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I am submitting herewith a thesis written by Brian J. Goszkowicz entitled “Sidestick Controllers During High Gain Tasks.” I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

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SIDESTICK CONTROLLERS DURING HIGH GAIN TASKS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Brian J. Goszkowicz
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DEDICATION

This thesis is dedicated to all of the Naval Aviators who have deployed aboard ships and endured the rigors and hazards associated with the shipboard environment.

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ABSTRACT

This research attempts to demonstrate the feasibility of a sidestick controller in a high gain environment. The research is assembled from several historical precedents and various projects.

New technologies have re-ignited interest in the use of sidestick controllers for commercial and military aircraft. There are many advantages and disadvantages utilizing a sidestick in fighter aircraft. Many pilots prefer the feel of a centerstick controller and the designer only needs to develop a few sets of command gradients or gearings to produce adequate handling qualities. However, centersticks require more cockpit room due to their larger size and range of motion. Consequently, designers would have a difficult time fitting a centerstick in small cockpits such as the F-16. The presence of a centerstick could obstruct the view of a center panel Multi-Function Display, preventing the pilot from quickly assimilating valuable information. Sidestick controllers are light-weight, can fit in small cockpits, and are better suited for aircraft capable of sustained high normal load factors. From a pilot-vehicle interface standpoint, sidesticks offer an unobstructed view of displays, a clear pathway during an emergency cockpit egress, and allows access to full command inputs for the diverse statures of today's pilots.

The sidestick controller is not without its deficiencies. A sidestick controller prevents easy access to the console under the armrest forcing the designers to use that space for controls that may be set prior to flight. A sidestick also prevents the pilot from using the non-sidestick hand to control the aircraft while trying to do other tasks, such as writing on a kneeboard or using the console under the armrest. Additionally, the

tendency toward PIO is more prevalent in aircraft equipped with a sidestick than a centerstick. Flight test and simulation has shown that different Command Gradients and Gearings optimize performance for different tasks. However, it is not feasible to collapse the control laws into one usable set for all tasks.

Technology has provided designers a means to overcome this challenge. Active stick technology allows designers to use the optimum control laws for each task instead of compromising on a single set of gradients used for each task. Current aircraft under development have shown that it is feasible for an aircraft equipped with a sidestick controller to effectively employ this concept. The benefit of such advances is highlighted during high gain tasks such as aerial refueling, guns tracking, or during aircraft carrier landings. Tasks that had previously resulted in poor handling qualities ratings with sidesticks are now providing results as good or better than legacy aircraft equipped with a centerstick.

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LIST OF ABBREVIATIONS

AoA	Angle of Attack
ACM	Air Combat Maneuvering
APC	Aircraft Pilot Coupling
CTOL	Conventional Take-off and Landing
DFCS	Digital Flight Control System
F_{AS}	Lateral Side-Stick Force (positive to right), lb
F_{ES}	Longitudinal Side-Stick Force (positive to right), lb
FDR	Flight Data Recorder
HOTAS	Hands On Throttle And Stick
HQDT	Handling Qualities During Tracking
IFPC	Integrated Flight and Propulsion Control
JSF	Joint Strike Fighter
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
Nz, n	Normal acceleration at center of gravity, positive for pull-up
PA	Precision Approach Configuration (landing configuration)
PIO	Pilot In-the-loop Oscillations
PVI	Pilot Vehicle Interface
qbar	Dynamic Pressure
STOVL	Short Take-Off and Vertical Landing

UA	Up and Away (Gear up and Flaps Up)
USAF	United States Air Force
USMC	United States Marine Corps
USN	United States Navy
VAAC	Vectored thrust Advanced Aircraft Control
V/STOL	Vertical/Short Take-Off or Landing
δ_{AS}	Lateral Stick Deflection
δ_{ES}	Longitudinal Stick Deflection
ω_{SP}	Short Period Natural Frequency

INTRODUCTION

With the advent of fly-by-wire and fly-by-light systems coupled with advances in controller technology, interest in sidestick controllers has increased substantially. The use of a sidestick has many advantages over the conventional centerstick controller, including Pilot Vehicle Interface, light-weight compared to a centerstick, and unobstructed cockpit egress. However, there are many pilots who prefer the traditional feel of a centerstick for highly maneuverable aircraft. A sidestick controller also prevents easy access to the console under the armrest forcing the designers to use that space for controls that may be set prior to flight. A sidestick also prevents the pilot from using the non-sidestick hand to control the aircraft while trying to do other tasks, such as writing on a kneeboard or using the console under the armrest. Or, if there is injury to the pilot's arm, during combat for instance, he may not be able to control the aircraft. Despite these grievances, the sidestick controller is becoming more popular in military, commercial, light civil industries.

A major factor in the renewed interest in the sidestick has been the industry's acceptance of the use of electrical commands as the primary or sole means for a pilot to control the airplane. As a result, the use of a small displacement controller, such as a sidestick is feasible. The use of a sidestick with electrical commands, nonlinear gains, command pre-filters, response feedbacks, and signal shaping gives a designer a large number of parameters to manipulate to achieve good flying qualities.

Little work has been done either in assembling a generic database or defining and matching optimal aircraft dynamics and sidestick controller dynamics from a flying qualities standpoint.

While sidestick controllers are used in large and small aircraft, this thesis focuses on fighter sized aircraft and their applications. The concepts still apply to large, heavy aircraft but the gradients and displacements may differ from a highly maneuverable fighter sized aircraft.

CHAPTER I

HISTORICAL PRECEDENTS

General

Most people think of the sidestick controller as being a relatively modern concept. In actuality, the sidestick has been used in many different aircraft dating back to the designs of the Wright Flier. Since then, the sidestick has been used in many aircraft.

Wright Flyer

Many of the Wright Brother's early designs included a single axis sidestick controller for pitch control, including the Wright Flyer. The first aircraft they sold to the Army, however, used a wheel and rudder configuration and remains the primary configuration for aircraft not requiring extensive maneuvering. Highly maneuverable aircraft have historically adopted a center stick and rudder configuration, dating back to Armond Deperdussin's racing monoplanes of 1912.

XB-48

During the post World War II period, sidearm controllers were used as a formation stick on the XB-48. The sidearm controllers were used for gentle maneuvering and provided inputs to the autopilot vice the conventional flight control system. The conventional controls were used for all other flight tasks, such as take-off, aggressive maneuvering, non-autopilot flight, and landing.[1]

1957 NACA T-33 study

In 1957 the National Advisory Committee for Aeronautics (NACA) conducted experiments with sidestick controllers in a T-33. The T-33 was modified such that the pilot could use either a center stick or sidestick as the primary controller. The sidestick used a conventional left-right pivot at the base for roll commands. However, pitch control was accomplished with an up-down motion with the pivot point being at the wrist. NACA's results showed that the sidestick was comfortable and the aircraft flyable. However, the pilots noted the vertical movement of the pitch control was, "strange and uncomfortable especially when large stick motions and high force levels are required."[1]

1959-68 X-15

Basic studies for the X-15 flights began in 1954. Early in the X-15 program, a JF-101A was equipped with a sidestick controller to investigate pivot points for a sidestick controller implemented in the X-15. A stick with a pitch pivot at the wrist and roll pivot at the base of the controller were used. The JF-101A investigation also explored pitch and roll force-deflection gradients and gearings. The X-15 flight test program included 199 flights between June 8, 1959 and October 24, 1968. Ultimately, the design of the X-15 included three control sticks in the cockpit. The primary controller was a conventional center stick. This center stick was directly linked to a sidestick on the right side of the cockpit. This sidestick was operated by hand movement only so the pilot's arm could remain fixed during high accelerations experienced during powered flight and re-entry. This feature proved to be essential by enabling the pilot to maintain precise control during these conditions. The sidestick on the pilot's left side was used to control the X-15 when it was above the atmosphere and actuated reaction jets that utilized man's oldest harnessed energy form – steam. [2]

1966-68 Air Force Flight Dynamics Laboratory

From 1966 to 1968 the Air Force Flight Dynamics Laboratory sponsored a pitch-axis fly-by-wire program on a JB-47E. Second phase of this program evaluated a sidestick. Results were favorable with comments discussing ease and preciseness of control.

1969 Air Force Aerospace Research Pilot School –F-104D

In 1969 the Air Force Aerospace Research Pilot School (now USAF Test Pilot School) designed, built, and installed a sidestick fly-by-wire control system in two F-104Ds. The evaluation included various tasks including aerobatics, formation flight, and landings. Additionally, X-15 profile flights were performed. The profiles included a 270° overhead, high-drag straight-in approach, and zoom profiles. Overall, the F-104 evaluation generated a significant amount of qualitative data but little quantitative data. [1]

1974 YF-16

The General Dynamics YF-16 flight test program unintentionally highlighted the use of a sidestick controller to the aviation world. The YF-16's unexpected first flight was an excellent example of how control laws and controllers are very dependent on one another. The following narrative is printed on pages 27-28 of Jay Miller's Aerograph I "General Dynamics F-16 Fighting Falcon," ISBN 0-942548-01-9. It quotes Phil F. Oestricher's personal flight report from the incident, which was originally provided to Jay Miller by General Dynamics personnel.

The prototype YF-16, following its delivery flight from Fort Worth to Edwards AFB on January 8, 1974 aboard a Lockheed C-5A, had been reassembled and prepared for initiation of its flight test program. General Dynamics YF-16 project test pilot, Phil Oestricher, was assigned preliminary flight test duties. High-speed taxi tests got underway on January 20th. During one of these tests, an unexpected first flight inadvertently took place.

What follows is Oestricher's flight report describing the events of January 20th:

"The purpose of this series of tests was to perform a limited functional check of various systems (including the instrumentation system and test control at Bldg. 3940 and the trailer) and to determine the taxi characteristics at various speeds.

The test configuration was that of the basic airplane with an AIM-9 missile mounted on each wingtip. The airplane was fully fueled at the start of the tests and was flight ready in all respects.

Taxiing at normal speeds was evaluated while moving the airplane to the "last chance" check area for runway 22. Periodic application of brakes was required to prevent an excessive speed buildup. The braking effort expended by the pilot (product of pedal force and duration of pedal displacement) was perhaps 30% to 50% more than required in the case of a fully fueled, clean configured RF-4C. Nose wheel steering was used throughout the run and proved to be precise and easily controlled.

Following a check by the mobile crew, the airplane was positioned on runway 22 for an idle power taxi run without brake restraint. A taxi speed of around 30 knots was noted during this test. After a period of straight ahead taxiing, several S-turns were made with no difficulty. The airplane was stopped after traversing about 5,000 feet.

Following an inspection by the mobile crew, the airplane was accelerated toward a target speed of 80 knots. It is believed that an overshoot of about 10 knots occurred on this run. The nose wheel steering appeared to be overly sensitive at speeds of 50 knots or higher and was accordingly disengaged. Directional control by rudder was very satisfactory after the NWS disengagement. The airplane was stopped using moderate brake pedal force after traveling about 5,000 feet. It was then towed back to the "last chance" check area for runway 22 for brake cooling.

The brakes were checked and found to have cooled sufficiently to resume taxi tests. A normal start was accomplished as were the pre-takeoff check list items. The IIRS was aligned and checked for proper operation. The airplane was positioned on runway 22 for the planned 135 knot high speed taxi run. The brakes were held and the power lever slowly advanced to determine the RPM at which wheel slide would occur. This was determined to be about 87% rpm. The gross weight at this time was about 21,200 pounds. The corresponding C.G. was 34.3% M.A.C. The engine was kept at idle RPM until the runway winds (as reported by the tower) dropped below the 12 knot maximum agreed to for the taxi run. Upon tower clearance for the run, the brakes were released and intermediate power selected for a period of about six seconds after which a substantial power reduction was made. Nose wheel steering was disengaged at an estimated 50 knots. At about 130 knots (but apparently with the airplane still accelerating somewhat) the airplane rotated to about 10 degrees angle of attack and small lateral stick inputs were made in an attempt to get a feel for control response. No response was noted by the pilot (doubtless because the main gear was still restraining the airplane from rolling) and the angle of attack was intentionally increased a small amount. The airplane had continued to accelerate during this time but the pilot was unaware of the fact. Immediately upon rotating the second time the airplane lifted off with the left wing dropping rather rapidly. Right roll command was applied and the airplane was immediately involved in a fairly high frequency pilot induced oscillation (10 cycles in 14.3 seconds). Eventually the roll oscillation was stopped but not before lightly touching the rolleron wheel on the lower outboard fin of the left AIM-9 to the runway, striking the right horizontal tail tip (at the trailing edge) on the runway, bouncing off of the main landing gear several times in a nose-high and generally symmetrical manner and developing a substantial heading deviation from the runway axis.

The latter factor prompted the decision to fly out of the situation as it was felt that it would be impossible to steer the airplane so as to remain on the runway even if the nose wheel could be quickly brought down to the surface. Intermediate power was applied for a short period of time after which a fairly low thrust level was held. The airplane was allowed to slowly climb away in a shallow left turn, with a minimum of pilot control inputs being made. A downwind leg to runway 22 was established at about 600 feet AGL at 175 KIAS. The ADC (Air Data Computer) caution light was noted to be on at this time. No attempt was made to turn the light out by resetting. A wide pattern was flown to a long, decelerating final approach with 12-degrees angle-of-attack being established just prior to touchdown. A very slight (low amplitude and frequency) lateral motion was noted prior to touchdown. The ground effect was quite pronounced and the engine was brought to idle while still airborne. Aft stick force was relaxed after touchdown and the nose wheel fell gently to the runway at which time the speed brakes were commanded open. It should be noted that the pitch trim was still in the neutral position at landing since no pilot trim had been applied during the flight. Moderate braking was applied until the airplane was stopped. Following an inspection by the mobile crew, the engine was shut down and the airplane was towed to the hangar.

The tactics attempted during the pilot induced oscillation are evident from watching the excellent movie films available. Briefly the attempt was to:

1. Keep the wingtips off of the runway and stop the roll oscillation with the wings level.
2. Recover from the nose high attitude when the lateral control problem had been solved.
3. Control altitude and vertical velocity with thrust. It is believed that this particular attempt was relatively successful.

No sideslip was noted by the pilot at any time despite the violent nature of the oscillation and the full lateral commands being applied. The roll control problem appeared to be the most serious by far and accounted for most of the pilot's attention at the time. Once away from the ground and the need to keep roll angle within tight bounds, the pilot was able to relax with the results which are evident in the movie film. The pattern and landing were understandably somewhat conservative although a small rudder doublet was performed during the final portion of the approach in an attempt to assess directional control sensitivity. No dihedral effect was noted and the airplane felt somewhat sensitive compared to other tactical airplanes.

Takeoff and landing gross weight/ C.G. combinations were 21,100 lbs./ 34.3% M.A.C. and 20,000 Ibs/35.0% M.A.C., respectively.”

Post flight evaluation uncovered the fact that Oestricher had discovered that the combined flaperon and slab stabilator (rolling tail) roll gain control was significantly more sensitive to stick input than necessary. This sensitivity had led to severe roll control oscillations during the high speed taxi run and though these were quickly brought under control, Oestricher discovered that the airplane had turned somewhat and was now heading off the side of the runway and into the desert sand. Accordingly, he elected to takeoff rather than risk damaging the aircraft landing gear or worse, completely losing the airplane. At the time of this decision, the YF-16 was moving at 142 kts and was in a critical nose-high attitude.

Replacement of the stabilator consumed several days and following an additional week in fly-by-wire gain control analysis and test, the airplane was once again cleared for flight. Corrections incorporated included manually reducing the gain to 50% for takeoff and then manually restoring it to 100% once the aircraft was in the clean (cruise) configuration (this was later to be made a standard feature of all production F-16's-though it would be fully automated and would not require manual input).

The left roll on rotation suggests the sidestick's longitudinal axis may not have been aligned with the pilot's arm. Additionally, the non-movable stick using a force sensor offered little feedback to the pilot. During the high stress of an emergency situation, the pilot may have been unknowingly or unintentionally commanding full stick deflection while in the oscillations. A movable stick would have at least given the pilot a cue as to the magnitude of his inputs. The sensitive gains and stick characteristics resulted in severe Pilot In-the-loop Oscillations nearly resulting in the loss of the aircraft.

1974 NT-33A Variable Force, Variable Motion Sidestick[3]

In the wake of the YF-16 flight, several questions arose from the experience with the fixed force command controllers and the USAF TPS launched a study of sidestick controllers. The bulk of information concerning sidestick handling qualities comes from this evaluation. The primary concern during the trial was to determine optimal sidestick force-deflection characteristics. It was desirable to determine if a fixed stick provides adequate cues to the pilot or if a sidestick with some movement would provide optimal handling qualities for various tasks. If a stick with movement was found to be desirable, how much motion would provide optimal flying qualities? Should the amount of motion change with different phases of flight? The evaluation used a variable stability NT-33A airplane with a sidestick controller.

