DIGITAL SIMULATION OF FLIGHT CONTROL SYSTEMS FOR POST-STALL AIRCRAFT

Lisa McCormack, Captain, USAF
United States Air Force Academy
USAFA, CO 80918

Daniel Gleason, Major, USAF
Air Force Institute of Technology
WPAFB, OH 45433

ABSTRACT
The design of future fighter aircraft will allow flight in the post-stall (PST) regime. The Air Force wishes to evaluate the dynamics of several aircraft configurations in this portion of the envelope. Since current aircraft do not possess this ability, evaluations must rely on digital simulation. A digital aircraft simulation maintained by the Flight Dynamics Laboratory was modified to remove angle of attack restrictions. The original simulation contained a normal-acceleration or g-command flight control system. Modifications allowed simulation of pitch-rate command and angle-of-attack command flight control systems in addition to the normal-acceleration command system.

INTRODUCTION
The aircraft design community wants to determine if fighter aircraft can achieve a tactical advantage over enemy aircraft by using post-stall angle of attack maneuvering. Post-stall (PST) capability requires an aircraft to complete controlled tactical maneuvers from its maximum lift angle of attack through approximately 70°, while maintaining a low sideslip angle [1]. Any maneuvering advantages will result from the pilot’s willingness to trade kinetic energy for positional advantage over the enemy.

The Air Force’s Flight Dynamics Laboratory (FDL), in support of research aimed at extending the operationally useful envelope of fighter aircraft, wishes to evaluate the dynamic characteristics of several aircraft configurations in the high angle-of-attack regime. Since current fighter aircraft do not possess this ability, these evaluations are accomplished using digital simulation. This analysis is developed using a digital simulation for the YF-16 which includes a 30-state rigid airframe model, a thrust-vectoring system, and a normal-acceleration command flight control system [2]. Aerodynamic and flight data provided by General Dynamics has produced simulation results which duplicate the character of YF-16 flight tests up to Mach .6 and 90° angle of attack.

The original YF-16 simulation flight control system prevents flight beyond 30° angle of attack. This study extended that capability into the PST regime by removing the angle of attack restriction. Modifications to the YF-16 program allow simulations of a normal-acceleration command, a pitch-rate command, or an angle-of-attack command flight control system. These modifications allowed study of representative aircraft dynamics in the PST regime.

Initial flight control system designs resulted from a linear analysis of the unstable aircraft dynamics and a simplified model of the flight control system. Although linear analysis provided a good starting point for the design, it failed to predict problems such as control surface saturation and pitch-roll coupling. Minor changes to the designs minimized most problems.

METHOD
The longitudinal flight control system of the YF-16 is a normal-acceleration command system which also blends pitch-rate and angle of attack feedbacks. It contains a proportional-plus-integral (PI) controller to force steady-state errors to zero. Several modifications to the original YF-16 digital simulation program were made, including the addition of pitch-axis thrust vectoring with user selection of the gain on the thrust-vectoring to elevator deflection. Vane deflections are limited to ±20°. When the aircraft is not flying at any control power limits, thrust vectoring should be transparent to the pilot. Aircraft states, particularly those commanded directly by the flight control system, should remain nearly the same with or without thrust vectoring. Differences will occur in elevator deflections, however. Thrust vectoring increases the aircraft’s control power and becomes apparent when the pilot exceeds the control power limits of the non-thrust-vectored aircraft. Two other input parameters control the engine power setting, which maintains trim power setting, increases throttle to maximum power, or decreases throttle to idle.

g-Command Flight Control System
Establishing the g-command flight control system involved few modifications to the original program. All three programs required removal of the angle-of-attack limiter. In addition, restrictions on the angle-of-attack sensor, which could normally only measure values between -5° and 30° were removed. Though physically unrealistic, this allows the aircraft to achieve angles of attack in the region of interest. Aircraft built with a PST capability will require an angle-of-attack sensor with improved range and accuracy.

U.S. Government work not protected by U.S. copyright.
α-Command Flight Control System

Linear analysis of a simplified YF-16 α-command flight control system showed that feeding back angle of attack alone did not stabilize the system. Since pitch rate feedback increases stability, it was added to the system as an inner loop feedback after the PI controller. Figure 1 gives the system block diagram, where:

\[
\frac{q}{K_q} = \frac{-22.01(s + 1.58)}{(s + 4.32)(s - 1.31)}
\]
for a flight condition of Mach .6 and 10,000 feet.

