and if possible to help formulate new design guidelines for such vehicles.

TEST ITEM DESCRIPTION

Three primary test items were used to accomplish the objectives of this effort. The main aircraft was the NF-16D VISTA, which was capable of simulating various aircraft ICRs. In order to simulate aerial refueling, a T-38C Talon was used as a target aircraft. The up-and-away tasks flown in the VISTA were recreated in the NASA Ames VMS, operating in full-motion and fixed-base (motion off) modes, in order to compare handling qualities results across simulator platforms.

NF-16D VISTA

The NF-16D VISTA, pictured in figure 2 was employed to collect in-flight handling qualities data for varied ICR configurations. The aircraft was a Block 30 F-16D that had been highly modified for stability and controls research. It featured a 5-degree-of-freedom (DOF) Variable Stability System (VSS) which enabled it to simulate the flying qualities of aircraft other than the host F-16.



Figure 2 The NF-16D VISTA

The VISTA flight envelope is shown in figure 3. The light blue region encompasses the limits of the aircraft flight regime with the VSS disengaged. The dark blue region encompasses the flight regime with the VSS engaged. In both cases, the VISTA flight envelope was significantly smaller than that of a production F-16. The green area in figure 3 represents the region where testing occurred. Since this test primarily aimed to evaluate handling qualities during refueling tasks, the aircraft was operated in the cruise configuration at 20,000 feet Pressure Altitude (PA) and 300 knots calibrated airspeed (KCAS). The aircraft was also flown in the powered approach configuration (altitude and airspeed as required) to link handling qualities results to previous landing task research.

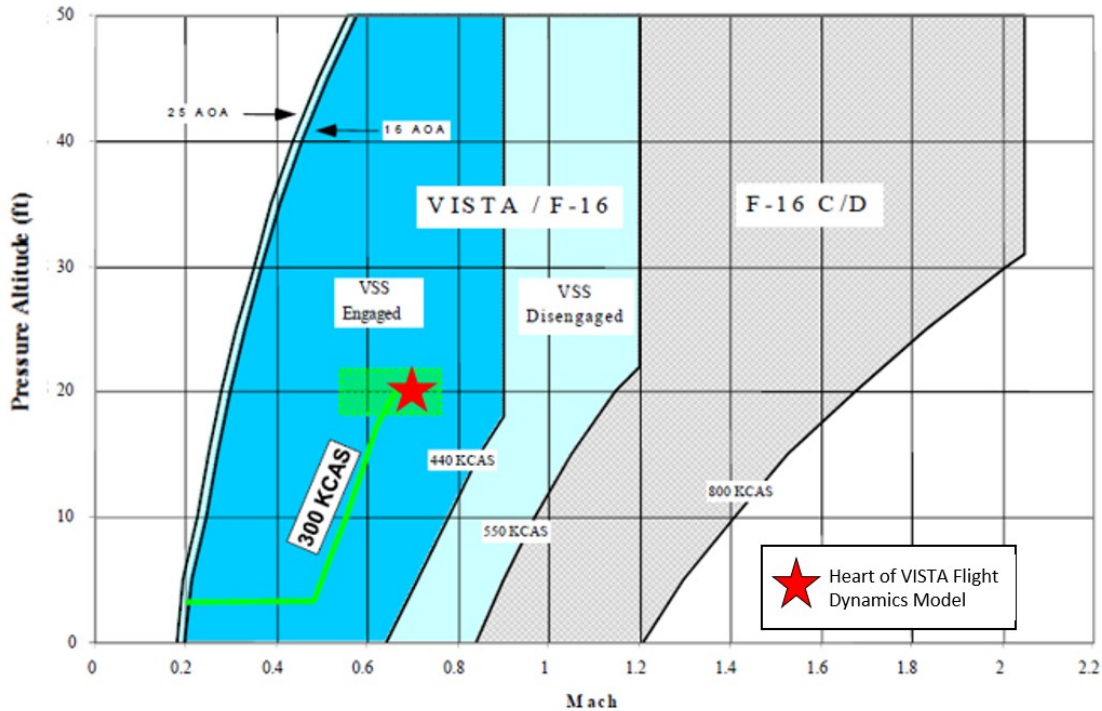


Figure 3 The NF-16D VISTA Flight Envelope

All essential aircraft controls were located in the aft cockpit, which was occupied by a safety pilot (SP). The SP could make changes to the aircraft flying qualities by loading parameters from VSS software configuration files. The evaluation pilot (EP) sat in the front cockpit, which featured a center stick controller. It also featured a Heads-Up Display (HUD) that could display customizable and programmable pilot cueing symbology such as an aiming reticle or moving target.

The VISTA had a Digital Flight Control Computer (DFLCC) which continually monitored pilot inputs and ensured safety of flight. If VSS commands to the control surface actuators approached aircraft limits, the DFLCC disengaged the VSS and reverted to the basic F-16 control mode to protect the airframe. The VSS also included dual sensors for measuring all aircraft states. In case of a sensor failure, the system automatically disengaged. Additionally, either pilot could initiate a manual safety trip from the control stick. Following a safety trip, aircraft control immediately returned to the SP occupying the rear cockpit. The VISTA could be operated in one of the following four basic flight control modes:

1. Disengage Mode: Only the rear cockpit controls were operative with basic F-16 controllaws.

2. VSS Mode: Only the front cockpit controls were operative with simulated control laws and aircraft response. Front cockpit throttle control authority was selected by the rear cockpit pilot.

3. F-16 (Convenience) Mode: Only the front cockpit controls were operative with basic F-16 control laws. Front cockpit throttle control authority was selected by the rear cockpit pilot.

4. Emergency Mode: Only the front cockpit controls including the throttle were operative with basic F-16 control laws.

Table 1 shows aircraft safety trip limits for cruise and powered approach configurations.

Table 1: Safety Limits in Cruise and in Powered Approach Configurations

Parameter	Cruise Limits	Powered Approach Limits
AOA (Angle of	+16 / -10 deg	+15 / -5 deg
AOS (Angle of	± 10 deg	± 10 deg
Normal Acceleration	+6.8 g / -2.4 g	+3.0 g / 0 g
Sideforce	± 0.5 g	± 0.5 g
Airspeed	Lesser of 440 KCAS or 0.9	Lesser of 440 KCAS or 0.9
Horizontal Tail Rate	70 deg/sec (7 frames)	70 deg/sec (7 frames)
Flaperon Rate	100 deg/sec (1 frame)	100 deg/sec (1 frame)
Pitch Acceleration	+8.0 g / -5.0 g	+6.0 g / -3.0 g
Roll Rate	300 deg/sec	200 deg/sec
Yaw Rate	30 deg/sec	15 deg/sec

For this project, the VISTA VSS was configured with an Angle of Attack (AOA) and AOA-rate command flight control system. The ICR was modified by changing a control system gain that tied longitudinal stick commands to aircraft flaperon actuation along with the conventional horizontal tail. When the EP actuated the centerstick aft, commanding the trailing edge of the horizontal tail to move upward, the flaperons also moved so as to decrease some portion of the total lift on the wings. This caused the aircraft to initially sink and rotate about some forward ICR. The initial sink was characterized by a vertical acceleration in the aircraft Z-body axis, as a result of some horizontal tail (or elevator) deflection (δ_e), thus it was known as the $Z\delta_e$ gain. A block diagram of this control system is shown in figure 4.

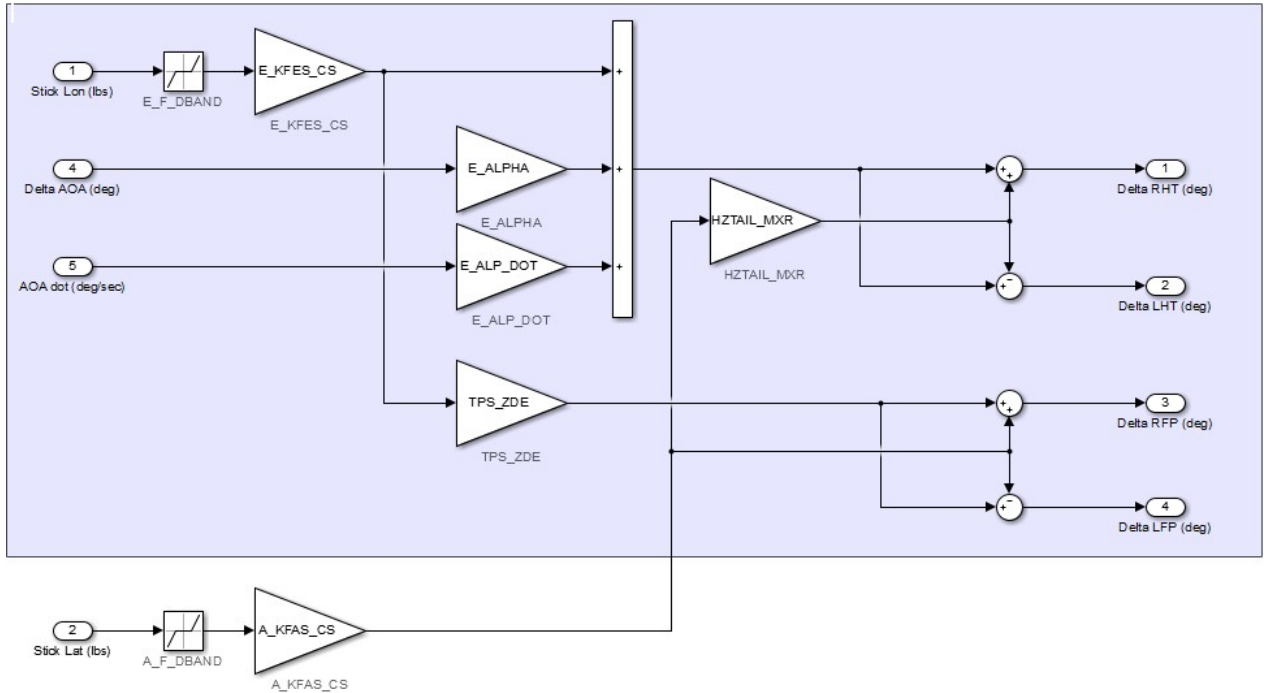


Figure 4: The NF-16D VISTA VSS AOA, AOA-Rate Command System with $Z\delta_e$ Gain

A computer based flight dynamics model of the VSS was used to determine a range of $Z\delta_e$ gain values that could be flown on the VISTA without triggering safety trips. Each gain setting was given a VSS configuration number. The stick feel for up and away (UA) configurations (801–809) were the same. The stick feel system for powered approach (PA) configurations (831 and 205), used for the offset landing, matched. These values were loaded on the VSS and tested in flight. The results of the testing and calculated ICR locations are presented in the forward ICR implementation test results section.

T-38C TALON

A T-38C Talon aircraft was required to act as a target aircraft for up-and-away flight path tracking tasks. The T-38C was a two seat (tandem), twin turbojet engine, supersonic trainer aircraft built by Northrop Corporation. It had hydraulically activated speed brakes located on the lower surface of its fuselage center section that were used as part of testing. The speed brakes were operated by actuating a control switch on the throttle. The T-38C is shown in figure 5 with speed brakes deployed.



Figure 5 T-38C Talon with Deployed Speed Brakes

The speed brakes were used as visual references for the EP flying the VISTA, along with the colored adhesive decal shown in figure 6. The decal was made of 3M “Scotchcal” 220 film and was designed to provide a visual reference of aircraft position relative to a refueling boom envelope representative of current USAF aerial refueling tankers. The decal dimensions are shown in Figure 7. The decal was positioned with the red edge 21.5 inches forward of the bottom edge (the edge extended down) of the speed brake, aligned parallel to the speed brake edge. The position of the speed brakes relative to the colors on the decal was used to judge how well the VISTA EP was able to perform the simulated aerial refueling task. Figure 8 below shows an inflight view of the speed brake versus the decal during the simulated aerial refueling task. More information on task execution is described in the test and evaluation section.



Figure 6 T-38C Undercarriage Decal

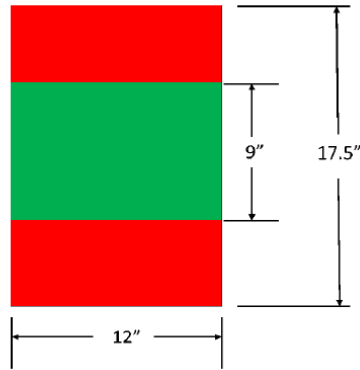


Figure 7 Dimensions of Colored Target Decal

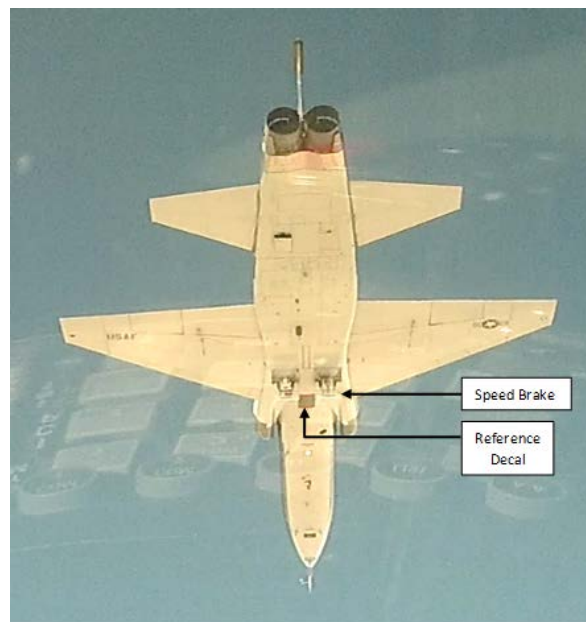


Figure 8 Simulated Aerial Refueling Task In-Flight References

VERTICAL MOTION SIMULATOR (VMS)

The VMS, pictured in figure 9, was employed as a fixed-base and full-motion simulator to allow for handling qualities comparisons to be made with in-flight data. The VMS was a 6-DOF flight model simulator located at the NASA Ames Research Center at Moffett Federal Airfield in Mountain View, CA. To allow for comparisons between motion and visual cues, the VMS was used in fixed-base and full motion modes. The VMS was programed to replicate the same ICR locations as used for flight test with the VMS flight dynamics tuned to match those of the VISTA for each ICR configuration.

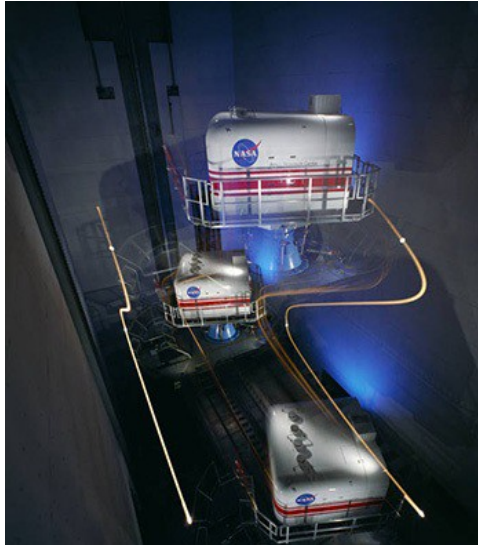


Figure 9 Time-lapse Image of NASA Ames VMS

The motion capable base has the largest vertical displacement of any simulator in the world. The VMS can travel 60 feet vertically, 40 feet laterally, and 8 feet longitudinally. This allowed the system to operate with three translational degrees of freedom. Additionally, the simulator was able to move in pitch, roll, and yaw, granting it an additional three degrees of freedom. It could also perform at maximum capability in all axes simultaneously. The system was capable of accelerations up to 24 ft/s^2 . The motion platform of VMS employed safety cutoffs to protect the physical hardware within the motion capabilities of the facility.

The VMS had five different interchangeable simulator cabs which could be customized to recreate the cockpits of different aerospace vehicles. This project used the f-cab, which simulated fighter type aircraft. Controls and displays were modified to emulate the VISTA cockpit as closely as possible.

The test team used a T-38C graphical model with the same flight test markings used during formation station-keeping tasks. Due to field-of-view constraints a KC-135 refueling tanker aircraft model was used in place of the T-38C during the simulated aerial refueling task.

The VMS also had a lab, shown in figure 10, from which engineers could monitor and record data, in addition to communicating with simulator pilots. The same flight test parameters recorded on VISTA flights were also recorded in the VMS.



Figure 10 NASA Ames VMS Lab

PROJECT PILOTS

Four pilots conducted the handling qualities testing. Pilot 1 was a Dassault Rafale pilot with over 1100 flight hours in the Rafale. Pilot 1 brought delta wing/canard fighter experience to the test team. Pilot 2 was an F-22 Raptor pilot with over 700 hrs in the F-22. Pilot 2 brought digital flight control system (FLCS) fighter experience to the test team. Pilot 3 was a B-2 pilot with over 350 hrs in the B2 as well as 1500 hrs in the C-17. Pilot 3 brought flying wing experience as well as class III aircraft experience to the test team. Lastly, pilot 4 was an F-15E pilot with 1300 hrs in the F-15E. Pilot 4 brought non-FLCS fighter experience to the test team. The collective background of the test team provided a variety of perspectives when evaluating handling qualities.

TEST OBJECTIVES

The general test objective (GTO) of this project was to investigate the effects of forward ICRs on aircraft handling qualities during tasks that include simulated aerial refueling, using in-flight, full motion, and fixed-base simulators. The specific test objectives were to:

1. Determine the implementation of forward ICRs on the NF-16D VISTA.
2. Determine longitudinal flying qualities of VISTA and VMS for selected ICRs.
3. Compare handling qualities of forward ICRs to previous research during the terminal phase of flight.
4. Demonstrate the effect of forward ICRs on handling qualities during pitch tracking tasks.
5. Investigate the effect of forward ICRs on handling qualities during simulated aerial refueling.

6. Compare the handling qualities of selected ICR configurations in the VISTA, and VMS with motion on and with motion off.

All test objectives were met.

CONSTRAINTS

The NASA Ames Vertical Motion Simulator had a field of view (FOV) limited to $\pm 12^\circ$ vertically and $\pm 60^\circ$ horizontally as shown in figure 11. In-flight replication of aerial refueling was given priority when developing handling qualities tasks for this test. This was done to provide the highest fidelity understanding of actual in-flight effects of forward ICRs on handling qualities. The VMS field of view negated the ability to accomplish the same tasks in the simulator thus the aerial refueling flight path tracking tasks were modified for execution in the simulator. This created some variation between in-flight and simulator tasks. The Test and Evaluation section details the specific changes made for the simulator tasks.

Flight path tracking tasks were not accomplished at the forward most ICR configuration (21 ft forward) during the second VISTA flight for each pilot as well as during most VMS testing. It was determined during initial testing in each platform that the forward most ICR configuration resulted in extremely poor handling qualities that were both not useful for collection of handling qualities ratings and in some instances resulted in tripping safety limits that negated the ability to complete the task. For test efficiency, the forward most ICR configuration test points were truncated.

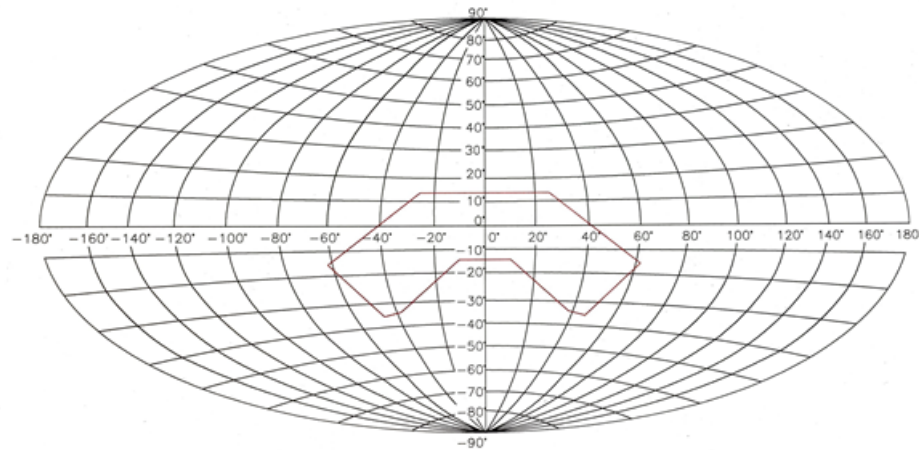


Figure 11 NASA Ames VMS F-Cab Field of View

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TEST AND EVALUATION

The effects of forward ICRs on aircraft handling qualities were investigated in flight as well as in fixed-base and full motion simulation. The implementation of forward ICRs was first determined across all three test platforms. Next, the short period dynamics were determined for each platform. These two specific test objectives formed the foundation upon which handling qualities testing could be executed in the respective platform. In-flight handling qualities evaluations in VISTA were conducted first. These evaluations were conducted using a randomized order of ICR location and kept blind to the pilot. The order of ICR location test points was determined prior to testing by the project engineers. In order to keep the ICR location blind to the EP, a lineup card of test point sequence was given to the SP prior to the flight and the VSS display was dimmed in the front cockpit prior to testing. Handling qualities evaluations consisted of Cooper-Harper Ratings (CHRs) in accordance with the scale shown in figure C1 in appendix C. Pilot comments were also collected during testing and pilot induced oscillation ratings (PIORs), also in appendix C, were collected only when a pilot noted PIO tendency. Simulator testing in the VMS was conducted during the second week of the test window using the same randomized and blind procedures as in-flight testing. Handling qualities tasks consisted of formation station keeping, simulated aerial refueling, simulated emergency separation, pitch tracking, and offset landings. After completion of handling qualities testing in all three platforms, the results were compared.

