NASA Technical Memorandum 104322

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September 1996

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EVALUATION OF HIGH-ANGLE-OF-ATTACK HANDLING QUALITIES FOR THE X-31A USING STANDARD EVALUATION MANEUVERS

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ABSTRACT

The X-31A aircraft gross-acquisition and fine-tracking handling qualities have been evaluated using standard evaluation maneuvers developed by Wright Laboratory, Wright-Patterson Air Force Base. The emphasis of the testing is in the angle-of-attack range between 30° and 70°. Longitudinal gross-acquisition handling qualities results show borderline Level 1/Level 2 performance. Lateral gross-acquisition testing results in Level 1/Level 2 ratings below 45° angle of attack, degrading into Level 3 as angle of attack increases. The fine-tracking performance in both longitudinal and lateral axes also receives Level 1 ratings near 30° angle of attack, with the ratings tending towards Level 3 at angles of attack greater than 50°. These ratings do not match the expectations from the extensive close-in combat testing where the X-31A aircraft demonstrated fair to good handling qualities maneuvering for high angles of attack. This paper presents the results of the high-angle-of-attack handling qualities flight testing of the X-31A aircraft. Discussion of the preparation for the maneuvers, the pilot ratings, and selected pilot comments are included. Evaluation of the results is made in conjunction with existing Neal-Smith, bandwidth, Smith-Geddes, and military specifications.

NOMENCLATURE

AOA	angle of attack, deg
CHR	Cooper-Harper rating
CIC	close-in combat
EFM	Enhanced Fighter Maneuverability
HARV	High Angle of Attack Research Vehicle
HUD	head-up display
KIAS	knots indicated air speed
LOES	lower-order equivalent systems
MATV	Multi Axis Thrust Vectoring
MAX AB	maximum afterburner

PIO	pilot-induced oscillation
PST	poststall
RPC	roll performance classification
SSLA	slow-speed line-abreast
STEM	standard evaluation maneuver

INTRODUCTION

Controlled flight at high angles of attack (AOAs) provides a modern fighter aircraft with the ability to turn rapidly, providing enhanced nose-pointing capability. The ability to accurately point the nose of the aircraft in a timely manner is the basis for handling qualities criteria and ratings. With the exception of recent flight programs such as the F-16 Multi Axis Thrust Vectoring (MATV),[1] F-18 High Angle of Attack Research Vehicle (HARV),[2] and X-29A,[3] an opportunity for flight test evaluations at poststall (PST) angles of attack has not existed. The Handling Qualities Military Standard (MIL-STD-1797)[4] provides a summary of criteria for handling qualities that have been derived primarily for a more conventional flight regime. Simulation-based criteria[5,6] have been developed to specifically address flight in the PST regime. Additional criteria[7–9] have also been developed to address handling qualities of modern augmented aircraft. Using the X-31A linear simulation, analytic evaluations of the handling qualities at high AOAs were performed to predict the characteristics of this aircraft.[10]

Designed specifically for investigation of flight in the PST regime, the X-31A Enhanced Fighter Maneuverability (EFM) program evaluated the benefits of thrust vectoring in a close-in combat (CIC) environment with emphasis on PST or flight at greater than 30° AOA. Following the completion of the original X-31A CIC objectives, a high-AOA handling qualities flight test program was performed. Standard evaluation maneuvers[11] (STEMs) were used to assess longitudinal and lateral gross acquisition and fine tracking at high AOAs. Pilot ratings and comments were collected immediately following each maneuver. These data were analyzed and compared with existing handling qualities criteria.

The development and preparation for the high-AOA handling qualities flight testing, a summary of the flight test data, a comparison of the results with existing handling qualities criteria, and a summary of lessons learned during the flight testing are covered in this paper.

AIRCRAFT DESCRIPTION

The X-31A airplane (fig. 1) is a single-seat fighter configuration with an empty weight of approximately 12,000 lbm that uses a single GE-F404-400 engine (General Electric, Lynn, Massachusetts). Fuel capacity is approximately 4000 lbm. Two aircraft were built by Rockwell International (Downey, California) and Daimler-Benz Aerospace (Germany). The wing planform

EC 94-42478-1

Figure 1. X-31A airplane in poststall flight.

is a double delta with an inboard leading-edge sweep of 56.6° and an outboard sweep of 45°. The wing area, span, and mean chord are 226.3 ft^2, 22.833 ft, and 12.35 ft respectively. Four trailing-edge flaps on the wing can be deflected symmetrically for pitch control and differentially for roll control. The leading-edge flap is scheduled to deflect as a function of AOA. The aircraft has an all-moving canard for pitch control and to meet the requirement for aerodynamic recovery from extreme AOAs. The vertical tail contains a rudder for directional control at AOAs less than 40°. Pitch and yaw moments can be generated by the three thrust-vector vanes. The inlet lip is moveable and is deflected as a function of AOA. These control effectors were all integrated into a control system[10,12] that provided the capability for good control throughout the AOA range.

In the longitudinal axis, the control system uses load factor command to a maximum 30° AOA. In the PST regime, from 30° to 70° AOA, deflections of the control stick command a specific AOA. Three in. of aft stick commands 30° AOA; and full deflection, or 4.5 in., commands 70° AOA. This characteristic results in a stick sensitivity in AOA command of 33.3 deg/in of stick deflection. The nominal stick force is 5 lbf/in. The rate of change of AOA command was limited to 25 deg/sec. The longitudinal control system also includes an AOA command limiter that was set by the pilot. The AOA limiter provided the capability for the pilot to set the limit for the AOA command in 5° increments from 30° to 70° AOA.

For the lateral–directional axes, deflection of the control stick commands velocity-vector roll rate. The roll stick deflects 3 in. left and right. The maximum allowable roll rate is 240 deg/sec at a low AOA. In PST, the velocity-vector roll rate is between 30 and 50 deg/sec, scheduled as a function of dynamic pressure and AOA. During envelope expansion, the pilots had difficulty using full-lateral stick when using full-aft pitch stick because of interference with their legs. To accommodate this, the lateral-stick deflection–to–roll command gain was changed linearly from 1 to 2 between 30° and 70° AOA. This change results in full–roll rate command being generated with half-stick deflection at 70° AOA. The rudder pedals can be used to command sideslip at low AOAs, and their command authority is reduced to 0° at an AOA greater than 40°. The basic operation of the aircraft is designed for "feet-on-the-floor" flying.

The primary source of information for the pilot was the head-up display (HUD) (fig. 2). This display contained a conventional pitch ladder and heading display. Altitude and altitude rate were displayed on the upper right, while airspeed and Mach number were shown on the upper left. On the left side of the display were two tapes that showed the AOA and load factor. These data were displayed digitally at the top of the tapes. The current AOA command limit was indicated by an arrow next to the AOA tape. The HUD also contained a 2-mrad fixed pipper, depressed 2° from the waterline with an inner 20-mrad and outer 40-mrad reticle. Flight test instrumentation allowed in-flight recording of the HUD.

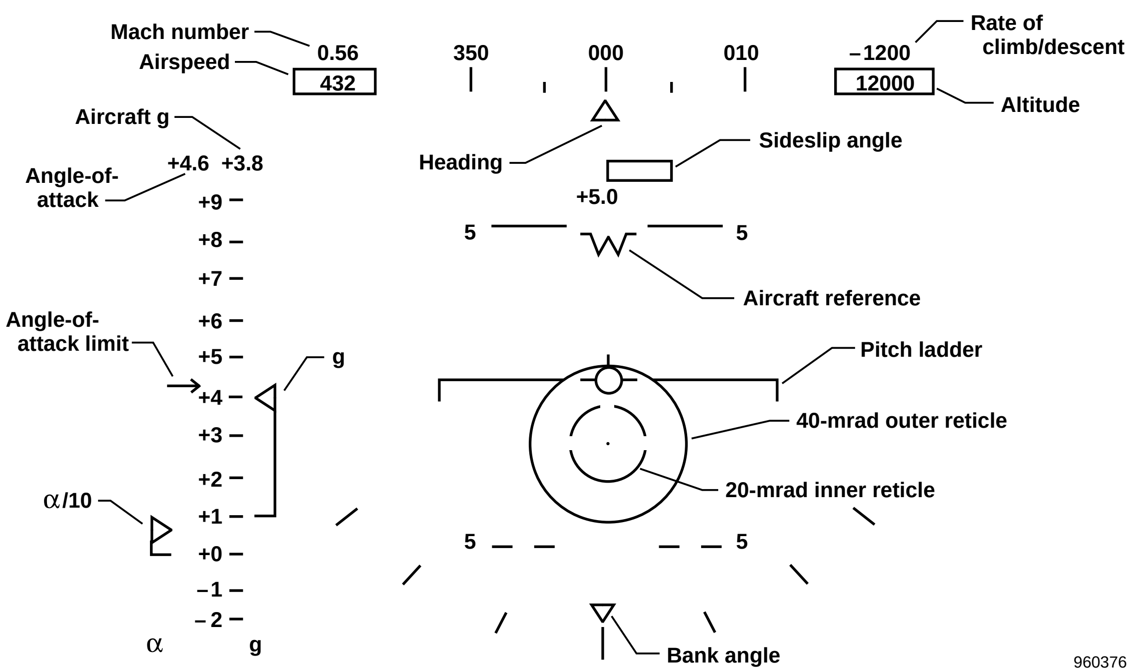

Figure 2. Head-up display symbology.

AIRCRAFT SIMULATIONS

Three simulations were used in the preparation for and analysis of the flight test maneuvers: a six-degrees-of-freedom, nonlinear simulation[13] that incorporated flight hardware and a fixed-base cockpit mock-up; a batch version of the six-degrees-of-freedom simulation; and linear simulations of the longitudinal and lateral–directional axes.

The cockpit for the piloted simulation incorporated the pilot displays and controls. A 5 ft by 6.5 ft flat screen projection provided the pilot a limited view out of the cockpit. The field of view for this screen was approximately 30 deg laterally and 20 deg vertically. One feature of the simulation was the capability to project a target aircraft that could be used for practicing the maneuvers. The target aircraft trajectory could be "flown" and recorded to allow for training with a repeatable maneuver.

The batch version of the simulation was used primarily for the generation of linear state-space models. Using these plant descriptions from the batch simulation, the linear simulation was used to generate transfer functions for use in the handling qualities criteria. These transfer functions could be used directly in the criteria evaluation or in the calculation of lower-order equivalent systems (LOES) parameters. The aerodynamic models for the linear simulation were fourth order. The control system included sensor models, filters, and high-order actuator models.

HANDLING QUALITIES EVALUATION

During the X-31A flight testing, an informal handling qualities evaluation was conducted during the CIC testing and formal evaluation using STEMs. The CIC testing was performed to evaluate the effectiveness of PST maneuverability.[14] From a predetermined set of starting conditions, the X-31A airplane was flown against an adversary aircraft. Both pilots were free to maneuver as required to try to establish a tracking situation. In addition to the test pilots assigned to the program, service pilots demonstrated the ability to become quickly familiar with the aircraft and to fly aggressively without any limitations on control stick inputs in the PST flight regime. In all of the CIC engagements, the pilots flew the aircraft aggressively to try to "win" the simulated combat.

CIC testing is used as a comparison with the formal handling qualities testing because of the demonstrated ability of the X-31A pilots to successfully accomplish gross acquisitions and perform fine tracking in a high-gain environment at high AOAs. During CIC evaluation, the X-31A aircraft was generally able to outperform adversary aircraft by using PST maneuvers. Although no handling qualities ratings were made during these tasks, the general consensus was that the X-31A aircraft had good handling qualities (Level 1 or Level 2) in this flight regime, and no major handling qualities deficiencies were noted. Similar handling qualities were expected from the STEM evaluations. A disadvantage of using CIC to evaluate handling qualities is that the AOA varies considerably and the handling qualities characteristics cannot be sorted out as a function of AOA.

