FLYING QUALITIES LESSONS LEARNED - 1988

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Abstract
In this paper, we will review five major areas of lessons learned in the discipline of flying qualities in 1988. Specifically, we will look at flight-control system automatic limiters, the effects of small aerodynamic changes, the effect of thrust increases, the effect of discretization of existing analog systems, and simulator evaluation results of some new flight-control modes. Aircraft from which we will draw our lessons are the F-16, a conceptual agile fighter design, the E-8A, YA-7F, F-14A+/D, F-15, and F-15 S/MTD.

1. Limiters, Revisited
In his 1988 NAECON paper, Kogler (Reference 1) discusses the rationale for modern automatic limiters within aircraft flight control systems, and provides case studies of three aircraft: the F-111, F-16, and B-1B. In these cases, as well as all others with which we are familiar, limiters are designed and implemented to prevent the pilot from exceeding an aircraft state, such as angle of attack, roll rate, etc., which would result in loss of control, aircraft damage, or both. The idea is to provide "carefree maneuvering", allowing the pilot to safely "maneuver with abandon" without having to manually observe limitations, thus allowing him to concentrate his energies on the task at hand.

However, in reviewing flight test and simulator results, and in discussions with operational pilots, it has become evident that pilots of aircraft possessing maneuver limiters often use the limiters in a different fashion than the designers envisioned. To the flying qualities engineer, limiters are used to protect the pilot from the airplane and to protect the airplane from itself. Pilots, however, view limiters as devices which allow the maximum possible maneuvering performance to be obtained from the aircraft, implicitly assuming that the aircraft possessing the greater maneuvering performance has the tactical advantage. As a result, pilots often simply pull the aircraft to the limiter and hold it there during tasks requiring hard maneuvering.

Some recent "1 v 1" (i.e., 1 against 1) testing with the F-16, however, yielded some interesting results. Due to the calibration of the air data computer, the angle of attack limiter on the aircraft was actually allowing the F-16 to achieve more angle of attack than intended at low g. In recalibrating the system to allow for this, it was feared by some that the decreased angle of attack limit would significantly degrade the air-to-air capability of the aircraft. In fact, when fought against an unmodified F-16, the aircraft with the revised (i.e., reduced angle of attack) limiter gained the advantage on the unmodified aircraft in some situations. One of the pilots further experimented with using the more restrictive "Cat III" limiter, normally used when carrying air-to-ground external stores, during engagements with the other F-16, and was also able to gain the advantage on his opponent in the same situations. Figure 1 shows the F-16 angle of attack limiter concept.

Conventional wisdom would say that less restrictive limiters are better, yet the results of these tests would seem to indicate otherwise. This paradox may be explained by the nature of 1 v 1 air combat. Shaw (Reference 2) divides 1 v 1 combat into two basic types: the angles fight, and the energy fight, in which "the labels refer to the first objective of the engagement. In the angles fight, the tactician first seeks to gain a position advantage (angles), even at the expense of relative energy, and then he attempts to maintain or improve on this advantage until he achieves his required firing parameters. The purpose of the energy fight is to gain an energy advantage over the opponent while not yielding a decisive position advantage." This energy advantage is used...
to methodically "wear down" an opponent, and may be converted to a firing position or used to disengage at the appropriate time. (For a complete discussion of this subject, a review of Reference 2, particularly Chapter 3, is strongly recommended.) In general, angles fights tend to be short, with the proverbial "quick kill" going to the aircraft which can rapidly bring its nose to bear on the opponent. The "agile" or "supermaneuverable" fighters advocated by Herbst, Maaté (Reference 3), Skow (Reference 4), and others are optimized for this type of combat.

The danger of angles tactics, however, is that the angles fighter usually sacrifices energy in the process. This can leave it vulnerable to its opponent if the quick shot fails to disable or kill its opponent, or vulnerable to any other unfriendly fighters in the neighborhood. (It should be noted that an analogous problem exists for the energy fight: the time taken to achieve a firing solution allows more time for an adversary to gain advantage on the energy tactician.) For this reason, experienced fighter pilots generally try to balance nose pointing capability against energy loss, converting to a pure angles fight only when a "safe" kill is assured. Anderson (Reference 5) found this to be the case in a simulated 1 v 1 simulation of an agile fighter against a conventional fighter: even when possessing a decisive nose-pointing-capability advantage, pilots employed less than the maximum capability, maintaining a higher energy level until a kill could be assured. Only then was the agile aircraft's energy exchanged for an angular advantage. In further reviewing the F-16 results, it was seen for the referenced cases that, while the opposing pilot was employing "angles tactics", they were actually in a situation favoring energy tactics. There the ultimate "winner" maintained an energy advantage and slowly wore down his opponent.