All pilot comments, CHRs, and PIORs collected during testing are available in the digital appendix outlined in appendix A.

IMPLEMENTATION OF FORWARD ICRS ON THE NF-16D VISTA

The ICR is the location, along the X-body axis of an aircraft, about which it initially rotates when a climb is initiated (see figure 1). Although located aft of the pilot station in most conventional airplanes it can also be located forward of the pilot station in some delta wing or flying wing aircraft.

Test Methods and Conditions

ICR location was manipulated in VISTA by linking longitudinal stick command to flaperon deflection in addition to horizontal tail deflection via a value in the VSS flight control system (FLCS), known as the Z_{δ_e} gain. A positive Z_{δ_e} gain would cause the flaperons of the VISTA to deflect upward with upward horizontal tail deflection. Thus, the horizontal tails would cause an upward pitching moment, while the loss of camber on the wing would result some loss of lift, causing a downward heave. The opposite case was also true, in that downward horizontal tail would be accompanied by downward flaperon—causing a slight increase in lift force with downward pitching moment.

A range of Z_{δ_e} gains from 0 to 3.5 were set on the VISTA VSS, and the aircraft was flown to an up-and-away (UA) flight condition at 300 KCAS and 20,000 ft PA. The value of 3.5 was selected as the maximum value for Z_{δ_e} gain to allow for successful completion of airborne tasks. The VSS math model predicted that values beyond 3.5 would result in safety trips that would disengage the VSS. For each Z_{δ_e} gain, a single 120 sec pitch frequency sweep programmable test input (PTI) was executed. During the maneuver, the VSS commanded an oscillatory forward and aft stick input with a stick force of 5 lbs, increasing in frequency from 0.5 to 15 rad/sec exponentially. The frequency sweep PTI was repeated in the

powered approach (PA) configuration, at an altitude of 10,000 ft PA and an AOA of 11° (approximately 150 KCAS). In the powered approach configuration the frequency sweep was executed for a nominal Z_{δ_e} gain of 0 and a forward ICR Z_{δ_e} gain of 1.5. The Z_{δ_e} gain value of 1.5 was used for the forward ICR in the PA configuration as it was previously approved for use as a landing configuration. Flight test frequency sweep data were analyzed using techniques detailed in Appendix C.

Test Results

Table 2 summarizes the ICR locations determined in-flight. All distances are relative to the VISTA evaluation pilot (front seat pilot) station.

Table 2 VSS Z_{δ_e} Gain and ICR Location from Evaluation Pilot Station

VSS Config Number	Configuration Type	Zde Gain	ICR Location from Eval Pilot Station (ft)
801	UA Nominal ICR	0	-7
802	UA Forward ICR	1	2.5
809	UA Forward ICR	1.5	8.6
803	UA Forward ICR	2	14.6
808	UA Forward ICR	2.5	16.3
804	UA Forward ICR	3	17.0
805	UA Forward ICR	3.5	21.0
831	PA Nominal ICR	0	0
205	PA Forward ICR	1.5	12

The ICR locations are visually depicted in figure 12.

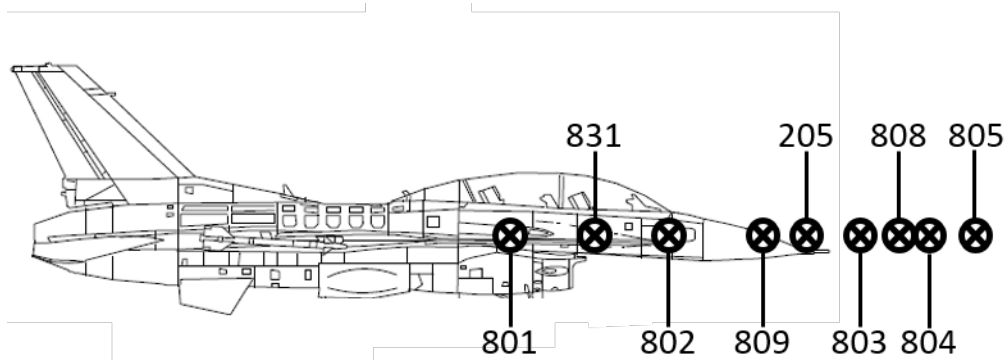


Figure 12 ICR Locations

LONGITUDINAL FLYING QUALITIES OF VISTA AND VMS FOR SELECTED ICRS

The equivalent time delay, short period natural frequency, short period damping ratio, and Control Anticipation Parameter (CAP) were determined for each ICR configuration in VISTA. For VMS, bode plots of pitch-rate to longitudinal stick deflection were compared to bode plots of the same parameters from

VISTA to ensure consistent short period dynamics between platforms tested. Equivalent time delay is the measure of time between aircraft control input and aircraft response. The short period natural frequency is a measure of the frequency of undamped oscillations of the aircraft short term pitch response. The short period damping ratio is a dimensionless measure of how oscillations in the aircraft's short term pitch response decay and CAP is the ratio of initial pitching acceleration to steady-state normal acceleration.

Test Methods and Conditions

Data from the PTI frequency sweeps described above were analyzed using techniques detailed in Appendix C, in order to determine longitudinal flying qualities.

Test Results

The equivalent time delay for each ICR configuration is shown in table 3, while the short period frequency, damping ratio, and control anticipation parameter are summarized in table 4. Time delays were determined to be level 2 based on MIL-STD-1797B for all ICR configurations except 805, 808 and 809 which were just barely level 1. Despite the variation in MIL-STD level, the maximum difference in time delay was observed to be only 0.07 seconds. In all configurations short period frequency, damping and CAP values were level 1.

Table 3 VISTA VSS Equivalent Time Delay

	UA							PA	
VSS Config Number	801	802	809	803	808	804	805	831	830
ICR Location from Eval Pilot Station (ft)	-7	2.5	8.6	14.6	16.3	17.0	21.0	0	12
Equivalent Time Delay (sec)	0.16	0.15	0.09	0.12	0.09	0.11	0.10	0.12	0.11

Table 4 VISTA VSS Short Period Frequency, Damping and Control Anticipation Parameter

	UA							PA	
VSS Config Number	801	802	809	803	808	804	805	831	830
ICR Location from Eval Pilot Station (ft)	-7	2.5	8.6	14.6	16.3	17.0	21.0	0	12
Short Period Frequency (rad/s)	3.78	3.53	3.72	3.66	4.26	3.46	3.06	1.82	1.85
Short Period Damping	0.71	0.76	0.83	0.72	0.93	0.8	0.89	0.4	0.42
CAP ($\text{g}^{-1}\text{sec}^{-2}$)	1.15	1.12	1.28	1.26	1.84	1.52	2.01	0.76	1.32

CAP and short period damping ratio are plotted against MIL-STD-1797B flying qualities envelopes for the UA and PA aircraft configurations in figures 13 and 14 respectively.

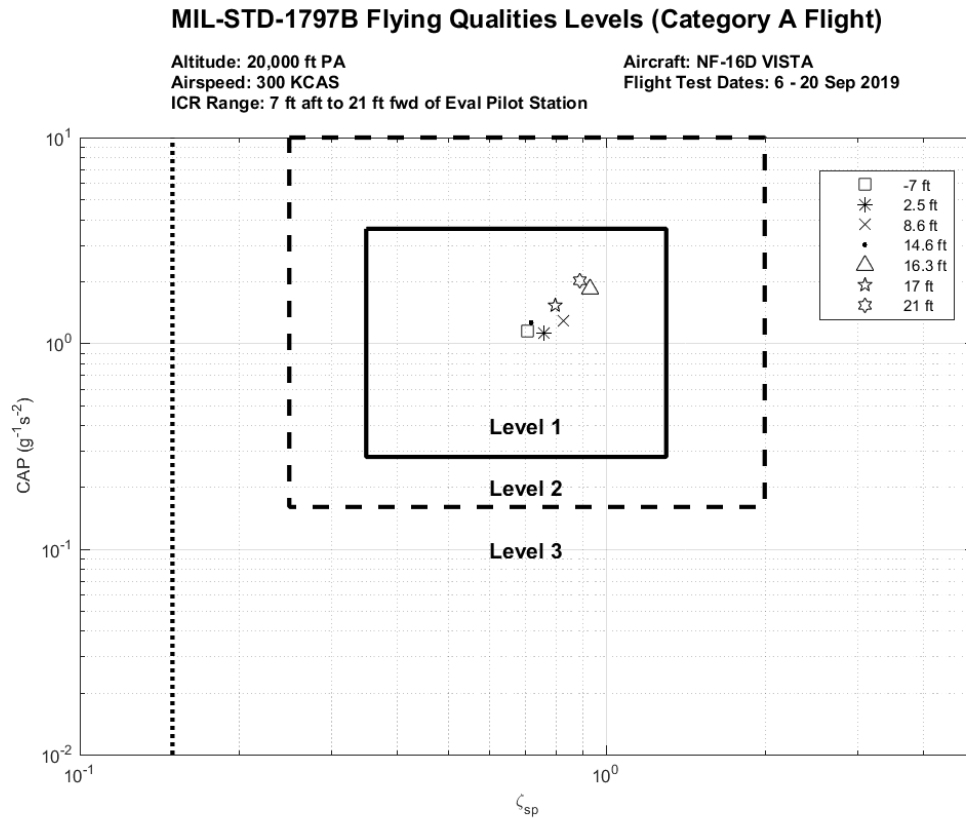


Figure 13 CAP vs Short Period Damping Ratio for UA Configuration

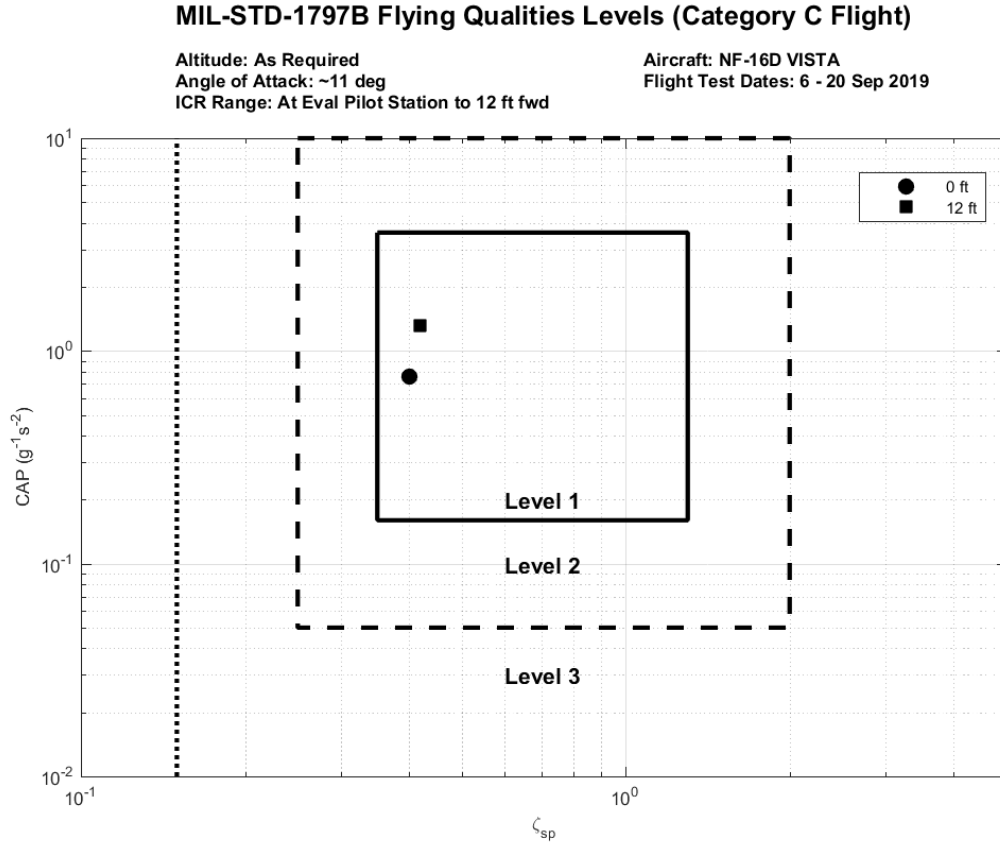


Figure 14 CAP vs Short Period Damping Ratio for PA Configuration

Comparison of longitudinal flying qualities for each ICR configuration showed that despite changes in the ICR location, longitudinal flying qualities remained consistent. Although equivalent time delay showed some variation between MIL-STD-1797B level 1 and 2 the difference was minimal and not expected to have an impact on the associated Cooper-Harper Ratings (CHRs) provided during testing; indicating changes in CHRs could be mainly attributed to the changing ICR location.

The VISTA VSS flight dynamics model was implemented in VMS and then tuned to match the dynamics of the VISTA. Figure 15 shows how the VMS matched the VISTA in pitch rate response to longitudinal stick input for the nominal ($Z_{\delta e}=0$) UA configuration. Figure 16 shows the same for the most forward ICR ($Z_{\delta e}=3.5$). Additional Bode plots for VISTA and VMS for the remaining configurations are in appendix A. In all cases the bode plots for VISTA and VMS closely matched for each configuration, validating the implementation of the VISTA dynamics on the VMS. The implementation of VISTA dynamics onto the VMS was performed in a separate verification and validation effort detailed in reference 6.

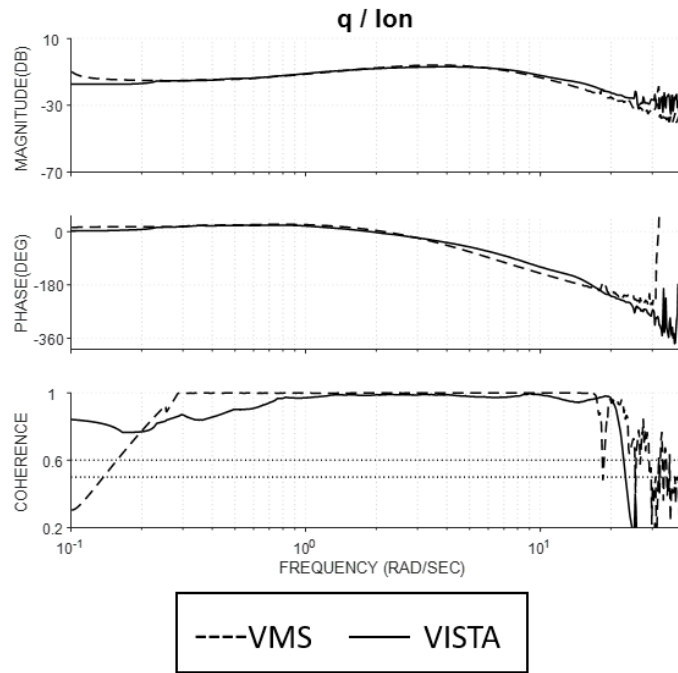


Figure 15 Bode Plots of Pitch-rate to Longitudinal Stick Deflection for VISTA and VMS
(Configuration 801, $Z_{\delta e}=0$, ICR = 7 ft aft of Evaluation Pilot Station)

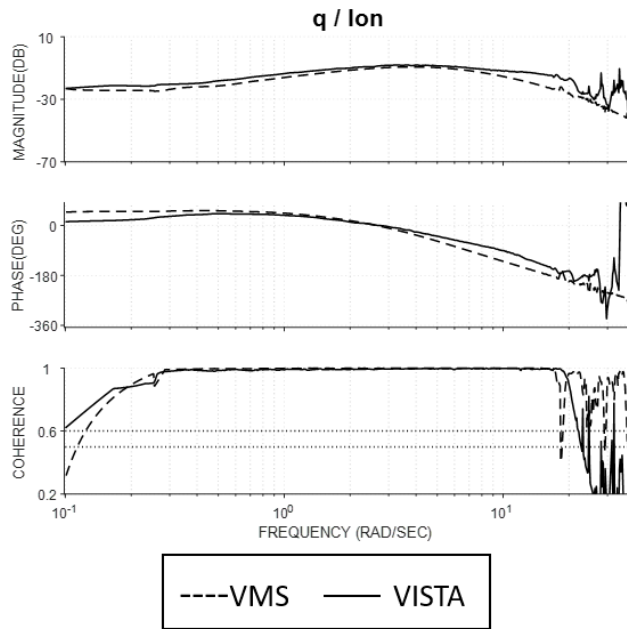


Figure 16 Bode Plots of Pitch-rate to Longitudinal Stick Deflection for VISTA and VMS
(Configuration 805, $Z_{\delta e}=3.5$, ICR = 21 ft forward of Evaluation Pilot Station)

COMPARISON OF HANDLING QUALITIES OF FORWARD ICRS TO PREVIOUS RESEARCH DURING THE TERMINAL PHASE OF FLIGHT

Previous research on forward ICR handling qualities was conducted looking at the terminal phase of flight (reference 2 & 5). This previous research found that ICRs forward of the pilot resulted in degraded handling qualities, sluggish aircraft response, harder landings with touchdowns short of the intended aim point, and in some cases a pilot-induced oscillation (PIO) occurred. In order to compare data collected to previous work; offset landing tasks were conducted with one nominal Z_{δ_e} gain and one Z_{δ_e} gain that resulted in a forward ICR.

Test Methods and Conditions

Testing consisted of offset landing tasks replicating the task used in previous research (reference 2 & 5). Each project pilot flew an offset landing to a touch and go in configurations 831 and 205. Configuration 831 resulted in an ICR located at the evaluation pilot station while configuration 205 was a forward ICR configuration with the ICR located 12 ft forward of the evaluation pilot station.

The offset landing task consisted of positioning the aircraft on a 2.5-3 degree glide path on a 5NM final to the Runway 22L threshold, offset to the right of the centerline by 400 ft. The HUD pitch ladder and flight path marker were used to align the desired glide path while the lateral offset was accomplished using the Runway 22L hold short line on taxiway C as a visual marker, which also corresponded to the location of the infield brush line as shown in figure 17 below. At 300 feet AGL the EP maneuvered the aircraft to runway centerline, and attempted to land the aircraft within the desired criteria.



Figure 17 Offset Landing Task Lateral Reference

For desired performance, the EP was required to touchdown between 500 and 1,000 feet from the threshold without having a hard landing, as qualitatively assessed by the SP/EP. For adequate performance, the landing zone was defined as zero to 1,500 feet from the threshold. These desired and adequate criteria are depicted in figure 18 below.

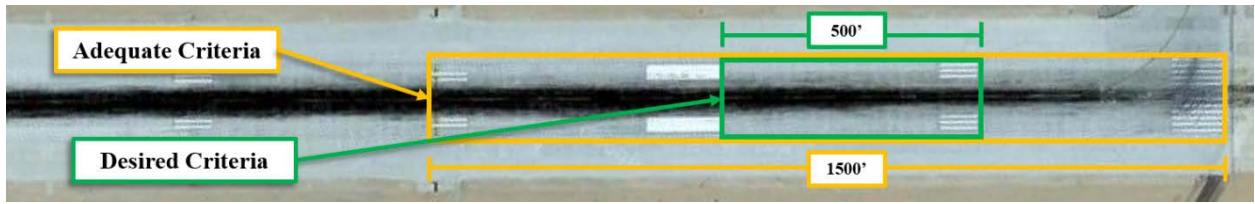


Figure 18 Offset Landing Task Performance Criteria

Offset landings were accomplished on each pilot's first test sortie with a low approach in the corresponding configuration accomplished prior to a data collection run. Each pilot executed a single evaluation run in each tested ICR configuration. Testing was conducted in day, visual conditions. The offset landing task was also performed in the VMS but were not analyzed as part of this study. The data for these test points are available in appendix A.