There are a large number of parameters a designer may use while developing a control system. This USAF TPS evaluation used a configuration representative of a modern high-performance fighter as the baseline for evaluating thirty-nine values of sidestick motion and control gains. Tasks were performed in Up-and-Away and powered approach during the evaluation. The Up-and-Away tasks, flight phase category A, included formation, air-to-air tracking, and aerobatics while the ILS and touch-and-go landings comprised the PA portion of the evaluation.

Providing adequate pitch and roll harmony is a complex task. The designer must account for the controller's force and deflection characteristics as well as the aircraft longitudinal and lateral response dynamics. During this USAF TPS evaluation, values for control harmony of a fixed stick were selected from a prior trial. Longitudinal short period frequency and damping ratio and lateral roll-mode time constant were held constant at values predicted to give good handling qualities according to MIL-F-8785B (version B at the time of the evaluation). The dynamics of the simulated airplane are presented in Table 1-1. Two values for stick motion were used. One value had barely noticeable motion while the other used larger, but not objectionable or unrealistic amount of motion. The control system is also an integral part of the pilot's opinion of the handling qualities. Changing the controller-to-control surface gearing or control gain was the major subject of this evaluation.

TABLE 1-1: AIRCRAFT DYNAMICS

	Up-and-Away Tasks (Flight Phase Category A)	Landing Approach Tasks (Flight Phase Category C)
v ft/sec	300	145
h ft	12,000	4,000
n_z/α g/rad	33	7
$1/t_{\theta 2}$	2.1	0.9
ω_{sp} rad/sec	5.0 and 3.7	2.2
ξ_{sp}	0.6 and 0.25	0.5
ω_ρ rad/sec	0.09	0.15
ξ_ρ	0.05	0.05
t_R sec	0.2 and 1.0	0.5
t_s sec	∞	∞
ω_d ,ω_ϕ rad/sec	3.2	1.2
ξ_d, ξ_ϕ	0.4	0.25
$/\phi/B/_d$	0.5	3

The values of modal parameters are strictly true only at the reference v and h. During maneuvers the values vary with dynamic pressure.

The basic layout of the test program is shown in Table 1-2 and sidestick characteristics are listed in Table 1-3.

Control System Mechanization

Force commands were used in both axes to command the appropriate control surface servo and surface deflection. For the stick configurations with motion, the feel system was in parallel with the force command channel. Therefore, when the pilot applied a stick force, commanding movement of the stick, and commanding control surface motion. As a result, the stick force/deflection gradients and the control surface deflection per unit force input were independently variable.

TABLE 1-2: TEST PROGRAM

Force-Response Gain	Fixed Stick	Small Displacement	Large Displacement
Light	X	X	X
Medium	X	X	X
Heavy	X	X	
Very Heavy	X		

Sidestick Motion

TABLE 1-3: SIDESTICK CHARACTERISTICS

Motion Deg/lb		
Sidestick motion	δ_{ES} / F_{ES}	δ_{AS} / F_{AS}
Fixed	0	0
Small	0.50	0.77
Large	0.91	1.43

Nonlinear gearings were used in pitch and roll and consequently the steady-state airplane responses were nonlinear as well. Flight control Force-Response Gains during Up-and-Away tasks (Flight Phase Category A) at 300 kts and 12,000 feet are presented in Figures 1-1 and 1-2.

The control force-response gains during Powered Approach (Flight Phase Category C) are presented in Figures 1-3 and 1-4.

Two first-order 20 rad/sec filters were used in the roll axis in order to suppress noise in the roll channel. The 20 rad/sec filter was chosen since the rate was far enough from the roll dynamics of the aircraft, thus not a significant factor in lateral control. However, the addition of a filter causes a slight delay and a high frequency phase shift. The pitch axis used two filters. One filter was used during Up-and-Away tasks and another for the Powered Approach tasks. Breakout force was 1.0 lb in the pitch and roll axes.

Feel System Mechanization

As previously mentioned, the feel system was mechanized in parallel with the force command channels of the pitch and roll surfaces. Table 1-4 shows the gradients of force versus displacement (F/δ) during the evaluation.

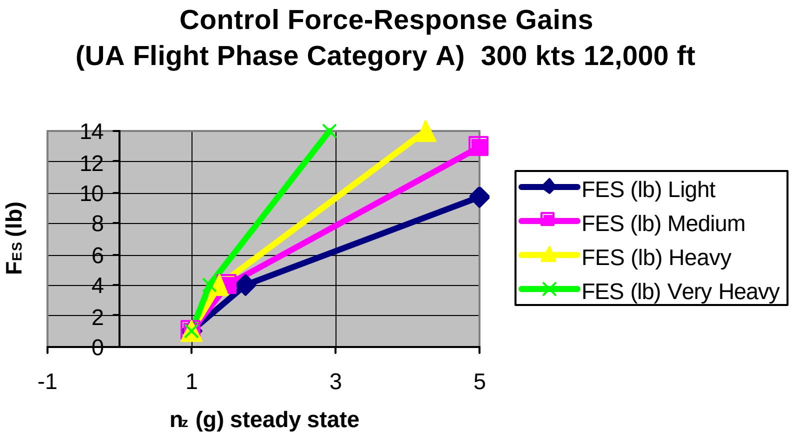


FIGURE 1-1: PITCH RESPONSE GAINS – UA

Source: *Flight Investigation of Fighter Side-Stick Force-Deflection Characteristics, May 1975*

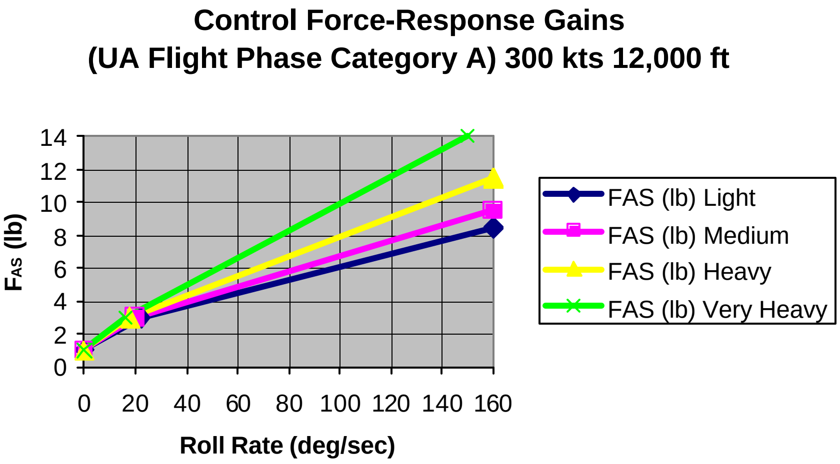


FIGURE 1-2: ROLL RESPONSE GAINS - UA

Source: Flight Investigation of Fighter Side-Stick Force-Deflection Characteristics, May 1975

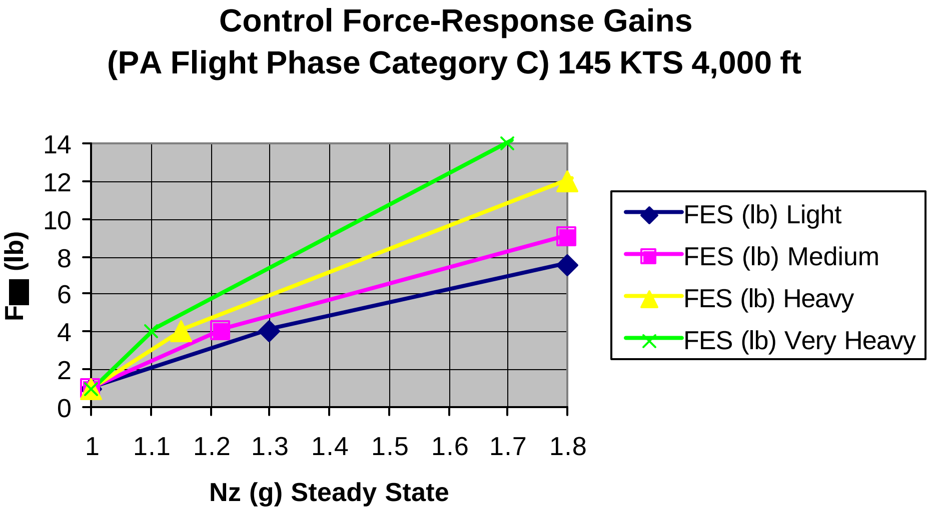


FIGURE 1-3: PITCH RESPONSE GAIN – PA

Source: *Flight Investigation of Fighter Side-Stick Force-Deflection Characteristics, May 1975*

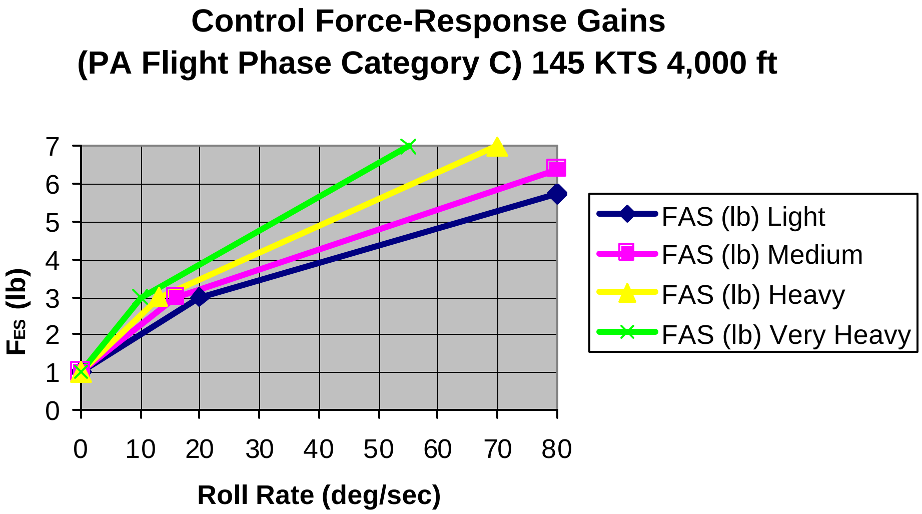


FIGURE 1-4: ROLL RESPONSE GAIN – PA

Source: *Flight Investigation of Fighter Side-Stick Force-Deflection Characteristics, May 1975*

TABLE 1-4: FORCE VS DISPLACEMENT GRADIENTS

Gradient	$1/K_{FS}$	
	F_{ES} / δ_{ES}	F_{AS} / δ_{AS}
Fixed	Fixed	Fixed
Small	2.0 lb/deg (27 lb/in)	1.3 lb/deg (17 lb/in)
Large	1.1 lb/deg (15 lb/in)	0.7 lb/deg (9 lb/in)

Note: The distance from the sidestick pivot point to the reference point was 4.25 inches. The levels were named for identification purposes during the trial and should not be considered absolute indicators of control force-response gain levels.

Equipment

The project used an NT-33A airplane which was an in-flight simulator, capable of reproducing the dynamic response and control system characteristics of another airplane with a high degree of fidelity. The front cockpit controls were disconnected from the aircraft control system and the evaluation was performed from the front cockpit via a fly-by-wire control system. The safety pilot, in the rear cockpit, had controls to vary the computer gains and effectively change the airplane dynamics and control system characteristics in flight.

Variable feel sidestick controller

The sidestick used during the evaluation was an electrohydraulic variable feel controller capable of operating as a rigid force controller or as a moveable controller with independently variable spring gradients in each axis. During operation with motion, the control surfaces could be commanded through either force or position of the sidestick. The safety pilot could vary the parameters of the sidestick in flight. Figure 1-5 shows the sidestick deflection limits.

Results

Two experienced test pilots were used during the evaluation and their comments were the bulk of the data retrieved during the trials. Pilots used the Cooper-Harper Rating Scale (Figure A-1) in addition to pilot comment cards for each task. Pilots were instructed to make comments at any time but were required to make specific comments

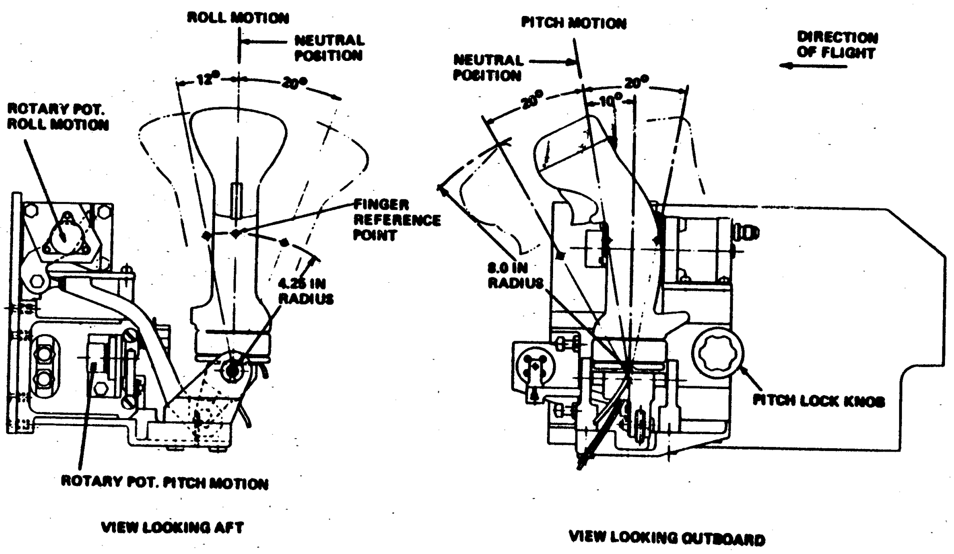


FIGURE 1-5: SIDESTICK DEFLECTION LIMITS

Source: *Flight Investigation of Fighter Side-Stick Force-Deflection Characteristics, May 1975* about items listed on the card. The pilots were asked to provide ratings for each of the tasks and an overall rating for the mission. Finally, the pilot ratings for each task and configuration were averaged and are presented in the following paragraphs.

Close formation

Table 1-5 shows the results of the close formation task. For the fixed stick, it is clear that there was a large variation in pilot ratings with the various force-response gain levels. The medium gain provided the best results. There was a dramatic improvement in pilot ratings when even a small amount of movement was introduced into the sidestick. The greatest improvement was the case for the lightest force-response gain. Very similar results were obtained with either small stick motion or large motion. As previously mentioned, the variations in force-response gain were made simultaneously in both pitch and roll but tried to maintain good control harmony.

Air-to-Air Tracking Task

The air-to-air tracking task was the highest gain task evaluated during this evaluation. Like the close formation task, the ratings for the fixed stick showed a significant change in pilot ratings with force-response gain. The medium force-response gain yielded the best results for the fixed stick. Introducing movement into the sidestick was clearly beneficial for the medium and light force-response gain. Increasing the movement to the large displacement seemed to show a slight degradation in pilot ratings. The results are presented in Table 1-6.

TABLE 1-5: AVERAGE PILOT RATINGS OF CLOSE FORMATION TASK

	Sidestick Motion		
Force Response Gain	Fixed Stick	Small Displacement	Large Displacement
Light	6	3	2
Medium	3	2	3
Heavy	4.5	2.5	
Very Heavy	7		

TABLE 1-6: AVERAGE PILOT RATING FOR AIR-TO-AIR TRACKING TASK

	Sidestick Motion		
Force Response Gain	Fixed Stick	Small Displacement	Large Displacement
Light	8	3	5.5
Medium	5	3.5	4
Heavy	6.5	5	
Very Heavy	7		

Gross Maneuvering Tasks

The gross maneuvering tasks are not as high gain as the tracking tasks but involved sufficient rolling and overhead aerobatic maneuvers to assess the gross maneuvering capability of the configuration. The results of the gross maneuvering tasks were very similar to the tracking tasks and are presented in Table 1-7.

Overall Up-and-Away Fighter Mission (Flight Phase Category A)

After completion of each of the individual Up-and-Away tasks, the pilots provided an overall rating for the mission. The average pilot ratings for the overall Up-and-Away mission are presented in Table 1-8.