A method for providing consistent techniques for flight-test handling quality evaluation has been addressed by the definition of a set of STEMs.[11] These maneuvers can obtain evaluations at a constant AOA that can then be compared to analysis. During a limited flight test evaluation, the X-31A aircraft used four evaluation maneuvers: three STEMs, and a maneuver developed from CIC testing. The flight test maneuvers were derived from STEM 10 (High-AOA Longitudinal Gross Acquisition), STEM 3 (High-AOA Lateral Gross Acquisition) and STEM 2 (High-AOA Tracking). The chase airplane for the X-31A aircraft, an F-18 aircraft, was used as the target airplane. Data were collected using a pilot rating sheet that was completed immediately following each maneuver, postflight interviews, a review of in-flight video recordings made through the HUD, and a comprehensive set of telemetered data. The techniques for performing these maneuvers were developed using experience gained from the F-18 HARV program. In order to emulate the acquisition and tracking tasks that were performed during the CIC investigation using the X-31A airplane, an additional evaluation maneuver was flown. This maneuver used slow-speed line-abreast (SSLA) initial conditions and resulted in acquisition and tracking tasks at a variety of AOAs. The formal handling qualities testing covered a 5-month period and used five different pilots during the performance of 19 flights.

Flight preparation involved practice in the simulator to establish guidelines for maneuvering the test and target aircraft. The initial starting positions, target maneuver, and timing were defined so that the gross-acquisition or fine-tracking tasks occurred at a specific AOA. To accurately achieve consistent initial starting conditions, two operational ground radars were required because the X-31A aircraft was not equipped with a radar. During testing, the pilots could achieve consistent spacing without the ground radars by comparing the relative target size with the HUD reticle.

Pilot comments were recorded on a questionnaire immediately following each maneuver. The completion of the questionnaire required a pilot rating using the Cooper-Harper rating (CHR) system[15] (fig. 3) and an evaluation of the confidence class (fig. 4). The confidence class rating was used to help assess the effectiveness of the maneuvers for rating handling qualities. Changing the initial conditions or additional practices improved the confidence class ratings. Pilot comments were solicited regarding difficulty, predictability, aggressiveness effects, and control system effects. Following these comments, a pilot-induced oscillation (PIO) rating (fig. 5) and a second CHR were recorded. For lateral gross acquisitions, a rating using the roll performance classification (RPC)[16] (fig. 6) was also solicited. The RPC was developed through simulation studies to address the open-loop nature of lateral gross acquisition. The RPC is intended to judge the initial rate and rate onset and is not based on the ability to arrest the roll rate. The pilot comments were transcribed using the HUD video recordings that were available for every flight.

Each maneuver was also evaluated using the telemetered data. Linear models were calculated for each maneuver based on the AOA, airspeed, altitude, and estimated fuel state. The linear models were used to generate the parameters and frequency responses required for the handling qualities criteria.

Longitudinal Gross Acquisition

STEM 10 was used as the basis for the longitudinal gross-acquisition task. The X-31A airplane started 3000 ft in trail of the target aircraft. At the initiation of this maneuver, the target aircraft entered a steady turn to the conditions indicated in Table 1. After predetermined time delays, the X-31A pilot selected maximum afterburner (MAX AB), rolled the aircraft so that the target aircraft was in the pitch plane, and then aggressively pulled to capture the target in the pitch plane within the criteria (fig. 7). The pipper and reticles in the HUD provided a reference for evaluating the gross-acquisition and fine-tracking tasks. The goal of the tasks was not to drive the pipper to the target, but to acquire or track the target within the specified criteria in relation to the pipper. The

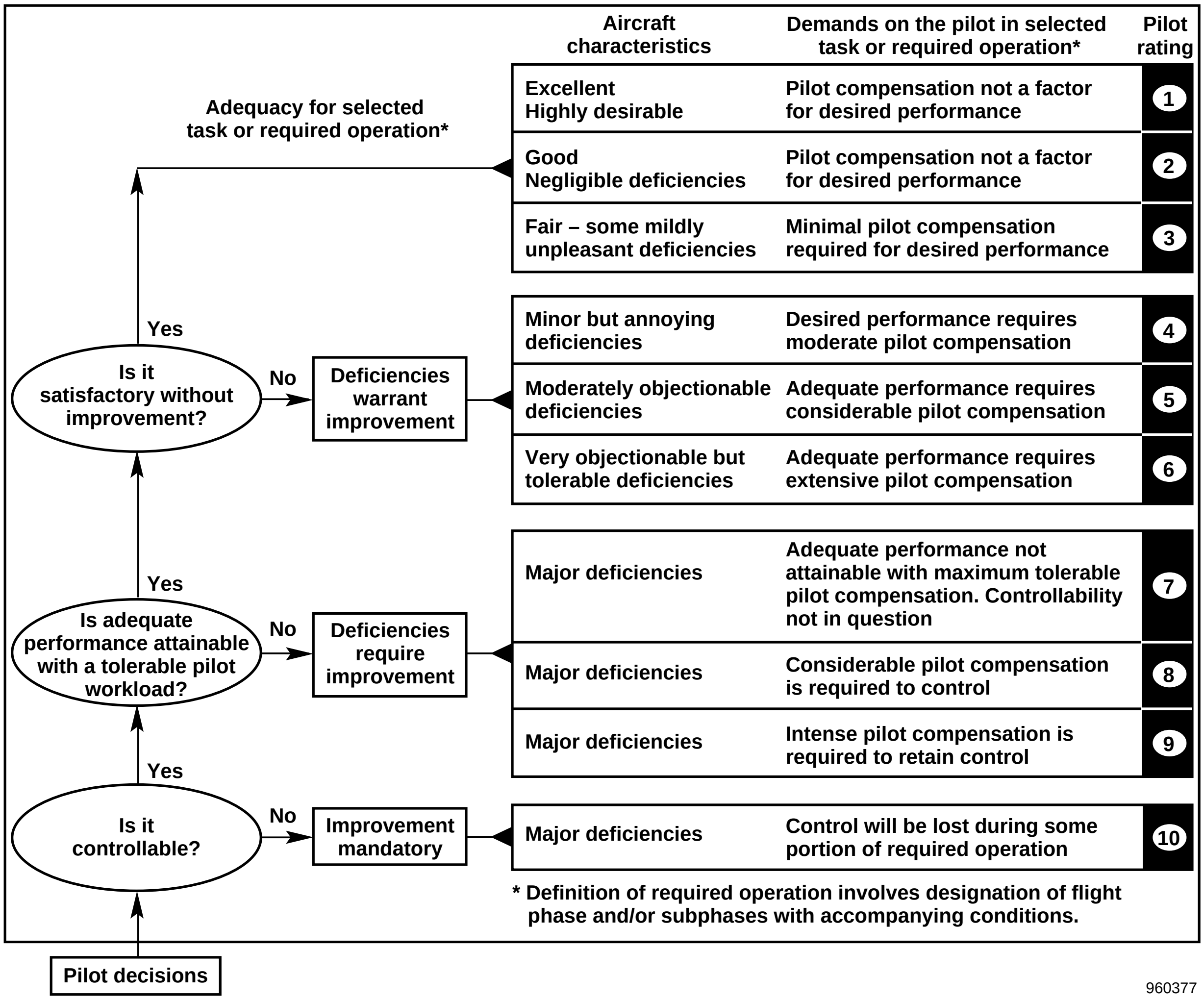

Figure 3. Cooper-Harper rating scale.

Classification	Description
A	The pilot rating was assigned with a high degree of confidence.
B	The pilot rating was assigned with only a moderate degree of confidence because of uncertainties introduced by moderate differences in environmental conditions, or in aircraft configuration or state, or in task, from what was desired.
C	The pilot rating was assigned with minimum confidence because of important differences between the desired and actual environmental conditions, aircraft configuration or state, or task, requiring considerable pilot extrapolation.

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Figure 4. Classification of pilot confidence factor.

Numerical rating	Description
1	No tendency for pilot to induce undesirable motions.
2	Undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.
3	Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort.
4	Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.
5	Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open loop by releasing or freezing stick.
6	Disturbance or normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing stick.

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Figure 5. Pilot-induced oscillation rating scale.

Roll performance for mission effectiveness	Improvements in roll performance	Numerical
Enhancing – tactically superior	None warranted	1
Satisfactory – mission requirements met	May be warranted, but not required	2
Unsatisfactory – mission requirements not met	Required	3
Unacceptable – tactically useless	Mandatory	4

2.5

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Figure 6. Roll performance classification.

Table 1. Task descriptions for longitudinal gross acquisition.

Flight condition	Maneuver timing	Maneuver description
30° AOA, Mach 0.45	T = 0	Target begin maneuver: MAX AB, constant 20° AOA turn, maintain 200 KIAS.
	T + 4 sec	X-31A advance throttle to MAX AB.
	T + 4 sec	X-31A roll in plane with target, perform rapid pull to 30° AOA.
30°AOA, Mach 0.60	T = 0	Target begin maneuver: MAX AB, constant 20° AOA turn, maintain 200 KIAS.
	T + 4 sec	X-31A advance throttle to MAX AB.
	T + 5 sec	X-31A roll in plane with target, perform rapid pull to 30° AOA.
45°AOA, Mach 0.50	T = 0	Target begin maneuver: MAX AB, constant 25° AOA turn, maintain 170-180 KIAS.
	T + 5 sec	X-31A advance throttle to MAX AB
	T + 7 sec	X-31A roll in plane with target, perform rapid pull to 45° AOA.
60°AOA, Mach 0.50	T = 0	Target begin maneuver: MAX AB, constant 25° AOA turn, maintain 170-180 KIAS.
	T + 5 sec	X-31A advance throttle to MAX AB.
	T + 8 sec	X-31A roll in plane with target, perform rapid pull to 30° AOA.

Desired:	**Aggressively acquire target within 25* or 40** mrad longitudinally of pipper with no overshoot and within a desirable time to accomplish the task.**
Adequate:	**Aggressively acquire the target within 25* or 40** mrad longitudinally of pipper with no more than 1 overshoot and within an adequate time to accomplish the task.**

*** Criterion for 30°and 60° AOAs ** Criterion for 45° AOA**

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Figure 7. Performance criteria for longitudinal gross acquisition.

timings were selected so that the gross acquisition would occur at the desired AOA of either 30°, 45°, or 60°. The AOA limiter was not used during this testing. Table 1 shows the maneuver timing for each flight condition.

Lateral Gross Acquisition

Lateral gross acquisitions were flown using STEM 3 as a baseline. For these maneuvers, the target aircraft established a steady turn at specified conditions, and the pilot of the X-31A aircraft maneuvered the aircraft to the target AOA (30°, 45°, or 60°) at maximum afterburner. Depending on how rapidly the pilot applied aft stick, the aircraft could be at 1 *g* or an elevated load factor at the desired AOA. When the target aircraft was at a prespecified angle away from the nose of the X-31A aircraft, the X-31A aircraft was maneuvered aggressively using only lateral stick to acquire the target in the roll plane within the criteria (fig. 8). Table 2 shows the initial conditions for these maneuvers. To assist the pilot in remaining at the targeted AOA and to try to constrain the maneuver to the lateral axis, the AOA command limiter was set to the desired value.

Desired:	**Aggressively acquire target within 25* or 40** mrad laterally of pipper with no overshoot and within a desirable time to accomplish the task.**
Adequate:	**Aggressively acquire the target within 25* or 40** mrad laterally of pipper with no more than 1 overshoot and within an adequate time to accomplish the task.**

*** Criterion for 30° AOA ** Criterion for 45° and 60° AOAs** 960382

Figure 8. Performance criteria for lateral gross acquisition.

Table 2. Task descriptions for lateral gross acquisition.

Angle of Attack	Test Condition	Test Description
30°	170 KIAS X-31A 1500 ft Echelon and behind F-18 AOA limit = 30°	F-18 (target): Roll and pull to 170 KIAS/ 30° AOA, adjust power/attitude to maintain conditions. X-31A: MAX AB, pull to 30° AOA. When target is 30° off nose, acquire target laterally.
45°	170 KIAS X-31A 1500 ft Echelon and behind F-18 AOA limit = 45°	F-18 (target): Roll and pull to 170 KIAS/ 30° AOA, adjust power/attitude to maintain conditions. X-31A: MAX AB, pull to 45° AOA. When target is 30°-45° off nose, acquire target laterally.
60°	170 KIAS X-31A 1500 ft Echelon and behind F-18 AOA limit = 60°	F-18 (target): Roll and pull to 170 KIAS/ 30° AOA, adjust power/attitude to maintain conditions. X-31A: MAX AB, pull to 60° AOA. When target is 30°–45° off nose, acquire target laterally.