Examining the inner loop provided the root locus of Figure 2, which is stable for \(K_q < -163\). Although choosing a less negative gain allows for a higher damping ratio for the complex closed-loop roots, a more negative gain moves the real closed-loop root further into the left-half plane. Choosing \(K_q = -2.0\) allows for a damping ratio of .36 and a real pole at -1.41.

Figure 3 shows the root locus diagram for the outer loop of Figure 1, including the closed-loop roots for \(K_\alpha = 3.0\). The branches of the locus represent the short-period and flight control system modes. For \(K_\alpha = 3.0\), the short period damping ratio is .825 while the other mode has a .318 damping ratio.

To make these changes in the original digital simulation, the angle-of-attack limiter and normal acceleration feedback were removed, and the pitch rate and angle of attack feedbacks were moved appropriately. The trim initialization routine was modified to reflect these changes.

Pitch-Rate-Command Flight Control System

Transforming the longitudinal flight control system into a pitch-rate command system required eliminating the angle of attack and normal acceleration feedbacks. A linear analysis similar to that described for the angle-of-attack command system showed the pitch-rate command system could be stabilized using only pitch-rate feedback. A pitch-rate gain of -1.25 resulted in a .37 short-period damping ratio.

Current versions of these programs require the user to enter lateral stick commands used for each flight control system. Additional results also include responses to pitch doublets and step inputs in rudder. Test inputs were selected based on the range of force inputs the flight control system will accept. The maximum longitudinal stick force that will affect the aircraft, 30 pounds, was included as a step input for each configuration. In lieu of a step command in roll, each configuration performed a 300° roll. The sequence of lateral stick commands used for each flight control system were identical, with no rudder or longitudinal stick forces included.

Once aircraft velocity decreases below approximately 200 ft/sec, dynamic pressure drops significantly and the aircraft has insufficient control power to maneuver effectively. For this reason, simulations ended when velocity dropped below 200 ft/sec.

Response Analysis

This discussion addresses the manner in which each configuration responded to the same pitch and roll inputs. GSTICK, QSTICK, and ASTICK were each given 30-pound step inputs while in level flight and in 2 g turns. Because dynamic response while in PST flight is of primary concern, results emphasize maximum achieved angle of attack, but also consider maximum normal acceleration, maximum pitch rate, and rise and settling times.

Figures 4 through 6 show time responses for GSTICK, QSTICK, and ASTICK to a 30-pound step input in pitch. QSTICK achieves a 58° angle of attack while GSTICK and ASTICK reach 56° and 46° angles of attack respectively before their velocities fall below 200 ft/sec. The QSTICK response shows the highest normal accelerations and pitch rates as well. For 30-pound step inputs, the QSTICK aircraft reaches maximums of 10.1 g's and 64 deg/sec pitch rate in approximately 1 second. These characteristics indicate QSTICK is too sensitive to large pitch commands. In contrast, GSTICK and ASTICK responses both show normal accelerations of up to 6.5 g's and pitch rates of up to 33 deg/sec and 24 deg/sec respectively. Velocity bled off most quickly for QSTICK.

The angle of attack response for ASTICK, shown in Figure 6, seems rather odd at first glance. Results show ASTICK reaching a steady state angle-of-attack rate as if it were an angle-of-attack rate command system. The rate at which velocity bleeds off for this input makes it difficult to verify this, so time responses for smaller magnitude pitch command were also examined. These responses showed that this flight control system does command angle of attack, but the rise time is much longer than anticipated. For 10-pound and even 5-pound pitch commands, aircraft velocity falls off significantly before angle of attack can reach a steady-state value.
Slow rise times appear in other responses as well and indicate compensation, perhaps a lead-lag filter, would improve ASTICK's responsiveness. Properly chosen lead and lag frequencies will lower ASTICK's rise time and allow the angle of attack to reach the desired steady-state value.

Time responses which make ASTICK appear to command angle of attack rate also result from a rapid decrease in elevator effectiveness once angle of attack exceeds 10°. The ASTICK aircraft begins increasing angle of attack slowly, as indicated earlier, and the aircraft begins to slow. Once it has achieved the desired angle of attack, it lacks dynamic pressure and elevator effectiveness. Nulling the elevator deflection has little effect and angle of attack continues to increase.