TABLE 1-7: AVERAGE PILOT RATING FOR GROSS MANEUVERING TASKS

Force Response Gain	Sidestick Motion: Fixed Stick	Sidestick Motion: Small Displacement	Sidestick Motion: Large Displacement
Light	6	2	3
Medium	3	2.5	3
Heavy	5	3	▨
Very Heavy	7	▨	▨

TABLE 1-8: AVERAGE PILOT RATINGS FOR OVERALL UA MISSION

Force Response Gain	Sidestick Motion		
	Fixed Stick	Small Displacement	Large Displacement
Light	6.5	3	4.5
Medium	4.5	3	4
Heavy	6	4.5	
Very Heavy	7		

Table 1-9 shows typical comments about the various combinations of response gain and displacement. The overall results show that a fixed stick was unacceptable for all values of force-gain response tested with the best rating coming from the medium force-response gain. It appears that fixed stick handling qualities are very sensitive to the value of sidestick force-response gain. That is to say, the range of acceptable values of force-response gain is quite narrow for the fixed stick. Such a narrow range of force-response may prove to be unacceptable for other high-gain tasks such as in-flight refueling. Typical comments about the light and medium force-response gains were that of over-sensitivity in pitch. The heavy and very heavy force-response gains had problems with over-controlling and heavy forces, particularly in the roll axis.

In each of the force-response gains, introducing even a small displacement controller resulted in an improvement in pilot ratings. The most significant improvement came in the light force-response gain where the overall rating for the Up-and-Away

TABLE 1-9: PILOT COMMENTS ABOUT RESPONSE GAINS FOR THE OVERALL UP-AND-AWAY MISSION

Force Response Gain	Fixed Stick	Small Displacement	Large Displacement
Light	too sensitive, over-controlling in pitch	good tracking, very slight tendency to PIO in formation	stick motion too large, bobble in tracking
Medium	bobbling in pitch during tracking	smooth in pitch, good aircraft	small tendency to over-control in pitch
Heavy	bobble in roll, heavy, not satisfied with performance	roll tracking difficult, heavy	
Very Heavy	solid aircraft, too slow responding, extremely heavy forces, lateral PIO		

Sidestick Motion

fighter mission went from an average of 6.5 to 3. In this case the comments went from being too sensitive and over-controlling in pitch to being a good tracking airplane. Apparently, introducing even slight stick motion smoothes the pilot's input sufficiently to reduce the initial response to a satisfactory level. Apparently, the motion acts like a filter on the pilot's stick-force input, similar to an electronic pre-filter.

As sidestick motion increased to the large displacement category, a slight degradation in handling qualities occurred. It seems that the degradation in performance was a result of slow initial response vice the abrupt initial response in the fixed stick.

Excessive motion apparently interferes with the pilot's force input, consequently affecting the control surface motion and control response was less predictable.

The results also showed that, for a given amount of stick motion, the pilot ratings were insensitive to the higher force-response gains.

Landing Approach Tasks (Flight Phase Category C)

For the landing approach evaluations each pilot flew an ILS approach followed by several touch-and-go landings. A single overall average pilot rating was given for each configuration with the averaged results presented in Table 1-10.

The configuration with heavier than nominal gains was evaluated with a fixed stick and the stick with small displacement. Both configurations were given an HQR-6 but for different reasons. The fixed stick tended to have pitch bobble in the flare while the stick with motion had complaints of over-rotation and ballooning. The pilots also complained of sloppy lateral control with the small displacement controller while there was no mention of lateral control issues in the fixed stick. Overall, the light and medium force-response gains resulted in the best HQRs. The results were about the same for stick motion except the light gain with large displacement.

Two configurations with nominal force-response gain and two levels of stick motion (fixed and small) were selected for variations in short-period damping ratio and roll mode time constant. The short period damping ratio was changed from 0.6 to 0.2 and the roll mode time constant increased from 0.2 to 2.0 seconds. In both cases, the variation produced the most dramatic results in the fixed stick while the configuration with small motion showed little change in pilot rating. This limited data showed that the

TABLE 1-10: AVERAGE PILOT RATING FOR LANDING APPROACH TASK

Force Response Gain	Sidestick Motion		
	Fixed Stick	Small Displacement	Large Displacement
Light	3	2.5	4.5
Medium	3	4	3
Heavy	6	6	
Very Heavy	7		

fixed stick is more sensitive to small changes in aircraft characteristics than a stick with motion, affecting precise control.

Conclusions

The evaluation produced some informative conclusions. However, there was a caveat that the conclusions were based on limited combinations of feel systems, airplane characteristics, and control systems used during the tests. The configurations with the best results for Up-and-Away and landing approach were those that had low control force-gain response and small amount of side-stick motion. The fixed stick was satisfactory for landing but not Up-and-Away flight tasks. For the Up-and-Away tasks, a small amount of side-stick motion was beneficial in smoothing the initial response, improving the flying qualities of an airplane that was considered overly sensitive with the fixed stick. A pre-filter could yield the same results. Finally, the report concluded that before a general conclusion could be reached about side-stick controller characteristics, more research would be required. Additional testing to include systematic variations in the characteristics of the various elements in the overall pilot-vehicle machine, including the feel system, aircraft dynamics, and control systems.

1976-1978 USAF Test Pilot School Study

During the mid to late 1970s, the U.S. Air Force Test Pilot School expanded the matrices of the previous tests. Each class had a specific direction they wanted to explore. The following is a summary of their experiments:

Class 76B – Longitudinal and lateral force and deflection characteristics evaluated in tasks representative of Flight Phase Categories A (precision and gross maneuvering) and C (approach and landing). Same aircraft dynamics with slight variations in gradients, non-linearities, and breakout forces. For the air-to-air task, pilots preferred large control stick motion with light control force gradients. Increasing pitch breakout force from ½ to 1 pound increased pitch sensitivity. The approach tracking task did not enable the pilots to finely discriminate between configurations. [1]

Class 77A – Expanded test matrix of class 77B to include larger stick deflection and heavier forces. [4]

Class 77B – Investigated the effects of varying the corner frequency of first-order lag pre-filters in the longitudinal and lateral axes. Each axis had identical pre-filters while using optimum response/force gradients from the previous tests and used two values of deflection/force gradient. [1]

Class 78A – Investigated varying short period frequency and roll mode time constants. Three short period frequencies were evaluated using a medium roll mode time constant and three roll mode time constants were evaluated using a medium short period frequency. Controller characteristics were two response/force gradients in each axis with a constant force/deflection gradient value. [1]

Class 78B (AFFDL-TR-79-3126) – Explored a matrix of lateral force/deflection gradients and force/response gradients against the two preferred pairs of longitudinal short period frequency and sidestick force/deflection from class 78A. They also used two non-linear longitudinal force/deflection gradient ratios.

The results of these studies are summarized and partially included in the Department of Defense Handbook of Flying Qualities of Piloted Aircraft, MIL-STD-1797A. The lateral force deflection characteristics were varied to maintain control harmony. Table 1-11 summarizes pilot comments during air-to-air tasks for the 16 configurations tested. Generally, pilots preferred increased control stick motion with decreased control force gradients and decreased control stick motion with increased control force gradients. Configurations 13, 14, and 15 provided the best Cooper Harper ratings and comments. However, these configurations did have comments concerning control motion being large but not uncomfortable. The Heavy configurations with large control force / deflection gradients proved to be fatiguing. The remaining control configurations showed that with medium control stick motion, the control force gradient selected had essentially no effect on pilot ratings other than a trend of pilot comments indicating sluggishness as the control force gradient increased. The evaluation pilots did

TABLE 1-11: PILOT COMMENTS FOR AIR-TO-AIR TASKS WITH STANDARD HARMONY

Fes / n	Very Light (3.0)	13 – No pitch Bobble tendency but imprecise positioning. AVG CH 3.7	9 – Pitch and lateral are both too sensitive. AVG CH 4.4	5 – Pitch and lateral both a little too sensitive Avg CH 5.1	1 – Pitch Extremely sensitive. Lateral Fair. Avg CH 6.7
	Light (4.0)	14 - Pitch and lateral steady and responsive. Motion noticeably large. Avg CH 2.9	10 – Pitch a little sensitive. Lateral bobble. Avg CH 4.3	6 – Slight pitch bobble, Better at highter g's. Lateral sluggish (control harmony) Avg CH 4.5	2 – Pitch too sensitive. Lateral wandering and sensitive. Avg CH 6.0
	Medium (5.0)	15 – Motion noticeably large. No pitch bobble, slightly sluggish. Avg CH 3.3	11 – Very slight pitch bobble tendency, but good. Large lateral corrections difficult. Forces high and bobble. Avg CH 4.4	7 – Pitch steady once on target. Lateral forces high (control harmony) Avg CH 3.85	3 – Pitch a little sensitive. Lateral slow to respond. Ave CH 5.0
	Heavy (8.6)	16 – Aircraft very sluggish and forces uncomfortable. Avg CH 5.0	12 – Aircraft sluggish but stable. Forces heavy. Avg CH 4.5	8 – Pitch steady but forces too heavy. Lateral forces too heavy. Tiring. Avg CH 4.3	4 – Pitch very stable at higher g's but forces tiring. Avg CH 4.1
		1.1	1.4	2.0	5.0
	Control Force / Deflection Gradient (lb/deg)				

not feel that extreme force gradients, such as the current F-16 configuration, were desirable when given the opportunity to compare the gradients across the spectrum.[5]

The effect of breakout force on pilot ratings was investigated by increasing the breakout force from ½ to 1 lb for control configurations 7 and 11. The Cooper Harper ratings increased from 3.8 to 5 for configuration 7 while configuration 11 remained essentially unchanged. Pilot comments indicated that an increase in breakout unfavorably increased pitch sensitivity.

This series of tests highlighted the importance of including aircraft dynamics in the aircraft control system. If the short-period frequency of the aircraft is low, the pilots tend to overdrive the airplane with large pulse-like inputs to speed up the response. Consequently, pilots may not dislike the control motion gradients as much if the short-period response of the aircraft is faster.

F-16

The initial design of the F-16 incorporated a fixed sidestick. The fixed stick worked well during Up-and-Away tasks. However, when the pilot tried to quickly and precisely control the position of the aircraft, handling qualities quickly degraded resulting in Pilot In-the-loop Oscillations. It was quickly determined that some movement of the sidestick would be required for adequate handling qualities. The control force per control displacement was very high and did not meet that category of the military specification. A rubber grommet was installed in the sidestick assembly providing limited movement. The stick displaces 0.122 inches in roll, 0.017 inches forward, and 0.178 inches aft. The seemingly small increase in motion provided improvements in handling qualities and F-16 pilots have adapted to the essentially fixed stick. Although, it should be noted that F-16 pilots have no alternative but to adapt to the controller.[5] There are still some roll PIO tendencies in the aircraft today.

The USAF TPS conducted an evaluation of the F-16 with a fixed and moveable sidestick. The tests included operational type tasks as well as a high-gain tracking task known as Handling Qualities During Tracking or HQDT. HQDT tasks involve tracking a target during a predictable maneuver such as a constant g turn or a loaded reversal. The purpose was to obtain closed-loop-tracking data, both qualitative and quantitative, in an environment similar to an operational task. Good HQDT results do not necessarily mean good operational results. However, poor HQDT comments on workload, pilot preference, or task performance would be a good indicator of an operational task that may be difficult to perform.

During interviews with current F-16 pilots and the author's own experiences flying the F-16, there are still some grievances with the sidestick. There were numerous occasions in the cockpit when the pilot was faced with tasks which required the use of the pilot's right hand forcing him to release the sidestick. The tasks ranged from writing down a clearance while straight and level to reconnecting a facemask that became disconnected from the right side of the helmet during a Air Combat Maneuvering (ACM), requiring the right hand to attach it. During benign tasks it is easy for the pilot to engage the autopilot to keep the airplane tracking in the proper direction. During dynamic maneuvering, as in the case of the disconnected facemask, the sidestick is not accessible by the left hand and the pilot must continue maneuvering without the facemask, supplying vital oxygen to the pilot, or stop maneuvering to reattach the mask. The author of this thesis has had a facemask disconnect while flying a centerstick fighter during ACM and was able to reattach the mask with the right hand while continuing the fight, maneuvering the aircraft with the left hand.

Another common complaint of the F-16 sidestick and its mechanical characteristics is that the only feedback to the pilot is aircraft response. Force sensors can lead to overshoots, roll ratcheting, or Pilot In-the-loop Oscillations. Since the force controller has limited motion, it is difficult for the pilot to determine how much stick force is required for a full deflection input. The pilot could be applying 50 lbs of stick force when only 20 lbs of stick force would provide maximum response. With a displacement controller, the pilot knows that when he reaches full stick deflection any more stick force will not result in increased performance.

F-22

The F-22 uses a moveable sidestick with different gains for Up-and-Away (UA) and Precision Approach (PA). Gradients and gains are variable with dynamic pressure. No specific information was available due to its proprietary nature.

1994 Comparison of Sidestick and Centerstick Controllers

In 1994 Robert Malacrida presented a project paper comparing sidestick and centerstick controllers in the performance of high gain control tasks. His results were based on a short experiment utilizing an F-16 and a T-38 to fly identical high gain tasks. An offset landing was performed and data were taken on stick force and roll rate.

His research found that a particular concern to designers and pilots is the level and frequency of vibrations experienced in fighter aircraft. The vibrations may be caused by aerodynamic flow around the aircraft or engine noise. The vibrations can contaminate control inputs as they propagate through the airframe to the pilot and aircraft control inceptor. Sidesticks showed better tracking performance than centersticks in the presence of low frequency vibrations. Centerstick controllers tend to resist contamination from higher frequency cockpit vibrations above 4 hertz which is common in fighter aircraft.

The report concluded that centersticks have provided better feedback to the pilot than sidesticks and are therefore better suited for high gain tasks. However, sidestick controllers are better suited for aircraft capable of sustained high normal load factors. Centersticks do provide natural damping of high frequency inputs with less tendency toward PIO than the sidestick controllers. [6]

Non-Fighter Aircraft Testing

Although this discussion is focused on fighter sized aircraft, there are some lessons to be learned from sidestick utilization for large aircraft or aircraft in the civilian sector.

1994 Investigation of controllability Criteria of Class III Aircraft Equipped with a Sidestick

The Central Aerodynamic Institute, Moscow (Russia) in December 1994 conducted a study of sidestick controllers. Sidesticks are currently being used on several different aircraft including the F-16, F-22, the Space Shuttle reentry vehicles, and the Airbus 320 and 340 series aircraft. The sidestick offers many advantages over centersticks. However, the optimization of handling qualities and controllability characteristics for aircraft is more obscure. Due to the lack of experience in the use of sidesticks, the perceived differences in aircraft controllability between sidestick-equipped aircraft and those equipped with other controllers has limited the use of sidesticks in aircraft.

The report showed that handling qualities with a sidestick are better in longitudinal control and somewhat worse in the lateral control channel compared with centersticks and control wheels. Additionally, from an ergonomic standpoint, pilots prefer sidesticks over conventional control levers. A sidestick with properly fixed elbow-rest provides a more comfortable working position than centersticks and wheels.

Sidestick damping was also investigated. The trials showed that the introduction of sidestick damping leads to improved pilot control and improved ratings. In ground simulation and flight research pilots noticed an increase Pilot In-the Loop Oscillation (PIO) tendency for sidesticks without damping, especially in the lateral axis.[7]

C-141 fly-by-wire program

During the initial evaluation of the C-141 the aircraft was equipped with a sidestick. While the evaluation was not geared specifically to evaluate the sidestick, there were very few comments about it, indicating it was not objectionable.

Commercial Aircraft

Aerospatiale's Concorde experienced some problems with installation and positioning of their sidestick. The initial positioning of the stick and throttle were spaced too far apart making simultaneous control of each inceptor awkward. However, the aircraft provided excellent handling qualities during 10 hours of flight test over a wide range of conditions. [1]

Airbus utilizes sidesticks for some of their most popular aircraft such as the A319, A320, and A340. Discussions with Airbus pilots have shown that they are pleased with the mechanical characteristics of the sidestick. Most pilots found it fairly easy to adjust from the right-handed controller of the right seat to the left-handed controller of the left seat.

Light aircraft

Several light civilian aircraft have also incorporated a sidestick. The Rutan Varibreeze, Rutan model 40 Defiant, and the BD-5 series aircraft are several. The BD-5J was evaluated to assess its potential as a low-cost trainer. Part of the evaluation included assessing the viability of sidestick during a series of maneuvers including Basic Fighter Maneuvers (BFM), Air Combat Maneuvering (ACM), and Air Combat Tactics (ACT). Significant qualitative data but very little quantitative data were obtained. [1]

CHAPTER II

HIGH GAIN TASKS

General

Gain is the term used to describe the pilot workload or stress while performing a task. A high gain task generally puts the pilot in a situation where he needs to quickly and precisely change the attitude or position of the aircraft. High gain tasks may highlight the differences between a large displacement controller (centerstick) and a small displacement controller (sidestick). The same task performed with the two different controllers may produce dramatically different results. Occasionally, the task results in Pilot In-the-loop Oscillations (PIO) in which the pilot's control inputs will get out of phase with the aircraft response. The oscillations can dampen out quickly, stay the same, or diverge.