Fine-Tracking Evaluation

The fine-tracking evaluation consisted of two phases. Phase 1 testing was performed at AOAs of 10°, 15,° and 20° to establish a reference point for comparison with other conventional AOA evaluations and testing in the PST regime. During phase 1, fine tracking was performed only in the longitudinal axis. Phase 2 testing, based on STEM 2, evaluated fine tracking at AOAs of 30°, 45,° and 60° for the longitudinal and lateral axes. The AOA command limiter was not used in fine-tracking evaluations.

Initial testing in Phase 2 concentrated on longitudinal fine-tracking evaluations while the maneuver setup was refined. Because only one axis was being evaluated at a time, the maneuver had to be set up with the target approximately in the reticle so that maneuvering could be performed only in the axis being evaluated. After an acceptable set of starting conditions was developed, the same setup was used for the longitudinal and lateral tracking tests at each AOA. The X-31A pilot would practice the maneuver to ensure that the setup would result in the desired AOA and then perform the maneuver twice. First, a longitudinal fine-tracking task was performed and pilot ratings were given. Then a second maneuver was performed where lateral tracking and ratings would be done. Table 3 shows the maneuver sequence and figure 9 shows the criteria. To test the ability to make precise longitudinal changes in track point, the maneuver description called for the pilot to move the pipper from nose to tail. Similarly, the lateral tracking task required the movement of the pipper from wing tip to wing tip.

Table 3: Task descriptions for fine tracking.

Angle of Attack	Test Condition	Test Description
10°	0.80 Mach number X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 3 *g*, adjust power/attitude to maintain conditions. X-31A: Roll and pull to 10° AOA for longitudinal tracking. (Repeat with target at 1.8 *g* and initial Mach number of 0.60.)
15°	0.75 Mach number X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 3.5 *g*, adjust power/attitude to maintain conditions. X-31A: Roll and pull to 15° AOA for longitudinal tracking. (Repeat with target at 2.1 *g* and initial Mach number of 0.55.)
15°	0.70 Mach number X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 4.0 *g*, adjust power/attitude to maintain conditions. X-31A: Roll and pull to 20° AOA for longitudinal tracking. (Repeat with target at 2.4 *g* and initial Mach number of 0.50.)

Table 3: Continued.

Angle of Attack	Test Condition	Test Description
30°	180 KIAS X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 180 KIAS/ 25° AOA, adjust power/attitude to maintain conditions. X-31A: MAX AB, at 20° angle off, roll and pull to 30° AOA for tracking.
45°	180 KIAS X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 160 KIAS/ 30° AOA,. adjust power/attitude to maintain conditions. X-31A: MAX AB, at 30° angle off, roll and pull to 45° AOA for tracking.
60°	180 KIAS X-31A 1500 ft behind F-18	F-18 (target): Roll and pull to 170 KIAS/ 30° AOA, adjust power/attitude to maintain conditions. X-31A: MAX AB, at 45° angle off, roll and pull to 60° AOA for tracking.

Desired:	**Pipper within +/– 5 mrad band for 50 percent of task and within +/– 25 mrad for the remainder of the task; no objectionable PIO.**
Adequate:	**Pipper within +/– 5 mrad band for 10 percent of task and within +/– 25 mrad for the remainder of the task; no objectionable PIO.**

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Figure 9. Performance criteria for fine-tracking tasks.

Combined Maneuvers

Pilots consistently commented on the difference between the types of maneuvers used in the handling qualities evaluations and the maneuvering performed during CIC. To address the perceived handling qualities differences between CIC and STEMs, a combined maneuver was evaluated during one flight. For this maneuver, the starting conditions were those of the SSLA setup from the CIC flight tests. The X-31A and F-18 aircraft started side by side at the same speed and altitude—215 knots indicated airspeed (KIAS) and 25,000 ft—separated by 1500 ft. For the handling qualities evaluation, the maneuvering began on the call of the X-31A pilot. The aircraft initially turned towards each other with the X-31A aircraft going over the target aircraft. Then the F-18 aircraft performed a single heading reversal and maintained a steady turn at 30° AOA and 170 KIAS. The X-31A aircraft maneuvered as required to acquire and track the target. Multiple acquisitions were achieved by lagging off of the target aircraft and then maneuvering aggressively to reacquire the target. Figure 10 shows the rating criteria.

Gross acquisition	**Desired:**	**Aggressively acquire target within 25 mrad of pipper with no overshoot and within a desirable time to accomplish the task.**
	Adequate:	**Aggressively acquire the target within 25 mrad of pipper with no more than 1 overshoot and within an adequate time to accomplish the task.**
Fine tracking	**Desired:**	**Pipper within +/– 5 mrad band for 50 percent of task and within +/– 25 mrad for the remainder of the task; no objectionable PIO.**
	Adequate:	**Pipper within +/– 5 mrad band for 10 percent of task and within +/– 25 mrad for the remainder of the task; no objectionable PIO.**

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Figure 10. Performance criteria for the combined maneuvers.

HANDLING QUALITIES RESULTS

Handling qualities testing was done during 19 flights over a 5-month period in 1994. Five pilots participated in the testing, using both X-31A aircraft. When acquiring the pilot comments at the completion of each maneuver, a CHR was solicited before and after the detailed comments. Having the pilot repeat the CHR at the end of the questionnaire allowed a reassessment of the rating in light of the more detailed comments and discussion. The second rating given is used as the reference for this report. The first and second CHR were generally the same.

Longitudinal Gross Acquisition

Longitudinal gross-acquisition tasks were flown on five flights by three pilots. The initial timings for these maneuvers were based on the piloted simulation. Because of the limited field of view provided by the projection television display in the simulator, transferring this simulation experience to flight was difficult. A total of 49 gross-acquisition tasks were performed with 28 receiving pilot ratings. Twenty tasks were practices and one task was an unsuccessful gross acquisition. Eleven of the practice maneuvers occurred on the first flight. Results from this first flight were used to refine the maneuver timing, and consequently, each of the other pilots typically required only one practice at each target AOA. The goal was to collect data at 30°, 45°, and 60°, with the actual AOA for acquisition falling between 22° and 65°.

It became apparent after testing started that horizontal bands located in relationship to the pipper as specified by the performance criteria (25 or 40 mrads) rather than a circular reticle would have provided the pilot with the appropriate reference for the task. Review of the HUD data and telemetry data showed that, during acquisition, if the target was entering the HUD field of view on either side of the reticle, a lateral input to bring the target within the reticle often occurred.

Figure 11 shows the CHRs plotted as a function of AOA. These data show a trend for CHRs increasing from “2” to “4” as AOA increased from 20° to 65°. The one CHR of “5” was the result

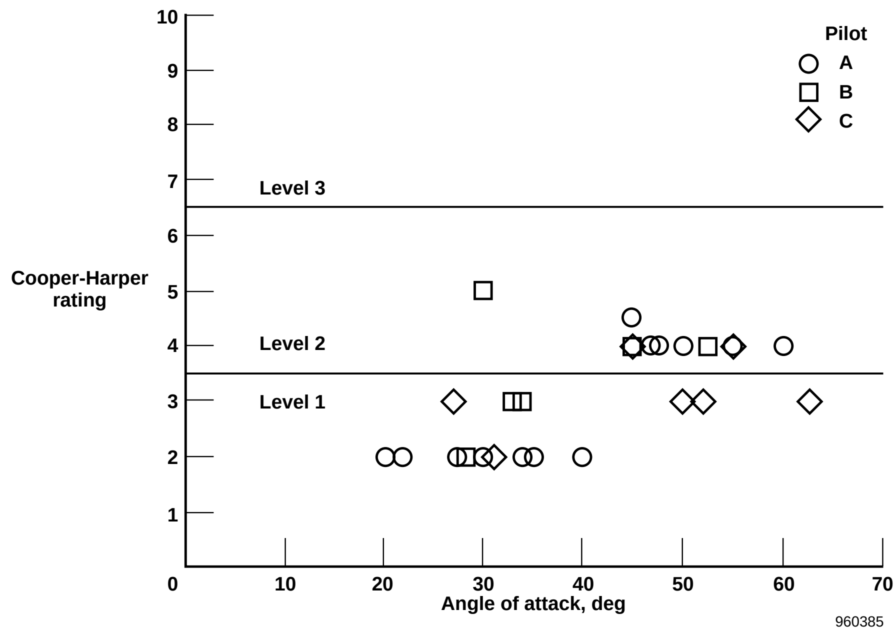

Figure 11. Cooper-Harper ratings as a function of angle of attack for longitudinal gross acquisition.

of a very large overshoot during capture. For these maneuvers, the pilots developed a technique to put in a nearly full–aft stick initial input and then leading the AOA capture with forward stick. As a compensation technique, Pilot B noted, “I’m starting to get a feeling for when I need to lead the pitch rate to get the capture task.” Figure 12 shows this phenomenon where maximum pitch rate during the maneuver is plotted as a function of AOA. At the higher AOAs, the pilots would hold aft stick longer, allowing a larger buildup of pitch rate prior to the countering control movement.

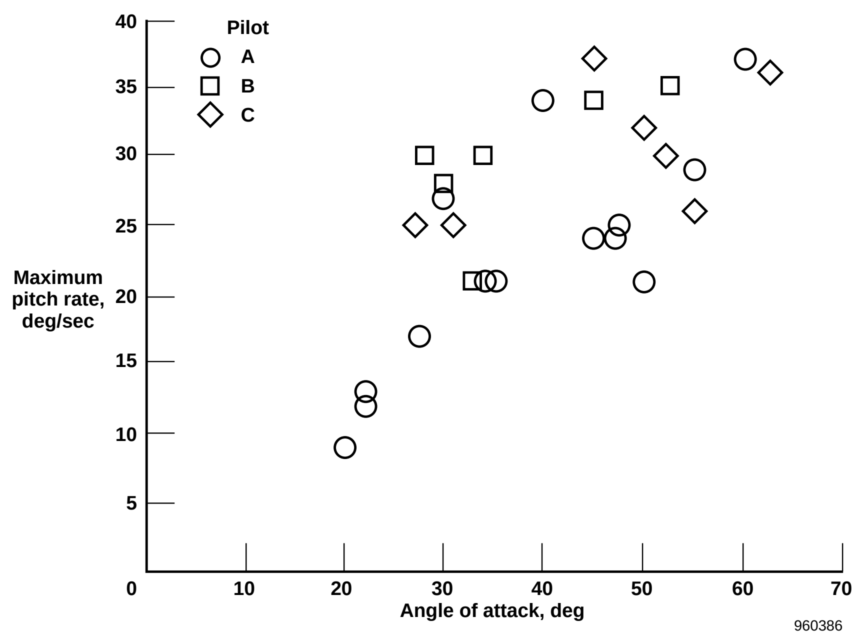

Figure 12. Maximum pitch rate as a function of angle of attack for longitudinal gross acquisition.

A confidence class rating of "A" was given for all but one of the maneuvers, meaning that the pilots' ratings were assigned with a high degree of confidence. The PIO ratings for 18 of the 28 tasks were "1," indicating that the pilots observed no undesirable motions. The remaining tasks received a PIO rating of "2," indicating undesirable motions that did not compromise task performance. These data indicate that the X-31A aircraft would have Level 1 performance at less than 40° AOA. The trend would be for borderline Level 1/Level 2 at AOAs greater than 40°. These ratings matched the expectations from the CIC testing.

In conjunction with these pilot ratings, a number of pilot comments add insight into the data. During the testing where the target AOA was 30°, Pilot A reported, "Thirty is the critical point. It's better [for the evaluation] to be above 30; below 30 is too easy." For the PST AOAs, the pilots consistently noted that the stick forces were too heavy and that the stick motion was too large. For the acquisitions at 45° and 60°, the pilots noted a lateral disturbance that complicated the task. This disturbance was noted during envelope expansion and was attributed to asymmetric forebody vortex cores that changed as a function of AOA.