The pitch-rate command was designed to reach a maximum pitch rate of 60 deg/sec. Figure 5 shows pitch rate climbing quickly to 63 deg/sec and then falling off just as quickly. A better response would have shown pitch rate increasing until it reached the desired value with several comparatively small overshoots. Properly designed compensation should adjust the response to make the response more reasonable. A normal-acceleration limiter may also be an appropriate addition to this flight control system.

The maximum desired angle of attack for ASTICK is 80°. Figure 6 shows a 50° angle of attack resulted from a 30-pound input. However, angle of attack was still increasing as velocity bled off below 200 ft/sec. If the aircraft had maintained a higher velocity or generated a higher angle of attack rate, it would have reached a higher angle of attack. The proposed lead-lag compensation should alleviate this problem.

Pitch-Roll Coupling

Commands to make each configuration perform a 360° roll and stop were designed to assess the ease with which each flight control system could be more precisely controlled and its susceptibility to pitch-roll coupling. The same roll commands were used for each configuration. Lateral-directional responses for each flight control system were very similar because the original lateral-directional flight control system was not modified. However, the pitch-roll coupling characteristics of each system differ.

Figures 7 and 8 show the amount of angle of attack and pitch rate response which occurred during a 360° roll. QSTICK time responses show the greatest amount of pitch-roll coupling. Angle of attack varied between -1° and 6.5° while pitch rate ranges from 9 to 10 deg/sec. Normal acceleration responses are very similar to angle of attack results. Although the excursions for QSTICK are quick and it returns to trim, coupling poses a real problem.

QSTICK and ASTICK exhibit small amounts of roll coupling. However, if rolls are continued past 360° all systems, especially QSTICK, become more susceptible to a pitching departure.

CONCLUSIONS

Digital simulations of aircraft with normal-acceleration, pitch-rate, and angle-of-attack command flight control systems capable of PST flight were successfully developed. Analysis of test cases showed the shortcomings as well as the strengths of each configuration. These shortcomings are functions of the design selected, not characteristics of the type of flight control system implemented. The flight control systems require fine adjustment to achieve desired responses.

The aircraft configured with the pitch-rate command flight control system exhibited the greatest pitch-roll and pitch-yaw coupling problems and was oversensitive in pitch. Adjusting the gain slightly, adding pitch-roll and pitch-yaw crossfeeds, and modifying the existing aileron-to-rudder and roll-rate-to-rudder interconnects should minimize this problem. In addition, modifying the g-limiter to make it more anticipatory will prevent the aircraft from exceeding the range of reasonable normal acceleration. If these strategies fail to bring about the desired response, future work should consider lowering the maximum desired pitch rate of 60 deg/sec.

The angle-of-attack command aircraft reacted sluggishly to pitch inputs. Adding lead-lag compensation will lower the vehicle's rise time, so that configuration should achieve higher angles of attack than it did for the results presented here. Subjecting each configuration to more complex, realistic maneuvers, including those typical of combat in the PST regime, will allow a more rigorous evaluation of each configuration. Examples of such maneuvers include rolling while at a high angle of attack or acquiring a target aircraft flying at the same or different velocity as the pursuer while in PST flight. Including a wind gust model in the digital simulations would also allow evaluation of the ability of each system to reject disturbances.

The current simulations make no provisions for investigating this potentially serious problem.

The simulations developed in this study hold a great deal of promise for research on PST flight. Applications to flight control system design for a post-stall aircraft include examination of typical post-stall dynamics, particularly combat maneuvers, and the ability to predict flight control problems which may not occur in flight at low-to-moderate angles of attack.

References

Figure 1 $\alpha$-Command Flight Control System

Figure 2 $\alpha$-Command Flight Control System Root Locus (Inner Loop)

Figure 3 $\alpha$-Command Flight Control System Root Locus (Outer Loop)
Figure 4 Normal Acceleration Time Response

Figure 5 Pitch Rate Time Response

Figure 6 Angle-of-Attack Time Response

Figure 7 Angle-of-Attack Time Response

Figure 8 Pitch Rate Time Response