Pilot technique is also important during these high gain tasks. There are generally two types of pilots; high gain and low gain. The low gain pilot methodically guides the airplane to where he wants it to go. However, the high gain pilot likes to feel very connected to the aircraft. He makes many sample inputs even during straight and level flight. During a task, he aggressively maneuvers the aircraft into position with comparable control inputs. During aircraft development, pilots will fly tasks aggressively trying to discover any PIO tendencies.

During some cases of PIO, unintended excursions in aircraft attitude and flight path can be caused by anomalous interactions between the aircraft and pilot resulting in aircraft-pilot coupling. The pilot's interaction with the aircraft can form either an open or closed loop system, depending on whether or not the pilot's responses are tightly coupled to the aircraft response. When the dynamics of the aircraft, including the flight control system, and the dynamics of the pilot combine to produce an unstable pilot-vehicle system, the result is called an Aircraft Pilot Coupling (APC) event. APC events usually occur when the pilot is engaged in a highly demanding closed-loop control task. For example, many of the reported APC events have taken place during air-to-air refueling operations or approaches and landings, especially if the pilot is concerned about low fuel, adverse weather, emergencies, or other critical circumstances. Under these conditions, the pilot's involvement in closed-loop control is intense, and rapid response and precise performance of the pilot-vehicle system are necessary. [8]

The PIO problem of the early F-16 was due in part to a command gradient which produced acceptable responses for small, precise stick inputs. However, pilot comments indicated that excessive sensitivity "when encountered, was usually related to the small-amplitude, high-frequency inputs associated with the closed-loop, high-gain tasks of formation, refueling, tracking and landing."[5]

Aerial Refueling

Aerial refueling has been a challenging task since the first in-flight refueling attempt when a daredevil with a fuel can climbed from one airplane to another, effectively transferring fuel from one aircraft to another. Today, aerial refueling is not as dangerous as that first attempt but it still has its challenges. Aerial refueling is essential for military applications by providing longer on-station time or a deep strike capability. There are two methods for aerial refueling:

1. Boom – Boom Refueling is primarily used by the USAF in which a large tanker aircraft has an extendable hose or boom. A boom operator flies a nozzle into a female receptacle in the receiving aircraft. The pilot of the receiving aircraft must maneuver the aircraft to a position to allow the boom operator to engage the aircraft. Once the boom is plugged in, the pilot must maintain a stable position in close formation. Thus, boom refueling is primarily a close formation maintenance task.
2. Probe and Drogue – Probe and Drogue refueling is used by the USN and USMC. In order to probe and drogue refuel, the pilot must fly the probe into the drogue or "basket." The drogue may move significantly while the pilot of the receiving aircraft is attempting to enter the basket. Some reasons for the movement include turbulence, prop/jet wash from tanker, or the tanker turns. Additionally, the bow wave of the receiving aircraft also tends to push the basket away from the probe during the final seconds of the approach. During the approach and contact phase, the task at hand is pitch pointing. The pilot must be able to quickly adjust the probe to engage a moving basket. Pilots have commanded up to full stick deflection during engagement attempts. If the pilot misses the basket or hits its rim, the basket may strike some other part of the aircraft. For example, there have been many bent pitot tubes and AOA vanes torn off the FA-18 during tanking. Unfortunately, loss of the AOA vane

not only results in the loss of air data supplied to the flight control computers, the vanes also tend to go down the engine inlet, causing significant damage.

In addition to the pointing task, the pilot must also control closure. If the approach is too slow, the bow wave will push the drogue away from the probe. Conversely, if there is excess closure of more than a few knots, a wave will form in the drogue's hose. The sine-wave will reflect off the tanker and move back toward the receiving aircraft. The approaching sine-wave could act like a whip, strong enough to rip the probe from the receiving aircraft. Once the probe is in the drogue, the pilot may relax his gains and fly close formation. Maintaining proper aircraft position during this close formation task is not as stringent as boom refueling.

Take-off

While the take-off is not typically considered a high gain maneuver, several incidents have occurred involving sidestick controllers during this phase of flight. During rotation the pilot generally tries to capture a fly-away pitch attitude or angle of attack. External disturbance such as cross winds, wind gusts, or an in-flight emergency may drive the pilot into high gain mode. The aforementioned discussion of the YF-16's unintentional first flight is an excellent example of the pilot being forced into the high gain regime while countering an unexpected aircraft response during rotation. The mechanization of the sidestick could also make the take-off a high gain task. Airbus has had several mishaps during take-off with the side-stick implementation listed as a causal factor.

In 1998 an Airbus A320-231 had a tailscrape during takeoff. The aircraft was fully loaded and the weather was unremarkable. A full power take off was planned. The take-off roll was normal and the speeds were called by the captain who was acting as co-pilot. The commander rotated the aircraft and shortly afterwards felt a bump. The flight attendants confirmed the tailstrike. The aircraft returned for an uneventful landing. The flight data recorders were removed and the data analyzed. The data indicated the commander had initiated the rotation at the correct speed. However, his input was more aggressive and in greater magnitude than any other pilot within a sample of seven other flights. Additionally, the commander applied a large lateral sidestick deflection during rotation which was sufficient to deploy the roll spoilers on the left wing. Figure 2-1 shows some of the data taken from the Flight Data Recorder. It is apparent that the lateral stick input came with the aft stick input. If the spoilers deploy during take-off, there are two undesirable effects: First, the wing lift is reduced and secondly, the nose-up pitch rate is increased. The combined effect of the aft and lateral sidestick input was a sustained pitch rotation rate of more than twice the recommended rate of 3° per second. Airbus also stated that magnitude of the sidestick input alone was sufficient to cause a tailscrape with a normal pitch input. Sidestick training was brought up as a causal factor of this mishap. There is no mechanical linkage between the pilot and co-pilot sidesticks in the fly-by-wire aircraft, hence a trainee cannot learn the correct technique by following an instructor through the actions in a trainer. To complicate matters, the amount of aft stick required to achieve a satisfactory rotation varies with conditions and configuration and therefore is not practical to specify or teach a standard technique. The difficulty in achieving the recommended rotation rate is highlighted by the fact that the Airbus test pilots commonly achieved a rate of 4° per second. The pilots usually learned by making an input, assessing the aircraft reaction, and then making a follow-on input as required. Although not directly a factor in this instance, some A320 training organizations had given pilots inconsistent advice on sidestick handling during crosswind take-off. Following several tailscrapes, the following change to take-off was made to the flight manual of several Airbus aircraft: Minimize any lateral sidestick input during a crosswind take-off and centralize the sidestick (laterally) during rotation. If some lateral control has been applied on the ground, center the stick during rotation so that the aircraft gets airborne with a zero roll rate demand.[9]

Wave-Off / Go Around

Frequently, a pilot initiates a wave-off or go-around in response to an unplanned event. During this task, depending on technique, the pilot may rotate to maintain a pitch attitude or maintain an optimal angle of attack, while simultaneously advancing the throttles. As in the take-off task, the mechanization of the sidestick also could also make the go around a high gain task. The following incident highlights the importance of proper mechanization:

On 12 August 1991, a McDonnell Douglass DC-10 was landing on runway 34 at Sydney Airport. At that time an Airbus A320-211 was on short final for landing on intersecting runway 25. Simultaneous Runway Operations (SIMOPS) are common for Sydney Airport. The landing instructions given to the DC-10 crew were to hold short of

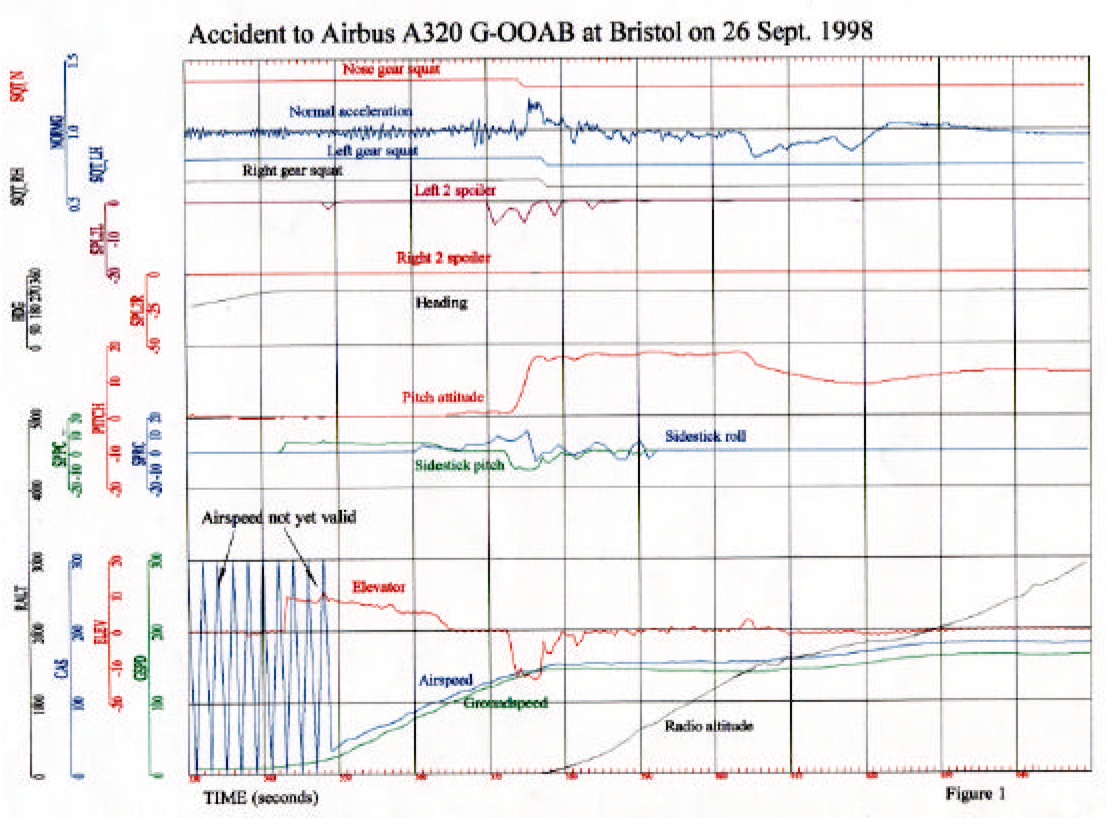


FIGURE 2-1: AIRBUS FLIGHT DATA RECORDER INFORMATION
Source: *United Kingdom Air Accidents Investigation Branch Bulletin, December 1998*

the intersection of runways 34 and 25. While observing the DC-10's landing roll, the captain of the A320 judged that the DC-10 might not stop before the intersection of the runways and elected to initiate a go-around from a low height above the runway, nearly hitting the DC-10. During the course of the investigation is became apparent that anomalies existed with regard to the attitude control inputs of the A320 and the braking system of the DC-10. One of the sited anomalies concerned the sidestick controller of the A320. The first officer was the pilot at the controls during the approach. During the go-around the captain took control and the first officer said there was no doubt that the captain was taking control of the aircraft and relaxed his grip on the sidestick. However, he did not remove his hand from the sidestick. The flight data recorder showed that for twelve seconds after the captain took control the first officer was making neutral to nose down inputs. The first officer stated he was not aware of making any subsequent intentional control inputs. The two sidesticks of the A320 are essentially independent in contrast to traditional systems in which the two control columns are mechanically interconnected. The flight control computers of the A320 coordinate the inputs from BOTH sidesticks and base the control response on the sum of the inputs. Since there is no mechanical linkage connecting the two controllers, inputs made by each pilot on his stick cannot be sensed by the other. The A320 design makes provisions for either pilot to take full control with his stick with a "take-over button." As soon as the button is activated, control authority is transferred to that sidestick. However, the button must be held down for 30 seconds before control priority is permanently allocated to that sidestick. In this incident the captain did not feel the need to utilize the take-over button. The braking system of the DC-10 and crew resource management were also cited as causal factors for this incident.[10]

Guns Tracking

Fighter pilots must adhere to certain rules of engagement prior to employing weapons on an enemy aircraft. In many cases, he/she may be forced to enter the visual arena with his/her adversary. At close range, the pilot has several weapons in his/her arsenal with a gun being one of them. During aggressive maneuvering, the gun may be the first or only opportunity for a kill. The chances of a gun shot may be fleeting, therefore it is essential that the pilot be able to quickly align his/her aircraft with the plane of motion of the target. If attacking from the rear quarter, the pilot may be able to arrive at a tracking solution in which the gun pipper remains on the target. More than likely, the target will not remain in a steady state condition and the attacker must quickly and precisely readjust the pipper position. If the aircraft handling qualities and performance do not allow the pilot accurate pipper control, the time required to shoot down the enemy increases. The longer it takes to kill the target, the more vulnerable the pilot is to other threats.

Landing

A normal, routine field landing can be driven into the high gain regime during adverse conditions such as poor weather, wind shear, or if the aircrew are dealing with an emergency. The F-16 has been known to experience PIO in roll, triggered by wind gusts on landing. Additionally, if the pilot overcontrolls the flare he may scrape the ventral fins located on the tail of the aircraft. Airbus has also had over a dozen tailscrapes during landing. These tailscrapes have resulted from a combination of three effects: One, there is a pitch up effect with the automatic deployment of spoilers at touchdown. Two, the sidestick input at touchdown is further aft than nominal landings that usually use between 25-37% of available aft stick. The flight data recorders show that the aft stick input during the tailscrapes was 75-100% of the available nose up demand at touchdown. The third effect contributing to tailscrapes is the pitch inertia which develops during the landing flare.

Carrier Landing

At a symposium several years before Alan Shephard's death, someone asked Admiral Shephard what was the toughest aviation challenge he ever faced. They expected him to say "the Lunar Lander" – he answered "the night carrier landing." Undoubtedly, the carrier landing puts the pilot in a very high gain environment, particularly at night during poor weather. Throughout the approach, the pilot must maneuver the aircraft through a series of windows, each one getting progressively smaller as the aircraft approaches the ship for the arrested landing. Figures A-2 and A-3 show the day VMC approach and the Night/IMC approaches respectively. Throughout the approach, the pilot must maintain tight control over three things: Glideslope, line-up, and Angle of Attack.