Test Results

The VISTA offset landing results are shown in figure 19. The plot shows that the CHR degraded as the ICR was moved forward of the pilot station. When the ICR was 12 ft forward of the pilot station, all pilots gave ratings of 6 and 7. With the baseline configuration where the ICR was at the pilot station, pilots gave CHR ranging from 3 to 5.

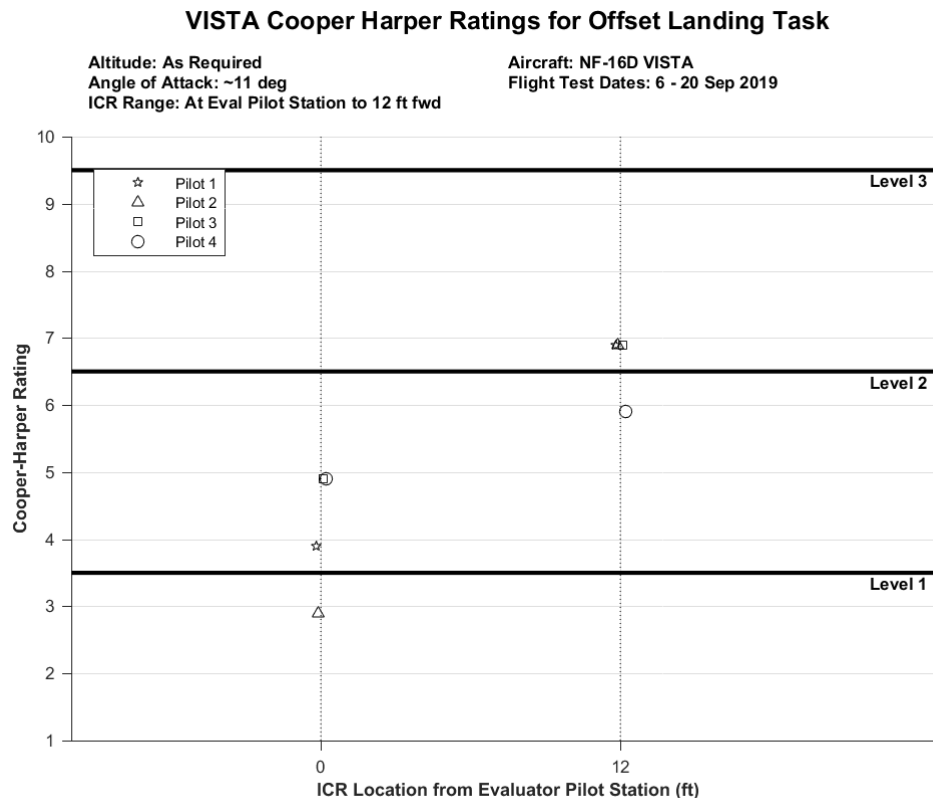


Figure 19 VISTA Cooper Harper Ratings for Offset Landing Task

Comments collected with the ICR forward of the pilot station showed that the response was “very objectionable” requiring “extensive compensation” using the power to control the rate of descent and minimize the unwanted sinking when back stick pressure was applied during the flare. Pilots also commented that the compensation technique of using power rather than stick to flare was required to avoid hard landings and was difficult to execute due to the need to be timed precisely to control the flare height. Overall the forward ICR configuration was deemed unpredictable and not desirable. These results demonstrated the same trend in degraded handling qualities as the ICR moved forward as previous research (reference 2 & 5).

FORWARD ICR EFFECT ON PITCH TRACKING HANDLING QUALITIES

Project pilots accomplished a pitch tracking task in each ICR configuration and provided a Cooper-Harper Rating with associated comments after each run. The pitch tracking task was performed in both the VISTA and VMS at all ICR locations.

Test Methods and Conditions

Each pilot conducted a HUD pitch tracking task in each selected ICR configuration. This task consisted of a programmed moving target line that displayed a pitch error based upon a sum of sines forcing function while the pilot attempted to track the target line using a stationary HUD pipper. The HUD symbology used for this task is shown in figure 20

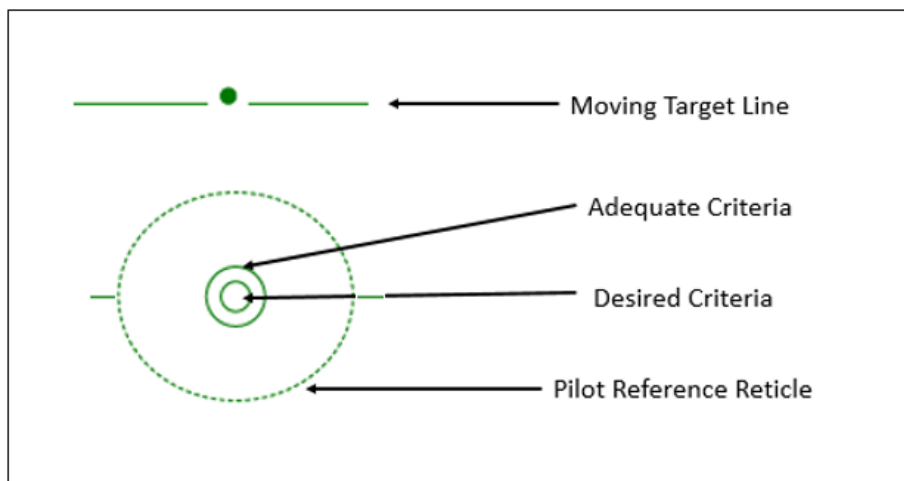


Figure 20 HUD Pitch Tracking Symbology

All pitch tracking tasks were conducted from a trim condition at 20,000 feet PA (+/- 1,000 feet) and 300 KCAS (+/- 20 KCAS). The sum of sines program was run for 30 seconds. Desired criteria was achieved if the EP was able to keep the target within the Desired Criteria pipper for greater than 50% of the task. Adequate criteria was met if the EP was able to keep the target within the Adequate Criteria pipper for greater than 50% of the task. The VSS software automatically calculated the amount of time the EP was able to maintain adequate and desired criteria, and displayed the percentage for each in the lower right of the HUD at the completion of each run.

This task was conducted in the VMS for comparison to in-flight results. The only difference between the VISTA and VMS tasks was the duration of the sum of sines. In the VMS, the task ran for 60 seconds. This was done to enable more pilot comments but was not considered a significant factor to the results collected as the criteria were based on a percentage of time within each boundary level.

Flight Test Results

The results of in-flight pitch tracking testing are shown in Figure 21 below. This plot shows a flat trend with CHRs of 3-4 from all pilots for ICRs between 7 ft aft of the pilot station to 14.6 ft forward of the pilot station. With the ICR more forward than 14.6 ft, there was some variation in CHRs with pilot 4 rating the handling qualities as a CHR of 2 at an ICR of 16.3 ft forward of the pilot station and with pilot 1 providing a CHR of 5 with the ICR at 17 and 21 ft forward. Pilot 4 also provided a CHRs of 5 at an ICR of 21 ft. The CHRs of 5 were associated with pilot comments describing a “weird” or “unusual” mismatch between pitch and g as well as a notable heave sensation. However, the same pilots commented that the mismatch did not affect task performance. The CHR of 2 was associated with pilot comments stating that the “response felt more coordinated.” Even in these cases, the CHRs were within 1 rating of the 3-4 range observed at all other ICRs, and the majority of ratings remained constant between a CHR of 3 to 4.

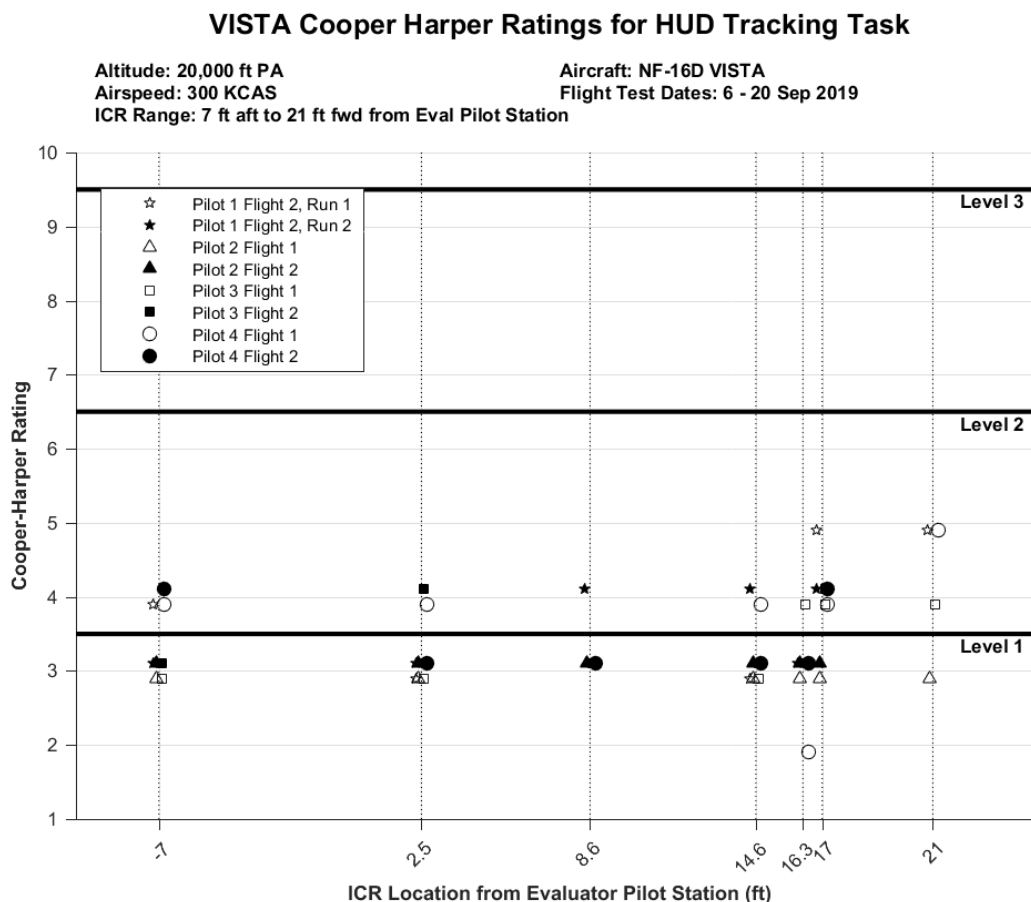


Figure 21 VISTA Cooper Harper Ratings for HUD Tracking Task

Comments collected from all pilots during testing showed that they began to notice the heave of the aircraft as the ICR was moved forward of the pilot station, first being observed at 2.5 ft forward. The further forward the ICR was located the more the heave was noticed. Pilots began commenting on a pitch vs g mismatch as the ICR reached 14.6 ft forward. In all cases, pilots commented that although heave and mismatch was “weird” or “unusual”, it did not impact the ability to execute the task. The ability of pilots to keep the pipper on the target, which was scored by the VISTA, remained relatively constant for each pilot throughout testing with all pilots able to keep the pipper inside the desired criteria for 51-82% of the time and within the adequate criteria for 86-99% of the time.

It was expected that the ICR location would not affect pitch tracking handling qualities of the aircraft. Testing demonstrated that this was correct. Although pilots commented that the heave and mismatch of the aircraft at forward ICRs felt odd or unusual, the location of the ICR did not impact the ability to complete the task.

Fixed-Base Simulation Test Results

The results of the VMS fixed-base pitch tracking testing are shown in Figure 22 below. This plot shows a flat trend with CHRs ranging from 1 to 4 consistently for all ICR configurations (7 ft aft to 21 feet forward of the pilot station).

Comments collected from all pilots during testing showed that they used minimal to moderate compensation, and that all the configurations flown resulted in very similar performance. The performance consistently remained in the desired criteria between 69% and 84% of the time regardless of ICR location. No PIO tendencies were noted in any of the configurations that were flown.

It was expected that the ICR location would not affect the handling qualities during pitch tracking tasks, especially without any motion in the VMS. The test results validated this prediction.

VMS Fixed Cooper Harper Ratings for HUD Tracking Task

Altitude: 20,000 ft PA

Airspeed: 300 KCAS

ICR Range: 7 ft aft to 17 ft fwd of Eval Pilot Station

VMS Mode: Fixed

Test Dates: 16 - 19 Sep 2019

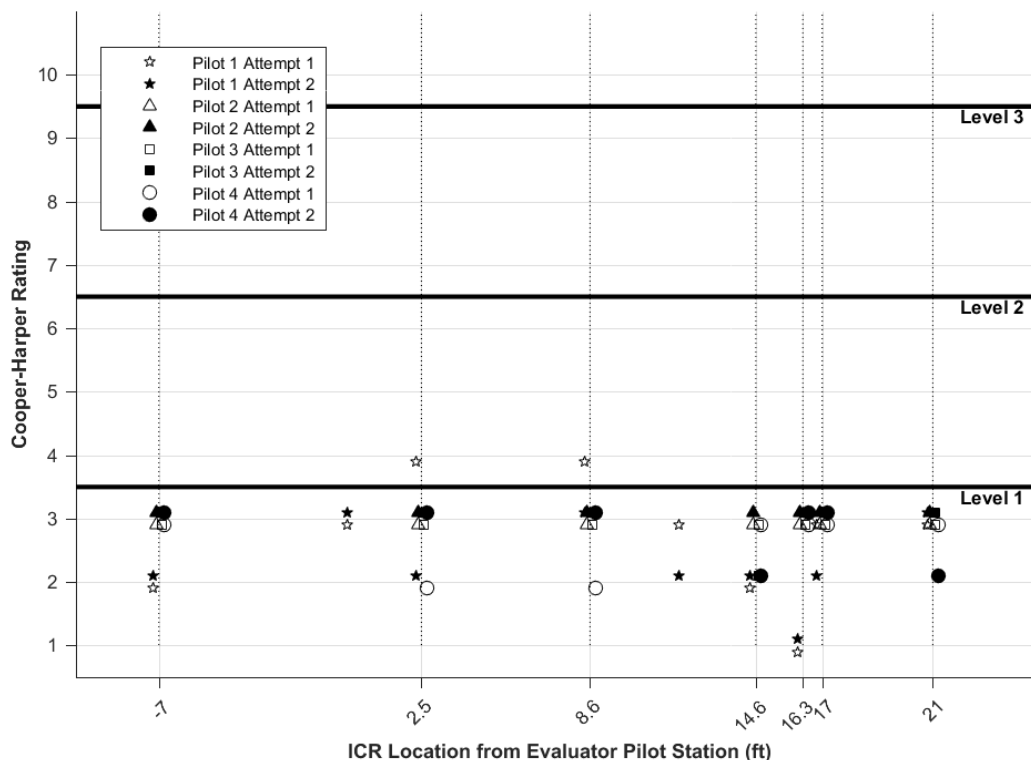


Figure 22 VMS Fixed Cooper Harper Ratings for HUD Tracking Task

Motion Simulation Test Results

The HUD tracking task was performed by all four pilots in the VMS with motion on. The results are shown in figure 23 below. Despite a variation in ICR location, the mode of the CHRs collected remained constant at a CHR of 3. The ratings provided by pilots were split with mostly level 1 ratings and some level 2 ratings. While performing the task, pilots commented that some compensation was required with “leading” as well as “sampling for fine control,” and “stick pulsing.” Pilot comments indicated that the ratings were mostly given due to “unpleasant motions” that were “annoying” but had “no impact” on the task. Comments also showed that the pitch-vs-g mismatch became more apparent around 8.6 ft to 14.6 ft forward. Desired performance ranged from 64.9 - 84.5% and adequate from 94 - 99%. At forward ICRs, no degradation in performance was observed. This indicated that the forward ICR did not impact performance for the HUD tracking task. This was similar to what was observed when the task was performed airborne in the VISTA.

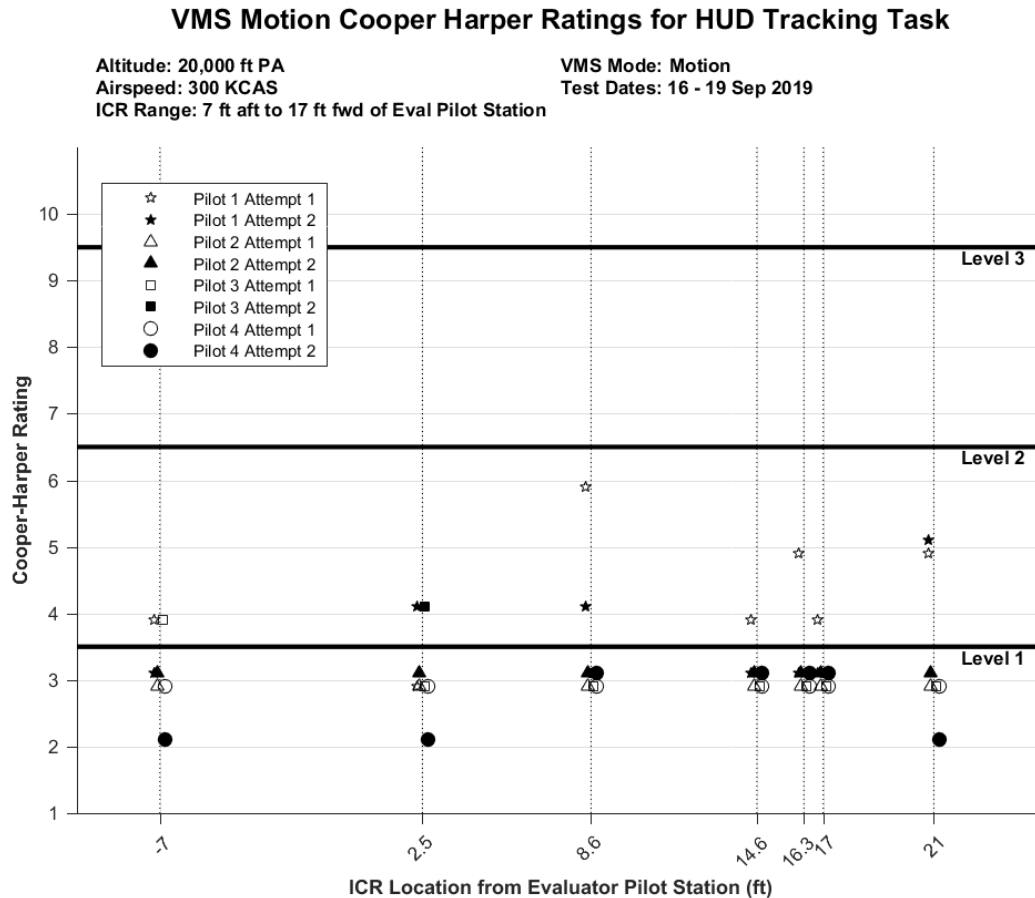


Figure 23 VMS Motion Cooper Harper Ratings for HUD Tracking Task

Outliers averaged within 1 CHR deviation from the 3 to 4 rating trend. Pilot 1 tended to assign higher CHRs than other pilots once the ICR was 8.6 ft forward or greater. At 8.6 ft, during attempt 1, the pilot stated “Whoa!” and commented that it was “very uncomfortable” with a “disturbing” g-mismatch for the task. A CHR of 6 was given. During attempt 1, with the ICR at 16.3 ft forward pilot one assigned a CHR of 5 and commented that the pitch-vs-g mismatch was “objectionable.” At 21 ft forward pilot 1 assigned a CHR of 5 during both attempts. Attempt 2 comments were that the g-mismatch was “annoying” and “more compensation” was noted by Pilot 1. These comments indicated that the g-vs-pitch mismatch was the most undesirable characteristic observed by the pilot. Analysis of the desired and adequate performance achieved by Pilot 1 on these runs showed that task performance was not impacted although higher CHRs were assigned.

PIORs were recorded for Pilot 3 on several runs and are shown in figure 24 below. All PIORs assigned by the pilot were a ‘2’ and did not vary with changing ICR locations. The pilot commented that abrupt maneuvers led to undesirable motions but that task performance was not compromised. Pilot 3 noted a “drop out feeling” for at least 3 test runs as well as pitch-vs-g mismatch that was “slight for abrupt movements.” No oscillations were noted. Overall, it was observed that tighter control and abrupt maneuvers led to the undesirable motions. Pilot 3 was able to reduce the undesirable motions by “decreasing gain.”