Figure 13 shows an example time history for gross acquisition at 45° AOA. To show pitch-stick movement, a comparison of AOA command with AOA response and pitch-rate response are shown. Nearly full-aft stick is used to initiate the maneuver, followed by a number of stick inputs on the order of one-half inch. These small stick displacements result in a rate-limited AOA command. An inspection of the trailing-edge flaps and thrust-vector vanes also showed periods of rate limiting. None of the pilot comments indicated that rate limiting in either the command path or in the control surface response affected the handling qualities.

Lateral Gross Acquisition

The lateral gross-acquisition task was performed by four pilots during five flights. Nineteen of the total 49 acquisitions received pilot ratings (fig. 14). The remaining 30 maneuvers were practices. Two of the pilot ratings are not included in the summary of data because the AOA varied from 60° to 35° during attempted gross acquisitions at 60° AOA. The large number of practices required for this task shows the increased difficulty over the longitudinal gross acquisitions. Unlike the longitudinal acquisitions, where the task was primarily confined to one axis after the X-31A aircraft was banked into the correct plane, the lateral acquisitions required motion in multiple axes. First, the aircraft is performing velocity-vector rolls that result in a significant coning motion at high AOA. This motion is further complicated by the fact that the velocity vector settles during the maneuver. During extended maneuvers, the velocity vector is almost straight down, allowing the "helicopter gun attack." It should be noted that Pilot E had two sorties on one day and required the same level of practice maneuvering in both flights. This pilot had also practiced similar maneuvers in a domed simulation, which increased familiarity with the task being performed.

During the initial flight practices, the acquisition was not occurring at the desired AOA with the target in the HUD field of view. Adjustments were made in the distance the X-31A aircraft was trailing the target aircraft, the lateral displacement from the target aircraft, and the offset angle after the target began maneuvering before the X-31A pilot initiated acquisition. Typical difficulties with

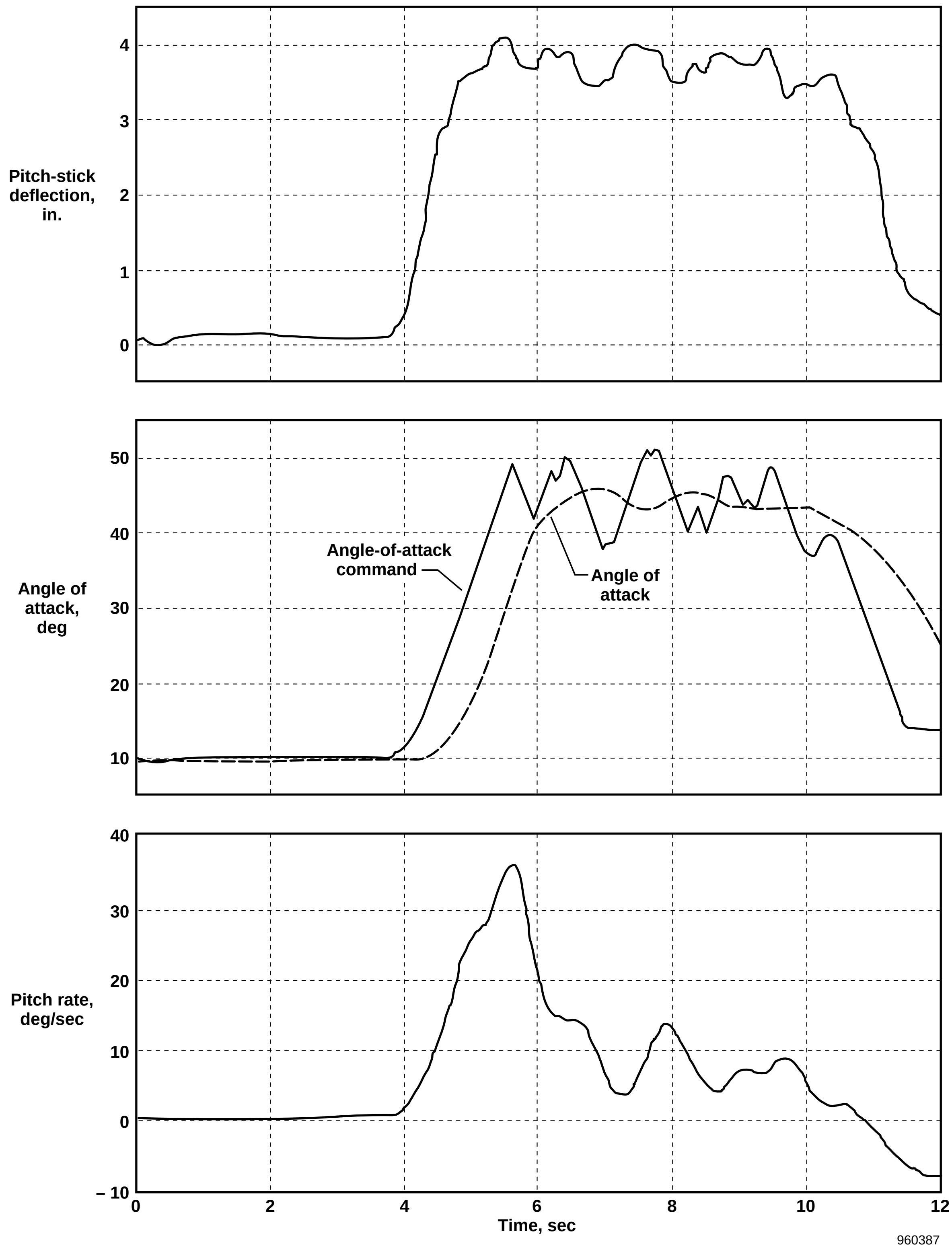

Figure 13. Time history from longitudinal gross acquisition.

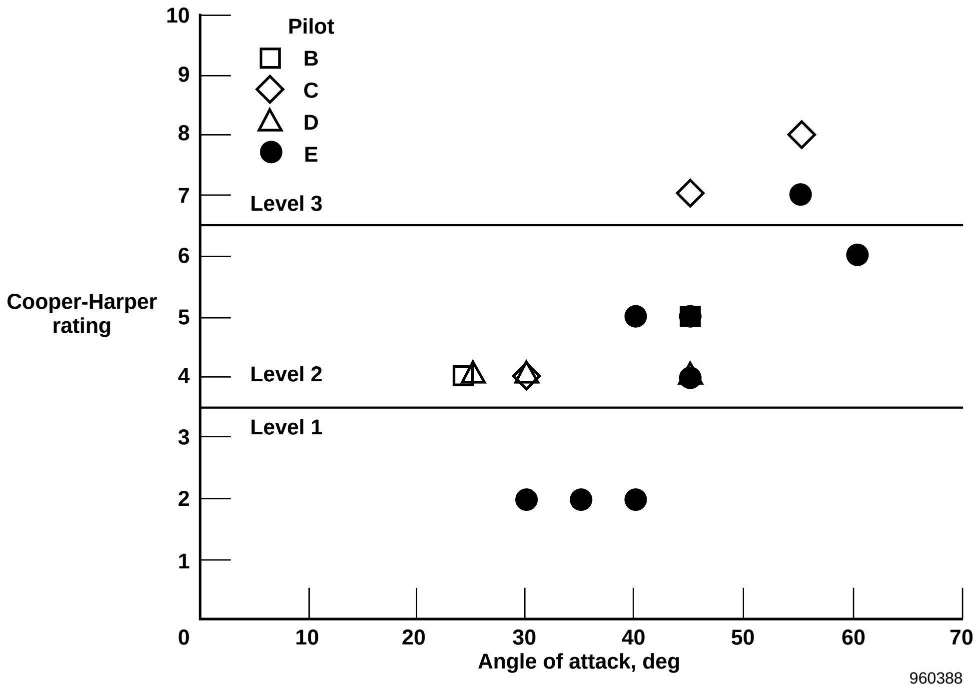

Figure 14. Cooper-Harper ratings as a function of angle of attack for lateral gross acquisition.

the performance of these maneuvers were loss of sight of the target aircraft by the pilot under the nose of the X-31A aircraft, causing termination of the maneuver for safety concerns, and acquisition of the target above or below the HUD field of view as a result of improper initial lateral offset.

Figure 14 shows a comparison of CHRs with AOA, revealing a degradation in handling qualities as AOA is increased. The cases near 30° AOA generally fall into the Level 1 category. At 45°, the pilot ratings are consistent with Level 2 handling qualities. At 60 °, the trend is for Level 3 handling qualities. For this task, the majority of the maneuvers (11 of 17) were given a confidence class rating of “B,” which shows only a moderate degree of confidence in the ratings. All of the data at AOAs greater than 50° were rated confidence class “B.” Based on pilot comments, this rating can be attributed to the difficulties with adjusting the initial conditions to account for the multiple-axis maneuvers required of the X-31A aircraft. The general trend for increased CHRs with increasing AOA is present in the ratings regardless of the confidence class rating.

This task did not emulate the lateral acquisitions performed during CIC testing. During simulated combat, the X-31A aircraft typically maneuvered within the turn radius of the target aircraft. The X-31A velocity vector was nearly straight down, resulting in a “helicopter gun attack.” The CIC results did not indicate a tendency for Level 3 handling qualities at the higher AOAs. While this task did identify handling qualities deficiencies, it is not clear that the STEM task is representative of the maneuvering pilots may be required to perform in the PST flight regime. For the STEM, the pilot had to aggressively initiate the maneuver with full-lateral stick; while in CIC testing, the pilot input was proportional to the change in nose-pointing angle required.

The PIO ratings tended to increase as a function of AOA. Three cases had a rating of “2”; undesirable motions were present but did not affect task performance. An additional three cases had a rating of “3,” indicating that undesirable motions did compromise task performance. One case was given a rating of “2–3,” also falling into the category of undesirable motions. Two cases showed nondivergent oscillations and received a PIO rating of “4.” Two cases did not receive a PIO rating, and six cases had a rating of “1.”

Figure 15 shows stability-axis roll rate for each maneuver plotted as a function of AOA and shows that, for the PST range, that rate was relatively constant at approximately 40 deg/sec. The peak rate occurred for a maneuver at 25° AOA, and in general, the higher roll rates were the result of the pilot using roll stick before achieving the desired AOA while the aircraft was still pitching up. Nine maneuvers received an RPC rating of “2,” or satisfactory. Eight cases received ratings of “2.5,” which falls between the satisfactory and unsatisfactory levels. One maneuver received a RPC rating of “1,” which equates to enhancing or tactically superior. This maneuver had the second highest stability-axis roll rate. The pilot commented, “I would say it’s just fine tactically. I got around as fast as I wanted to.” Although the onset rate was good, the pilot was unable to accurately arrest the roll rate, resulting in a CHR of “8” and a PIO rating of “4.” Addressing the undesirable motions, the pilot stated, “Lots of them. Many overshoots; borderline PIO at the end.” The pilot also noted that the task was “very difficult.”

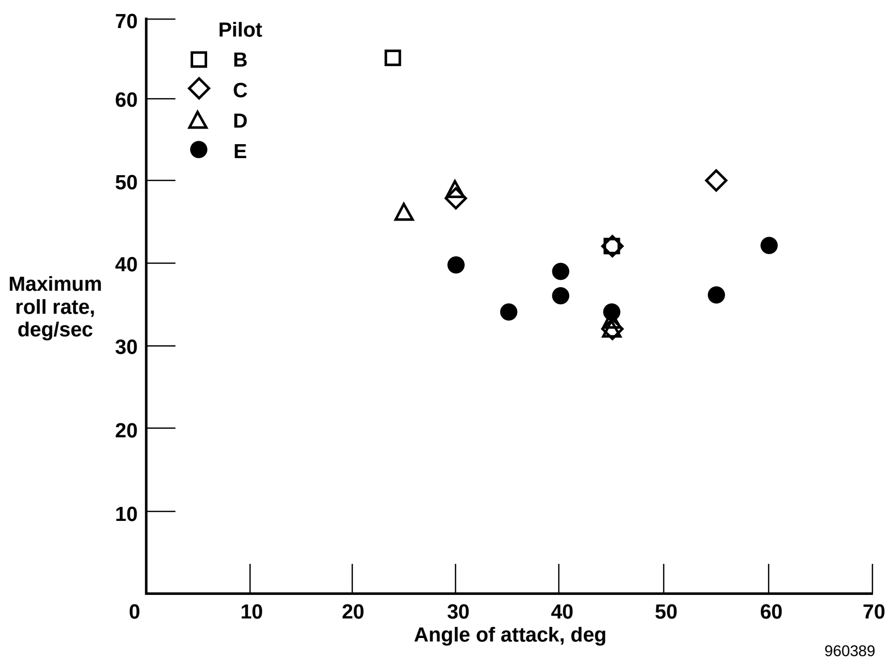

Figure 15. Stability-axis roll rate as a function of angle of attack for lateral gross acquisition.