Within ¾ of a mile from the ship, the pilot uses a Fresnel Lens, Figure 2-2, as a visual aid to fly a 3 ½ ° glideslope. The Fresnel Lens provides the carrier pilot an indication of his position relative to an ideal glidepath via the relative position of a bar-shaped virtual image (meatball) compared to a pair of datum arms. At ¾ NM from the intended point of touchdown, the lens offers enough visual acuity for the pilot to transition from an instrument scan to a visual scan. At this point, the desired tolerance for glideslope control is approximately ±14 feet. As the approach continues the tolerances decrease. At ½ NM the pilot is striving for a ±9 foot window and ±5 feet at ¼

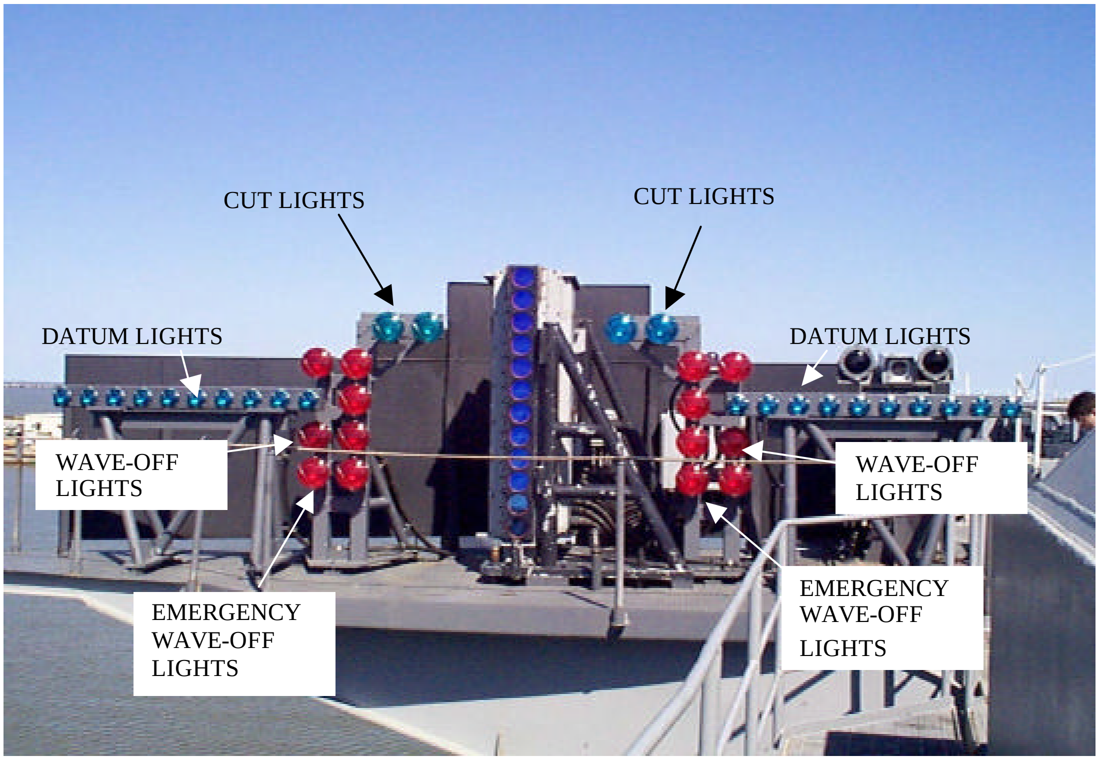


FIGURE 2-2: FRESNEL LENS

NM. An ideal approach would result in the hook touching down between the four sets of arresting gear, equally spaced 40 feet apart. However, every foot the aircraft is off glideslope at the intended point of touchdown results in the tailhook touching down 16 feet long or short. If the approach is just four feet high, the hook will touchdown 64 feet past the intended point of touchdown, flying over all four wires. This is called a bolter and the pilot must make another approach. On the other hand, if low, the pilot may have a frightening taxi into the first wire (one wire) touching down near the back edge of the carrier deck. More serious situations could develop as well. A hook slap occurs when the tailhook strikes the back edge of the ship. In this case, pilot will be forced to divert to a land-based airfield.

Glideslope is not the only task for the pilot; he must also maintain close control over Angle of Attack and line-up. The carrier landing is performed with a backside technique, where power is used to control glideslope deviations. In order to achieve the quickest flight path response, the aircraft is flown at an optimal angle of attack called "on-speed." Depending on the aircraft, if the pilot slows below on-speed angle of attack he may stall the wing. If the approach is flown faster than on-speed, the hook will be elevated and the pilot risks boltering or damaging the aircraft or arresting gear. To complicate the task further, the pilot must also tightly control line-up. Since US aircraft carriers have an angled flight deck (9-11°), the centerline of the landing area translates to the right as the ship moves forward. Consequently, line-up must be corrected throughout the approach. Generally, the pilot will drop line-up out of his scan while concentrating on another task. More than a few feet off centerline could result in striking aircraft or personnel lined up along the landing area.

Maintaining tight control of these three parameters is difficult enough during the day. Nighttime, inclement weather, and a pitching flight deck drive up the pilot's gains considerably. If any one of the three tasks gets out of parameters, the results could be disastrous. For example, the vast majority of ramp strikes, where the airplane crashes into the back edge of the ship, occur right on the centerline of the landing area indicating the pilot fixates on line-up, resulting in poor glideslope control and a major mishap.

STOVL tasks

Some military operations require aircraft to operate from austere locations including expeditionary airfields, roads, and staging areas. The locations could be a pad as small as 100 ft. by 100 ft. Fields such as this require non-conventional aircraft that are capable of Vertical/Short Take-Off or Landing (V/STOL) or Short Take-Off / Vertical Landing (STOVL). Additionally, STOVL aircraft operate off ships. Shipboard operations increase the complexity by adding a rolling, pitching, and heaving deck to the landing task. STOVL aircraft, such as the AV-8B Harrier, add another variable in the regime of high gain tasks that a conventional aircraft does not encounter. Unlike conventional aircraft that use aerodynamic surfaces to maneuver the aircraft, STOVL aircraft rely on the propulsion system for aircraft control when aerodynamic lift will no longer support the aircraft.

During an approach to landing in the AV-8B Harrier, the pilot must control flight path, airspeed, angle of attack (AOA), and line-up. STOVL aircraft do not decelerate to a specific speed or AOA throughout the approach and can continue to decelerate to zero airspeed and hover. At some point the functionality of the controls within the cockpit may change. For example, the stick may control flight path while wingborne and may control fore/aft and left/right movement (x-y controller) during a hover or jetborne flight. In order to hover over the intended landing zone, the pilot must null any fore/aft and lateral drift. Once established in a hover, the pilot must establish a safe, yet expeditious rate of descent, touching down with zero drift and at the proper attitude to avoid structural damage.

Sidestick Controllers During High Gain Tasks

Small displacement controllers, such as sidesticks, are challenging during high gain tasks since the pilot is making a rapid, albeit precise, input in order to achieve a certain aircraft response. There is little room for error. If a pilot overshoots his/her input with a large displacement controller, i.e. centerstick, by half an inch he/she will achieve approximately the same aircraft response as the desired input. On the other hand, if the pilot of a sidestick controller overshoots his/her input by that same amount, the magnitude of the error in terms of aircraft response is significant, possibly leading to an overstressed aircraft or triggering an Aircraft Pilot Coupling event.

CHAPTER III

ADVANCES IN SIDESTICK TECHNOLOGY

Active Stick Technology

Fly-by-wire and fly-by-light aircraft have opened the doors to other emerging technologies. Since the flight control systems are irreversible, aircraft designers have the opportunity to devise their own feel systems. Gradients can vary as a function of flight condition or control law mode. The designer is able to make control laws and stick characteristics fit the particular task being performed. For example, during an air-to-air gunnery tracking task, a pitch rate system with less dropback may be incorporated with stick forces appropriate for the high normal load factor environment.

Some terms have been developed to help describe the capabilities provided by these new technologies:

Stick Gradient - refers to the feel system which is pounds of stick force required for a given deflection of the stick.

Command Gearing - refers to the command path of the control law, or the response parameter (i.e. pitch rate/ roll rate/ pitch attitude/ roll attitude) commanded per a given stick deflection.

Command Gradient – combines Stick Gradient and Command Gearing and refers to the command path of the control law – the response parameter (i.e. pitch rate/ roll rate/ pitch attitude/ roll attitude) commanded per a given stick force in pounds.

Mode Change Harmony – as control modes are changed, and subsequently gradients, care must be taken to prevent a large disharmony from one mode to the next. To prevent a disharmony, the controls may need to be blended from one system to the next over time. The time required is directly proportional to the disharmony between the two modes.

Force gradients are utilized on movable sticks to resist pilot input as a function of stick displacement. Active stick technology may allow a force input controller to use motion while involving electronic, programmable stops and gradients. The shape of the stick gradient, command gradient, or command gearing is very important in determining the aircraft's perceived handling qualities. Modern flight control systems frequently use non-linear gradients to shape the control system. Shallow gradients near the neutral point allow small corrections to be made while steep gradients near the stick deflection limits allow the pilot to achieve maximum performance of the aircraft.

Like all systems, failure modes must be taken into consideration. Passive modes should offer level 3 handling qualities or better, providing a means for safe recovery of the aircraft.

VISTA

In 1998, the Joint Strike Fighter Program wanted to assess how control laws were progressing for each of the competing aircraft. Although fixed base simulation had gone well, inserting the control laws into another aircraft for an in-flight evaluation would prove very valuable. If there were problems, changes could be made before the concept demonstrators were even built. If the results were favorable, they would know they were on the right track and the simulations were effective. Veridian was contracted to provide the NF-16D Variable Stability In-Flight Simulator Aircraft (VISTA) and model the X-32 and X-35 control laws. The X-35 portion of the evaluation was performed with a side-stick controller. During that evaluation, handling qualities were evaluated during several high gain tasks, including Probe and Drogue in-flight refueling and simulated carrier landings. The evaluation proved successful in that it provided information allowing each contractor to make minor changes to their control laws. The evaluation also highlighted that fixed based simulation is helpful but does not provide all of the answers for the development of aircraft control laws and the real answers come during actual flight test.

VAAC Research[11]

A recent flight-test program in the United Kingdom utilized the Vectored-thrust Aircraft Advanced Control (VAAC) aircraft to study a variety of Short Take Off Vertical Landing (STOVL) control schemes. The goal of this research was to find a solution for a STOVL control scheme that would work for all STOVL tasks. Nine pilots of different experience levels and backgrounds took part in this research. Five of the pilots had previous STOVL experience and the remaining four had none. The pilots were asked to perform three maneuvers:

1. Approach to hover,
2. Translation to hover pad, and
3. Vertical landing.

VAAC Aircraft Description

The Ministry of Defense and the Defense Evaluation and Research Agency (DERA) incorporated a sidestick control system (SSCS) in a digital fly-by-wire AV-8B Harrier Aircraft. The VAAC Harrier is a two-seat Harrier I airframe powered by a Rolls-Royce Pegasus engine that has been extensively modified to provide a flexible test-bed for flight control research. The aircraft is equipped with a digital flight control system which, when engaged, has full-authority control of the ailerons, flaps, rudder, horizontal stabilators, throttle, nozzles, and roll/yaw auto-stabilizers.

The VAAC uses a safety pilot who flies in the front cockpit (production standard controls) and the evaluation pilot flies in the rear cockpit (modified controls). The front cockpit control inceptors (stick, pedals, throttle, and nozzles) are entirely conventional and are connected mechanically to their respective control surfaces. The front cockpit controls are mechanically "backdriven," and allow the safety pilot to monitor control activity and compare them to normal Harrier demands. The aft cockpit control inceptors are totally disconnected from the conventional flight control system, and all inputs are routed electrically through the Flight Control Computer (FCC). The aft cockpit has a programmable sidestick capable of varying the force gradients and overall stick characteristics. Thrust commands (or speed control depending on the mode selected) are commanded with a Harrier throttle quadrant, modified to incorporate several mechanical detents for advanced control modes. In addition, the nozzle lever is used for the three-inceptor control law mode evaluations. Primary flight information is obtained from the programmable HUD in the aft cockpit. Figure 3-1 shows the layout of the aft cockpit.

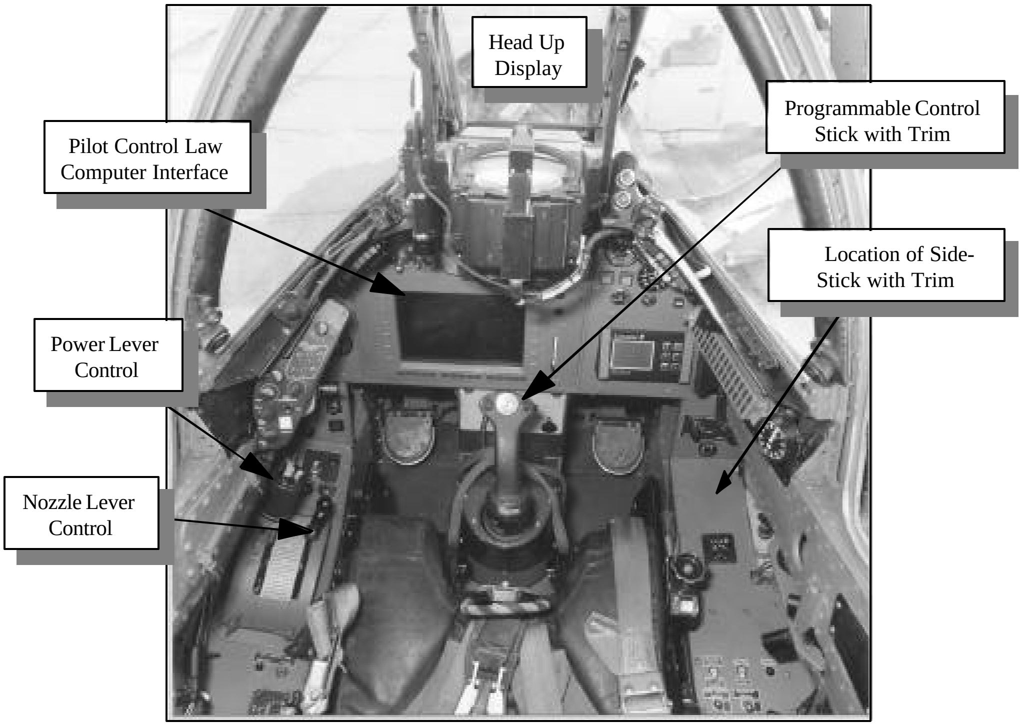


FIGURE 3-1: VAAC AIRCRAFT COCKPIT LAYOUT
Source: *VAAC Flight Trial Results, August 1999*

The overall control power of the FCC is limited to within the normal Harrier operating envelope.

Veridian was contracted to design a side-stick for the VAAC and DERA installed it for the evaluation, Figure 3-2. The Side Stick Control System (SSCS) is capable of variations in force gradient, hard stop location, breakout force, hysteresis, dynamic frequency, and damping values, and stores up to 9 different profiles per flight. The Side Stick Control System has four major elements: The sidestick servo assembly (SSSA), the feel system, a Hydraulic Supply Manifold, and a Status/Engine Interface.

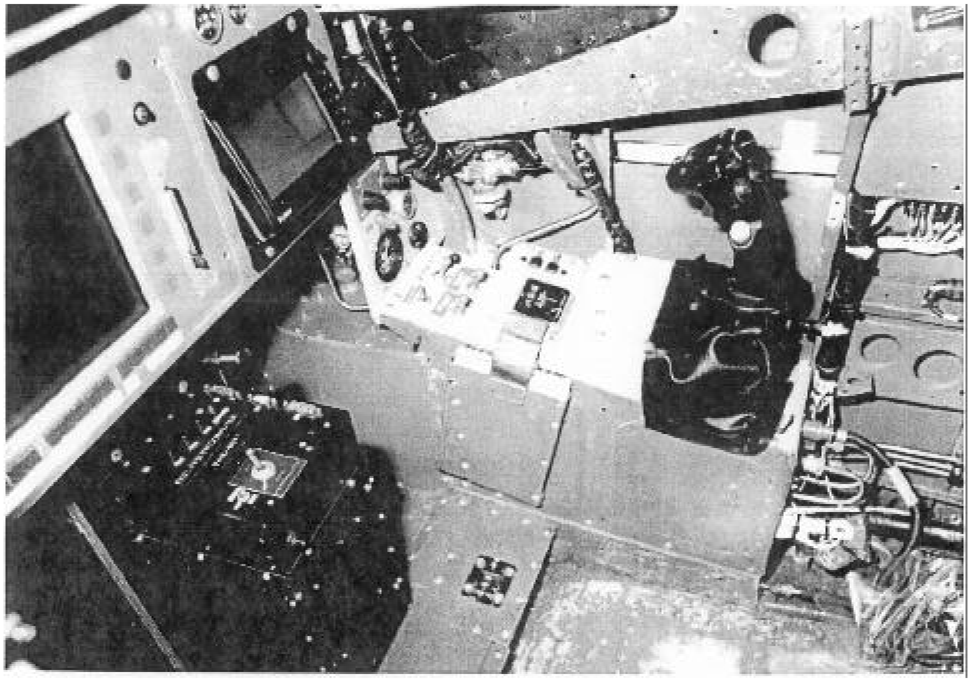


FIGURE 3-2: VAAC SIDE-STICK DESIGN
Source: *VAAC Flight Trial Results, August 1999*

Program objectives included an assessment of the handling qualities due to variations in several control system parameters for selected tasks and flight conditions. These parameters were: Sidestick gradients, control stops, and command path gearing. The following configurations were utilized:

Configurations

Conventional Take Off and Landing (CTOL)

CTOL pitch and roll stick displacements, gradients, pitch and roll maximum commands, and command gearings were based on known good characteristics for Up-