This raises some interesting questions concerning the design of maneuver limiters and/or control force-deflection gradients in tactical aircraft. While we agree that the ultimate limits mechanized through the flight-control system should be as permissive as possible (to allow for the use of angles tactics), a case could be made for a cue that indicates to the pilot that he is operating his aircraft at its maximum sustained \( p \) (i.e., an energy rate limiter). We postulate a change in force gradient ("soft stop") that when the pilot pulls to and holds it will result in a non-negative energy rate for the aircraft's speed, weight, thrust, and configuration; the necessary computations could be mechanized in one of the onboard computers. Should the pilot wish to use angles tactics, he would simply pull to the hard stop position, resulting in maximum angle of attack, angular rates and pointing capability, though with the accompanying energy loss. Alternative methods of mechanizing this concept are, of course, possible; however, we feel the concept has merit and warrants further exploration.

2. "Small" Changes Can Have Big Effects

With the development of new aircraft being a protracted and expensive undertaking, it has become common for existing airframes to have avionics, engines, or other components updated several times during the life of the airframe, or to be modified for missions not originally envisioned by the designers; it is expected that this trend will become even more common in the future. The effect of such modifications on air vehicle flying qualities can be significant.

An example of this is the E-8A Joint STARS aircraft, a modification of the Boeing 707-300C-series aircraft to perform real-time targeting of ground-based threats. The major external difference is the addition of a long, "canoe"-shaped radome along the centerline of the aircraft between the nose landing gear and the wing root leading edge (Figure 2). Any projected side or planform area added ahead of the center of gravity on an aircraft is destabilizing, and must be balanced by the vertical or horizontal tail. In the case of the E-8A, the radome causes an unstable break in directional stability at sideslip angles beyond which the vertical tail stalls (i.e., the airflow separates; see Figure 3).

While this could normally be countered by using opposing rudder to return the aircraft to lower sideslip angles, some other interesting characteristics exist. The limited wind-tunnel and flight-test data available indicate that for low angle of attack, high flap deflection conditions, rudder deflections exist for which the aircraft may diverge in sideslip angle, and opposing rudder may not halt the divergence (again, see Figure 3). The result of such a condition would be a departure from controlled flight, which could have serious consequences. The maneuvers during which this condition could arise are a crosswind takeoff or landing, or an engine-out condition at low airspeed. Simulation and flight test data indicate the latter does not exceed the critical sideslip angle, while the former may be dealt with by restricting the E-8A to lower crosswind limits than the basic B707. Should the user, however, find the lower limits overly restrictive, aerodynamic changes to the aircraft will be necessary.

While the E-8A represents a case of a
"small" change having a negative impact on aircraft flying qualities, the YA-7F represents the opposite. This aircraft, formerly called the A-7+, is a modification of the A-7D to take advantage of newer, more powerful engines available since the time of the original design. Externally, the YA-7F may be distinguished by a 29.5-inch fuselage plug forward of the wing, an 18-inch stretch aft of the wing, a 4.5-degree upward rotation of the aft fuselage for tail clearance, an enlarged, taller vertical fin cap, annulled (vs dihedraled) horizontal tails, and the addition of small leading edge root extensions (strakes) to the wing (Figure 4).

The basic A-7 aircraft exhibits directional instability above 15 degrees angle of attack, 7 degrees less than the angle of attack for maximum lift. This results in a typical "nose slope" departure characterized by one operational pilot as "the wildest ride you'll ever have". The addition of automatic maneuvering flaps (AMF) to the aircraft in 1973 dramatically tamed the departure characteristics, but the basic directional instability remains present, albeit at a higher angle of attack.