Figure 16 shows time histories. It can be seen that the pilot used full-stick displacement three times during the maneuver with a peak stability axis roll-rate command of 40 deg/sec. Although the stability-axis roll rate was high for this flight condition, the pilot had difficulty using it effectively for the aggressive gross-acquisition task. These data indicate that using the RPC to assess only the roll onset does not necessarily equate to good gross-acquisition performance.

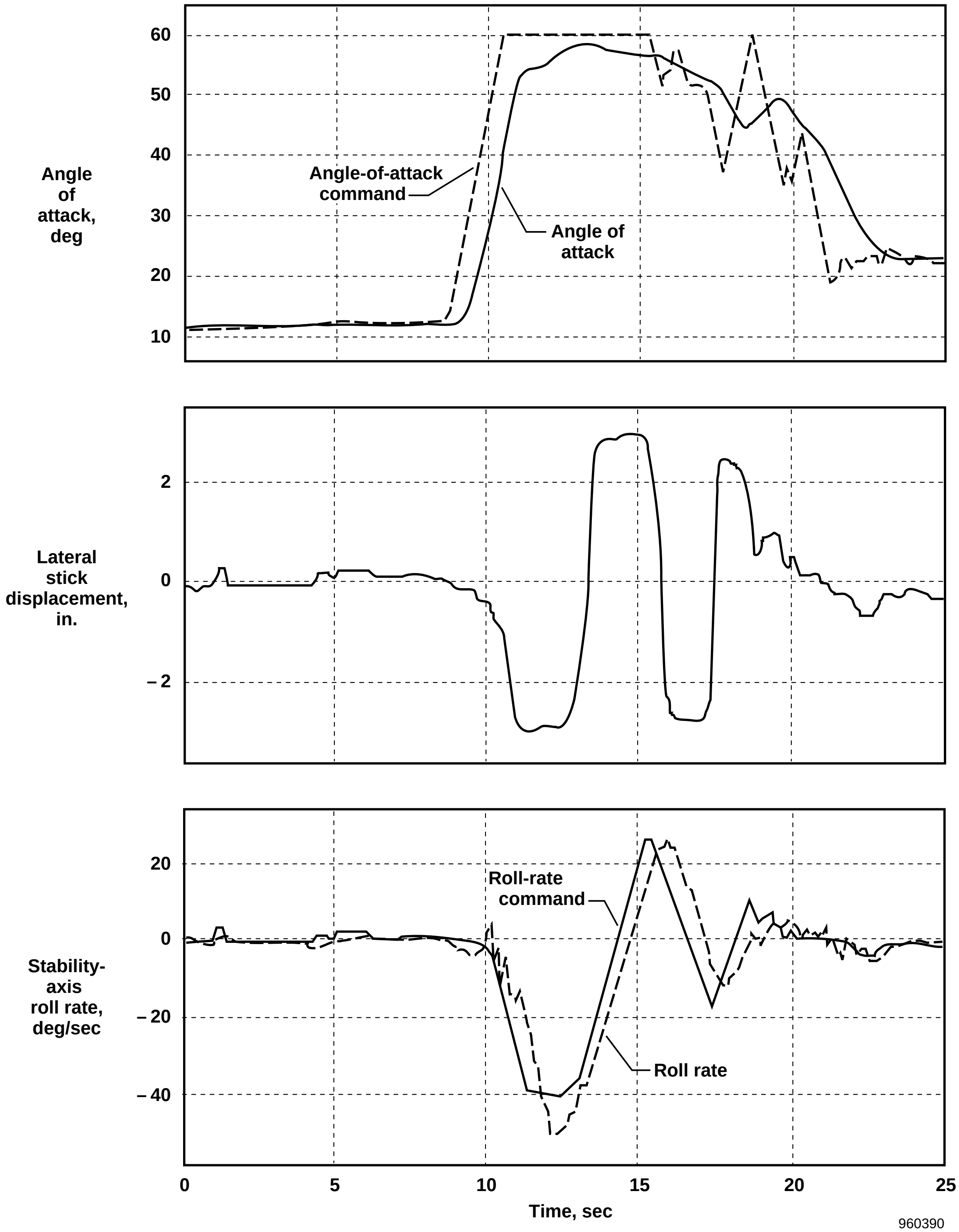

Figure 16. Time histories for lateral gross acquisition.

During the performance of this task, the pilots regularly used full–roll stick displacement, regardless of the AOA. For the high AOAs, this displacement would be more than required to get maximum roll command because of the modification in the relationship between stick deflection and full–roll rate command discussed above. One reason for this excess displacement would be that no feedback to the pilot exists when full-roll command is generated. No pilot comments were directed towards any effects caused by the limiter that result when the pilot stick deflection is larger than actually required for full-roll command. Examination of the time histories do not indicate any particular effects from the control inputs. Analogous to the longitudinal task, rather than a circular reticle, vertical bands at the specified distance from the pipper would have provided the pilot with a more appropriate reference for the task.

Fine-Tracking Evaluation

Fine tracking was evaluated during eight flights by three pilots. In Phase 1 testing at low AOAs, 17 tracking tasks were performed and 9 maneuvers rated. Of the eight practices, six were required in the first flight. During Phase 2 testing at high AOAs, 45 tracking tasks were performed. A total of 19 practices were required, and 16 longitudinal and 10 lateral fine-tracking tasks were rated. During the first flight, six practices were required to get initial conditions that allowed one scorable task. For the next 3 flights, efficiency improved, with 9 practices required to get 13 maneuvers that could be rated. As the target AOA increased, two or three practices were required to achieve the desired aircraft positioning at the target AOA. The last 2 flights required only 1 practice for 13 scorable maneuvers.

One factor that affected the pilot ratings was the amount of time spent tracking. The original flight cards called for 4 sec of tracking. However, the pilots often spent 20 sec or more performing the tracking task, resulting in significant variations in flight condition (particularly AOA). In one case where the intended AOA was 30° but the tracking occurred between 30° and 23°, the pilot commented, “There were two distinctive airplanes. When I was at the initial AOA around 30°, it was quite a bit harder to track than when I settled in. My rating will be associated with the initial values of the tracking.” Not all of the pilots were as concise in identifying the AOA range for their rating, and the engineers had to identify the AOA.

Longitudinal Fine Tracking

Initial difficulties with fine tracking resulted from the initial conditions of the aircraft. The spacing of 3000 ft used during the longitudinal gross acquisitions was reduced to 1500 ft, but the maneuver timing used for gross acquisition was not changed. This change resulted in the X-31A aircraft going a considerable distance downrange while the target was maneuvering. When the X-31A airplane was maneuvered, it was outside the turn of the F-18 airplane. Suggestions from the pilot in the control room to base the maneuver on the relative angle between the aircraft allowed the one scorable maneuver in the first flight. During the subsequent flights, the start time for the X-31A maneuver was based on the off-boresight angle and resulted in more repeatable tasks.

Figure 17 shows CHRs plotted as a function of AOA and shows an increase in rating (or decrease in handling qualities) as AOAs increases. For AOA less than 30°, the ratings are

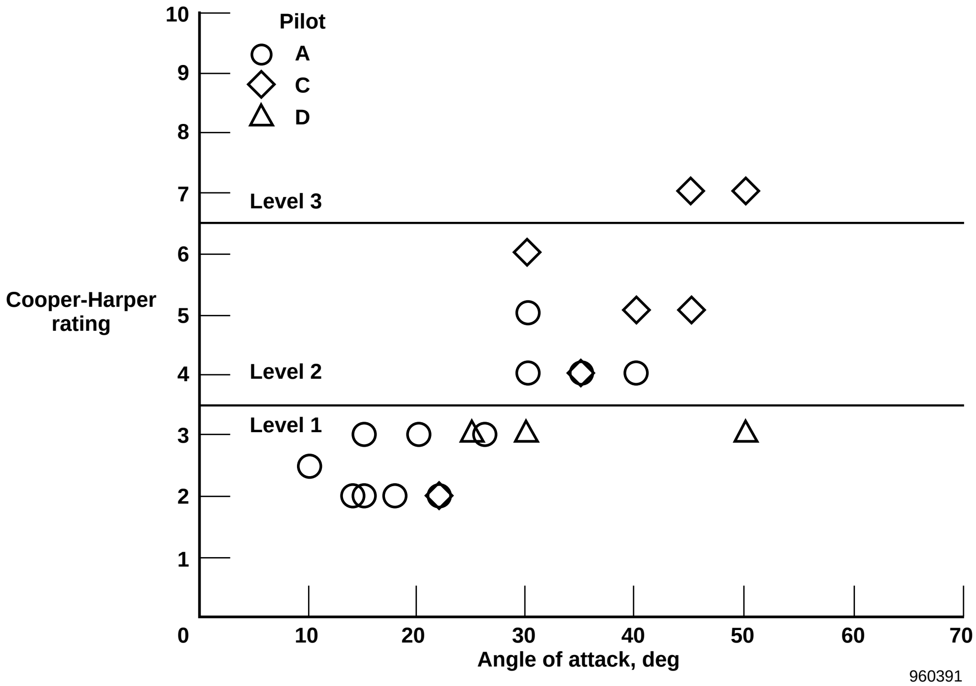

Figure 17. Cooper-Harper ratings as a function of angle of attack for longitudinal fine tracking.

consistently “3” or less, indicating Level 1 handling qualities. Between 30° and 50° AOA, the ratings ranged between “3” and “7.” The highest ratings are at the highest AOAs. This range would be rated Level 2 with two Level 3 ratings near 50° AOA.

All of the ratings were in confidence class “A” for AOAs less than 30°. For the PST ratings, ten were in confidence class “A” and six were rated “B.” These ratings reflect a high degree of confidence for most of the ratings. All the pilots noted that the tracking task used for the handling qualities evaluation was different from the type of tracking that was done during the CIC evaluations. One pilot summarized it by saying, “The tracking we’re trying to do here is kind of dynamic-pitch tracking and not the kind of tracking we typically did during the end game, which tended to be more in matching yaw rates.” PIO ratings also tended to increase with AOA for this task. The ratings ranged between “2” and “4,” indicating undesirable motions and oscillations throughout the PST range.

The initial instructions for the fine-tracking tasks called for nose-to-tail tracking. Because of the unique geometries that could result during the high-AOA maneuvering, the tracking tasks required both lateral and longitudinal stick inputs to perform the nose-to-tail tracking because the maneuver plane of the X-31A airplane would not correspond with the plane of symmetry of the target aircraft. This instruction was modified to state that tracking was not necessarily from nose to tail, but should use only pitch stick inputs and use the appropriate aircraft features as a reference. Even with the modified instructions, the pilots would often use diagonal stick inputs during the tracking tasks.

Longitudinal Fine-Tracking Handling Qualities Criteria

The X-31A data were evaluated using the Neal-Smith, bandwidth, and Smith-Geddes criteria to assess the applicability at high AOAs. These criteria are all based on the pitch stick–to–pitch attitude transfer function. An analytic study[10] had shown that other criteria based on LOES were not applicable to high-AOA flight. Transfer functions were generated using the linear models based on the mass properties and flight conditions (Mach number, altitude, and AOA) associated with the pilot ratings. The transfer functions were used in the criterion assessment and correlated with the pilot ratings. With the exception of a few data points, the linear analysis results correlate with handling qualities ratings obtained in flight. The low-AOA data and the data with CHRs of “3” tend to fall into the Level 1 regions for all of the criteria. The data with the higher CHRs seem to fall in clusters, and for all the criteria, these clusters move away from the Level 1 regions.