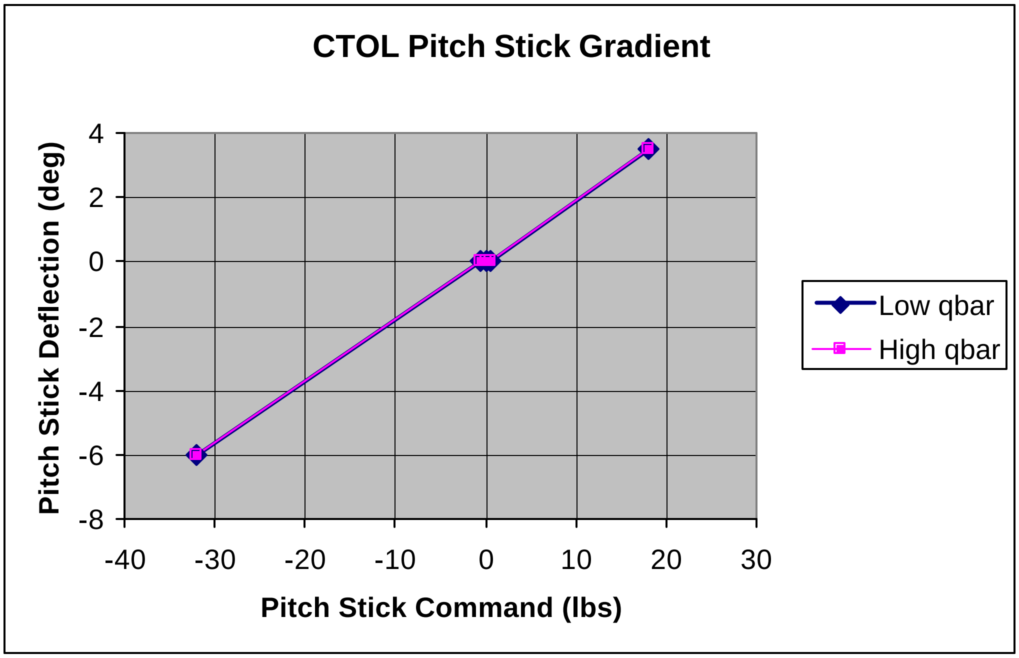


FIGURE 3-3: VAAC CTOL PITCH STICK GRADIENT

Source: *VAAC Flight Trial Results, August 1999*

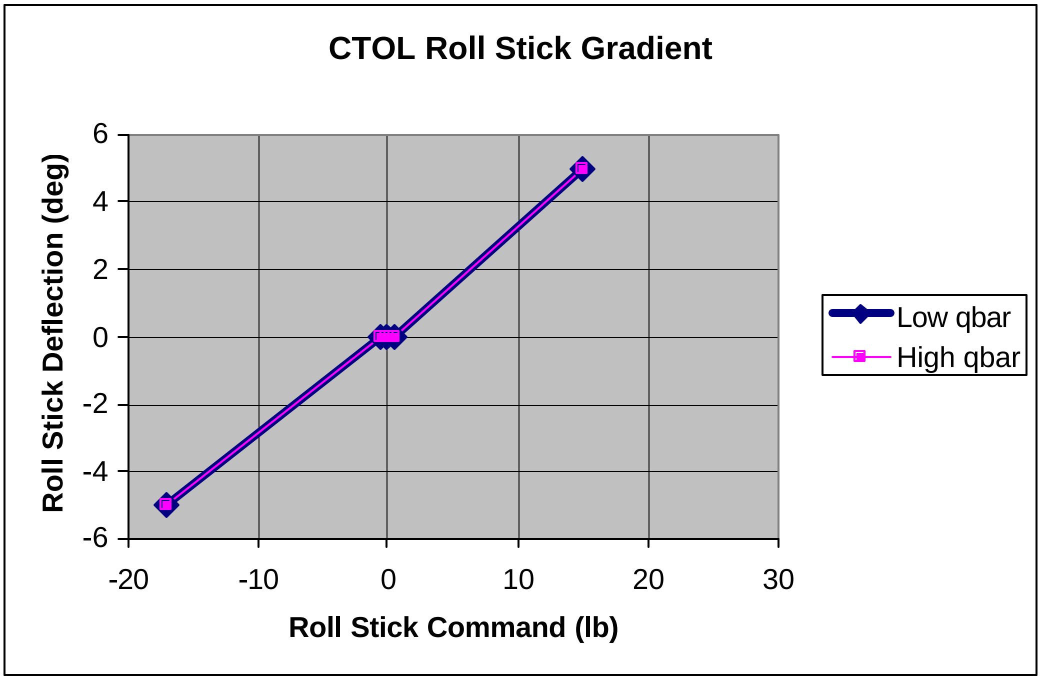


FIGURE 3-4: VAAC CTOL ROLL STICK GRADIENT

Source: *VAAC Flight Trial Results, August 1999*

and-Away tasks. Maximum command occurred at less than max deflection or “clipped.” Figures 3-3 and 3-4 show the CTOL pitch stick gradient and roll stick gradients.

STOVL Baseline

The STOVL Baseline used the CTOL pitch and roll stick displacements with lighter pitch and roll stick gradients but still used CTOL pitch and roll maximum commands. The pitch and roll command gearings were decreased such that maximum command occurs at maximum stick deflection. CTOL command gradients remained. Figures 3-5 and 3-6 show the CTOL pitch stick gradient and roll stick gradients.

STOVL Light

STOVL light used 40% larger stick deflections than CTOL, utilized lighter stick gradients than the STOVL Baseline (and thus CTOL), but kept the CTOL pitch and roll maximum commands. The pitch and roll command gearings were decreased to less than STOVL Baseline such that the maximum command occurred at maximum stick deflection. Figures 3-7 and 3-8 show the CTOL pitch stick gradient and roll stick gradients.

Results

The sidestick was acceptable for STOVL Operations. Decelerating transitions to the hover, hover, translational maneuvering, and vertical landing were all Level II or better and could be flown safely.

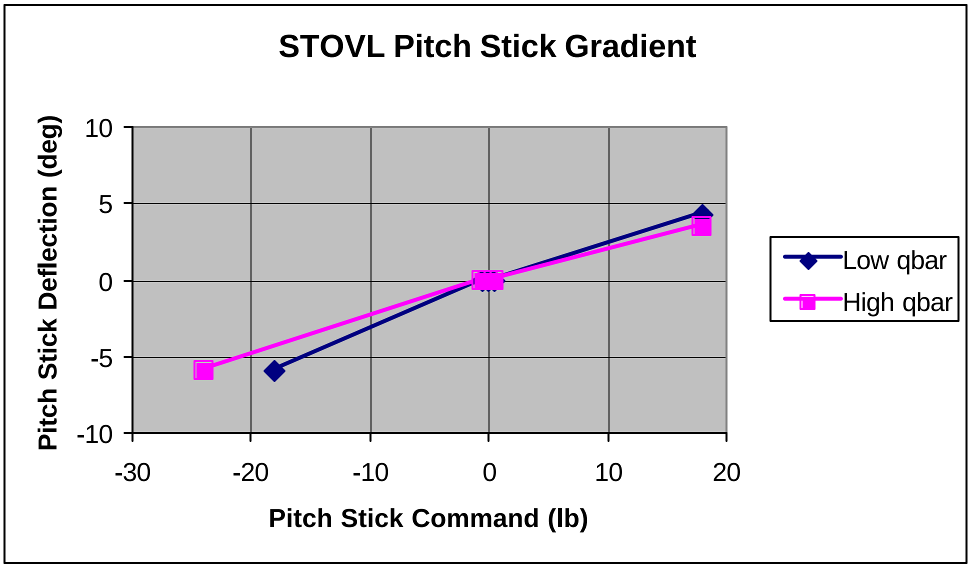


FIGURE 3-5: VAAC STOVL PITCH STICK GRADIENT

Source: *VAAC Flight Trial Results, August 1999*

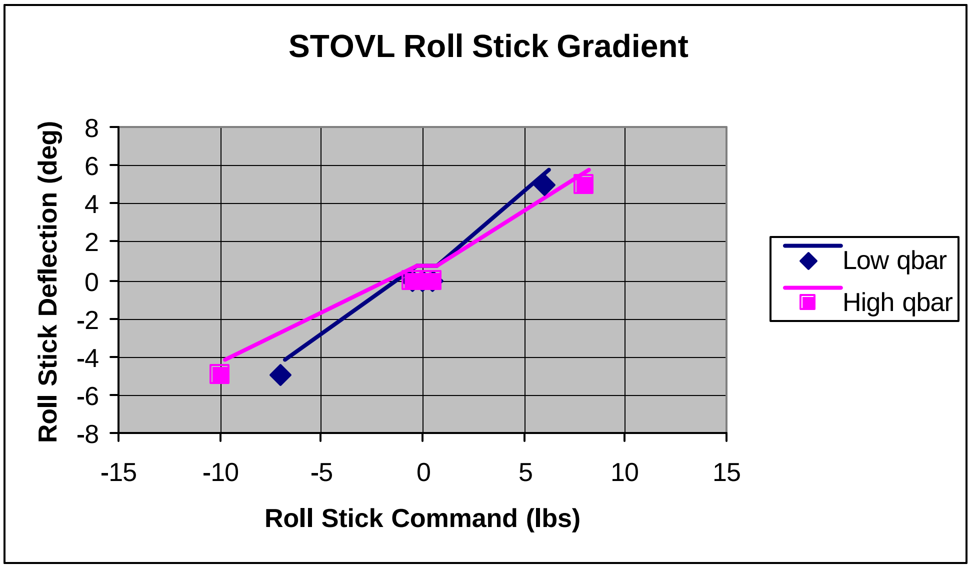


FIGURE 3-6: VAAC STOVL ROLL STICK GRADIENT

Source: *VAAC Flight Trial Results, August 1999*

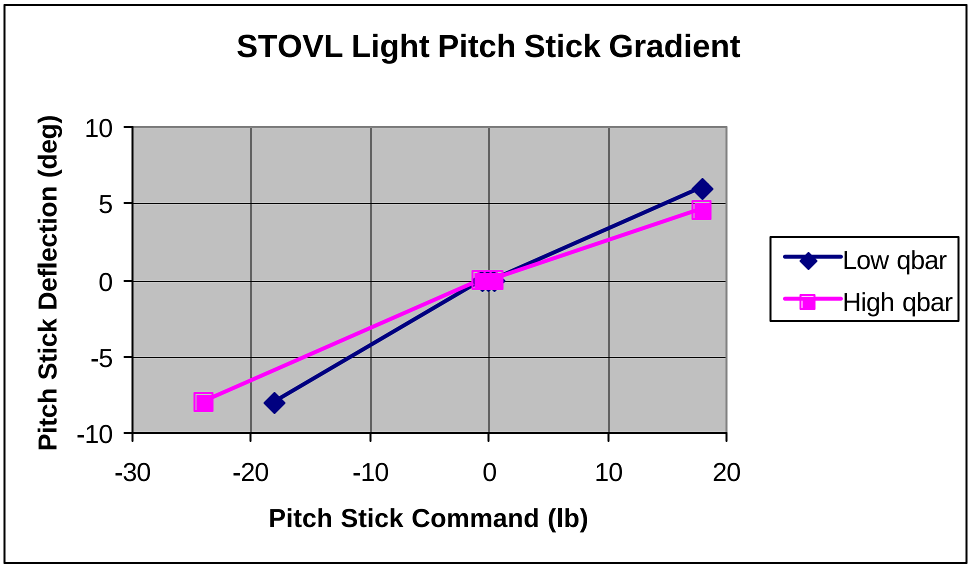


FIGURE 3-7: VAAC STOVL LIGHT PITCH STICK GRADIENT

Source: *VAAC Flight Trial Results, August 1999*

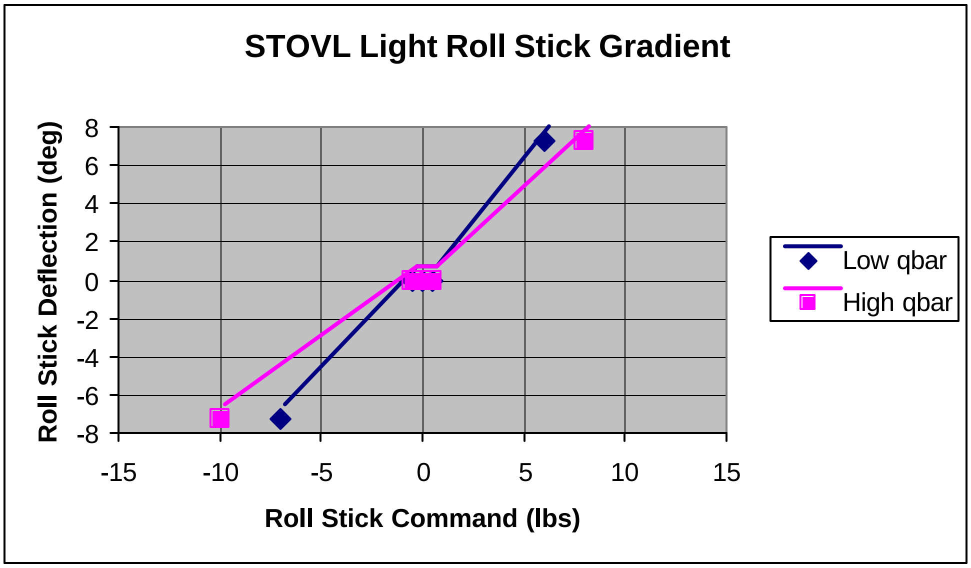


FIGURE 3-8: VAAC STOVL LIGHT ROLL STICK GRADIENT

Source: *VAAC Flight Trial Results, August 1999*

A set of stick characteristics with deflections and gradients consistent with a conventional take-off and landing aircraft, but with a different stick gradient and stick gearing was acceptable to perform all of the STOVL evaluation tasks. (Configuration 2)

Frequently the pilots commented on twitchiness, bobbling, or roll ratcheting during closed loop tasks. In each case the disturbance was caused by pilot inputs from the stick. These inputs were the root cause of the response perceived by the pilot. The inadvertent inputs had various causes including stick cross-talk due to pilot/stick misalignment, lack of an arm-rest, and the size of the stick electronic deadband (longitudinal and lateral). Small breakout forces also contributed to crosstalk when using heavy gradients. During an aggressive task the crosstalk was larger. The test team was confident that the absence of an armrest was the root of the problem.

The test team was satisfied with the results since the evaluation demonstrated that the use of a sidestick for the STOVL mission was feasible. They did admit, however, that improvement is needed in some areas. The report noted that an increase in handling qualities may be possible by varying stick characteristics not changed during the evaluation such as stick damping, deadband, and breakout. It was also found that each set of preferred stick characteristics were different for various tasks. CTOL tasks resulted in different feel requirements from STOVL characteristics for good handling qualities. The report also expressed concern that it would be difficult to collapse all of the results down to one set of stick characteristics for all tasks that will satisfy all pilots. Therefore, the use of active stick technology, in which the designers may vary control and stick characteristics with each mode of aircraft operation, will most certainly be required.

Joint Strike Fighter

The military was looking for an affordable replacement for the F-16, FA-18, AV-8B, and A-10, thus the concept for the Joint Strike Fighter (JSF) was initiated. The Joint Strike Fighter will be a multi-mission aircraft designed to replace each of these aging aircraft and their very different roles within the military. Boeing and Lockheed Martin each designed and constructed two concept demonstration aircraft showing commonality between the Conventional Take-Off and Landing (CTOL) aircraft, an aircraft carrier (CV) version, and a Short Take-Off/Vertical Landing (STOVL) version. Additionally, each contractor needed to demonstrate handling qualities during the carrier approach (flying the ball), and demonstrate a short take-off, transition from wingborne flight to a hover, and a vertical landing.

The Joint Test Force, a team of government pilots and engineers evaluating the JSF found the aircraft to have excellent handling qualities during various high gain tasks including field carrier landing practice, guns tracking, and in-flight refueling. The pilots had backgrounds from all many different airframes including the F-14, F-15, F-16, F/A-18, AV-8B, F-111, and F-117. Often during flight test, the pilots would practice their next test flight in another aircraft. This allowed a back-to-back comparison between legacy aircraft and the next generation fighter. Pilot comments during the high gain tasks highlight these comparisons. During guns tracking one pilot stated he had never seen a fighter track a target so smoothly. Another pilot commented that he could read a newspaper while in-flight refueling. Finally, while a Landing Signal Officer was observing the X-35 during field carrier landing practice, he stated that he had never seen an airplane with such solid performance. The landings included intentional deviations in glideslope, both high and low, and line-up, left and right of centerline.

Lockheed-Martin recently won the contract for the JSF and is the largest military contract in history worth an estimated value of $300 billion over the life of the airplane. Lockheed-Martin's X-35 included a sidestick controller.

Concurrent with the concept demonstration phase of the program, there was significant work accomplished in future weapon systems. Dozens of pilots including current fleet aviators, TOPGUN instructor pilots, and USAF Weapon School pilots took part in various exercises in which the pilots performed combat tasks in a simulator with new weapon systems. Although the purpose of the simulations was not a handling qualities evaluation, it is noteworthy that the majority of the comments centered favorably on aircraft capabilities with very few comments about the handling qualities. Pilots of legacy aircraft equipped with a centerstick quickly noted the unobstructed view of a multi-function display between their legs and adapted quickly to the sidestick. The test pilots who flew concept demonstration aircraft and the simulators stated the fidelity of the simulators was high enough to make a fair handling qualities assessment.