All of the changes listed above except for the strakes increase the directional stability limit to approximately 21 to 23 degrees angle of attack, yet it was desired to further improve this characteristic. Hence the addition of the strakes. While these strakes add less than 1 percent to the wing area, their effect is dramatic. To the limits thus far explored in wind tunnel tests (27 degrees angle of attack), the aircraft not only remains directionally stable, but shows a "stiffening" tendency above 21 degrees angle of attack. This can be seen in Figure 5. In contrast to the automatic limiting discussed by Kogler, this small aerodynamic addition yields an aircraft which is lift, not stability, limited, and promises the potential of allowing the aircraft to be flown to its full unstalled maneuvering capability.

3. Flying Qualities Implications of Increased Thrust

As mentioned in the last section, it is now common for an aircraft to go through multiple generations of avionics and engines in its lifetime. This has the effect of amortizing the cost of the airframe (as opposed to the expense incurred in the development of new airframes for each generation of avionics and/or engines), but can lead to flying qualities difficulties if not allowed for at the time of the original design. While historically some aircraft models tolerated the thrust increase well, such as the F-4, F-5, and F-111 series, others have presented some unique challenges. One example is the F-14. According to Reference 6, the majority of F-14 losses from out-of-control flight have involved thrust asymmetry, particularly due to engine operability and reliability problems in high-angle-of-attack flight. This plus the desire for higher performance has led to two versions, the F-14A+ and the F-14D, which use General Electric F110-GE-400 engines, yielding nearly a one-third increase in thrust. These engines utilize electronic control with a hydromechanical backup. With the large distance between the engines on the F-14 (9.7 feet) and the higher thrust levels, the concern with thrust asymmetry, particularly at low speed, is obvious. For this reason, the F-14 has an Asymmetric Thrust Limiting System (ATLS) which retards the operative engine's throttle to the minimum afterburner position in case of an engine failure or afterburner blowout. Reference 6 should be consulted for a full description of the flight test program and the results; however, the ATLS was found to improve departure recoveries and improve time to recover.

The high-speed portion of the flight envelope may be of concern, too. The problems with the early models of the B-58 with an outboard-engine failure in high-speed flight are well known; the aircraft had sufficient control power to halt the ensuing yaw, but extremely fast reflexes were required of the pilot. A triple-redundant yaw damper system was eventually designed and installed to handle this situation. With the F-15, the concern is not with the dynamics of the airframe response following an engine failure, afterburner blowout, or transfer to Secondary Engine Controller (SEC), but rather with yaw control power due to rudder hinge moment limitations. While this characteristic has been of minor concern in the past, the carriage of LANTIRN pods and Conformal Fuel Tanks (CFTs) on the F-15E has led to a reduction in the basic directional stability of the airframe (again, "small" changes can have big effects). Due to this reduction in directional stability, rudder control power (hinge moment capability) is no longer sufficient for control following a single engine failure/afterburner blowout/SEC transfer during high Mach/high dynamic pressure flight. The increased thrust provided by the Improved-Performance Engines (IPEs)--higher-thrust versions of the General Electric F110 and Pratt and Whitney F100 engines--coupled with this reduction in directional stability aggravates this characteristic and expands the portion of the aircraft's flight envelope in which it is susceptible to departures under these conditions. At
present, this has resulted in F-15E flight envelope limitations when carrying LANTIRNs and CFTs; ultimately, a system similar to the F-14's ATLS appears to be the most feasible solution.

4. Digitization of Analog Systems

The F-111 presents an interesting example of the flying qualities challenges resulting from the digitizing of an existing analog system. The purpose of the F-111 Digital Flight Control System (DFCS) program is to replace the existing analog pitch, roll, and yaw computers with a modern digital system in order to increase system reliability and reduce system maintenance and associated costs. However, due to delays inherent in digital systems, coupled with the large flight envelope of the F-111, it was not possible to simply discretize the existing analog pitch control laws.

To understand the reason for this, it is necessary to review the basic design concept of the flight control augmentation scheme in the F-111. The closed loop transfer function of a conventional feedback control system (Figure 6) is of the form

\[ \text{Output/Input} = \frac{G(S)}{1 + KG(S)H(S)} \]

If the feedback gain \( K \) is made sufficiently large, the open-loop transfer function of an inverse model becomes approximately \( 1/KH(S) \). This has the effect of rendering the feedback transfer function, \( H(S) \), the dominant element of the system. The desired system dynamics may be achieved by utilizing their inverse as the feedback transfer function; it is then referred to as the "inverse model". With careful selection of the inverse model and feedback gain, and due consideration of the effects of higher-order systems, adequate closed-loop dynamics may be realized.

In the case of the F-111, the stringent short-period flying qualities requirements coupled with the desire to avoid extensive gain scheduling based on air data signals led to the design choice of employing the inverse model concept to synthesize the desired short-period dynamics. The large flight envelope of the aircraft created challenges in implementing the concept; however, comparison of the aircraft's closed-loop dynamics with the requirements of the later flying qualities specification, MIL-F-8785C, indicate at least Level 2 flying qualities throughout the flight envelope.

The normal additional phase lag introduced by the digital system when the F-111 control laws were discretized increased the difficulty in meeting the flying qualities requirements. In high-speed flight, the use of the same inverse model as in the analog system could potentially result in a phenomenon called "mode switching". In this phenomenon, the adaptive mode deviates from the normal trajectory seen on a root locus and approaches the inverse model as the gain is increased (Figure 7). The result is that the actual short-period mode now becomes the lightly-damped mode sensed by the adaptive gain changer. Since the adaptive gain changer relies on isolating a frequency above 10 radians per second, the presence of a short-period frequency also above 10 radians per second may cause the adaptive profile to be unable to separate the two modes. The system may then select a feedback gain inappropriate for high-speed flight. A further complication is the fact that the digitized analog inverse model yields undesirable flying qualities in the low-speed portion of the aircraft flight envelope. In order to maintain the existing principle of gain changer operation, the inverse model roots must now be varied with flight condition. Since the parameter that accurately reflects the movement of the open-loop short-period poles is the adaptive gain magnitude, the concept of varying the adaptive gain magnitude is conceived. This is referred to as the "Adaptive Inverse Model". With this concept now in place, proper "tuning" of the system will maintain at least Level 2 flying qualities according to analysis and piloted simulations.

5. Implementation of New Control Techniques

The F-15 S/MTD flying qualities, as evaluated during simulation and initial flight testing, have been highly rated by both contractor and USAF test pilots; however, there have been some lessons learned. The F-15 S/MTD implements some new control features whose mechanization, according to piloted simulation, results in interesting flying qualities consequences. The specific features of interest are the aircraft's speed hold ability during the STOL landing (SLAND) mode and thrust reversing ability during the ground handling (STOL-GH) mode.

In the first case, the mechanization of a system designed to reduce pilot workload and increase flight safety can have interesting—and sometimes unforeseen—flying qualities effects. In the SLAND mode, the throttles become a closed-loop airspeed command which produces the desired airspeed response with minimum pitch-attitude change by rotating nozzle vanes (i.e., the thrust component) while the engines are operating at a constant intermediate power. The S/MTD gives the pilot airspeed information on the HUD in
two forms: a digital airspeed readout and an "E-bracket" (see Figure 8). When flying the F-15 S/MTD, the pilot uses the E-bracket by attempting to line up the center tick of the "E" with the aircraft velocity vector symbol via the throttle/speed hold control (i.e., the pilot flies using "front-side" techniques). When lined up, the aircraft is at the proper approach airspeed. The top and bottom ticks on the E-bracket correspond to a range of plus or minus 5 knots deviation from the center tick. However, the airspeed displayed by the E-bracket is not the airspeed measured by the air data system, but is a predicted airspeed derived from AOA via a computational algorithm. Thus the E-bracket is not the airspeed measured on this signal. Therefore, since the pilot E-bracket correspond to a range the aircraft is at the proper approach state airspeed will be if the current AOA is maintained; the airframe dynamics act as a combined low-pass filter and time delay transient between the time the pilot selects a throttle/speed hold position and the time that the E-bracket finally steadies. The pilot must then adjust the throttle/speed hold selector again and wait to get center tick and the velocity vector line up.

Initially, the pilots found this E-bracket mechanism tended to produce a pilot induced oscillation (PIO) with respect to airspeed as they attempted to find the correct throttle/speed hold selector position. This was a minor annoyance that pilots learned to adjust to by using a technique of slowly adjusting the throttle/speed hold selector (i.e., lowering their throttle gain and bandwidth). As would be expected, this annoyance got worse when flying in turbulence where AOA tends to have a higher frequency content. This results in excursions of the E-bracket when, in fact, airspeed itself is varying only slightly. Thus, in turbulence the pilots tended to use the digital airspeed indicator to capture the desired landing speed and ignored the E-bracket presentation. Even so, pilots routinely rated the system very highly. Thus, the "airspeed PIO" was noted as an annoying characteristic of an otherwise well-liked feature (the airspeed hold mechanism using the throttles) which could be dealt with via a minor alteration of pilot technique, and shows how the information presented to the pilot can affect the flying qualities assessment of an entire air vehicle.

Although some features can enhance aircraft performance, they may result in aircraft dynamics that adversely affect flying qualities and/or preclude realization of the full potential of the feature. An interesting example of this, again observed during the F-15 S/MTD simulation of approach and landing tasks, was the aircraft's landing characteristics utilizing the STOL-GH mode in a high (i.e., 25 knots or greater) steady crosswind on wet/icy runways. The S/MTD specification called for the ability to land on a runway 1500 feet long by 50 feet wide. Ground handling of conventional aircraft on wet/icy runways under crosswind conditions can be challenging, and with the S/MTD's stringent runway size requirement, the program office expected yet greater challenges; how this challenge was met was revealed in the piloted simulation. Upon touchdown, the pilots found that thrust reversing made the F-15 reverse directionally, with the nose going in the opposite direction of the slide (i.e., if the aircraft slid to the right, the nose diverged to the left). This behavior is similar to a slow-motion "ground loop". This forced the pilots to deselect full thrust reversing, let the aircraft re-establish a stable heading, and then reapply full reversing until the slide and/or divergence were objectionable, deselect full reversing again, repeating the cycle as many times as necessary until nose wheel steering was effective and full thrust reversing could be maintained. While this reversing modulation process added several hundred feet to the landing distance on the wet/icy crosswind runway, directional control was maintained and the aircraft remained on the 50-foot wide runway. This technique did not result in appreciably lower pilot ratings for the task, resolved an expected landing ground handling difficulty, and still demonstrated significant landing distance improvements relative to a conventional aircraft.

Conclusion

This paper has discussed flying qualities lessons learned in 1988 (and the previous year or two). We have derived our lessons learned from case studies of eight different aircraft. Our lessons learned include some insight into the way operational pilots view and use flight control system limiters, with the postulation of an "energy rate limiter". We have also seen that small changes to the aerodynamic configuration can have large effects and that increasing the thrust available to a particular design can have flying qualities implications. We have noted that an understanding of the unique characteristics of digital systems coupled with a proper concern for flying qualities as part of the design process does allow retention of good flying qualities when analog systems are replaced by their digital equivalents. Finally, we have seen that in implementing new control
concepts, interesting phenomena sometimes result even when good overall flying qualities are realized.

In retrospect, almost all of the lessons learned are actually lessons re-learned. In some cases, prudent design resulted in enhanced flying qualities, while in other cases flying qualities degradations ensued, sometimes resulting in operational limitations. In the former, the common denominator seems to be a careful, balanced engineering approach in which the goal is to produce a viable system, not simply to optimize subsystems.

Those of us who design aircraft and aircraft systems must keep this balanced approach in mind. In its essence, flying qualities are the measure of a real, human pilot's ability to control the aircraft, manage its systems, and perform the desired tasks to his satisfaction while operating in the "real world" environment. Proper consideration of growth and integration issues in the conceptual and preliminary design stages does produce aircraft which have good flying qualities, and are thus more capable of performing their primary tasks.

References:


FIGURE 3
E-8A JOINT STARS DIRECTIONAL STABILITY

CONDITIONS:
AOA = 0.5 DEG
FLAPS = 50 DEG

SIDESLIP ANGLE

YAWING MOMENT COEFFICIENT - Cn

0
10
15
25

RUDDER HINGE MOMENT LIMIT

FIGURE 4
YA-7F

CRUISE CONFIGURATION
M = 0.8

BASIC A-7D
STRETCH, CANT AND FIN CAP
STRETCH, CANT, FIN CAP AND STRAKES - YA-7F

ANGLE OF ATTACK - AOA

FIGURE 5
YA-7F DIRECTIONAL STABILITY VS ANGLE OF ATTACK

FIGURE 6
CONVENTIONAL FEEDBACK CONTROL SYSTEM
FIGURE 7
"MODE SWITCHING"

FIGURE 8
F-15 S/MTD HUD IN SLAND MODE