VMS Motion Pilot Induced Oscillation Ratings for HUD Tracking Task

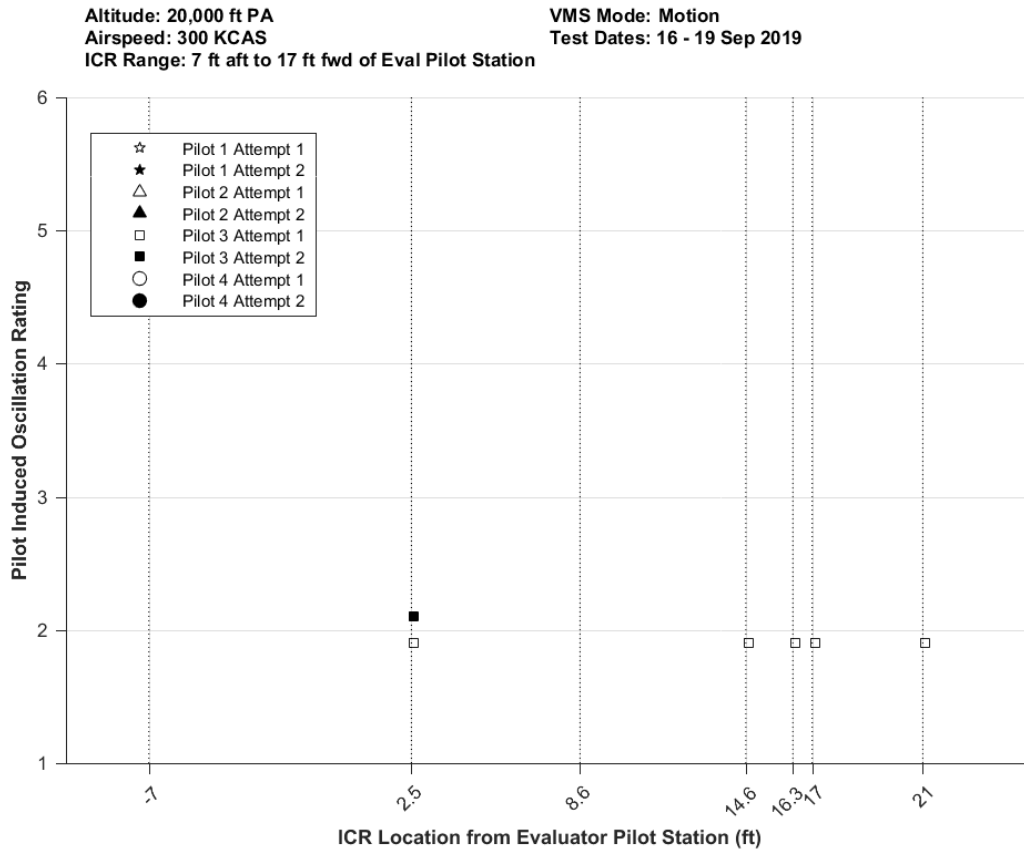


Figure 24 VMS Motion Pilot Induced Oscillation Ratings for HUD Tracking Task

FORWARD ICR EFFECT ON SIMULATED AERIAL REFUELING HANDLING QUALITIES

The effect of forward ICRs on simulated aerial refueling was investigated. Testing investigated three components of aerial refueling using a tanker simulated by a T-38; formation station keeping on the wing, maintaining the aerial refueling envelope, and executing an emergency separation.

Formation Station Keeping Test Methods and Conditions

Formation station keeping was accomplished in flight by positioning the VISTA aircraft in on the wing of the T-38 target acting as a simulated tanker, with a minimum of 1 ship length lateral spacing. The SP then selected the appropriate ICR configuration and transferred control of the VISTA to the EP with the VSS engaged on the center stick. The EP then closed spacing to approximately 1 ship width lateral spacing while maneuvering forward/aft as required to look down the leading edge of the target wing. The EP then attempted to maintain formation position while the target flew the following profile:

- Level, stable platform for 10 seconds
- 1.2–1.5g pull to a 2.5 degree climb angle that was held for 10 seconds
- 0.8–0.5g push over to level flight and held for 10 seconds
- 0.8–0.5g push over to a 2.5 degree descent angle that was held for 10 seconds

- 1.2–1.5g pull to level flight and held for 10 seconds

The target aircraft began the profile at a trim condition at 20,000 feet PA (+/- 1,000 feet) and 300 KCAS (+/- 10 KCAS) and maintained the same airspeed for the duration of the profile. During the maneuver, the EP attempted to maintain the tolerances shown in figure 25.



Figure 25 Formation Station Keeping Desired and Adequate Criteria

Due to the constraints of the VMS, the formation station keeping task was modified so as to be executable in the simulator. The primary constraint was the VMS field of view (FOV) as shown in figure 10. This restricted the ability to execute the task as defined for airborne execution. In order to best replicate the formation station keeping task with the limited FOV, the simulator task consisted of initializing as shown in figure 26, 45 degrees aft of line abreast and 3 ship lengths away with the ICR configuration loaded. Once on run, the pilot attempted to maintain the target aircraft's wingtip superimposed within the fuselage of the target aircraft while the T-38 maneuvered. The VMS T-38 target profile was recorded in the simulator, having a pilot execute the profile using the low end of the target g.

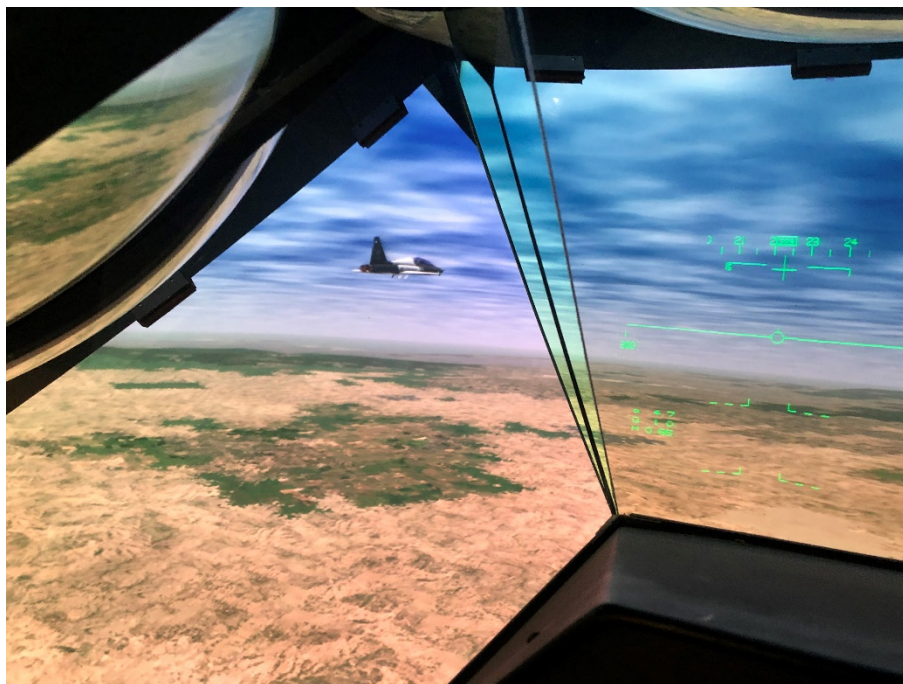


Figure 26 VMS Formation Station Keeping Initialization Position

Desired criteria for the VMS task consisted of maintaining the target wingtip within the fuselage of the target T-38 as shown in figure 27 and depicted by the green lines for the duration of the task with ≤ 2 deviations into adequate criteria for ≤ 2 seconds. Adequate criteria consisted of maintaining the aircraft's wingtip within the bounds created by the top of the canopy to the bottom of the speed brakes as shown by the red lines in figure 27.

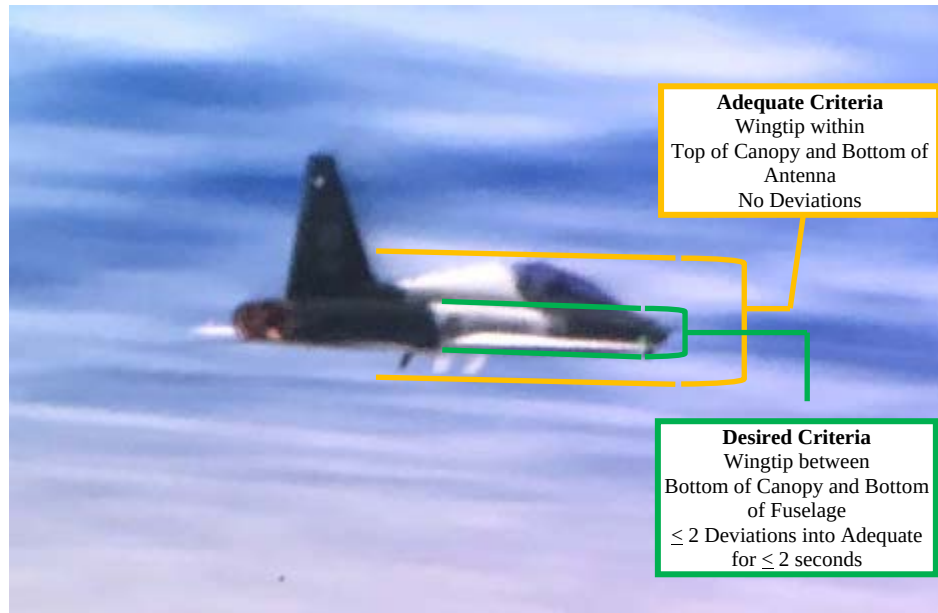


Figure 27 VMS Formation Station Keeping Desired and Adequate Criteria

Testing was conducted with the VMS in both full motion and in fixed-base. All simulator testing was conducted in simulated day visual conditions with no simulated turbulence or environmental effects.

Flight Formation Station Keeping Test Results

The data collected during flight testing is shown in figure 28 below. The plot shows the expected trend that as ICRs moved forward of the pilot station the CHRs increased. With the ICR located 7 ft behind the pilot station, all CHRs were 3 or less indicating level 1 handling qualities. As the ICR moved forward of the pilot station, CHRs increased to the point where handling qualities were rated level 3 by all pilots at an ICR of 21 ft forward of the pilot station. In the intermediate ICR locations, CHRs were split between level 1 and 2 when ICRs were between 2.5 ft forward to 8.6 ft forward. At an ICR of 14.6 ft forward CHRs were mostly level 2 with a single level 1 rating and a single level 3 rating. With the ICR 16.3 and 17 ft forward CHRs were all level 3 with the exception of pilot 2's first flight where a level 2 rating was assigned.

VISTA Cooper Harper Ratings for Formation Station Keeping Task

Altitude: 20,000 ft PA

Airspeed: 300 KCAS

ICR Range: 7 ft aft to 21 ft fwd from Eval Pilot Station

Aircraft: NF-16D VISTA

Flight Test Dates: 6 - 20 Sep 2019

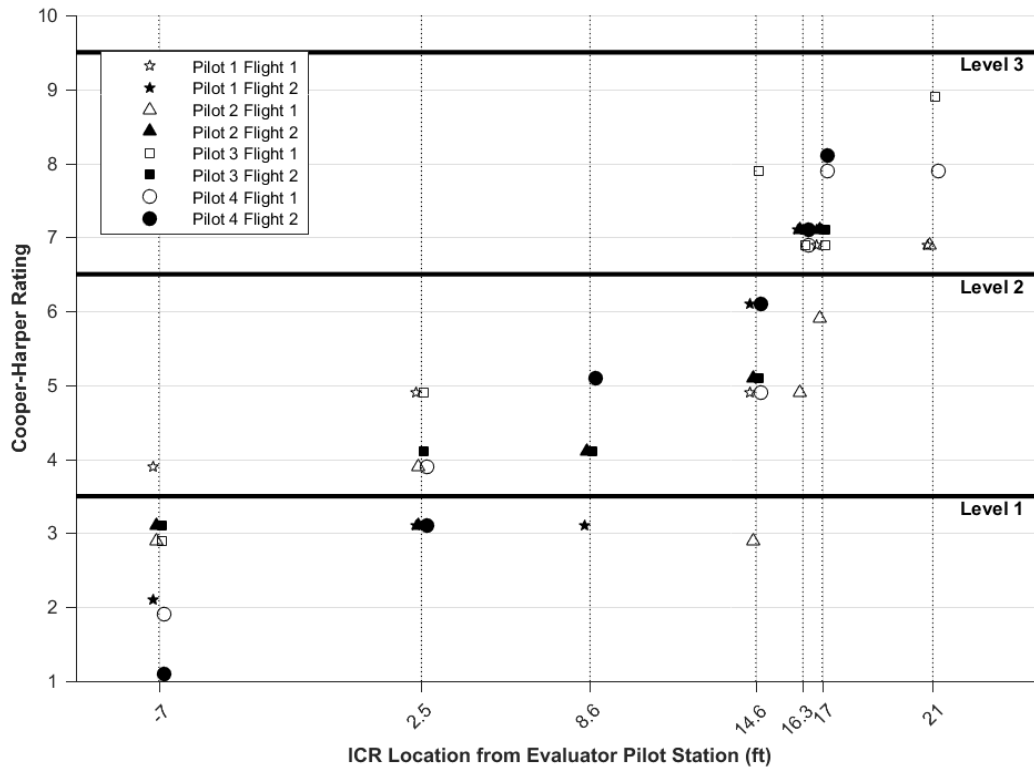


Figure 28 VISTA Cooper Harper Ratings for Formation Station Keeping Task

There were several notable outliers that occurred during testing of formation station keeping in flight. The first few outliers occurred on Pilot 2's first sortie where he rated the handling qualities two levels better than all other pilots. With the ICR located 14.6 ft forward of the pilot station, Pilot 2 gave a level 1 rating while the weight of the other ratings indicated level two handling qualities. At an ICR of 16.3 ft, Pilot 2 provided a level 2 HQ rating, while the other pilots indicated level 3 handling qualities. Although indicating better handling qualities than the other pilots, Pilot 2 commented that with the ICR at 14.6 ft the aircraft was pitch sensitive during flight path changes, and with the ICR at 16.3 ft he could feel the heave and was trying to match the target's flight path but was having overshoots. It is also notable that Pilot 2 conducted his evaluation of the ICR at 14.6 ft after having accomplished testing at ICRs of 21 ft and 17 ft forward; potentially making the less objectionable handling qualities appear better than they would have otherwise appeared. In Pilot 2's second flight he rated the handling qualities at 14.6 ft and 16.3 ft forward similarly to the other pilots giving a level 2 rating (CHR of 5) with the ICR at 14.6 ft and a level 3 rating (CHR of 7) with the ICR at 16.3 ft.

Pilot 3 also deviated from other ratings with the ICR at 14.6 ft forward of the pilot station, providing a level 3 rating (CHR of 8) with the preponderance of other ratings indicating level 2 handling qualities. This outlier also occurred during the pilot's first test flight and occurred after having attempted formation station keeping with the ICR located at 2.5 ft forward of the pilot station. Similar to Pilot 2, the large jump in ICR

location from just forward of the pilot station to dramatically forward may have impacted Pilot 3's perception of the aircraft's handling qualities. Although Pilot 3 provided an outlier rating with the ICR at 14.6 ft on his first flight, on his second flight his CHR fell in line with the other ratings, providing a level 2 rating (CHR of 5) at an ICR of 14.6 ft.

PIORs were also collected during testing when applicable. The PIORs collected during this task are shown below in figure 29. As shown in the plot, no PIORs were given with the ICR aft of the pilot station. A single PIOR of 2 was given at an ICR of 2.5 ft forward and a single PIOR of 3 was given at 8.6 ft forward. At more forward ICRs more PIORs were given with PIORs of 3 given at 14.6 ft forward and a split between 3s and 4s at 17 ft forward. With the ICR 21 ft forward of the pilot station, only two pilots gave PIORs with pilot 3 giving a PIOR of 2. Although a 2 was given, the pilot commented "familiarization with the task led to compensation techniques to minimize oscillations." Two pilots did not provide PIORs at the 21 ft forward ICR. Pilot 1 hit a VSS safety trip, thus disengaging EP control of the VISTA aircraft, and commented that the aircraft was "right on the edge of controllable." Pilot 4 commented that they "could not complete the task", and that they "backed almost completely out of the loop."

During testing pilot comments were collected in conjunction with the CHRs and PIORs to paint a more in-depth picture of the effect of different ICR locations. Comments collected during testing indicated that the effects of forward ICRs included a sense of time delay, a feeling of mismatch between pitch and g, and when the ICR got too far forward, the onset of PIO and a requirement to back out of the loop. Pilots commented that the first thing noticed as ICR moved forward was that there felt like some time delay between adding a stick input and seeing the response. As the ICR continued to move forward the sense of time delay increased and the mismatch between an initial pitch and actual vertical movement increased. All pilots observed at some forward ICR a requirement to reduce gain or back out of the loop completely by freezing the stick in order to not have excessive overshoots. These results show that as the ICR moved forward of the pilot station, all pilots followed the same trend when evaluating the handling qualities. At 16.3 feet forward of the pilot station, handling qualities degrade to level 3, and the task became unattainable.

VISTA Pilot Induced Oscillation Ratings for Formation Station Keeping Task

Altitude: 20,000 ft PA

Airspeed: 300 KCAS

ICR Range: 7 ft aft to 21 ft fwd from Eval Pilot Station

Aircraft: NF-16D VISTA

Flight Test Dates: 6 - 20 Sep 2019

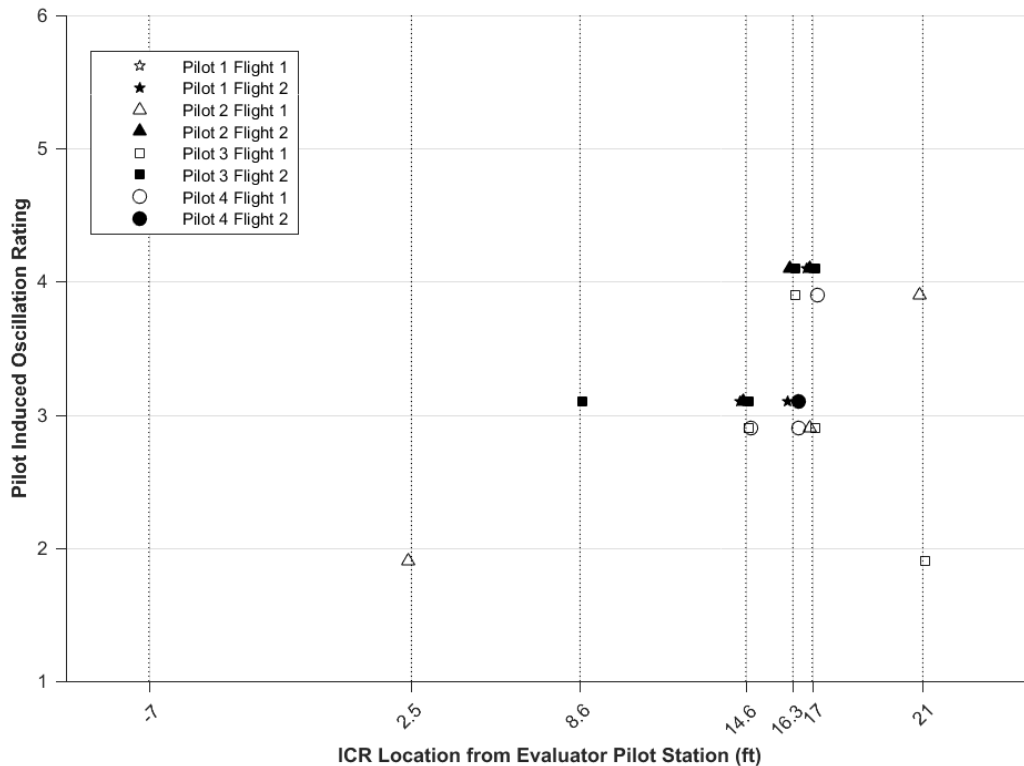


Figure 29 VISTA Pilot Induced Oscillation Ratings for Formation Station Keeping Task

Fixed-Base Simulation Formation Station Keeping Test Results

The CHRs collected during the formation station keeping task in VMS with motion off are shown in figure 30. This plot shows the overall trend that as the ICR is moved forward the CHRs degrade. The task was not performed with the ICR located 21 ft forward of the pilot station because the handling qualities had already been confirmed to be Level 3. With the ICR located 7 ft aft of the pilot station the CHRs were split between 3 and 4 with a single CHR of 5 given by pilot 1 on his first sortie. When the ICR was moved forward, CHRs increased. At 17 ft forward the CHRs were between 7 and 9 with a single CHR of 6 given by pilot 3 on his first sortie. At an ICR of 14.6 ft forward the CHRs given in the fixed-base simulator were between a 5 and an 8.