CHAPTER IV

SIDESTICK DESIGN

Location

The standard convention for control of a fighter is to have the right hand control the stick and the left hand control the throttle. Although pilots seem to adapt fairly quickly to the reverse convention in multi-place cockpits with pilot and co-pilot seated in tandem and the sidesticks placed outboard, it is recommended to keep the standard convention with the stick on the right ride of the cockpit. There should be an armrest included in the design and it should be positioned such that the pilot's forearm is approximately lined up with the longitudinal axis of the aircraft. Absence of an armrest can result in crosstalk and stick input bandwiths will vary if the wrist and forearm muscles are making the inputs. The absence of an armrest could also lead to PIO. The armrest should be adjustable in fore-aft positioning as well as vertically. An improperly placed armrest can limit the motion of the wrist, especially during a multi-axis input.

Consideration should be given to the various aircraft system controls located below the pilot's arm. The system controls located under the armrest should be for a system that is configured while on deck and not manipulated in flight. If manipulation is required, the task should be performed with minimum heads down time.

From a Pilot Vehicle Interface standpoint, designers need to account for a more diverse cadre of pilots. A tall person must be able to reach controls without being cramped while a small person must be able to reach the aircraft and system controls. A current problem with centerstick controllers is that a small person is not able to apply full forward and left stick. This combination of controls is not normally required except during aggressive maneuvering such as Air Combat Maneuvering. The F/A-18E/F utilizes this combination of control inputs to perform a "pirouette" maneuver commonly used during ACM. With a properly designed sidestick, it is easy for all pilots to achieve full stick deflections.

If a two seat aircraft is equipped with sidesticks, such as a trainer, there should be some means for the instructor to override the controls. If there is no mechanical linkage between the two sidesticks, it would not be possible for the instructor to observe the student control inputs, nor will the student be able to 'follow through' the actions of the instructor demonstrating a maneuver. If at any point the instructor deems it necessary to take over the controls to avoid a mishap, he must be able to do so immediately.

Deflection Geometry

The stick deflection geometry may not be directly in line with longitudinal and lateral axes of the aircraft. Most sidestick aircraft have the longitudinal axis displaced to the right for a right-handed sidestick. The optimum angle is different for different pilots. Shoulder width and lateral distance from the shoulder to the armrest are some of the key variables. If the alignment is not accurate, crosstalk is almost certain.

Fighters designed to operate off aircraft carriers have another aspect to keep in mind. During a catapult launch, it is preferred to have the launch occur with no pilot action required. In other words, the pilot should not be required to hold the stick in a certain position or rotate the aircraft. If the sidestick is designed with the longitudinal and lateral axes not in line with the aircraft's XY axes, the potential exists for an inadvertent multi-axis input due to the longitudinal acceleration of the catapult and the mass of the stick.

The physical characteristics of the controller affect the pilot's opinion of the handling qualities of a sidestick controller's force/deflection characteristics. The pivot point (base of stick or wrist) and the size and shape of the stick grip have also proven to be important.

Control Switches – Trim, HOTAS

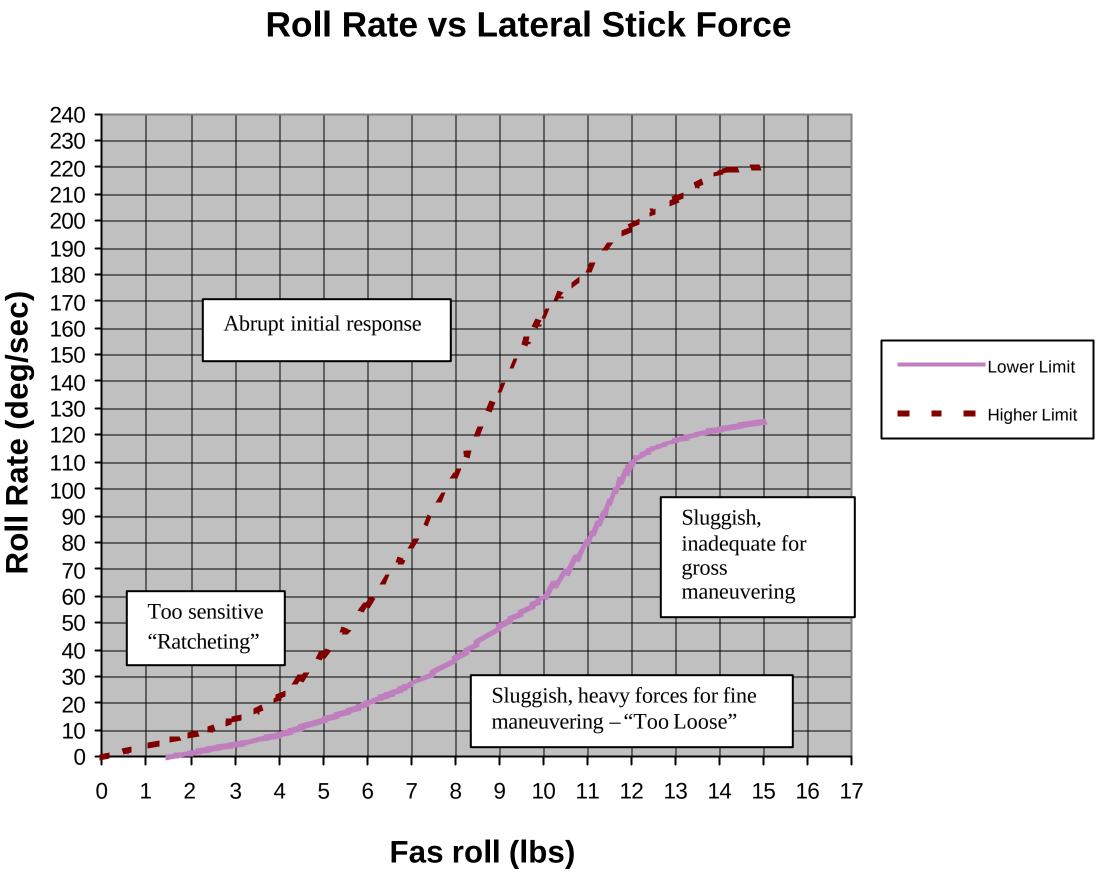
Flight test demonstrated that the results from fixed base simulation did not provide accurate feedback to the pilot while attempting to trim the aircraft. The trim rates derived from simulation started at 3°/sec in pitch and 5°/sec in roll. Flight test proved these rates to be too fast and were reduced to 1°/sec with a lead term incorporated.

HOTAS controls on the stick should have light breakout forces on the order of 1.0 pound. During various sidestick evaluations, breakout forces greater than 1 pound resulted in inadvertent stick inputs. Additionally, the HOTAS breakout forces should be no greater than 50% of the stick breakout force.

Longitudinal/Lateral Deflection-Force and Force Response Characteristics

The Military Specification – Flying Qualities of Piloted Aircraft provides a good starting point for boundaries of sidestick characteristics. Although, a good portion of the tolerances stated for sidestick controllers merely indicate that the characteristics shall not be objectionable. Designers may provide the pilot with different stick feel characteristics based on the task at hand. However, each task or phase of flight may require different characteristics. Active stick technology affords the designer the possibility to tailor the control laws and stick feel to each task. Non-linear command-responses are common in the latest generation of aircraft. Non-linearities are utilized to avoid over-sensitivities for small inputs while allowing maximum performance without excessive force requirements. Deflection limits for an active controller could be up to ±7° in pitch and roll. If the controller reverts to a passive mode, up to 15° in pitch and roll may be used. The deflections may be asymmetric. It is easier for the pilot to pull aft on the stick and roll left (right handed controller), consequently deflections, gradients, and response gain may be larger in those directions. Stick stops should be utilized at the deflection limits and should be easily discernible. The stops should be mechanized such that the maximum aircraft response occurs when the stick reaches maximum deflection.

Figure 4-1 shows a guideline for lateral stick force versus roll rate. Recent work shows that the low end of the spectrum is best suited for Precision Approach operations and the high end of the spectrum works well for Up-and-Away tasks.



Abrupt initial response

Too sensitive “Ratcheting”

Sluggish, inadequate for gross maneuvering

Sluggish, heavy forces for fine maneuvering – “Too Loose”

FIGURE 4-1: ROLL COMMAND GRADIENT GUIDELINES

Control Harmony

Control Harmony is a difficult challenge. The designer is provided the opportunity to tailor the stick characteristics for each phase of a flight or mission, he/she must develop harmonious gradients for each mode of operation. Pitch and roll harmony is a complex blending between the controller’s force and deflection characteristics in each axis coupled with the vehicle response dynamics. Not only must each mode be harmonious, but the transition from one mode to the next must also be seamless. Blending the control laws from one mode to the next over a finite period of time or within an airspeed band seem to be effective ways to ensure smooth mode change harmony.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

New technologies have re-ignited interest in the use of sidestick controllers for commercial and military aircraft. There are many advantages and disadvantages utilizing a sidestick in fighter aircraft. Many pilots prefer the feel of a centerstick controller and the designer only needs to develop a few sets of command gradients or gearings to produce adequate handling qualities. However, centersticks require more cockpit room due to their larger size and range of motion. Consequently, designers would have a difficult time fitting a centerstick in small cockpits such as the F-16. The presence of a centerstick could obstruct the view of a center panel Multi-Function Display, preventing the pilot from quickly assimilating valuable information. Sidestick controllers are light-weight, can fit in small cockpits, and are better suited for aircraft capable of sustained high normal load factors. From a pilot-vehicle interface standpoint, sidesticks offer an unobstructed view of displays, a clear pathway during an emergency cockpit egress, and allows access to full command inputs for the diverse statures of today's pilots.

The sidestick controller is not without deficiencies. A sidestick controller prevents easy access to the console under the armrest forcing the designers to use that space for controls that may be set prior to flight. A sidestick also prevents the pilot from using the non-sidestick hand to control the aircraft while trying to do other tasks, such as writing on a kneeboard or using the console under the armrest. Additionally, the tendency toward PIO is more prevalent in aircraft equipped with a sidestick than a centerstick. Flight test and simulation have shown that different Command Gradients and Gearings optimize performance for different tasks. However, it is not feasible to collapse the control laws into one usable set for all tasks.

Technology has provided designers a means to overcome this challenge. Active stick technology allows designers to use the optimum control laws for each task instead of compromising on a single set of gradients used for each task. Current aircraft under development have shown that it is feasible for an aircraft equipped with a sidestick controller to effectively employ this concept. The benefit of such advances is highlighted during high gain tasks such as aerial refueling, guns tracking, or during aircraft carrier landings.

Recent flight test programs have utilized these high gain tasks to test aircraft control systems and performance. The aerial refueling task has been a challenge since its inception. New control systems equipped with a sidestick have generated very favorable pilot comments during aerial refueling. One pilot felt so comfortable while in-flight refueling he even jokingly stated that he could read a newspaper during this high gain task. Another veteran test pilot commented that he had never flown a fighter that tracked a target so smoothly. Finally, during the high gain task of carrier landings, comments were performed with excellent handling qualities and performance. The pilots of these evaluations would routinely fly a practice flight in either the F/A-18 or F-16. The purpose of the practice flight was to refine technique or work on timing of the events. A byproduct was a back-to-back comparison of either a centerstick or the rigid sidestick and the new inceptor technologies. Tasks that had previously resulted in poor handling qualities ratings with sidesticks are now providing results as good or better than legacy aircraft equipped with a centerstick.

Active stick technology will allow the designers a multitude of options to incorporate the best mechanical characteristics matched to aircraft dynamics for the particular task at hand. Each task the pilot performs may have a completely different set of sidestick characteristics to optimize performance for that task. The challenge for designers is to ensure there is a seamless transition from one mode to the next. Effective mode change harmony may require the control laws to be blended from one mode to the next over a finite period of time or within an airspeed band. Equally as important for good handling qualities is the ergonomic challenge of incorporating a sidestick controller and armrest that will accommodate a diverse pilot community. If these challenges are met with this emerging technology, designers will have the means to overcome the inherent difficulties in sidestick controllers thus securing the future of the sidestick in fighter aircraft.

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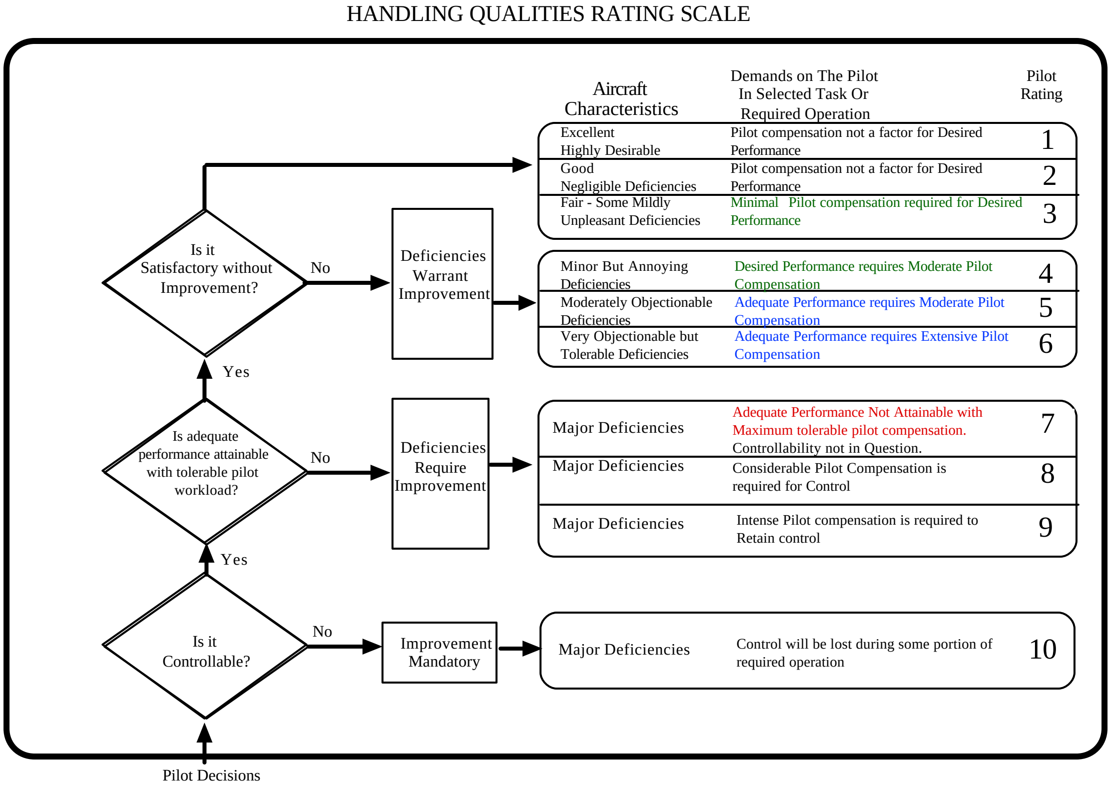
APPENDIX



FIGRUE A-1: COOPER HARPER HANDLING QUALITIES RATING SCALE

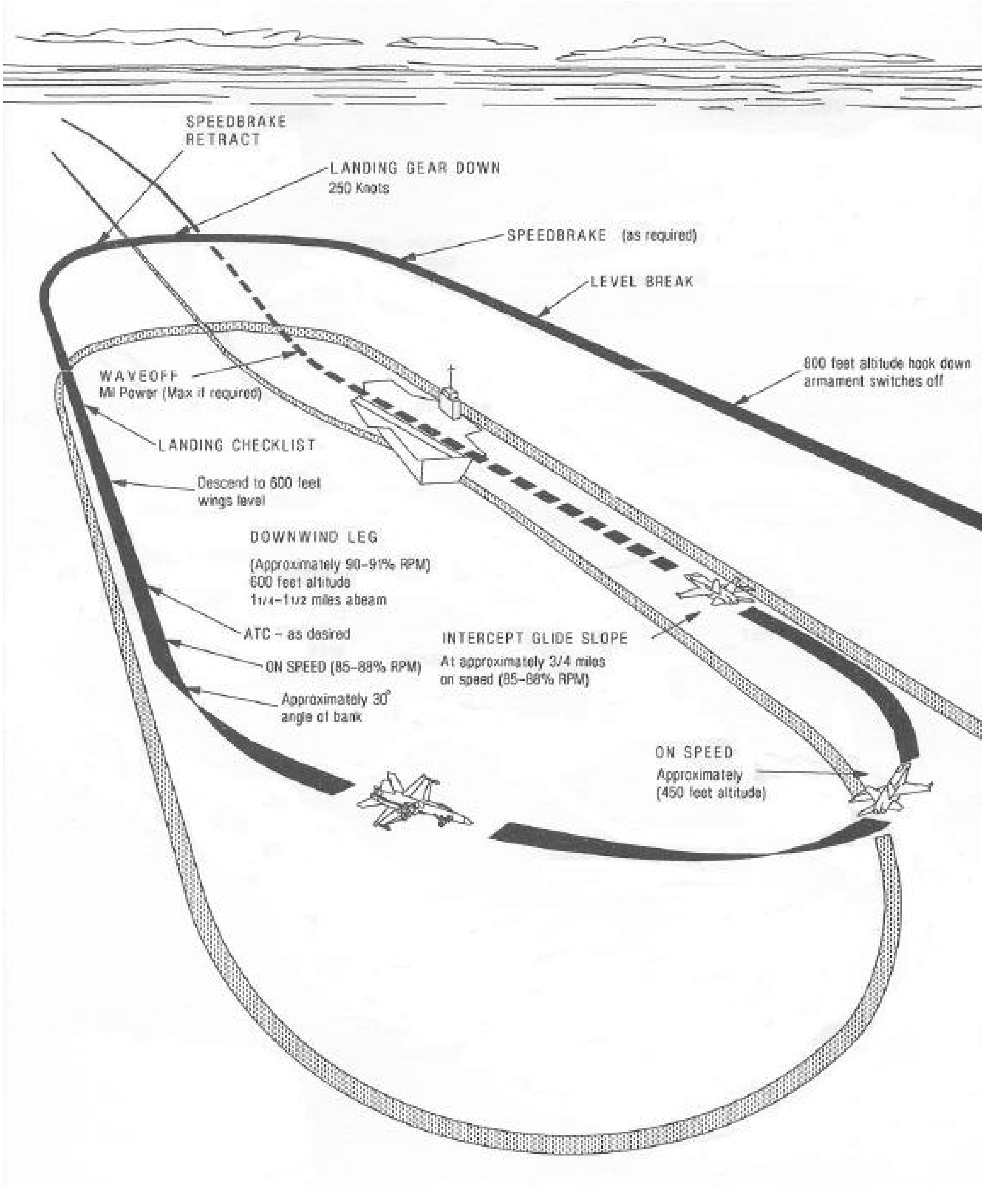
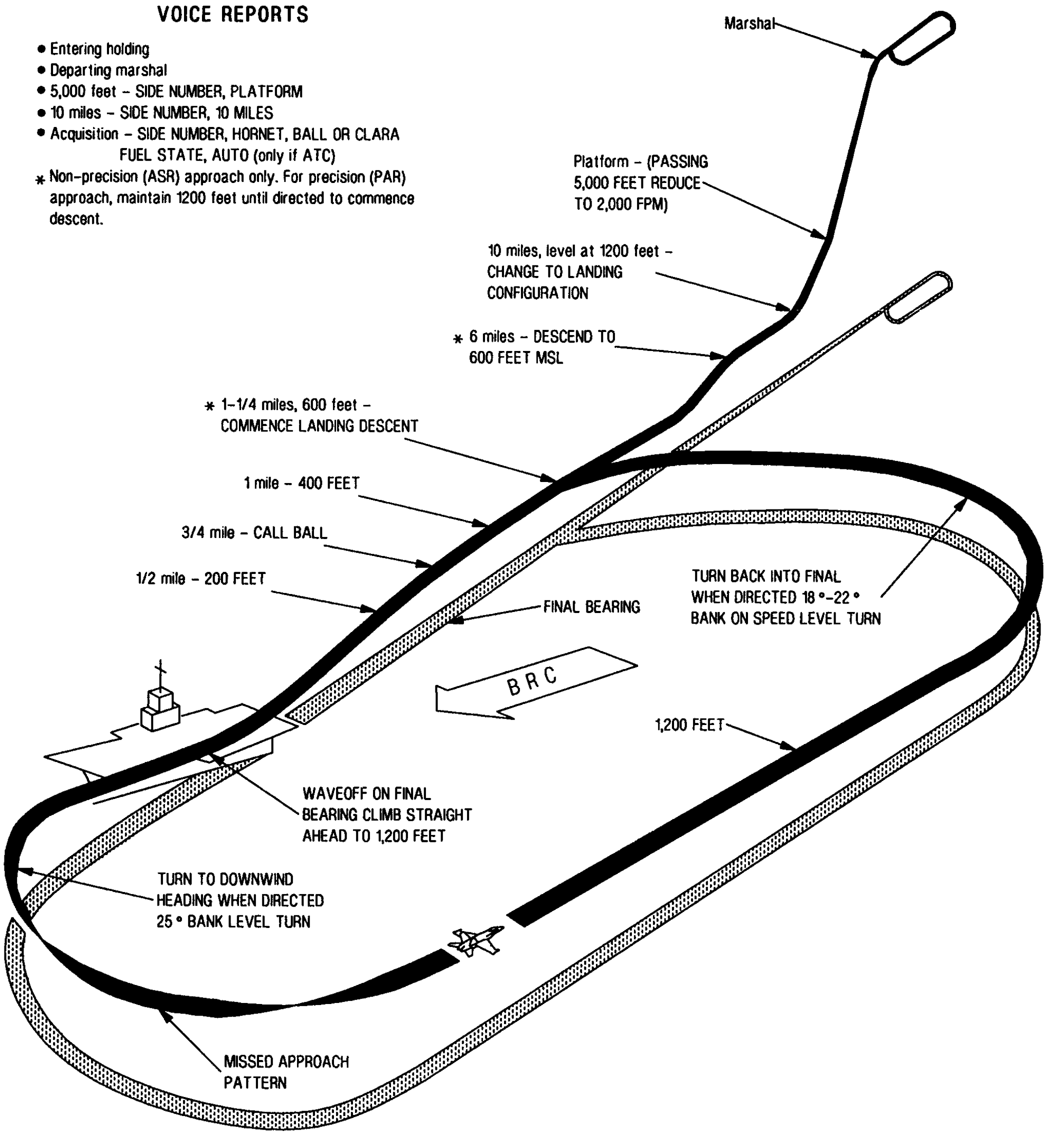


FIGURE A-2: DAY CARRIER LANDING PATTERN

Source: *NATOPS FLIGHT MANUAL NAVY MODEL FA-18* A1-FA18-NFM-000 15 December 2000



VOICE REPORTS

- Entering holding
- Departing marshal
- 5,000 feet – SIDE NUMBER, PLATFORM
- 10 miles – SIDE NUMBER, 10 MILES
- Acquisition – SIDE NUMBER, HORNET, BALL OR CLARA FUEL STATE, AUTO (only if ATC)

* Non-precision (ASR) approach only. For precision (PAR) approach, maintain 1200 feet until directed to commence descent.

FIGURE A-3: NIGHT/IMC APPROACH TO AIRCRAFT CARRIER

Source: *NATOPS FLIGHT MANUAL NAVY MODEL FA-18* A1-FA18-NFM-000 15 December 2000

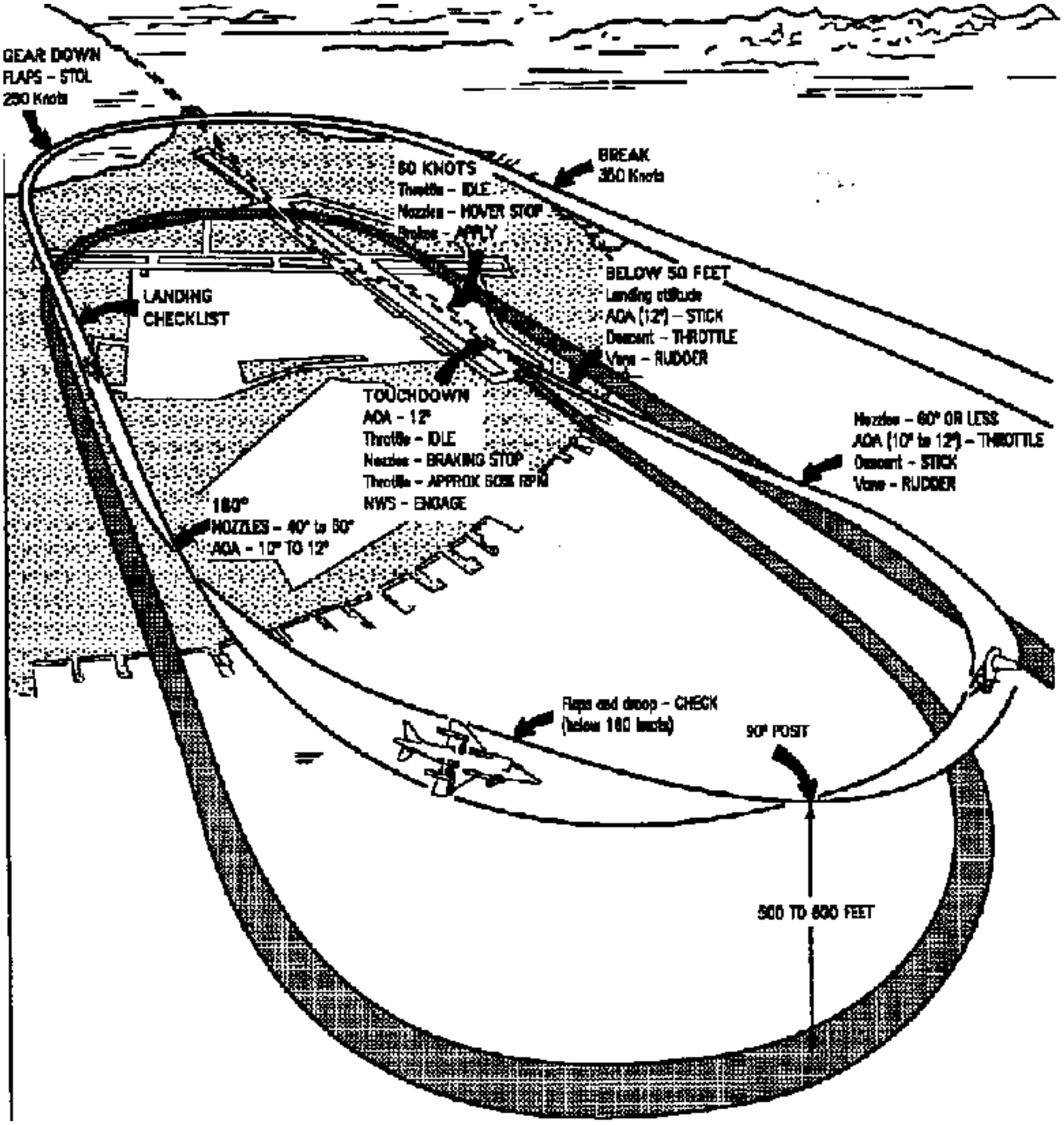


FIGURE A-4: HARRIER SLOW LANDING

Source: *NATOPS FLIGHT MANUAL NAVY MODEL AV-8B* A1-AV8BB-NFM-000 1 August 1995

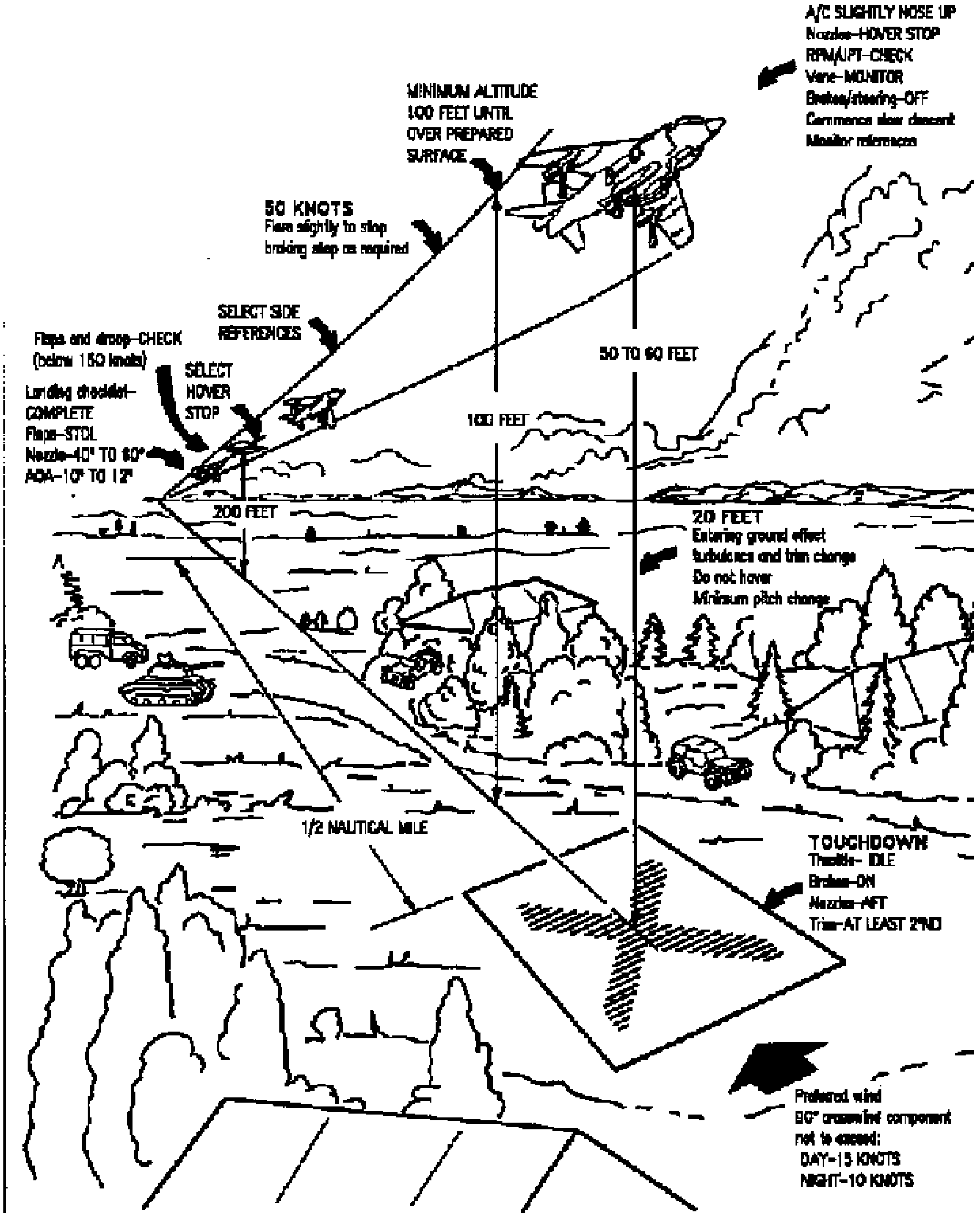


FIGURE A-5: HARRIER VERTICAL LANDING

Source: *NATOPS FLIGHT MANUAL NAVY MODEL AV-8B* A1-AV8BB-NFM-000 1 August 1995

VITA

Lieutenant Commander Brian Goszkowicz was born in Chicago, Illinois on August 8, 1967. He attended elementary school in Wauconda, Illinois and graduated from Wauconda High School in 1985. In 1990 he received a Bachelor of Science Degree in Aeronautical/Aerospace Engineering from the University of Illinois and was commissioned as an Ensign in the United States Navy. He was assigned to flight training at Pensacola, Florida. He was designated a Naval Aviator on 4 Sep 1992. While waiting for an opening in the FA-18 Hornet training squadron, he attended the Defense Language Institute where he learned French. In 1993 he attended Hornet training and joined VFA-137. While there, he was selected to attend the Navy Fighter Weapons School (TOPGUN) and became the squadron's Strike Fighter Weapons and Tactics Instructor. Lieutenant Commander Goszkowicz was selected to attend the US Navy Test Pilot School and graduated in 1998. He has flown more than 1,900 hours in more than 25 different types of aircraft, of which over 1,500 in the Hornet. He was a member of the Joint Strike Fighter Joint Test Force and was the Navy test pilot assigned to evaluate the Lockheed Martin X-35.

Lieutenant Commander Goszkowicz is currently assigned to Strike Fighter Squadron 151. His awards include the Air Medals for combat missions flown during Operation Southern Watch, the Defense Meritorious Service Medal, the National Defense ribbon, and the Navy Achievement Medal. Lieutenant Commander Goszkowicz is married to the former Kelly Williams and has one daughter and two sons.