Figure 18 shows X-31A data plotted using the Neal-Smith criterion.[7] The Neal-Smith criterion uses a simple compensator model to close the loop of the pitch stick–to–pitch attitude transfer function. The magnitude of the resonant peak in the resulting closed-loop transfer function is compared with the phase angle of the compensation. The high-AOA data indicate that less lead compensation can be allowed. With two exceptions, data with Level 1 ratings required less than 15° of lead compensation. A cluster of data near 40° of lead compensation with adjacent CHRs of “5” and “7” exists that may indicate the proximity of the Level 3 boundary. Figure 14 shows the existing boundaries as solid lines, and boundaries indicated by the X-31A PST data are shown as dashed lines. Additional data are required to determine if these boundaries are valid.

For the bandwidth criterion[9] (fig. 19), all of the data show an estimated equivalent time delay of approximately 0.04 sec. This criterion has correlated handling qualities with the estimated

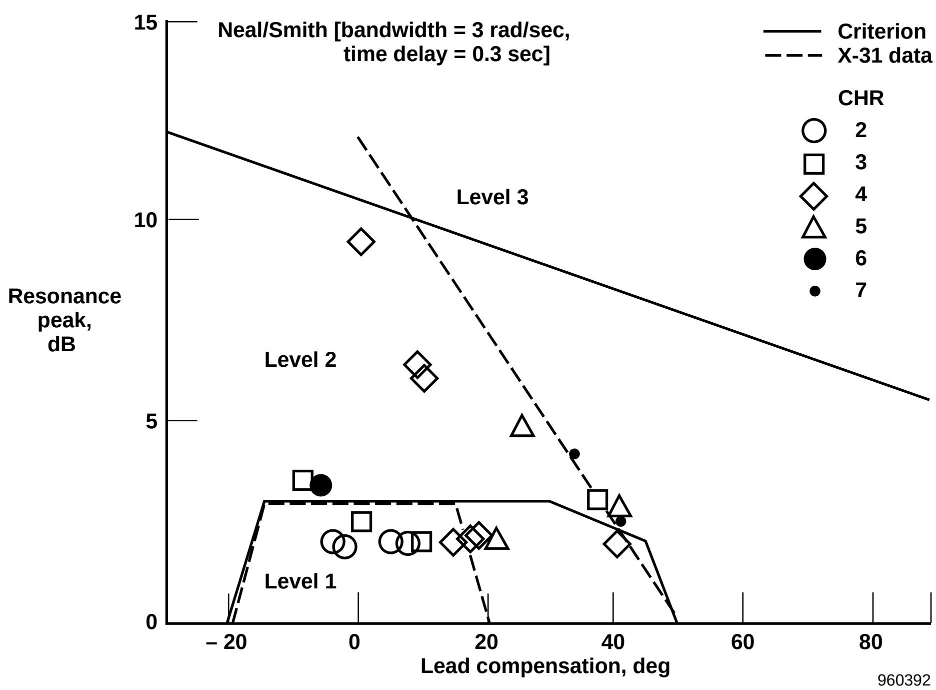

Figure 18. Comparison of X-31A data with the Neal-Smith criterion.

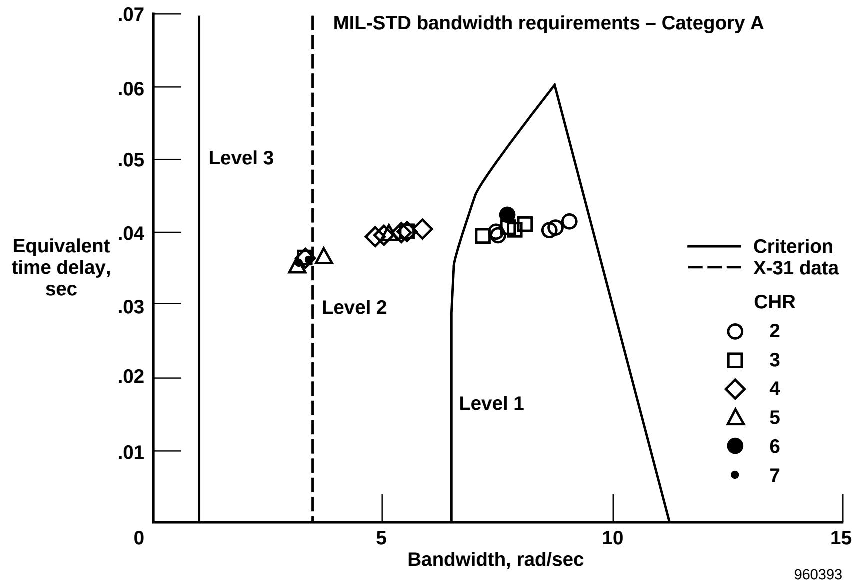

Figure 19. Comparison of X-31A data with the bandwidth criterion.

equivalent time delay and bandwidth frequency calculated from the pitch stick–to–pitch attitude transfer function. A reduction in bandwidth exists that is consistent with an increase in AOA and CHR. The X-31A data indicate that the Level 1 boundaries are reasonable. Several data points exist with a bandwidth of approximately 3 rad/sec that have CHRs of “5” and “7,” indicating that it might be appropriate to move the Level 3 boundary to this bandwidth as shown by the dashed line.

When compared with the Smith-Geddes criterion[8] (fig. 20), the X-31A data indicate that the slopes of average CHR as a function of phase angle at the bandwidth frequency need to be steepened. The criterion calculates the bandwidth frequency based on the slope of the gain

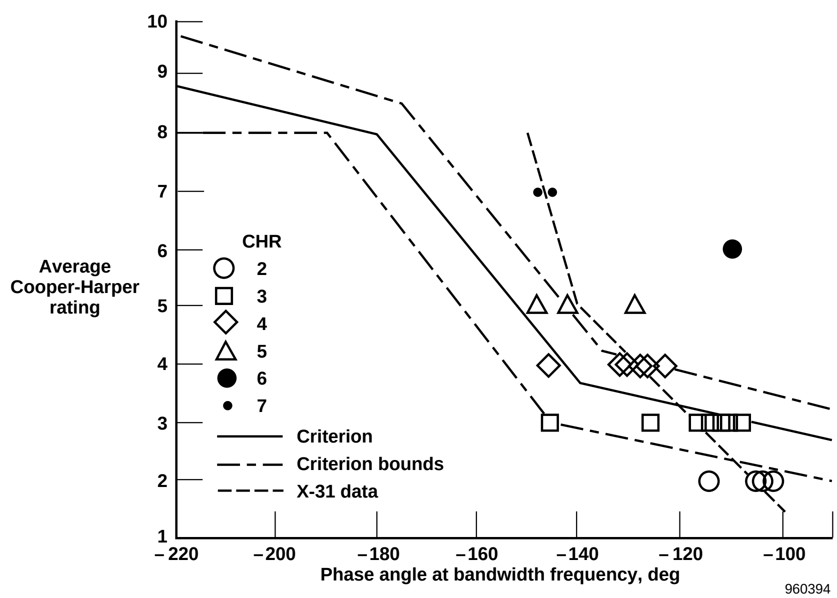

Figure 20. Comparison of X-31A data with the Smith-Geddes criterion.

relationship from the pitch attitude–to–pitch stick transfer function. In general, the tolerance bands for the average CHR would be valid for most of the data points with a pilot CHR of “3” or “4.” An alternate relationship between average CHR and phase angle at the bandwidth frequency is presented as a dashed line.

The one data point that is anomalous for all three criteria is the 30° AOA tracking case that received a CHR of “6.” The confidence class rating was “A,” indicating a high degree of confidence in the rating. In addition, the PIO rating of “3” indicated that undesirable motions affected the pilot’s ability to perform the task. The pilot did attribute some of the difficulty to aggressiveness, commenting, “The more aggressive you are, the more you oscillate.” Another pilot performing a similar maneuver gave a better CHR of “4,” but also commented, “If you are aggressive, you get undesired motions.” Other than pilot technique, one difference noted between the two tasks was that the task that received the degraded rating was performed at a higher airspeed. An analytic investigation of handling qualities[10] did show a degradation in predicted handling qualities during PST flight as airspeed increased with a constant AOA.

Lateral Fine-Tracking

Figure 21 shows CHRs plotted as a function of AOA. As with the longitudinal tracking data, some scatter in the ratings exists near 30° AOA, but the trend is toward higher CHRs as AOA increases. The three data points at an AOA at or greater than 40° had confidence class ratings of “B.” The lower AOA data received a confidence class rating of “A.” The PIO ratings are consistent with the other tasks in that an increase in undesirable motions as AOA increased existed, with oscillations being reported at the highest AOAs.

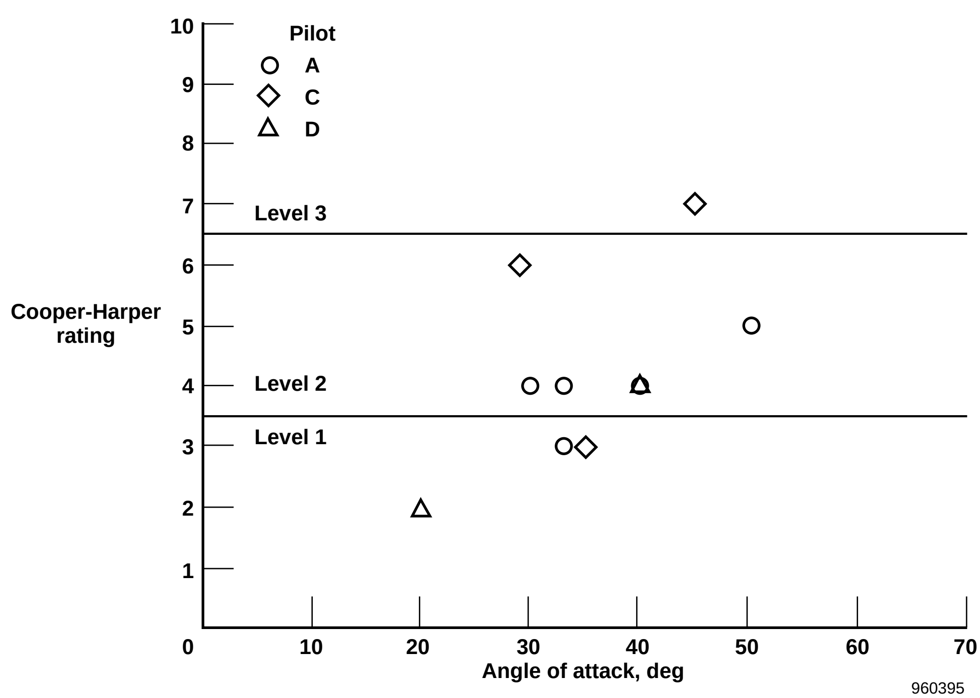

Figure 21. Cooper-Harper ratings as a function of angle of attack for lateral fine tracking.

A consistent pilot comment was, “The more aggressive you are, the harder the time you have tracking.” As well as the impact of aggressiveness on the task performance, the pilots also commented that the task frequently required diagonal stick inputs as opposed to pure lateral stick motions. Lateral tracking initially required wing tip–to–wing tip tracking. The tracking task was redefined to use only lateral stick inputs, but the pilots continued to use diagonal inputs.

Lateral Fine-Tracking Handling Qualities Criteria

Using LOES derived from the linear models, dutch roll frequency, dutch roll damping, the roll-mode time constant, and the equivalent time delay were calculated and compared with the criteria from MIL-STD-1797 (fig. 22 and 23). These criteria predict Level 1 handling qualities throughout the AOA range, which is not consistent with the handling qualities ratings. These data indicate that dutch roll frequency and damping and the roll-mode time constant are not the factors affecting high-AOA handling qualities.

The lateral fine-tracking ratings were also compared with the Smith-Geddes criterion[8] (fig. 24). Although a limited amount of data exists, there appears to be general agreement with this criterion.