Without motion pilots did not comment on heave or pitch vs g mismatch but did notice a requirement to add lead compensation throughout the testing and commented on a workload increase the further forward ICR was located from the pilot station. At an ICR of 14.6 ft forward, pilots began commenting on a need to reduce gain, which continued as the ICR moved more forward.

VMS Fixed Cooper Harper Ratings for Formation Station Keeping Task

Altitude: 20,000 ft PA

Airspeed: 300 KCAS

ICR Range: 7 ft aft to 17 ft fwd of Eval Pilot Station

VMS Mode: Fixed

Test Dates: 16 - 19 Sep 2019

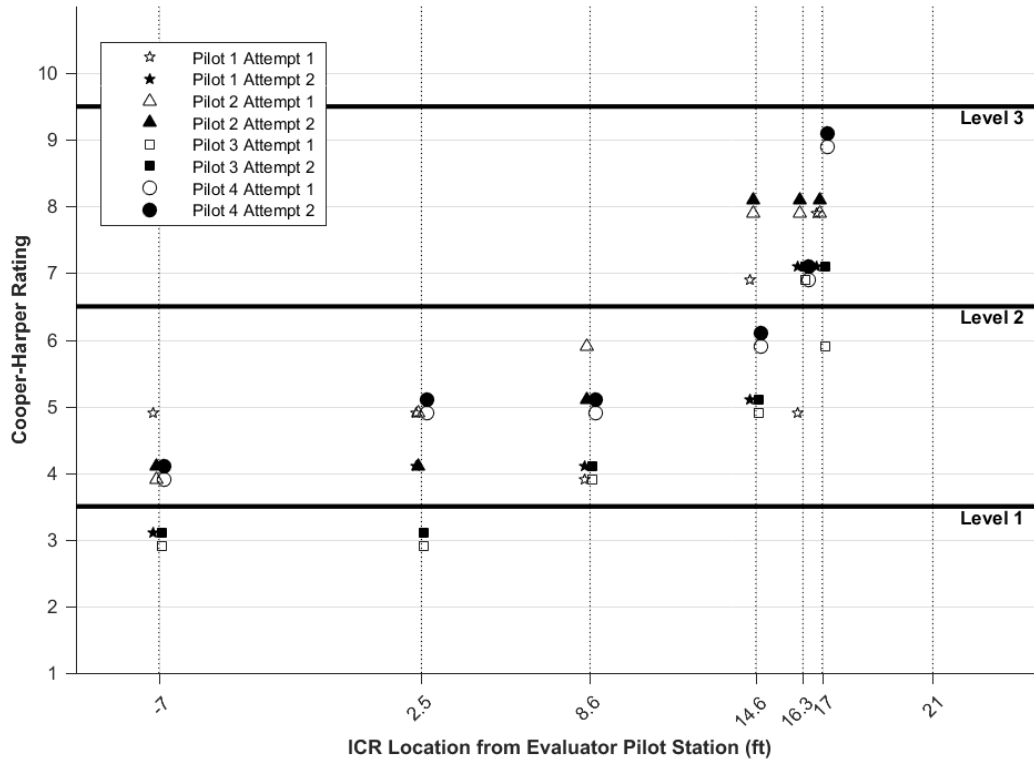


Figure 30 VMS Fixed Cooper Harper Ratings for Formation Station Keeping Task

The PIORs collected during fixed-base simulation are presented in figure 31. This plot shows the same overall trend that increasing ICR forward of the pilot station increased the PIORs with a dramatic increase in the number of PIORs given occurring at 14.6 ft forward of the pilot station. With the ICR at 14.6 and 16.3 ft forward, the lowest PIOR rating given was a 3.

VMS Fixed Pilot Induced Oscillation Ratings for Formation Station Keeping Task

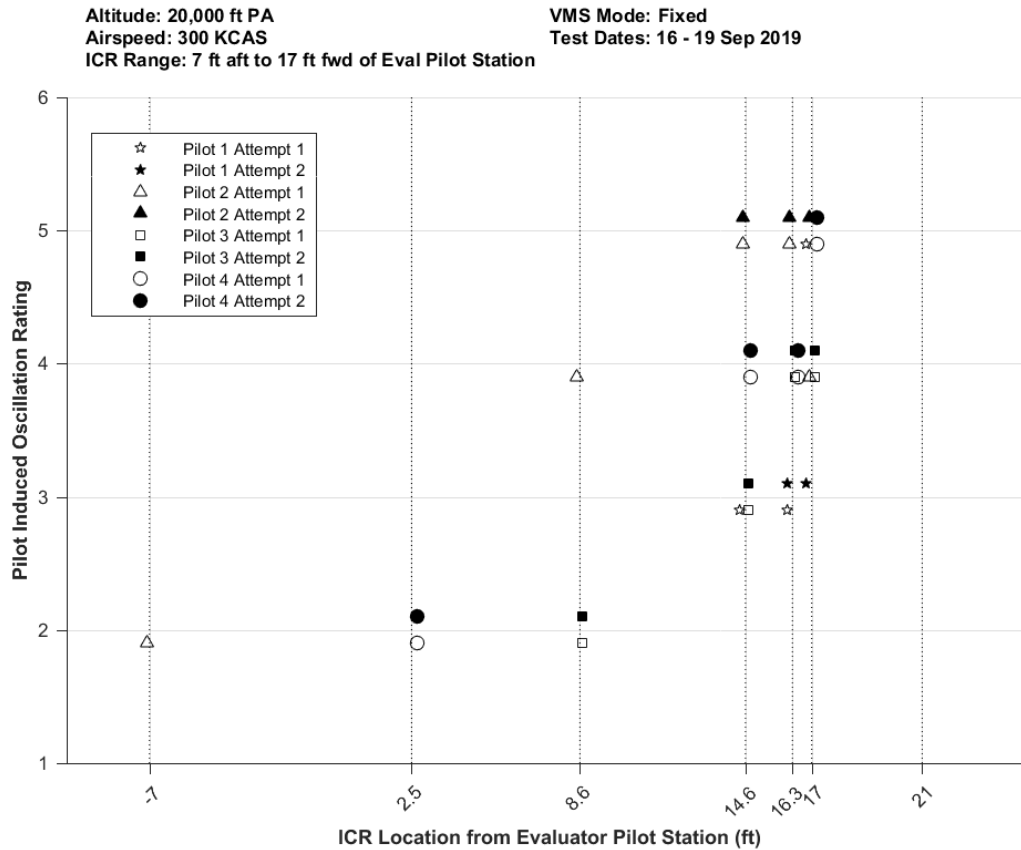


Figure 31: VMS Fixed Pilot Induced Oscillation Ratings for Formation Station Keeping Task

Motion Simulation Formation Station Keeping Test Results

The results of VMS full motion formation station keeping are shown below in figure 32. As the ICR began to move forward, the handling qualities began to degrade into the high Level 2 criteria, and ultimately in to Level 3 as the ICR reached 16.3 ft forward of the pilot station. With the ICR located aft of the pilot station (-7 ft), some level 2 CHR's were assigned, however these results remained mostly consistent at the ICR was moved forward of the pilot station by 2.5 ft. Once the ICR reached 8.6 ft forward of the pilot station, CHR's centered on a rating of 5 or 6. At 16.3 feet forward of the pilot station, all but one CHR was in level 3 criteria (all ratings 7 or greater). At an ICR of 17 ft forward of the pilot station, no pilots were able to complete the task while maintaining adequate criteria.

VMS Motion Cooper Harper Ratings for Formation Station Keeping Task

Altitude: 20,000 ft PA

Airspeed: 300 KCAS

ICR Range: 7 ft aft to 17 ft fwd of Eval Pilot Station

VMS Mode: Motion

Test Dates: 16 - 19 Sep 2019

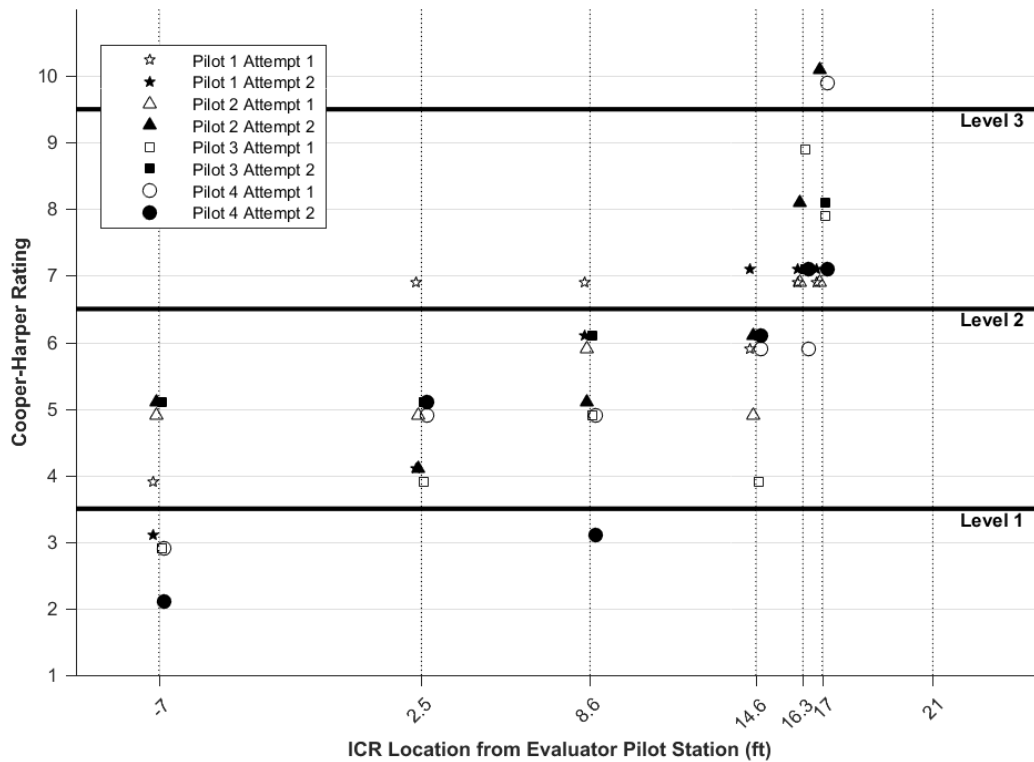


Figure 32 VMS Motion Cooper Harper Ratings for Formation Station Keeping Task

Several outliers are of interest. At 8.6 ft forward, pilot 1 assigned a rating of 7, with the comment that “no one wants to fly this.” This was the first attempt at this ICR for pilot 1. The subsequent attempt of this ICR resulted in a CHR of 6, with the comment that the pilot experienced a “little lag”, and that there was extensive “stick sampling.”

At an ICR of 16.3 ft, all but pilot 4 put all ratings in level 3. Pilot 4 assigned a CHR of 6 to this ICR on the first attempt, but elected to attempt this configuration twice before assigning a rating. Multiple attempts would only be performed before giving a rating if the pilot felt they could not set up properly or adequately evaluate the configuration. Additionally, the pilot stated that there was a large delay between stick input and flight path response, and that the response was “sluggish”, but pilot technique was adjusted to complete the task.

At an ICR of 17 ft forward, pilot 4 noted that two techniques were attempted over two runs. The first technique was smooth control inputs while remaining in the loop. The second was high frequency stick pulses to create a stair step response from the aircraft. In both cases, the aircraft response could not keep up with the target aircraft. On the initial target climb, the test aircraft would only sink lower in response to pitch up stick commands. Once the test aircraft flight path began to climb, the climb could not be arrested, and a large vertical overshoot was observed. The oscillations then became divergent. This resulted in a

CHR of 10. Pilot 2 also noted that oscillations grew, requiring the pilot to freeze the stick, and ultimately abandon the task. This also resulted in a CHR of 10.

The PIORs for VMS Formation Station Keeping are shown below in Figure 33. Starting at an ICR of 8.6 ft and forward, PIORs of 3 were assigned by most pilots. At an ICR of 14.6 feet, pilot 2 and 3 assigned PIORs of 2. Pilot 2 noted that some bobbling required a stick gain reduction. Pilot 3 noted that sampling was required for fine control. At an ICR of 17 ft, pilot 2 assigned a PIOR of 5 on the second attempt of the task. Of note, oscillations grew, and the pilot had to back out of the loop and abandon the task. Pilot 4's PIOR of 5 corresponds to the same task mentioned above where a CHR of 10 was assigned.

VMS Motion Pilot Induced Oscillation Ratings for Formation Station Keeping Task

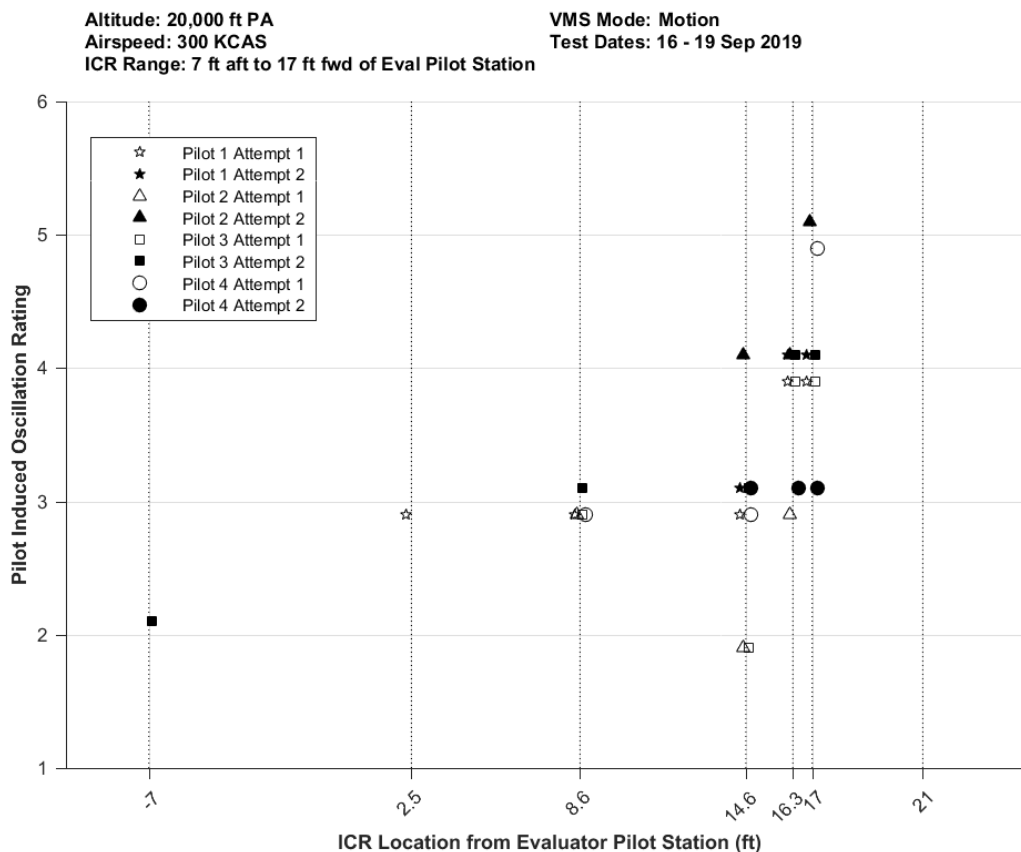


Figure 33 VMS Motion Pilot Induced Oscillation Ratings for Formation Station Keeping Task

Simulated Air Refueling Test Methods and Conditions

Simulated air refueling was accomplished by utilizing a T-38C acting as a simulated tanker stabilized at 20,000 feet PA (+/- 1,000 feet) and 300 KCAS (+/- 10 KCAS) with speed brakes deployed. The VISTA test aircraft maneuvered as required to stabilize one ship length behind, and one ship width below the target T-38C aircraft (out of the wake turbulence region). Once stable, the tested configuration was engaged by the SP and control was transferred to the EP. The test aircraft was then moved forward at a walking pace as required to position the aircraft within the simulated refueling envelope. This envelope was judged using the T-38C speed brakes and target decal as a visual reference. The bottom edge of the speed brakes of the T-38 were attempted to be visually aligned within the desired envelope of the target decal as illustrated in figures 34 and 35. This simulated refueling envelope was designed based on current USAF aerial refueling tankers, which have refueling boom envelopes that are 25–40 degrees of angular displacement from the tanker fuselage. The adequate performance envelope, represented by the outer limits of the decal, shown in figure 34, correlates to the full limits of the boom envelope, as shown in figure 35. The desired performance criteria represents a notional refueling receiver position within the heart of the envelope, providing a three degree buffer from the absolute boom limits. Testing was conducted from 1 ship width aft to no closer than nose tail clearance.

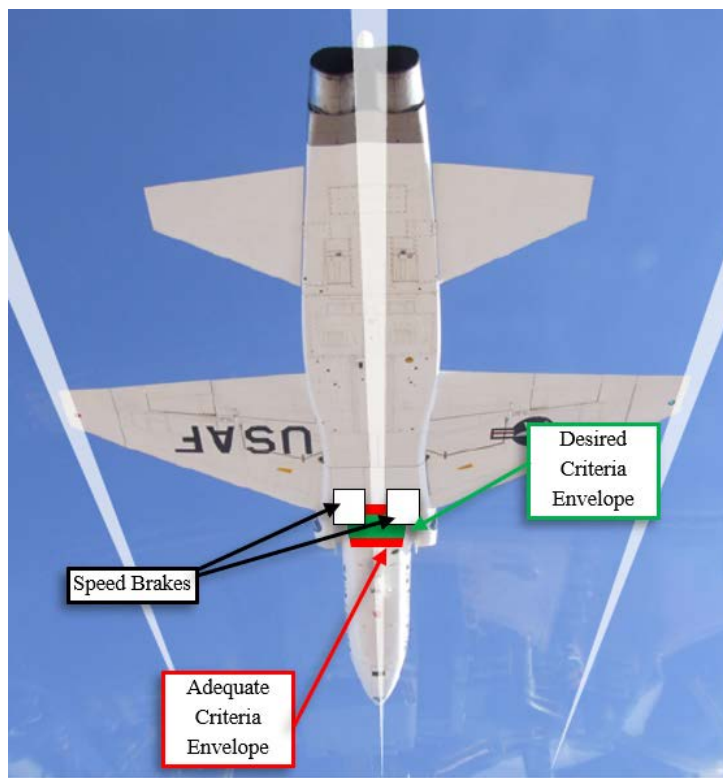


Figure 34 T-38C Target Simulated Air Refueling Task Criteria (Bottom View)

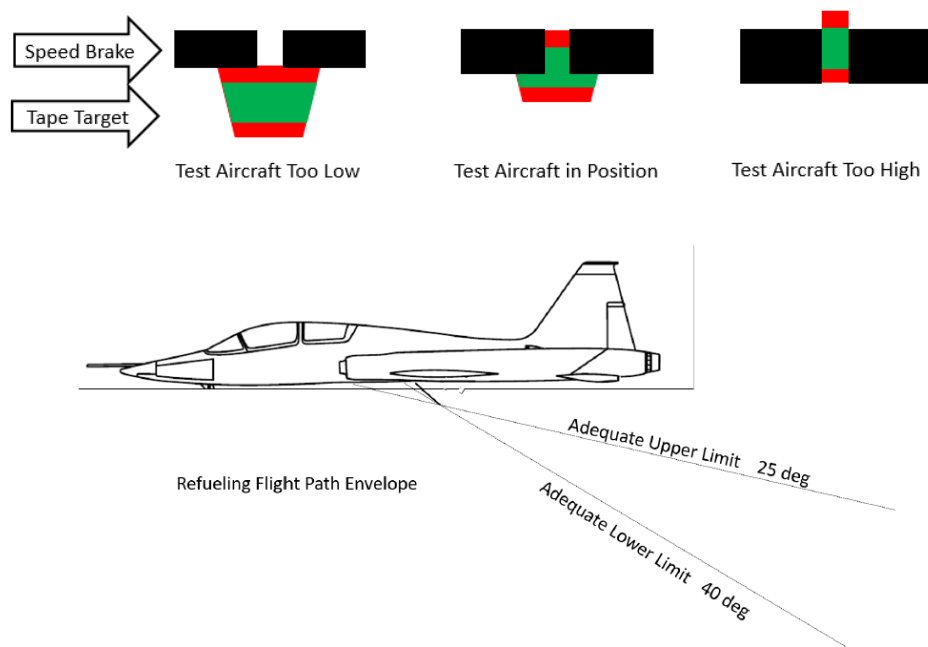


Figure 35 T-38C Target Simulated Air Refueling Task Criteria (Side View)

With the test aircraft stabilized in the simulated refueling position, a 30 second timer was started while the EP attempted to maintain the simulated refueling envelope. Adequate performance was defined as being able to maintain the bottom edge of the speed brake within the total length of the decal for 30 seconds without any deviations. Desired performance was defined as being able to maintain the bottom edge of the speed brake within the green envelope for 30 seconds with no more than two momentary (< 2 second) deviations into the red envelope. The EP rated their performance in real time and was recorded by the control room. All flight testing was conducted in day visual conditions with the target aircraft maintaining straight and level flight.

The simulated air refueling task was modified to be flyable in the VMS due to its visual constraints. The primary constraint was the simulator vertical field of view (FOV) which consisted of ± 12 degrees vertically as shown in figure 11. The simulator air refueling task in VMS consisted of initializing 400 ft aft of a KC-135R target aircraft. The boom of the tanker target was extended 30 degrees down from horizontal and consisted of red and green colored sections designating adequate and desired criterion similar to the inflight task as shown in figure 36. Once initialized the pilot advanced the throttle and moved forward at a walking pace to stabilize between 325 and 375 feet aft from the boom with the HUD horizon line bisecting the green “desired” section of the boom as shown in figure 37. The distance aft from the boom was used to keep throttle control as part of the task to replicate airborne workload required, in addition to keeping the target within the VMS FOV. The distance was communicated to the pilot by the test engineer. Once stable, a 60 second timer was started while the pilot attempted to maintain the green “desired” envelope. Adequate performance was defined as being able to maintain the horizon line within the red envelope section of the boom for the full 60 seconds without any deviations. Desired performance was defined as being able to maintain the horizon line within the green envelope for 60 seconds with no more than two momentary (< 2 second) deviations into the red envelope.

Testing was conducted with the VMS in both full motion and in fixed-base. All simulator testing was conducted in simulated day visual conditions with no simulated turbulence or environmental effects.

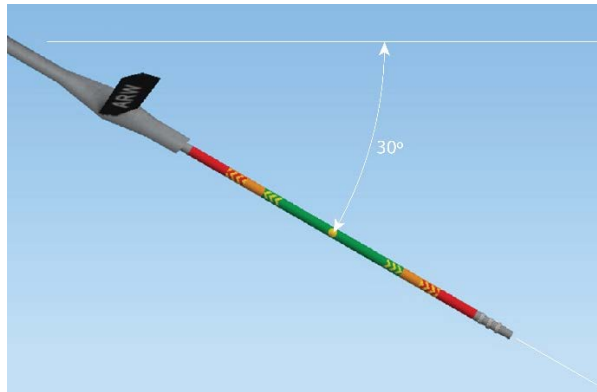


Figure 36 VMS Simulated Air Refueling Task Boom (Side View)



Figure 37 VMS Simulated Air Refueling Task

Flight Simulated Air Refueling Test Results

The data collected during the simulated air refueling task conducted in VISTA is shown in Figure 38. This plot shows the overall trend that as ICR increases forward of the pilot station, the CHRs increase. With the ICR located aft of the pilot station all CHRs were in the level 1 region with ratings of 2 and 3. With the ICR located just forward of the pilot station at 2.5 ft, the CHRs began to increase with a CHR of 7 and two CHRs of 4 provided. With the ICR located at 14.6 ft forward of the pilot station all but one CHR was in level 2 with a single CHR of 3 in the level 1 regime. At 16.3 ft forward all but one CHR was level 2 with a single CHR in the level 3 regime. As the ICR reached the maximum forward ICR tested of 21 ft forward, CHRs were split with two CHR 7s and two CHR 6s provided by the pilots. Overall the trend showed that as ICR increased, the CHRs increased.

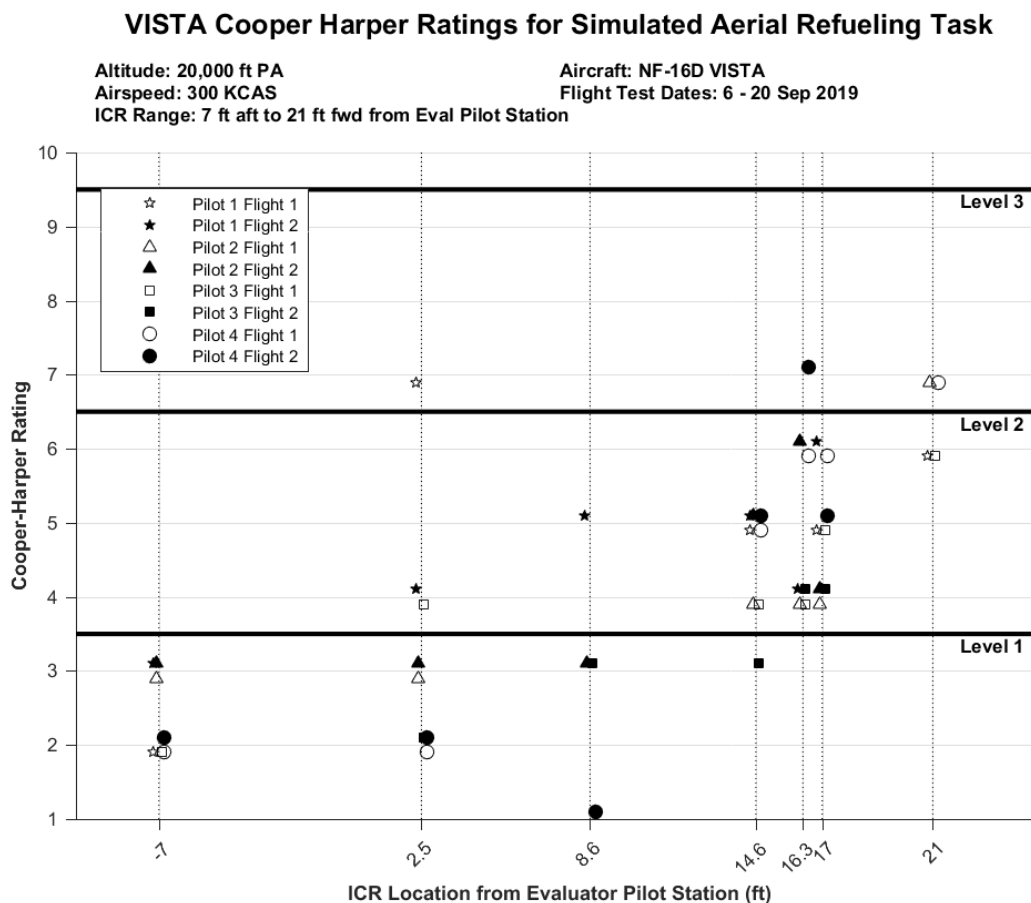


Figure 38 VISTA CHR for Simulated Aerial Refueling Task

Several data points collected deviated from the majority. With the ICR at 2.5 ft forward, pilot 1 gave a CHR of 7 commenting that the aircraft felt “twitchy” and required “maximum compensation”. On Pilot 1’s second sortie he rated the same ICR location a CHR 4, more in line with the other pilot ratings. With the ICR at 8.6 ft forward, pilot 4 gave a CHR of 1 commenting that “feeling met expectations” and that he only had to provide “low frequency inputs and corrections.” Only a single test point per pilot was conducted at this ICR configuration. However, it was notable that when the ICR increased to its next step of 14.6 ft forward, pilot 4 gave a CHR of 5 on both flights.

The PIORs collected during this task are shown in Figure 39. No PIORs were given with the ICR aft of the pilot station. With the ICR at 2.5 ft forward a single PIOR of 2 was given. With the ICR at 14.6 ft and 16.3 ft forward, PIORs of 2 to 5 were given but then saw a drop to 2s and 3s at an ICR of 17 ft forward. Two PIORs of 4 were given with the ICR at 21 ft forward. Although there was significant variation between ratings between pilots and between different runs by the same pilot, the trend that PIORs became more common with ICRs 14.6 ft forward or greater is notable.

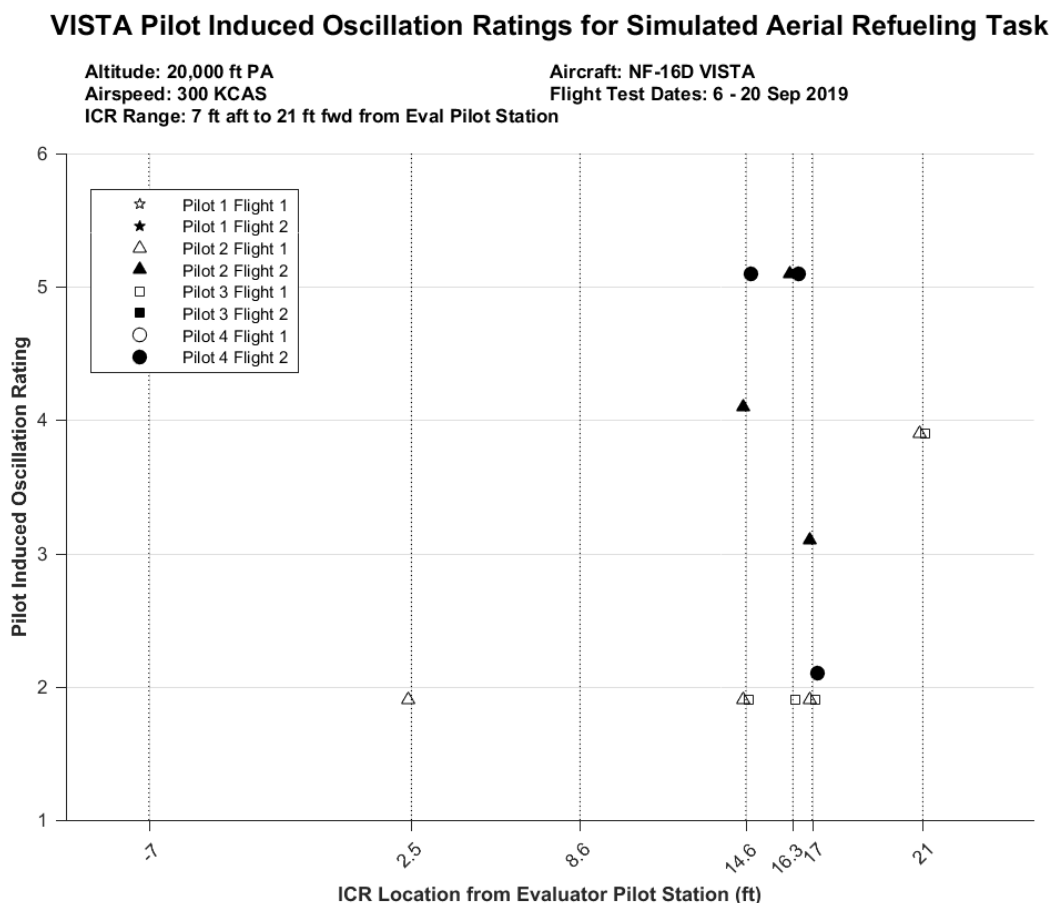


Figure 39 VISTA PIOR for Simulated Aerial Refueling Task

Pilot comments were collected during testing to better characterize the effects of ICR on the task. It was noted by all pilots that this task required lower gain than the formation station keeping task. If the aircraft was able to be stabilized within the simulated air refueling envelope, very small corrections were required. Multiple pilots mentioned being “light on the stick.” The propensity to stabilize on conditions and only make small corrections as needed likely created variability in the gain required to complete the task both between different pilots and between different runs by the same pilot. This likely is a factor in the variability of the PIORs seen at higher ICRs. As the ICR reached 14.6 ft forward, pilots began to comment on a feeling of time delay, pitch bobbles and low amplitude oscillations and needing to back out of the loop slightly. At an ICR of 16.3 pilots began sensing heave and backing out of the loop more with more pilots commenting on a PIO tendency. At an ICR of 21 ft forward pilots commented on large pitch oscillations,

backing completely out of the loop, and exhibiting difficulty in stabilizing on conditions prior to beginning the test run.

The same ICR configurations were flown in Simulated Aerial Refueling as were flown in the Formation Station Keeping. These same ICR configurations in the refueling tasks yielded lower CHRs than Formation Station keeping. Pilot's commented that in the Refueling tasks, once established in a trim condition, only small inputs were required to stay there. There was nothing forcing them into the loop or out of the trim condition, as was the case in Formation Station Keeping. As expected, the flight test results showed that the handling qualities degraded as the ICR moved forward.

Fixed-Base Simulation Simulated Aerial Refueling Test Results

The CHRs collected during the simulated aerial refueling task in the VMS with motion off are shown in Figure 40. The data collected showed significant variability between pilots and between different runs by the same pilot. With the ICR at 2.5 ft forward there was an observed decrease in the majority of CHRs as all but pilot 1 rated the task a CHR 2 or 3 and pilot 1 giving a CHR of 6 on both runs. With the ICR at 8.6 ft forward the largest variability in ratings was observed with two CHR 2s given by pilot 3 while pilot 1 gave a CHR of 10 on his first run. It is notable that pilot 1 later gave the same configuration a CHR 4 on his second run. Pilot 1 also deviated from the majority with the ICR at 16.3 ft forward, giving a CHR of 1 on both his runs while the other pilots provided CHRs of 5 and 6. In looking at the overall trend, ratings were mostly split between a level 1 and level 2 rating with ICRs up to and including 14.6 ft forward. With ICRs forward of 14.6 ft the ratings became mostly level 2 at 16.3 ft forward and split between level 2 and level 3 at 17 ft forward. Pilot 1 was the only pilot to attempt the task at 21 ft forward and rated the task level 3 (CHR 7).

VMS Fixed Cooper Harper Ratings for Simulated Aerial Refueling Task

Altitude: 20,000 ft PA

Airspeed: 300 KCAS

ICR Range: 7 ft aft to 17 ft fwd of Eval Pilot Station

VMS Mode: Fixed

Test Dates: 16 - 19 Sep 2019

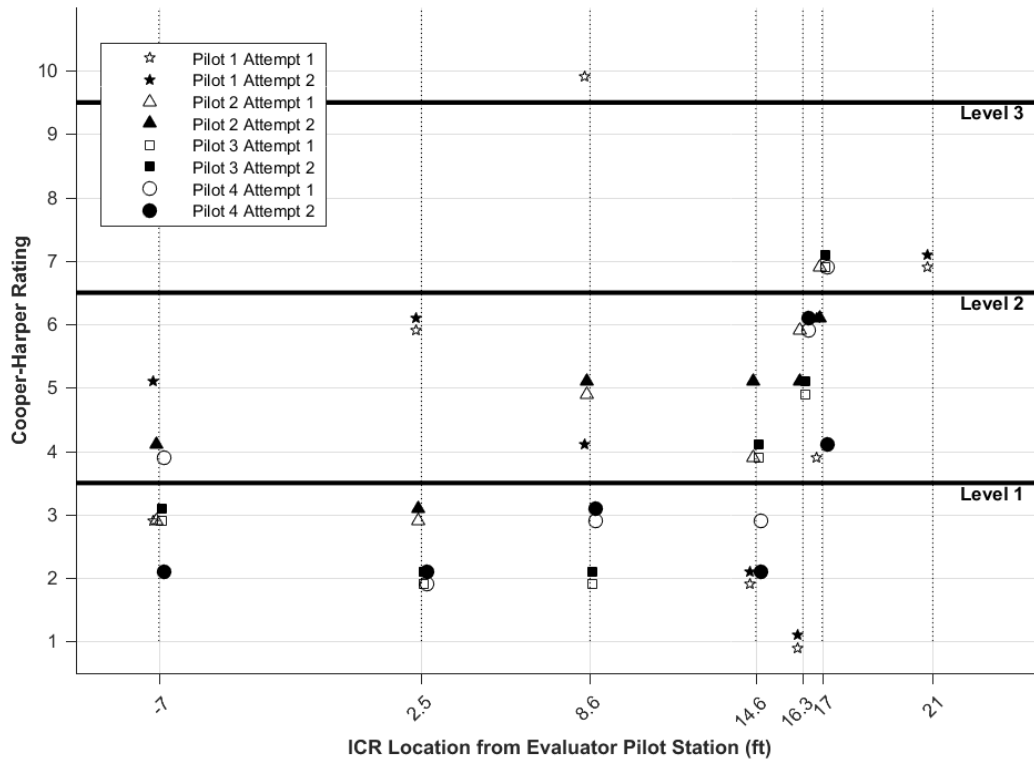


Figure 40 VMS Fixed CHR for Simulated Aerial Refueling Task

The PIORs for the simulated aerial refueling task in the fixed-base simulation are shown in figure 41. The PIORs show a similar trend to the in-flight results whereby the number of PIORs given dramatically increase when the ICR is 14.6 ft forward or greater with PIORs of 2 to 5 given. Several PIORs of 2 and 3 were given with ICRs less than 14.6 ft forward with a single PIOR of 5 given by pilot 1 at 8.6 ft forward, associated with his CHR of 10 discussed above.

VMS Fixed Pilot Induced Oscillation Ratings for Simulated Aerial Refueling Task

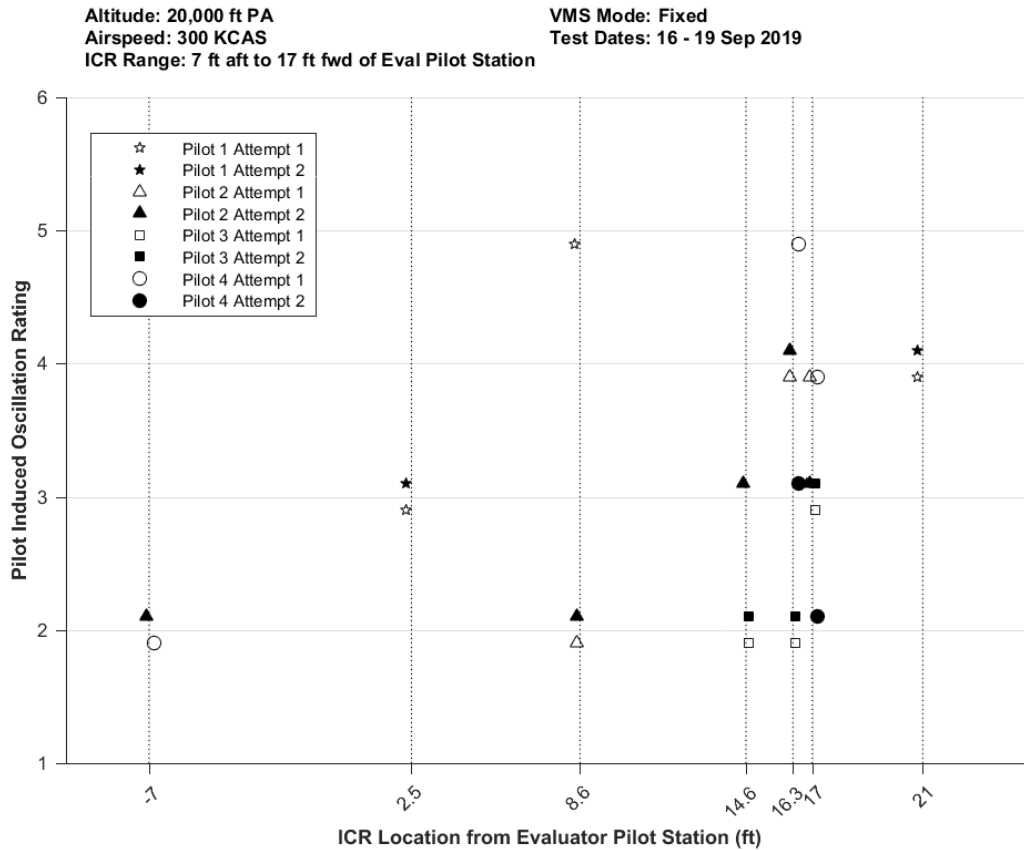


Figure 41 VMS Fixed PIOR for Simulated Aerial Refueling Task

Pilot comments collected in the fixed-base simulation for this task showed that aircraft response was more difficult to determine with one pilot commenting that they were seeing an initial response opposite input with the ICR behind the pilot station and another pilot commenting that they needed to reduce gains and back out of the loop with the nominal (aft) ICR configuration. Despite that, pilots began commenting on needing to reduce gain and back out of the loop starting at ICRs 14.6 ft forward of the pilot station. With ICRs further forward pilots continued to comment on gain reduction and in some cases mentioned having to back out of the loop entirely. This matched predictions.

Motion Simulation Aerial Refueling Test Results

The results of the VMS full motion simulated aerial refueling task are shown in figure 42 below. It was observed that as the ICR moved further forward of the pilot station handling qualities began to degrade and the CHRs increased. With the ICR located 7 ft aft of the pilot station, all but one EP rated the handling qualities as Level 2 with the majority of ratings a 4 or 5. Similar ratings were seen with mostly Level 2 ratings of 4 & 5 for an ICR 2.5 ft forward of the pilot station. The ratings were higher with the ICR 8.6 ft forward; two Level 3 ratings of 7 as well as an uncontrollable rating of 10 were given. With an ICR of 14.6 ft forward the ratings were split between Level 2 and 3. Pilot 4 provided a CHR of 4 & 5, Pilot 3 assigned 7's, and Pilot 2 a 4 & 8. At 16.3 ft and 17 ft the CHRs were again split between Level 2 and Level 3 with CHRs as high as 9 assigned. Only four test points were flown with the ICR 21 feet forward and a spread in

CHRs was also seen with one pilot assigning two CHRs of 4 and another pilot a CHR of 7 and 10 (leading to a VMS safety trip). The overall trend was that with the ICR at 8.6 ft or more forward of the pilot station the handling qualities were degraded. CHRs of 4 & 5 were scored at most all ICR locations but it was at 8.6 ft and beyond that a significant number of pilots gave CHRs of 7 or higher.

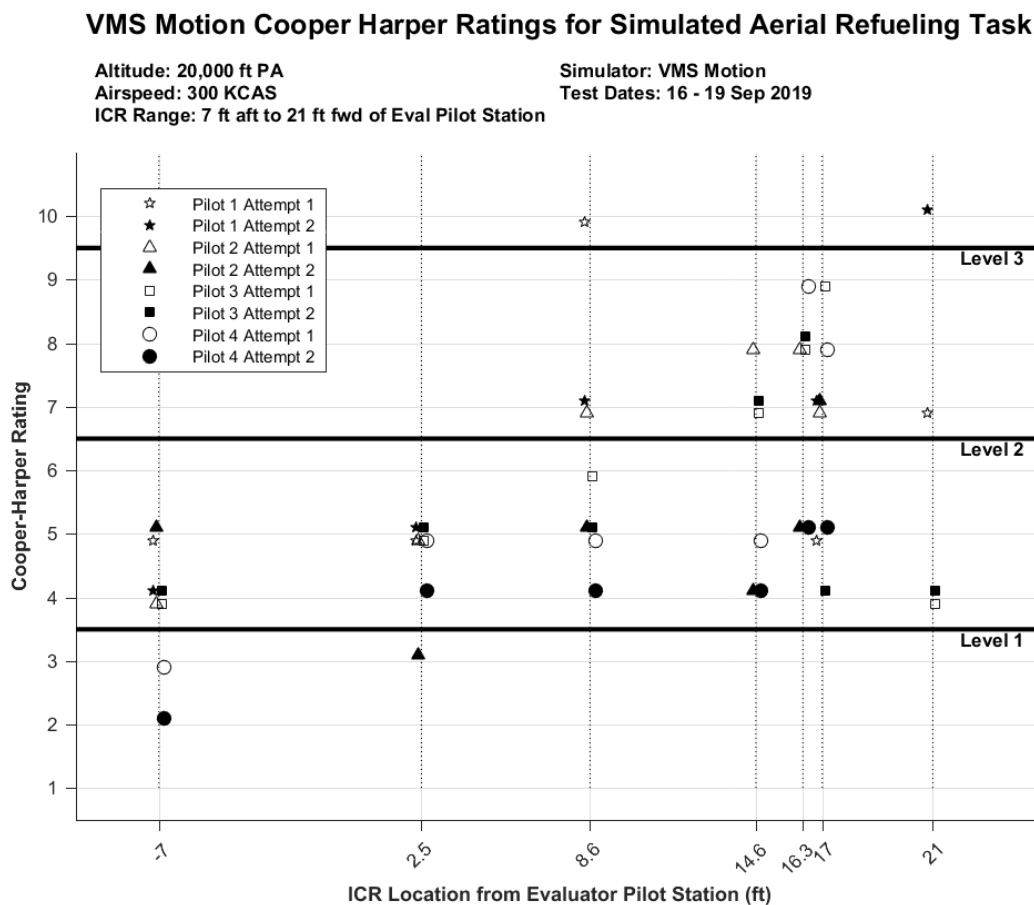


Figure 42 VMS Motion CHR for Simulated Aerial Refueling Task

Several CHR outliers were noted during data analysis. At 8.6 ft Pilot 1 felt that they were unable to retain control for the task and it was “not possible to stabilize.” The pilot’s deviations were likely driven at some point to be so large that control was difficult. For the ICR at 21 ft there was also a spread between pilot ratings. The CHR of 10 was recorded on a run when the pilot reached the VMS safety trip limit. For the CHRs of 4 from Pilot 3, they commented on using a compensation technique of backing out of the loop and decreasing gain and were able to remain within the adequate criteria.

The PIORs for the simulated aerial refueling task in the motion based simulation are shown below in figure 43. They follow a similar trend to that of the CHRs assigned for this maneuver and increase with more forward ICRs. PIORs of 2 and 3 were assigned for ICRs of 7 ft aft and 2.5 ft forward. This implied that undesirable motions were detected with one pilot observing that they affected task performance. PIORs between 3 and 5 were assigned with the ICRs between 8.6 ft and 17 ft. At a minimum, this meant that

undesirable motions compromised task performance (PIORs of 3). The PIORs of 4 and 5 showed that oscillations were observed on several runs and were divergent in nature for those scoring a PIOR of 5. For an ICR of 21 ft forward it appeared that the PIORs dropped slightly. This was attributed to the pilots sensing the undesirable motions were approaching and as comments show they “got out of the loop” and “decreased gain.” Overall, the PIORs indicated that ICRs of 8.6 ft forward of the pilot station and beyond led to task performance degradation with significant undesirable oscillations, some of which were divergent in nature.

VMS Motion Pilot Induced Oscillation Ratings for Simulated Aerial Refueling Task

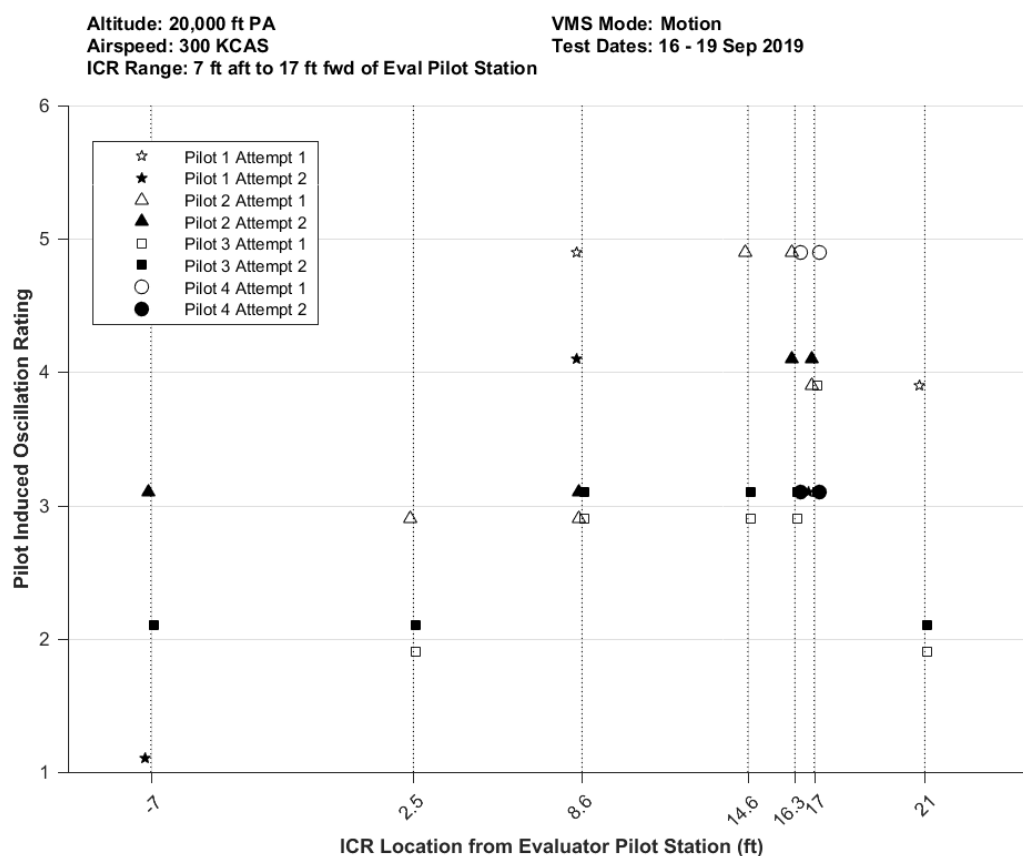


Figure 43 VMS Motion PIOR for Simulated Aerial Refueling Task

Pilot comments were also collected during the VMS simulated aerial refueling task for further analysis. At all ICRs the pilots commented on attempting to use lead and sampling compensation techniques. At an ICR of 7 ft aft, mostly desired or adequate criteria could be met. Pilot comments centered on compensation techniques which indicated they were able to focus on the task with one EP saying it “feels pretty smooth” and that they were “able to stay in the loop.” At an ICR of 2.5 ft forward several pilots made comments about having to back out of the loop and noticing slight time delay. Some undesirable pitch-vs-g motions were noted. One pilot commented that “underlying oscillation tendencies” were observed with another seeing “medium amplitude oscillations.” At an ICR of 8.6 ft forward several comments on undesirable motions were made such as “significant oscillations”, “low to medium heave”, and “pitch-vs-g mismatch.” Several pilots commented on having to decrease gain and back out of the loop. At an ICR 14.6 ft forward, time delay was noticeable and commented on by all pilots who flew this configuration. One pilot noted an “underlying PIO tendency” and another a “higher workload.” For compensation, one EP used “higher gain

for gross acquisition” and performing “fine tracking with low gain pulses” while another “backed out of the loop.” Another EP even observed that they were “accept[ing] adequate performance to not excite undesirable response[s],” further indicating that pilots were backing out of the loop. With an ICR of 16.3 ft forward, pilot comments were that they were definitely exiting the loop for control during the task and one EP had to “get out of the loop to reduce divergent oscillations.” Several commented on using stick sampling were made and the pitch-vs-g mismatch was more prevalent. With the ICR at 17 ft forward time delay was again a repeated comment with many pilots saying they had to “back off on gain” and take themselves “completely out of the loop.” Oscillations were also observed with some being divergent in nature. Similar characteristics were present when the ICR was 21 ft forward. Overall, the trend obtained from pilot comments was that greater reductions in gain and more backing out of the loop was required the more forward ICRs. Also, oscillations were observed at ICRs more forward of 8.6 ft with several being divergent in nature. As expected, the flight test results showed that the handling qualities degrade when the ICR is moved forward.

Simulated Emergency Separation Test Methods and Conditions

At the completion of a simulated air refueling test points a simulated emergency separation was accomplished. Without disengaging the VSS, the EP reduced power and executed a nose over to generate vertical and horizontal separation away from the target T-38. This was also executed in the VMS with motion on and fixed-base. Qualitative comments by the EP were collected on the execution of this maneuver.

Flight Simulated Emergency Separation Test Results

Comments were collected during the simulated emergency separation to resolve if ICR location had a detrimental impact on a pilot’s ability to execute a breakaway from a simulated tanker. Comments from pilots on this test point showed that even at the most forward ICR location, the ability to execute a breakaway was not impacted by ICR location. Pilots commented on feeling heave with forward ICRs but that a simple push forward on the stick generated the required opening vertical separation and the “weird” and “mismatched” feeling did not detract from the ability to execute the maneuver.

Fixed-Base Simulated Emergency Separation Test Results

When motion was turned off, pilots were still able to see the rise in flight path, and delay in flight path descent to pitch commands. Pilot 1 commented that with the ICR at 21 ft he could see the rise in flight path when pushing on the stick. Pilot 4 noted a perceived 0.5 second delay between longitudinal stick input and the desired flight path response with ICR at 16.3 ft.

Only pilot 3 felt that none of the configurations presented an issue during simulated emergency separation. In all cases, pilot 4 “continued pushing until the flight path descended.”

Motion Simulated Emergency Separation Test Results

During simulated emergency separation from the tanker with both motion on and motion off, pilots were able to perceive a time delay between the initiation of pushing forward on the stick, and the flight back beginning to descend away from the tanker altitude. This trend became worse as the ICR moved forward, and was present in both motion on and off. With motion on and ICR 17 ft forward, pilot 2

commented that there was time delay and heave present during the separation. With the ICR located 7 ft aft of the pilot station (configuration 801), pilot 4 noted that separation was in the right sense. However, when the ICR moved forward to 16.3 ft forward, pilot 4 perceived “a great mismatch between pitch and flight path response during the separation.”

COMPARISON OF HANDLING QUALITIES OF SELECTED ICRS IN THE VISTA, AND VMS WITH MOTION ON AND WITH MOTION OFF

Test Methods and Conditions

The results of flight testing conducted in VISTA were compared to the results obtained in the VMS to investigate the ability to use fixed-base or full motion simulation to replicate forward ICR effects.

The medians (midpoint of the distribution of values) of CHRs for each ICR configuration were plotted against their corresponding ICR location for the HUD pitch tracking task, formation station keeping task, and simulated air refueling task for all three test platforms.

HUD Pitch Tracking Test Results

The data in figure 44 showed that ICR location in the VMS did not have any effect on CHRs (motion and fixed-base). Lines between data points are included to aid the reader in following the trend for each of the three test platforms. The median CHR for all ICR locations were consistently a rating of 3. In the VISTA, the median CHR was 3 for ICRs up through 16.3 ft forward, degraded to a 4 at 17 ft, and ultimately a 4.5 at 21 ft forward. Pilot objections explained these differences which were attributed to annoying motions in the VISTA cockpit. The task performance was similar in VISTA and VMS, however the objectionable motions noted by the pilots drove higher ratings during in-flight conditions as compared to simulation despite no degradation in actual task performance. Comparison of flight vs simulation results showed that simulator data matched the flight until the ICR was 17 ft forward or greater at which point in-flight CHRs were higher.

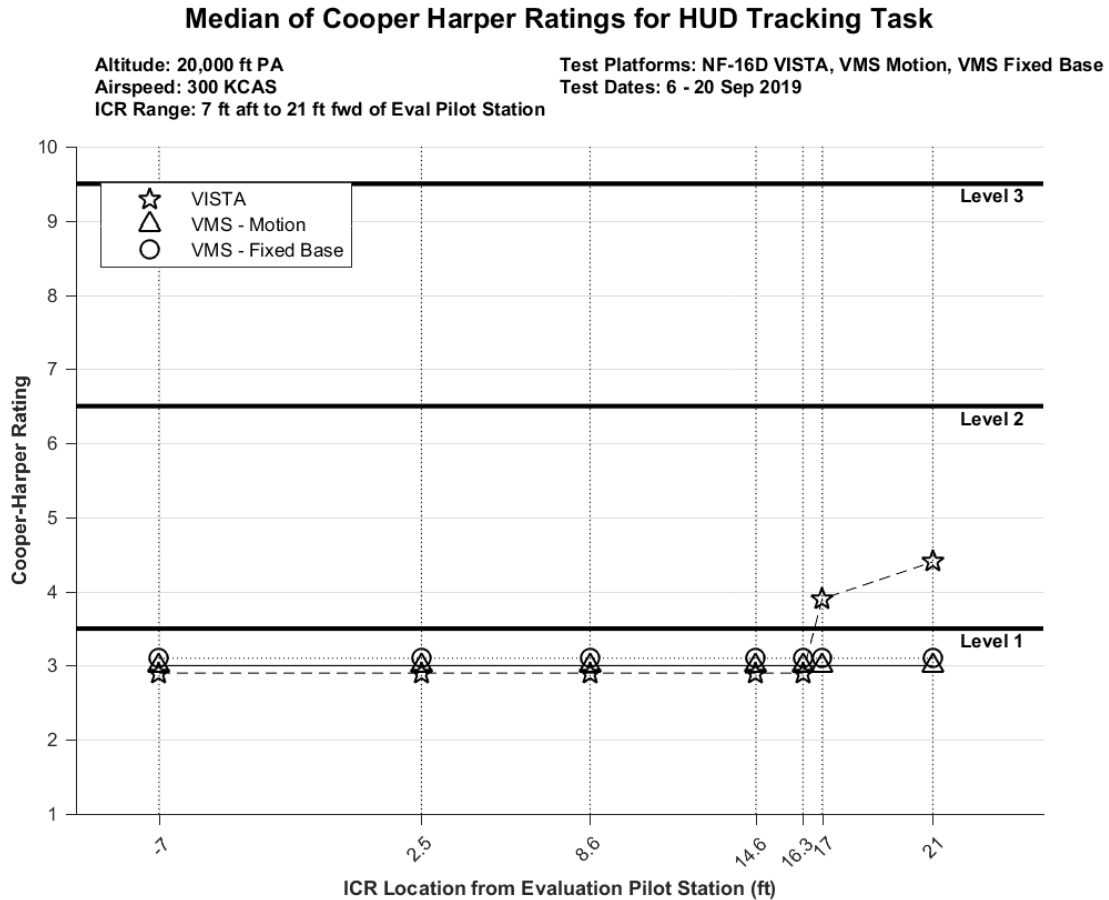


Figure 44 Median of Cooper Harper Ratings for HUD Tracking Task

Formation Station Keeping Test Results

The data in figure 45 show that the level of handling qualities matched across all three platforms for ICRs forward of the pilot station. With the ICR located aft of the pilot station, CHRs collected in the VMS were slightly worse than CHRs collected in VISTA. Although the median of CHRs varied across all three test platforms, in general, the VMS was an accurate predictor of handling qualities degradation with forward ICR- even with motion off. This indicates the importance of visual cues over other proprioceptive cues during flight path tracking tasks.

Median of Cooper Harper Ratings for Formation Station Keeping Task

Altitude: 20,000 ft PA

Airspeed: 300 KCAS

ICR Range: 7 ft aft to 21 ft fwd of Eval Pilot Station

Test Platforms: NF-16D VISTA, VMS Motion, VMS Fixed Base

Test Dates: 6 - 20 Sep 2019

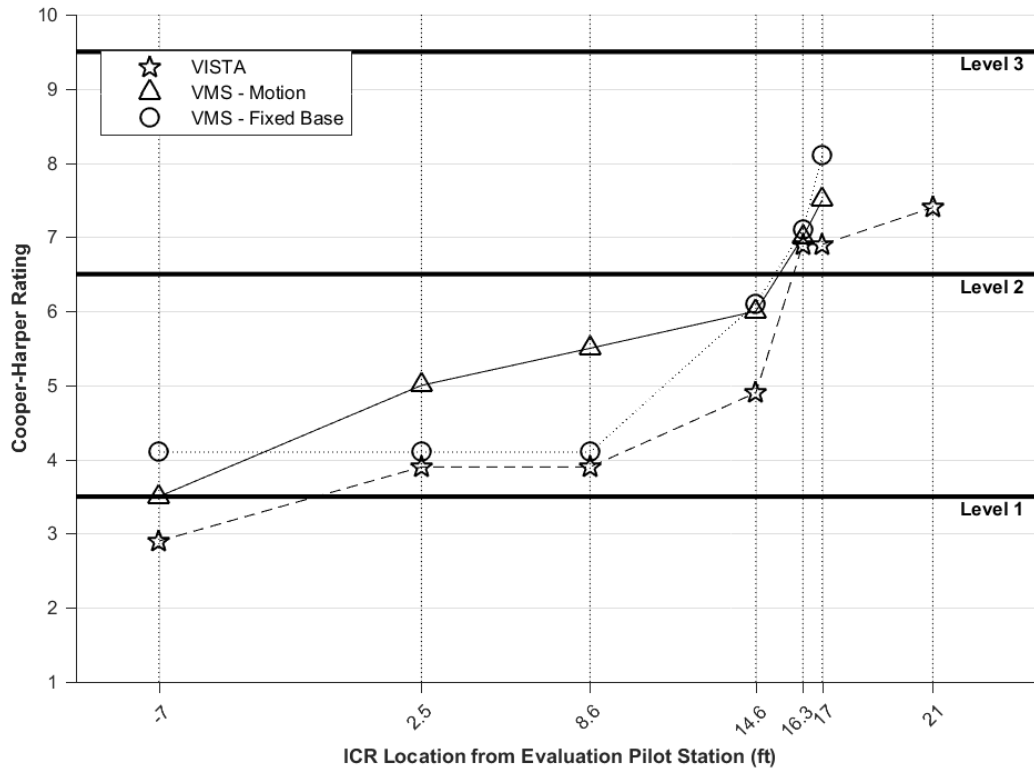


Figure 45 Median of Cooper Harper Ratings for Formation Station Keeping Task

Simulated Aerial Refueling Test Results

The data in figure 46 showed that more variation was present across all three platforms when executing the simulated aerial refueling task. This is likely due to the variation in the amount of pilot control required to execute this task as discussed in the simulated aerial refueling test methodology. Despite the variation in CHR modes, the data showed that during simulation in the VMS CHRs were relatively constant until rapidly degrading at ICRs 14.6 ft forward and greater. Data from VISTA showed a more gradual degradation of handling qualities with movement of the ICR forward. Of note, although the mode of CHRs at 16.3 ft forward in VISTA was a 4, the other CHRs given consisted of 6s and 7s, consistent with a continuing degradation of handling qualities. Across all three platforms, the trend of increasing CHRs with more forward ICRs was present.

Median of Cooper Harper Ratings for Simulated Aerial Refueling Task

Altitude: 20,000 ft PA

Airspeed: 300 KCAS

ICR Range: 7 ft aft to 21 ft fwd of Eval Pilot Station

Test Platforms: NF-16D VISTA, VMS Motion, VMS Fixed Base

Test Dates: 6 - 20 Sep 2019

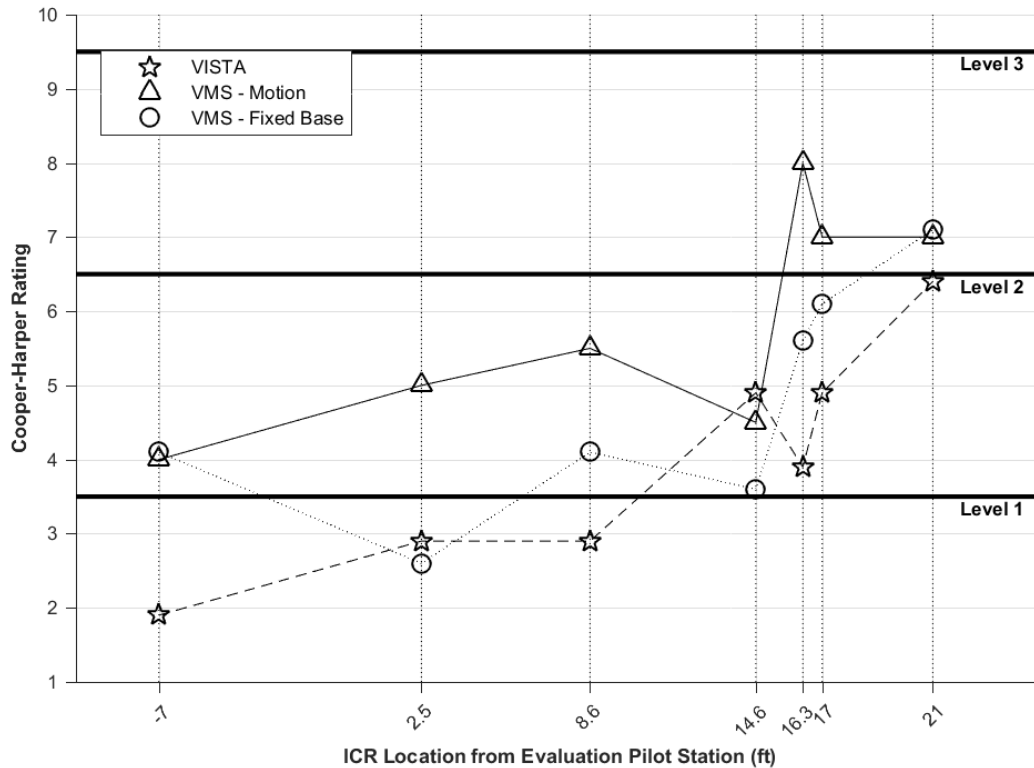


Figure 46 Median of Cooper Harper Ratings for Simulated Aerial Refueling Task

TEST RESULTS SUMMARY

The effects of forward ICRs on aircraft handling qualities were investigated in flight as well as in fixed-base and full motion simulation. Forward ICRs were successfully implemented on VISTA and short period dynamics were consistent for all configurations tested both in VISTA and in the VMS. Handling qualities evaluations were accomplished during offset landings and matched previous research. Handling qualities ratings and pilot comments collected during flight path tracking tasks such as formation station keeping and simulated aerial refueling conducted at 20,000 ft MSL and 300 KCAS showed that handling qualities degraded as ICRs moved forward; however it did not affect handling qualities during pitch tracking tasks conducted at the same flight conditions. The handling qualities ratings and pilot comments collected during the flight path tracking tasks conducted in the VMS both fixed-base and with motion on, simulated at the same conditions as in-flight testing, showed the same trends in handling qualities degradation with forward ICRs. The presence of the trend, even in fixed-base simulation points to the likelihood that the detriment to handling qualities was not a result of confusing pitch/g cues. Pilots overwhelmingly commented on a perceived time delay in flight path response across all three test platforms indicating that handling qualities were more closely tied to visual cues than proprioceptive cues. These results highlight the need for further investigation into the relationship between ICR location, delay in flight path response, and handling qualities.

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REFERENCES

1. Cooper, G., R. Harper, *The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities*, NASA-TN-D-5153, NASA, Moffett Field, California, April 1969.
2. Field, Edmund, James Armor, Kenneth Rossitto, David Mitchell, *Effects of Pitch Instantaneous Center of Rotation Location on Flying Qualities*, AIAA 2002-4799, American Institute of Aeronautics and Astronautics, Monterey, California, August 2002.
3. Klein, V., E. Morelli, *Aircraft System Identification: Theory and Practice*, American Institute of Aeronautics and Astronautics, Reston, Virginia, August 2006.
4. MIL-STD-1797B, *Flying Qualities of Piloted Aircraft*, Wright-Patterson AFB, Ohio, February 2006.
5. Weingarten, Norman, Charles Chalk, *In-Flight Investigation of the Effects of Pilot Location and Control System Design on Airplane Flying Qualities for Approach and Landing*, NASA-CR-163115, Arvin/Calspan Advanced Technology Center, Buffalo, New York, January 1982.
6. Knapp, Marit, *VMS Verification Plots*, PowerPoint, NASA AMES, September 2019

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APPENDIX A – DIGITAL SUPPLEMENTAL DATA

Raw flight test data (comments and ratings), consolidated data files, MATLAB® source code used to produce the flying qualities analysis, VMS verification data, and flight test and VMS data and videos are available by contacting the USAF Test Pilot School. The digital appendix contains six folders.

0. Test Comment Cards
 - a. All flight test data (pilot comments and ratings) gathered from flights 1-8 in their original format.
 - b. All VMS test data (pilot comments and ratings) gathered from flights 1-8 in their original format.
1. Consolidated Data Files
 - a. VISTA_ConsolidatedData.xlsx: Excel compilation of data contained in VISTA test comment cards used for plot generation.
 - b. VMS_ConsolidatedData.xlsx: Excel compilation of data contained in VMS test comment cards used for plot generation.
2. FQ Analysis
 - a. All MATLAB tools used to analyze VISTA frequency sweeps to generate VISTA flying qualities for all configurations.
3. VMS Verification
 - a. VMS Verification Plots.ppt: VMS frequency sweeps for configurations 801 through 809.
4. VISTA VSS and HUD Data
 - a. Digital data files of VSS parameters and HUD video for all flights and tasks.
5. VMS Data and Video
 - a. Digital data files of VMS parameters and screen video recordings of tasks.

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APPENDIX B – ABBREVIATIONS, ACRONYMS, AND SYMBOLS

<u>Abbreviation</u>	<u>Definition</u>	<u>Units</u>
AFB	Air Force Base	—
AFTC	Air Force Test Center	—
AFTCI	Air Force Test Center Instruction	—
AGL	Above Ground Level	—
AOA	Angle of Attack	—
CAP	Control Anticipation Parameter	—
CG	center of gravity	—
CHR	Cooper-Harper ratings	—
DAP	data analysis plan	—
DFLCC	Digital FLight Control Computer	—
DOF	degree-of-freedom	—
EAFBI	Edwards Air Force Base Instruction	—
EP	evaluator pilot	—
ETO	Executing Test Organization	—
FTE	flight test engineer	—
FTT	flight test technique	—
GTO	general test objective	—
HUD	Heads-Up Display	—
IAW	in accordance with	—
ICR	instantaneous center of rotation	—
JON	Job Order Number	—
KCAS	knots calibrated airspeed	—
LDTO	Lead Developmental Test Organization	—
MOP	measure of performance	—
NASA	National Aeronautics and Space Administration	—
PA	Pressure Altitude	—
PIO	pilot-induced oscillation	—
PIOR	pilot-Induced Oscillation rating	—
PTI	programmable test input	—
SP	safety pilot	—
STO	specific test objective	—
TIFS	Total In-Flight Simulator	—
TMP	test management project	—
TPS	Test Pilot School	—
TW	Test Wing	—
USAF	United States Air Force	—
VISTA	Variable stability In-flight Simulator Test Aircraft	—
VMS	Vertical Motion Simulator	—
VSS	Variable Stability System	—

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APPENDIX C – DATA ANALYSIS

C1.1 ICR Location

C1.1.1 Flight Condition Verification Data

In order to verify the flight condition, calibrated airspeed, pressure altitude, and time were collected from the VISTA VSS and data acquisition system (DAS), and from the NASA Ames VMS. Relevant parameters are shown in table C1.

Table C1 Flight Condition Verification Data

VISTA Data		VMS Data
VSS	DAS	
CADC_AMUX_SENSORS__CALIBR_AIR_SPEED	Callibrated Airspeed	VMS.CalAirspeed
CADC_AMUX_SENSORS__PRESS_ALT	Pressure Altitude	VMS.PA
CPU_TIME	IRIG Time	VMS.Time

C1.1.2 Aircraft CG Location Data

The aircraft CG was determined using the NF-16D VISTA burn curve and forward and aft fuel quantities recorded on test cards by the VISTA EP at the start of each maneuver. A nominal NF-16D CG location was set in the VMS.

C1.1.3 Maneuver Quality Data

Maneuver quality was determined by measuring longitudinal stick forces and displacements. Relevant parameters are shown in table C2.

Table C2 Maneuver Quality Data

VISTA Data		VMS Data
VSS	DAS	
FEEL_SYSTEM_COMMANDS__CH1_FEEL_SYSTEM__FES_ANALOG	FECS1	VMS.StickForce
FEEL_SYSTEM_COMMANDS__CH1_FEEL_SYSTEM__DES_ANALOG	DESS1	VMS.StickDisp

C1.1.4 ICR Calculation Data

In order to calculate the ICR, the aircraft normal acceleration, N_z , was required at the CG and at the pilot station, along with the pitch rate, q . VISTA and VMS parameter names are identified in table C3. The NZ_UPPER sensor is located close to the quarter chord point of the VISTA wing. The NZ_PILOT sensor is located at a known point from the pilot station.

Table C3 ICR Calculation Data

VISTA Data		VMS Data
VSS	DAS	
RAW_VSS1_SENSORS__NZ_UPPER	NzU2	VMS.Nz
RAW_VSS1_SENSORS__NZ_PILOT	n/a	VMS.NzPilot
RAW_VSS1_SENSORS__Q	q2	VMS.q

C1.1.5 Data Quality

Qualitative remarks on data quality were recorded by the FTE in the USAF TPS control room, and in the VMS control room. If data were unusable, the test point was repeated.

C1.1.6 Analysis Procedure

Using frequency sweep data, transfer functions were obtained for the normal acceleration and pitch acceleration response to longitudinal stick input, respectively. The frequency response of the ratio of the numerators of these transfer functions was used to determine ICR location. Further information is detailed in reference 2.

C1.2 Effective Time Delay, Short Period Frequency, Damping, and CAP

C1.2.1 Calculation Data

In order to calculate the effective time delay, longitudinal stick displacement (δ_{es}) and aircraft pitch rate (q) were required.

VISTA Data		VMS Data
VSS	DAS	
FILTERED_SENSORS__ALPHA	AOARI	VMS.AoA

The time history of the aircraft pitch rate (q) response and longitudinal stick displacement δ_{es} was analyzed for every executed PTI frequency sweep. Using techniques from reference 6, these data were used to generate a Bode plot of the following transfer function:

$$\frac{q}{\delta_{es}} = \frac{K_q(s + \frac{1}{T_{\theta 2}})e^{-\tau s}}{s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2}$$

where K_q is the pitch rate gain, s the Laplace operator, $\frac{1}{T_{\theta 2}}$ is the short-period numerator zero, and τ is the system equivalent delay.

Once the transfer function was determined, the longitudinal flying qualities values were easily identifiable. CAP was then calculated by the following equation:

$$CAP = \frac{\omega_{sp}^2}{N_z/\alpha}$$

C1.3 CHRs, PIORs, and Pilot Comments

For maneuvers flown in the VISTA, pilot ratings and comments were be audio recorded and annotated on flight cards by the FTE in the TPS control room. For maneuvers flown in the VMS, pilot ratings and comments will be audio recorded and annotated on flight cards by the FTE in the VMS control room.

The CHR scale is shown in figure C1. The PIOR scale is shown in figure C2.

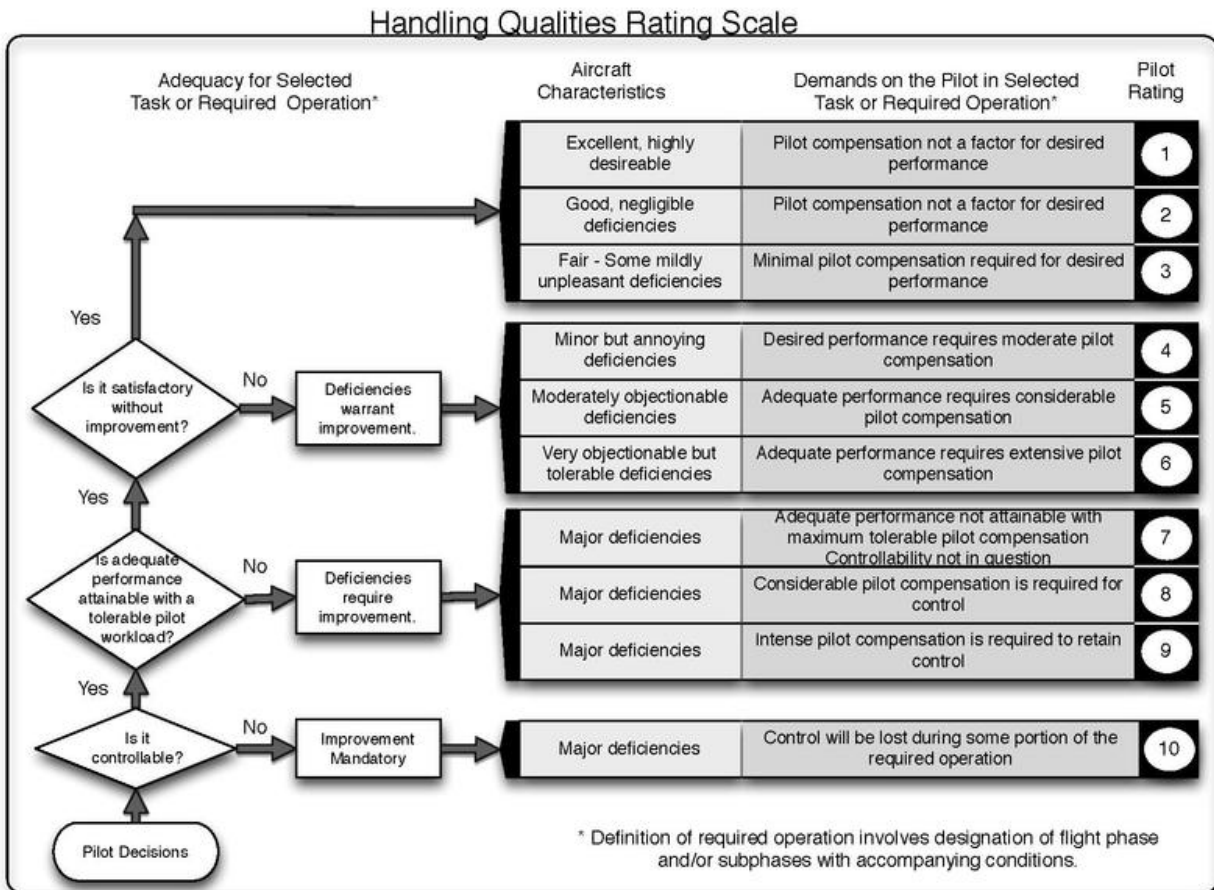


Figure C1 The Cooper-Harper Aircraft Handling Qualities Rating Scale

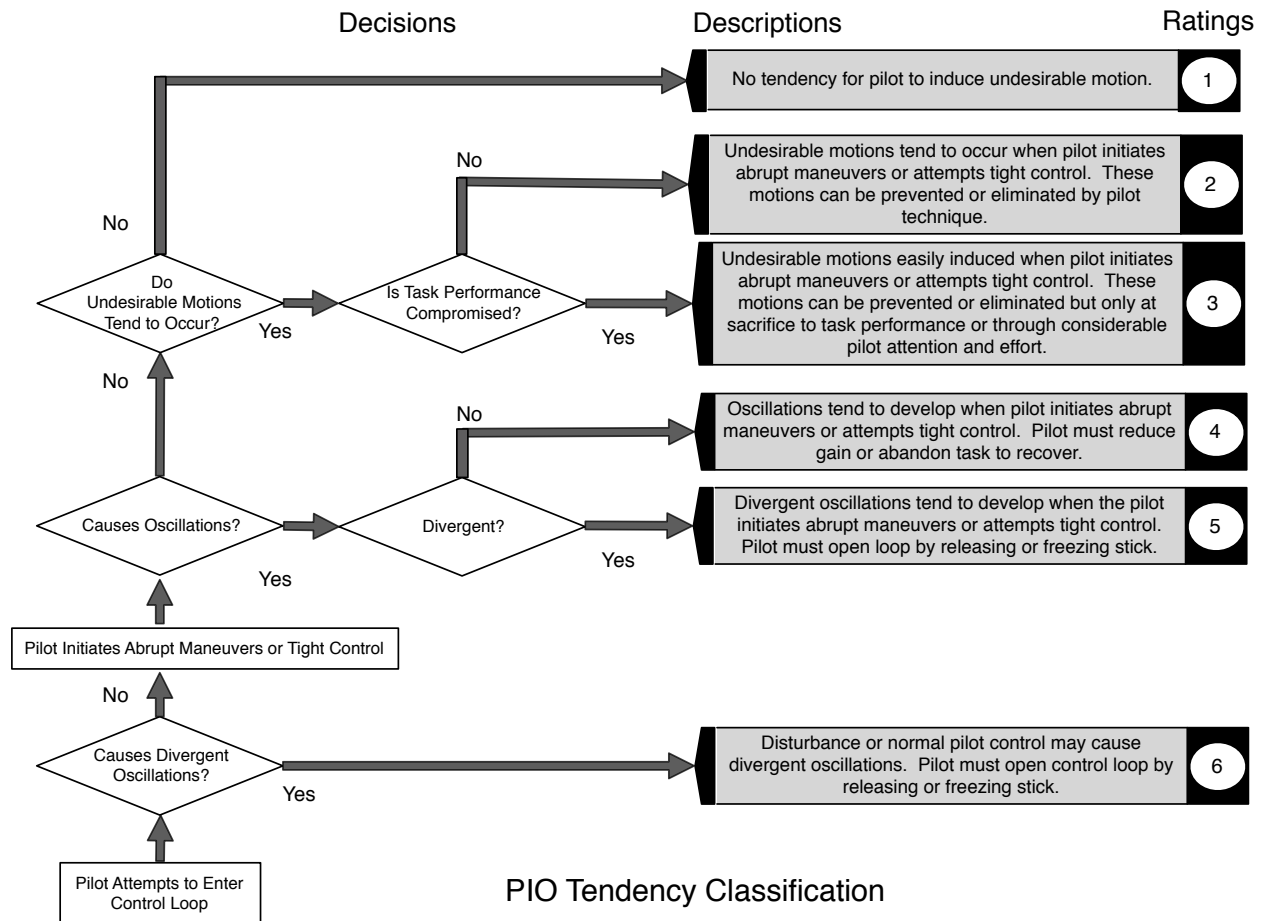


Figure C2 The Aircraft Pilot-Induced Oscillation Rating Scale

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APPENDIX D – DISTRIBUTION LIST

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