Some caution must be used when applying the results of linear analysis to the lateral–directional high-AOA tracking tasks. Several nonlinear effects are evident in the data. The flight condition changes rapidly during the task from a high-speed, high-AOA condition to a low-speed, reduced-AOA condition. The maximum roll-rate command is scheduled as a function of airspeed so that the pilot experiences a reduced command authority as the airspeed decreases. The rate limit for the stability-axis roll-rate command was reached several times during the

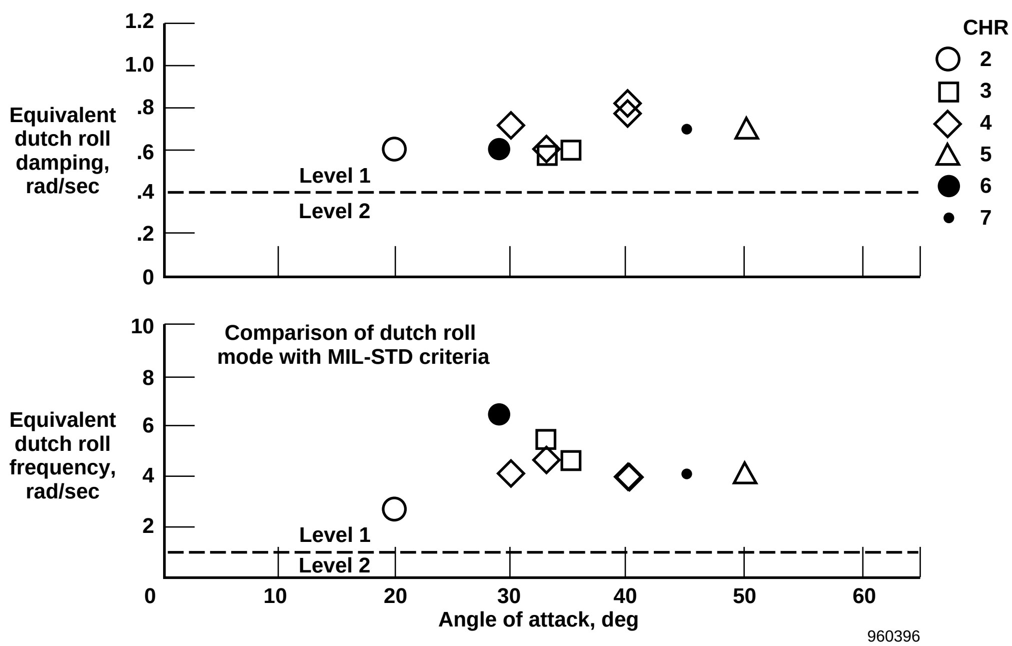

Figure 22. Comparison of X-31A data with MIL-STD-1797 dutch roll frequency and damping criteria.

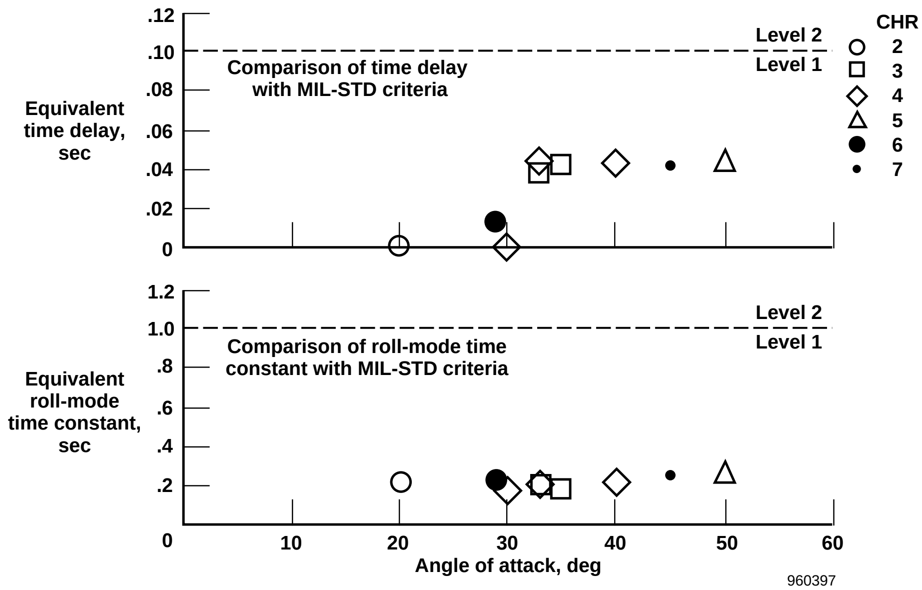

Figure 23. Comparison of X-31A data with MIL-STD-1797 roll mode time constant and time delay criteria.

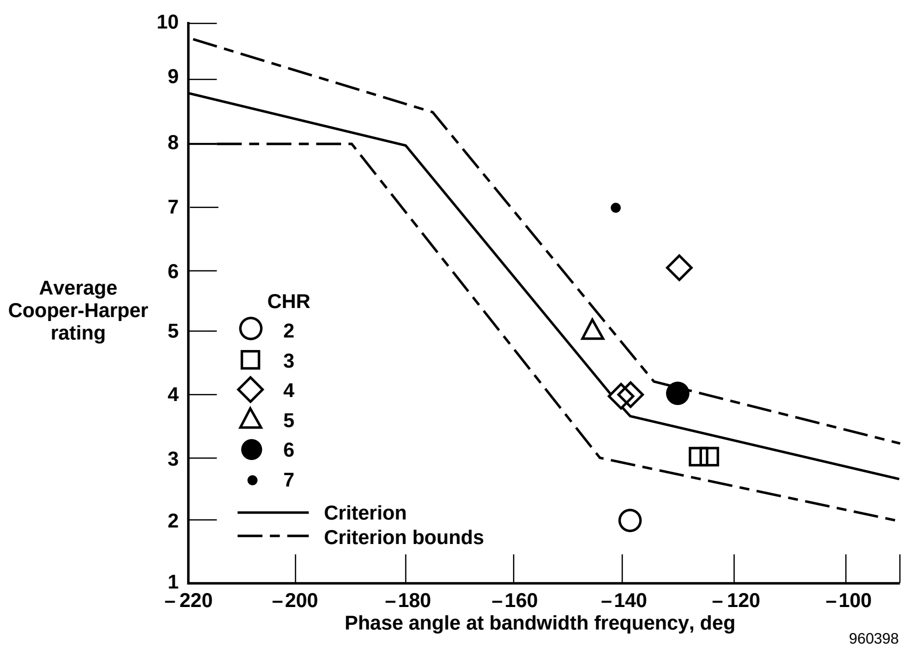

Figure 24. Comparison of X-31A data with Smith-Geddes criteria for the lateral axis.

fine-tracking tasks. The high workload demand on the thrust-vectoring system resulted in rate limiting of the thrust-vector paddles. Also, at high AOAs, moving the pipper from wing tip to wing tip required a combined lateral and longitudinal stick input.

Even a full six-degrees-of-freedom nonlinear simulation did not entirely reproduce the dynamics observed during some of the lateral fine-tracking tasks. Figure 25 shows some of the

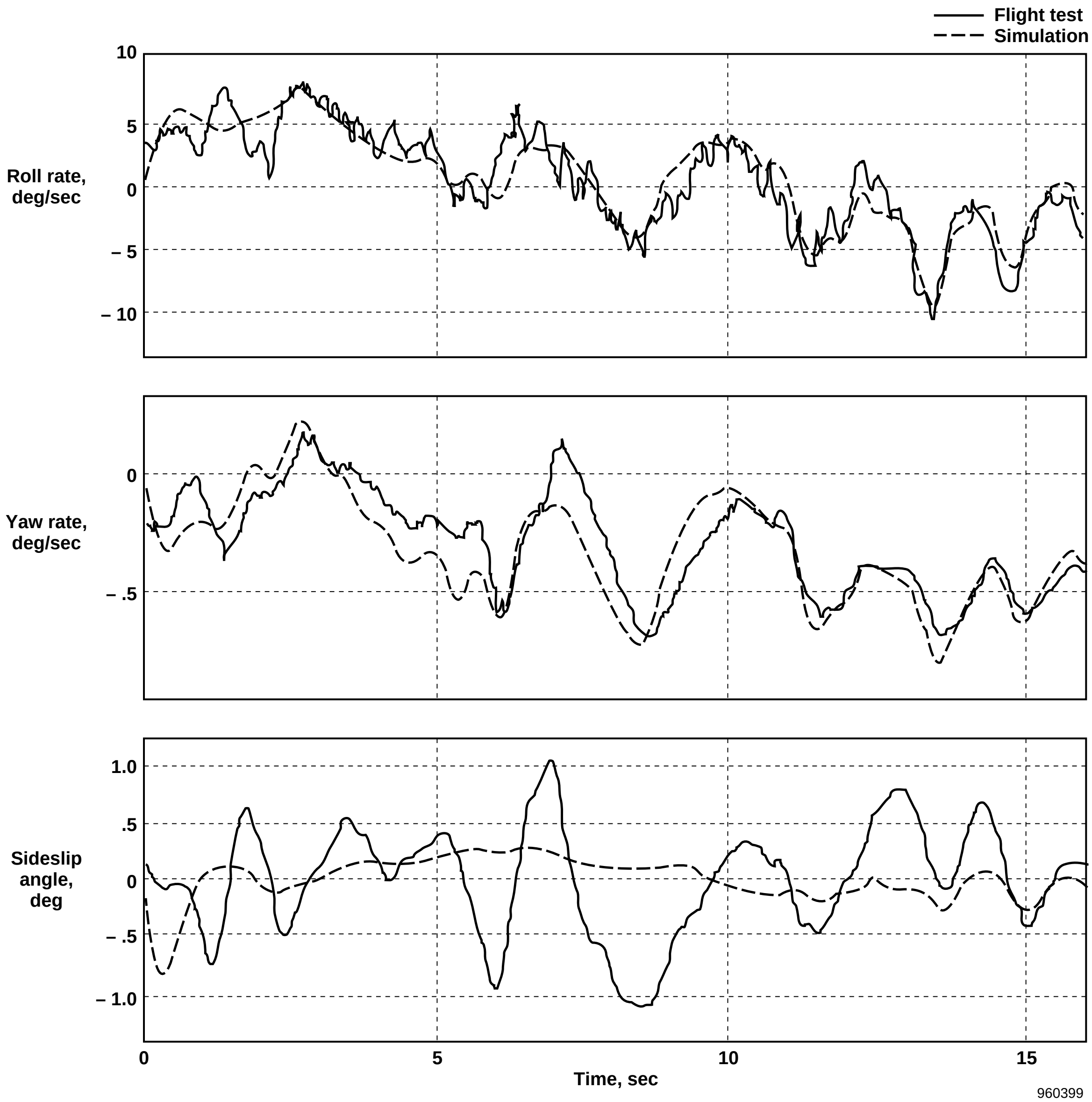

Figure 25. Comparison of flight and simulation data for a lateral fine-tracking case.

excursions in yaw rate and sideslip angle that were not duplicated with the nonlinear simulation. These excursions approximately correlate with target overshoots where the target wanders outside the 20-mrad reticle and may be related to asymmetric forebody vortex cores. To accurately predict handling qualities requires an analytic model that includes all of the dynamics, so the effect of these vortices should be included.

Combined Maneuvers

The combined maneuver was flown four times during one flight by one pilot. Two of the maneuvers were used for practice. Comments and CHR ratings of “3” and “4” were given on the other two maneuvers. No distinction existed in the ratings for lateral or longitudinal tasks, but fine tracking and gross acquisition were rated separately. In summary, the ratings were given with high confidence and were borderline Level 1/Level 2 for both tracking and acquisition. No undesirable motions were present during the gross acquisition, and the motions did not affect the task during fine tracking. Following the flight, the pilot reported, "The SSLA setup was an excellent starting condition to evaluate handling qualities in the PST regime."

Figure 26 shows time history data from the second rated maneuver, which spanned 60 sec. The AOA ranged between 30° and 70°. Pitch-stick sensitivity can be seen in the AOA command

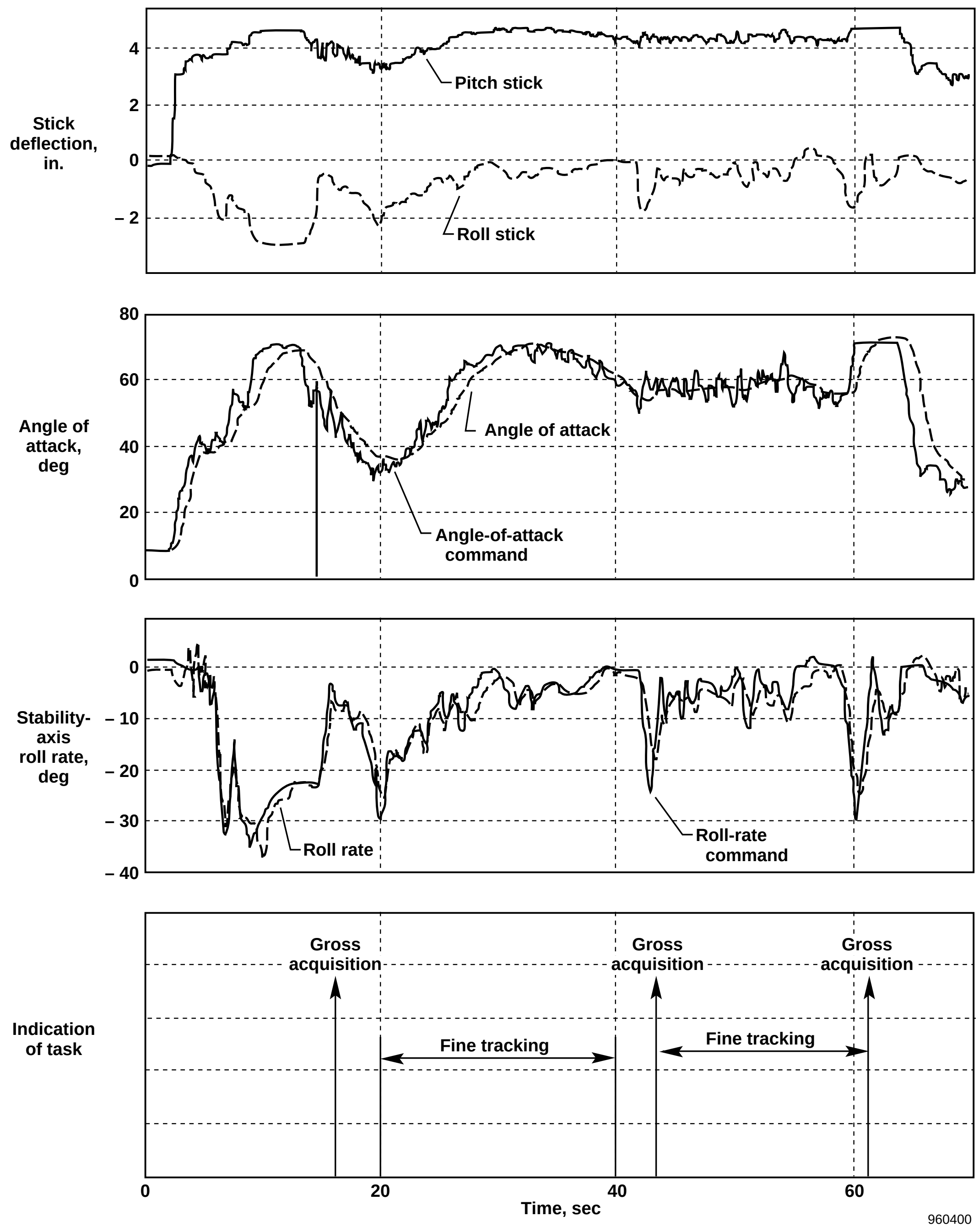

Figure 26. Time history from a combined maneuver.

where 15° excursions in the command at the AOA command rate limit of 25 deg/sec can be seen. Full-roll stick was used early in the maneuver, and approximately 66 percent of the stick deflection was used in a later acquisition. Peak velocity-vector roll rates of nearly 40 deg/sec were observed. The fourth trace shows the timing for the three gross acquisitions performed and the periods of tracking. This maneuver was initiated at an altitude of 25,000 ft and was completed at an altitude of 14,000 ft.

As with the other tasks, the pilot commented that the stick forces were "too heavy" and the motions were "too large." Because this maneuver intentionally used diagonal stick inputs, the pilot was able to comment on stick harmony, "The stick movement is much too high; and you have the nonharmony between the pitch stick, which is so sensitive, and the roll stick, which is not so sensitive."

Because the pilot ratings cover maneuvers that span a large flight envelope and encompass two axes of control, comparing them with analytic results is difficult. The pilot liked this maneuver better and felt it was more representative of the type of flying done during the CIC investigation. The maneuver also resulted in the Level 1/Level 2 ratings that were expected. Additional testing is required, but this type of maneuver may provide a better means of evaluating the PST handling qualities, but like CIC, it is of limited value for analysis or design because of the varying flight conditions.

LESSONS LEARNED FOR HIGH-ANGLE-OF-ATTACK HANDLING QUALITIES TESTING

When flying a new task, backup cards should be prepared for an established task in the event the first task is not working out. During the first PST fine-tracking flight, it was quickly apparent to the pilots in the airplane and on the ground that the test as designed would not result in an acceptable fine-tracking task. Almost an entire flight was used to get one data point. Testing of alternate flight cards would have collected additional data, and ground review would have adjusted the test setup for the acquisition of PST fine-tracking data.

Some of the pilots thought a domed simulation would have helped them better prepare for the tasks. But it is interesting to note that during the lateral gross acquisitions, the one pilot who had performed the maneuvers in a domed simulation required the same amount of in-flight practice as the other pilots.

Care should be taken in task definition. For the fine-tracking tasks, the pilots were asked to do separate longitudinal and lateral tracking tasks. Even with instructions that the inputs should be limited to pitch or roll inputs, the pilots continued to use diagonal stick motions to perform the more classical tracking tasks of nose-to-tail and wing tip–to–wing tip. The task definition should also include a reasonable time limit for the performance of the task. One of the reasons 4 sec was initially chosen was to try to minimize variation in flight condition during the performance of the task. This time limit was not enforced during the testing and resulted in a tracking task that lasted 20–30 sec with large AOA variations.

Modifications to the HUD could have provided the pilots with the proper cues for the tasks. For longitudinal gross acquisition, horizontal bars at 25 and 40 mrads would have provided the proper reference for the task that was being rated. Similarly, vertical bars could have been used for lateral gross acquisition in place of the circular reticles. This display might reduce the tendency of the pilot to try to place the pipper on the target.

CONCLUSIONS

The Standard Evaluation Maneuvers (STEMs) provided repeatable tasks that could be compared with analytic linear and nonlinear simulation results. With suitable initial conditions and practice, gross acquisition and fine tracking could be performed at the desired angle of attack (AOA). Pilot comments indicated that these maneuvers were not consistent with the types of maneuvering performed during the close-in combat (CIC) evaluations. This testing identified problems that may not be significant in actual tasks. Further testing is needed to resolve these differences.

The pilot-assigned ratings for gross acquisition and fine tracking for both the longitudinal and lateral axes were dependent on AOA. More undesirable motions and then oscillations existed as AOA increased.

The longitudinal gross-acquisition task was well-defined and provided an easily repeatable task. The pilot ratings and comments indicated a high degree of confidence. These ratings reflected the expectations from CIC testing with the aircraft having Level 1 or Level 2 handling qualities.

The lateral gross-acquisition task was one of the most difficult. The task required a significant amount of flight time to adjust the starting conditions to achieve the desired AOA with the target aircraft in the head-up display field of view for the X-31A airplane. The pilot proficiency for this task did not improve as significantly as it did for the other acquisition and tracking tasks. The pilot comments and ratings indicated a degradation in handling qualities as AOA increased, with Level 3 handling qualities at an AOA near 60°. The pilot comments noted that this type of acquisition was not similar to the acquisitions performed during CIC testing. The degradation in handling qualities was not expected from the CIC testing where the general assessment would have been Level 1/Level 2 handling qualities.

For the longitudinal fine-tracking task, consistent trends existed in regard to the Neal-Smith, bandwidth, and Smith-Geddes criteria. The maneuvers that received Level 1 ratings in flight were rated Level 1 by the criteria. The Levels 2 and 3 data from flight tended to produce consistent results when compared with the linear models and indicated potential modifications for the criteria. The X-31A handling qualities ratings showed a degradation with AOA that was not observed during the CIC testing.

Lateral fine tracking showed a degradation to Level 3 handling qualities as AOA increased. The X-31A program provided only a limited amount of data that could be compared with the existing criteria. The data showed good general agreement with the Smith-Geddes criterion. These data did not provide sufficient information to offer modifications to the existing criteria that predicted Level 1 or borderline Level 1/Level 2.

For both lateral and longitudinal fine tracking, the effect of the velocity-vector settling during the maneuver had a significant impact. Future use of this STEM may require modifications to allow a more stabilized starting condition for the fine-tracking tasks. During the X-31A testing, fully separating the lateral and longitudinal tasks was not possible. The pilots generally used diagonal stick inputs regardless of the axes being evaluated.

For control stick harmony, the majority of the comments were noted during the fine-tracking tasks. In these cases, the pilots were using diagonal stick inputs to perform the wing tip–to–wing tip and nose-to-tail tracking. The one other task that elicited a comment on control stick harmony was the combined maneuver. The pilot commented on the disparity in motion for longitudinal and lateral stick displacements (large for roll and small for pitch). Although the control implementation resulted in a limiter for large roll-stick deflection, no particular comments were given by the pilots.

The limited testing with the combined maneuver was commented upon favorably by the pilots, but these ratings are not amenable to comparison with analytic results because of the rapidly varying flight conditions. This type of maneuver may be useful for providing an overall evaluation of aircraft performance in the post-stall flight regime and should be considered as an additional STEM. Like the CIC results, these data are of limited value for analysis because of the varying flight conditions.

Dryden Flight Research Center
National Aeronautics and Space Administration
Edwards, California, June 5, 1996

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REPORT DOCUMENTATION PAGE

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2. REPORT DATE
September 1996

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Evaluation of High-Angle-of-Attack Handling Qualities for the X-31A Using Standard Evaluation Maneuvers

5. FUNDING NUMBERS
WU-505-68-30

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8. PERFORMING ORGANIZATION REPORT NUMBER
H-2128

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-104322

11. SUPPLEMENTARY NOTES
Presented at the High-Angle-of-Attack Technology Conference, NASA Langley Research Center, Hampton, Virginia, Sept. 17–19, 1996. Also presented at the AGARD Flight Vehicle Integration Panel Symposium on Advances in Flight Testing, Lisbon, Portugal, Sept. 23–26, 1996.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified—Unlimited
Subject Category 08

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The X-31A aircraft gross-acquisition and fine-tracking handling qualities have been evaluated using standard evaluation maneuvers developed by Wright Laboratory, Wright-Patterson Air Force Base. The emphasis of the testing is in the angle-of-attack range between 30° and 70°. Longitudinal gross-acquisition handling qualities results show borderline Level 1/Level 2 performance. Lateral gross-acquisition testing results in Level 1/Level 2 ratings below 45° angle of attack, degrading into Level 3 as angle of attack increases. The fine-tracking performance in both longitudinal and lateral axes also receives Level 1 ratings near 30° angle of attack, with the ratings tending towards Level 3 at angles of attack greater than 50°. These ratings do not match the expectations from the extensive close-in combat testing where the X-31A aircraft demonstrated fair to good handling qualities maneuvering for high angles of attack. This paper presents the results of the high-angle-of-attack handling qualities flight testing of the X-31A aircraft. Discussion of the preparation for the maneuvers, the pilot ratings, and selected pilot comments are included. Evaluation of the results is made in conjunction with existing Neal-Smith, bandwidth, Smith-Geddes, and military specifications.

14. SUBJECT TERMS
Flight controls; Handling qualities; High angle of attack; Pilot-induced oscillation; Standard evaluation maneuvers; X-31A aircraft

15. NUMBER OF PAGES
36

16. PRICE CODE
AO3

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited