Development of Flight Control Laws for the T-50 Advanced Supersonic Jet Trainer

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Abstract

The T-50 advanced supersonic jet trainer employs the Relaxed Static Stability (RSS) concept to improve the aerodynamic performance while the flight control system stabilizes the unstable aircraft and provides adequate handling qualities. The T-50 flight control laws employ a proportional-plus-integral type controller based on a dynamic inversion method in longitudinal axis and a proportional type controller based on a blended roll system with simple roll rate feedback and beta-betadot feedback system. These control laws are verified by flight tests with various maneuver set flight envelopes and the control laws are updated to resolve flight test issues. This paper describes several concepts of flight control laws used in T-50 to resolve those flight test issues. Control laws for solving the roll-off problem during pitch maneuver in asymmetric loading configurations, improving the departure resistance in negative angle of attack conditions and enhancing the fine tracking performance in air-to-air tracking maneuvers are described with flight test data.

Key Word : Relaxed static stability, Digital fly-by-wire flight control system, Angle-of-attack limiter, Departure resistance, Fine tacking performance

Nomenclature

K_f	: pitch stick feed-forward command
K_{ni}	: integral gain
K_n	: normal load factor feedback gain
K_q	: pitch rate feedback gain
K_α	: angle of attack feedback gain
K_{pn}	: desired pilot pre-filter gain
K_{pd}	: pilot pre-filter gain
K_{r1}	: roll command gain
K_{r2}	: stability axis roll rate feedback gain in roll axis
K_{r3}	: stability axis yaw rate feedback gain in roll axis
K_{r4}	: beta feedback gain in roll axis
K_{y1}	: yaw command gain
K_{y2}	: stability axis roll rate feedback gain in yaw axis
K_{y3}	: roll attitude gain in yaw axis
K_{y4}	: beta feedback gain in yaw axis
K_{y5}	: beta-dot feedback gain in yaw axis

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K_{rea}	: aileron-to-tail inter-connection gain
K_{rs}	: roll scaling gain
K_{raa}	: differential flap gain (split ratio)
K_{ry}	: aileron-to-rudder inter-connection gain
K_{ry}	: aileron-to-rudder inter-connection gain
K_{yea}	: rudder-to-tail inter-connection gain
K_{ys}	: yaw scaling gain
K_{yaa}	: rudder-to-aileron inter-connection gain
K_{yr}	: rudder gain (spilt ratio)
K_{r1a}	: roll command gain in beta-betadot feedback system
K_{r2a}	: stability axis roll rate feedback gain in beta-betadot feedback system
N_z	: normal load factor (g's)
Q_b	: pitch rate (deg/sec)
AoA	: Angle-of-Attack (deg)
F_{roll}	: pilot roll command (lbs)
F_{yaw}	: pilot yaw command (lbs)
p_s	: roll rate in stability axis (deg/sec)
r_s	: yaw rate in stability axis (deg/sec)

Introduction

A digital fly-by-wire (DFBW) flight control system (FLCS) using modern digital control technology is adapted to stabilize an unstable aircraft and attain adequate handling qualities. Consequently, the RSS concept and the highly augmented DFBW FLCS give a chance to optimize the handling qualities and enhance the performance in all flight envelops for T-50 advanced supersonic jet trainer.

These control laws are developed through the standard design process as shown in figure 1. First, the control law design requirements are determined using military specifications and requirement of customer (ROC). Second, the aircraft goes through the process of trimming for control law design flight conditions based on a database which is composed of aerodynamic, propulsion, weight and hinge moment data of the aircraft. And the aircraft linear models are made around those trim points. Third, the feed-forward and feedback control gains are optimized using aircraft linear model to achieve design goals such as short-period mode in longitudinal axis and dutch-roll, spiral and roll modes in lateral-directional axes. The optimized gains are evaluated by linear analysis with respect to military criteria (MIL-F-8785C, MIL-F-9490D) such as damping, frequency, control anticipation parameter (CAP) and roll mode time constant etc. [1-2] Fourth, the nonlinear control laws such as angle-of-attack (AoA) limiter, rudder fader, anti-spin control law, roll rate command limiter (RCL), etc. are designed using the optimized gain sets in order to improve the aircraft dynamic stability and safety in nonlinear flight range. In order to verify these control laws and the flight characteristics of an aircraft, a non-real time simulation is conducted using an in-house software. Fifth, the real-time pilot simulation is performed using HQS (Handling Quality Simulator). The handling qualities and controllability of an aircraft can be evaluated by HQS pilot simulation. Finally, the control laws are evaluated through flight tests and these test results are fed back to improve handling qualities of the aircraft by updating control gains or adding or modifying the nonlinear control laws, etc[3-6].

Currently, the flight tests of T-50 advanced supersonic jet trainer are in progress with various maneuvers in order to verify the control laws and flight characteristics. Flight tests reveals several issues that were not forecasted in design phase due to uncertainties of aircraft model and others. Those issues include the followings; the roll-off tendency occurred during pitch maneuver in asymmetric loading configurations, degrade of fine tracking performance during air-to-air tracking due to active stick characteristics. And, from non-real time simulation, a possible inverted departure was found during the aggressive negative pitch maneuver. These issues are resolved by designing and applying additional nonlinear control laws during FSD (Full Scale Development). This paper addresses the result of previous research and describes handling qualities analysis and flight test results.

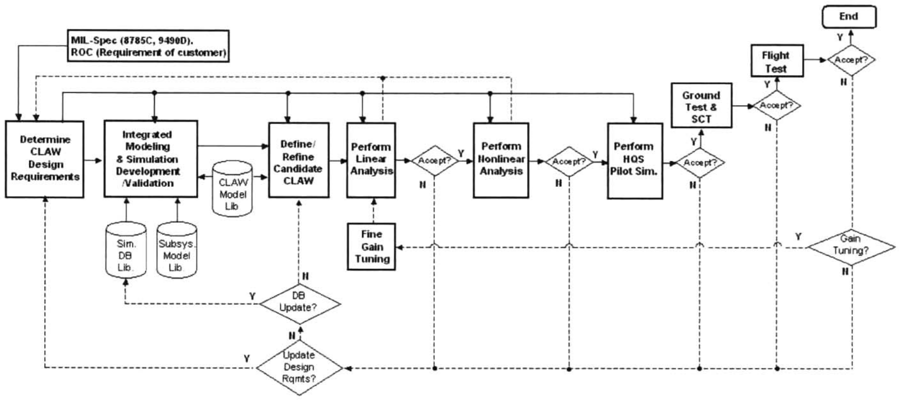

Fig. 1. Overall procedure of control law design and evaluation process

Flight Control Law

The primary role of the T-50 FLCS is to provide satisfactory aircraft handling qualities and ensure adequate level of flight safety. Implementing RSS concept for better performance in designing the airframe of T-50, smaller wing was required for lift than that of conventional aircraft. This also reduces horizontal trim drag. In order to maintain the control of an unstable aircraft with RSS, electronic augmentation of a DFBW FLCS with full authority is required. Excellent flying qualities can be attributed to the DFBW FLCS feature of full time command and stability (CAS) augmentation in all three axes. In pitch axis, the control is provided by symmetric horizontal tail deflections. The roll control is provided by a combination of flaperon and differential horizontal tail deflections. The flaperon provide the majority of roll power at lower airspeed but differential horizontal tails are mainly used at higher airspeed without causing aeroelastic loss due to flaperon deflections. Proper blending of these two control surfaces minimizes the variation in roll power for flight conditions. A conventional rudder provides yaw control

Longitudinal flight control law

Figure 2 shows the basic structure of longitudinal control law. The T-50 employs stability augmentation in the pitch axis using a proportional-plus-integral type controller with dynamics inversion (DMI) method.

The control law in longitudinal axis is a normal acceleration following system in flight phase category A (UA: Up and Away mode). The pilots' pitch stick command in a degree of control stick deflection with stick force is converted to G command by predefined command gradient. The G command, the pitch trim and autopilot command are summed to create the total G command. The total G command limited to prevent exceeding structural limits is compared against the measured aircraft load factor to form an error signal into the pitch integrator so that the horizontal tail moves to a direction to achieve the commanded load factor. If AoA is too high, the AoA limiter feedback reduces the amount of load factor of the aircraft. For the flight phase category C (PA: Power Approach mode), the control is a pitch rate following system. The pilots' pitch stick command is converted to a pitch rate command by the predefined command gradient. The resulting pitch rate command is summed to the pitch trim to create the total pitch rate command. The limited pitch rate command preventing departure is compared against the measured aircraft pitch rate to form an error signal into the pitch integrator so that the horizontal tail moves in a direction to achieve the commanded pitch rate. The AoA limiter feedback also reduces the amount of pitch rate of the aircraft to prevent departure in PA configuration. Note that the main difference between the UA and PA configurations is the command system. The normal load factor command optimizes the flight path control in the UA configuration. In addition, autopilot is not allowed in the PA configuration.

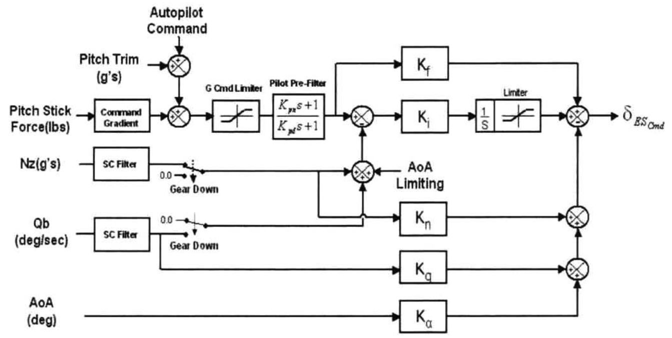

Fig. 2. Longitudinal Control Law

The feedback variables in pitch axis are AoA, pitch rate and normal acceleration. The AoA feedback augments the pitching moment coefficient against AoA (Cm) reinforcing the natural frequency of short-period mode as well as stabilizing the aircraft that is statically unstable. It also reinforces the aircraft stability by increasing the gain margin in the system. The pitch rate feedback augments the pitching moment coefficient against pitch rate (Cm_q). This feedback reinforces the damping ratio of short-period mode and increases the phase margin of the system. The feedback of normal acceleration at the location of accelerometer instead of that at the center of gravity is used. This approach brings favorable effect of simultaneous feedback of normal acceleration and pitch rate at the center of gravity. This also reinforces the natural frequency and damping ratio of short-period mode. In order to guarantee the stability margin of the controller, the lead filter is designed in pitch rate feedback loop. And the structural coupling filter is designed in pitch rate and normal acceleration feedback loop in order to suppress the structural resonance due to structural vibration

The T-50 uses the control law of AoA limiter to allow maneuvering up to the maximum usable AoA. This control law is provided to prevent aircraft from departure at high AoA region. In the UA mode, one of three limiters can be selected by using a store configuration switch. The FLCS limits the normal load factor to 8 g's maximum for AoA less than 15 degree. Above 15 degree AoA, positive speed stability is introduced with AoA feedback and maximum g is reduced as a function of AoA. The presence of roll rate further reduces the maximum achievable AoA. The 25-degree AoA is allowed for 1g flight in CAT I store configuration. When CAT II stores are selected, the 1g AoA limit becomes 22 degree and with CAT III selection, the limit is further reduced to 19 degree. In the PA mode, the AoA limiter is independent of the store configuration switch position. The AoA limiter allows 14 deg/sec of pitch rate capability up to 13 degree of AoA in PA mode. Above 13 degree AoA, strong AoA limiter command is introduced to create a positive speed stability system.

The manual pitch override (MPO) switch is designed in pitch control law to enhance recovery from departure. This function is provided to disconnect the symmetric tail command from control law and allow the pilot to take the full authority of pitch control. So, the pilot can "rock" the aircraft out of a deep stall by phasing pilot inputs with the aircraft motion.

Lateral-directional flight control law

Figure 3 shows the basic structure of lateral-directional control law. T-50 employs stability augmentation in lateral-directional axes using beta-betadot feedback system with proportional controller. The rolling and yawing motions of the aircraft are coupled each other. Minimizing the coupling between the roll and yaw axis is desirable for good flying qualities and precise tracking. Therefore, the FLCS includes the Aileron-Rudder-Interconnect (ARI) to accomplish the coordinated turn and provide required yaw rate corresponding to roll motion. Flying T-50 is a feet-on-the-floor task with no pilot yaw coordination for rolling maneuvers even at high AoA.

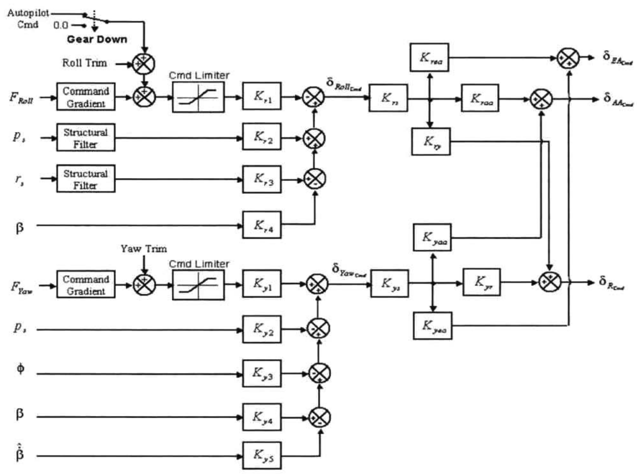

Fig. 3. Lateral-directional control law

The control in roll axis is a roll rate command system. The pilots' roll stick command, in a degree of control stick deflection with stick force, is converted to a roll rate command by the predefined command gradient. The resulting roll rate command is limited to prevent exceeding structural limits. The limited roll rate command the roll trim and roll autopilot commands are then summed to create the total roll rate command. The total roll rate command is compared against the measured aircraft roll rate to form an error signal so that the flaperons and differential horizontal tails deflect in a direction to achieve the commanded roll rate. The feedback variables are roll rate, yaw rate and angle-of-sideslip (AoS) in roll axis. The roll rate feedback augments the roll mode time constant and roll damping moment coefficient about Xs(L_p). The structural coupling filter is designed in roll rate and yaw rate feedback loop in order to suppress the structural resonance due to structural vibration.

The control in yaw axis is an AoS command system. The pilots' rudder command, in pounds of force, is converted to an AoS command by the command gradient. The resulting AoS command is limited to prevent from exceeding AoS maneuvering limits. The limited AoS command is then summed to the yaw trim command to create the total AoS command. The total AoS command is compared against the measured aircraft AoS to form an error signal so that the rudder deflects in a direction to achieve the commanded AoS. The feedback variables are roll rate, sideslip () and rate of sideslip () in yaw axis. These feedback variables augment natural frequency and damping of dutch-roll mode.

The rudder fader and roll rate limiter are employed in the lateral-directional control law in order to prevent aircraft from departure due to roll-yaw coupling. When a pilot uses the rudder pedals at high AoA, rudder commands faded out as a function of AoA and roll rate to optimize control effects and maximize maneuverability. This function prevents roll-coupled departures in rudder and rudder-assisted rolls and pilot-induced yaw departures during high AoA sideslip maneuvers. Rudder fader reduces the amount of pedal commanded rudder deflection as a function of AoA, Mach number, and roll rate. The rudder fader only affects the pedal-commanded rudder deflection.

A roll rate limiter has been incorporated to allow the pilot to command maximum usable roll rate without considering normal aerodynamic roll coupling characteristics of an aircraft. This function prevents roll-coupled departures during maximum command rolling maneuvers near the AoA limit. The roll rate limiter reduces the maximum roll rate as a function of airspeed, Mach number, AoA, normal load factor and store configuration switch position. Normally, the maximum allowable roll rate is 200 deg/sec in CAT I, 170 deg/sec in CAT II, 130 deg/sec in CAT III and 50 deg/sec in PA mode.

The yaw rate limiter provides automatic anti-spin control during departures. The limiter becomes active beyond 35 AoA in upright departure and below -10 AoA with calibrated airspeed less than 170 knots in inverted departure. During upright departures, yaw rate is fed back to flaperon, differential horizontal tail and rudder to counteract spin motions. While the anti-spin is active for upright departure, pilot commands to the roll and yaw axis are ignored by the FLCS. During inverted departure, yaw rate is fed back to the rudder to counteract the spinning motion. While the anti-spin is active for inverted departure, pilots' commands to the roll and yaw axis are ignored when the MPO switch is on.

Flight Test Issues

Definition of aircraft configurations

Figure 4 and 5 show the feature of T-50 advanced trainer and loading configurations. T-50 has several loading configurations to support combat/training missions. The F0 and F11 symmetric and F11D1 asymmetric loading configurations are representative forms of CAT 1. The aircraft has launchers at wing-tips (station 1, 7) in F0, AIM-9's at wing-tips in F11 and a launcher at station 1 and an AIM-9 at station 7 in F11D1 configuration. F10 configuration is a representative form of CAT 2, the aircraft carries AIM-9's at wing-tips and 150 lbs fuel tank at station 4. F12 configuration is a representative form of CAT 3, the aircraft carries AIM-9's at wing-tips, 150 lbs fuel tank at station 3, 5 and SUU-20 at station 4.

Flight test for asymmetric loading configurations

Military aircraft have several different weapon loading configurations to support air-to-air

Fig. 4. Flight test scene of T-50 advanced supersonic jet trainer

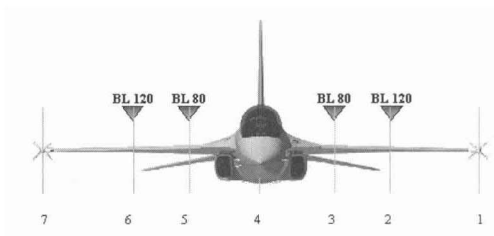

Fig. 5. Aircraft loading configurations

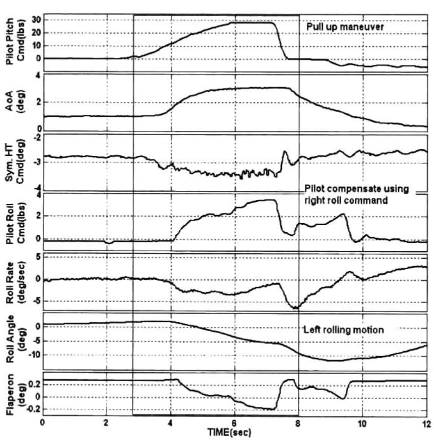

Fig. 6. Flight test result of pull up maneuver at M0.95, 10kft, UA and F11D1 configuration

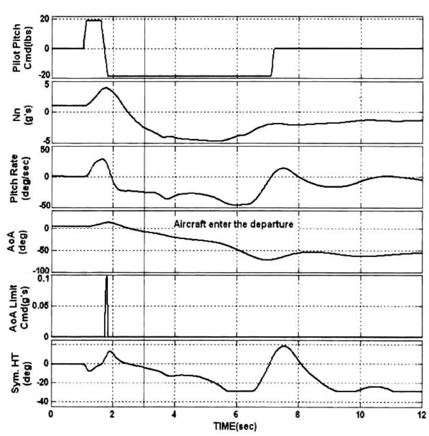

Fig. 7. Non-real time simulation of departure resistance in 300knots, 35kft, UA, c.g 41.1% MAC and F11

combat and air-to-ground weapon delivery modes. These various aircraft loading conditions could result in asymmetric loading to the aircraft once delivered. Consequently, the FLCS should guarantee good handling qualities and controllability in asymmetric loading configurations to accomplish the combat tasks.

Flight tests with pull up (PU) maneuver are performed to evaluate the handling qualities and controllability for F11D1 asymmetric loading configurations. Figure 6 shows a flight test result of PU maneuver at M0.95, 20kft, UA and F11D1 asymmetric loading configuration. The flight test result shows the aircraft rolls to left due to the asymmetric loading when pitch up command is applied. However, figure 6 shows that the roll compensation command was not applied and the aircraft still rolls to the left. This roll-off tendency is supposed to be caused by asymmetric lifting force distribution as AoA increases. The lift force distribution is affected by the asymmetry of wing-tip stores, launcher at left and AIM-9 at right. AIM-9 at right wing-tip is supposed to force help generating vortex lift as AoA increases. This tendency degrades the handling qualities and controllability in asymmetric loading configurations during combat missions.

Non-real time simulation for departure resistan

Flight tests are necessary to evaluate the stability of aircraft and resistance against the departure due to aggressive pilot input or external disturbances. Departure resistance test items consist of symmetric maneuvers such as push over/pull up (POPU) and pull·up/push over (PUPO), asymmetric maneuvers such as coordinate roll (same direction of roll and yaw command) and cross roll (opposition direction of roll and yaw command), etc. Flight tests near departure are highly risky, so departure resistance should be verified by precise simulations such as non-real time simulation and HQS pilot simulation before conducting flight tests.

The non-real time and HQS pilot simulation for departure resistance are performed with maximum aft c.g as a worst case. Figure 7shows the result of non-real time simulation with PUPO maneuver at 300 knots, 35kft, UA, c.g 41.1% MAC and F11 configuration. The PUPO maneuver examines the negative departure characteristics in pitch axis. The simulation results show that the aircraft could enter into departure due to pilots' aggressive negative symmetric input. As control law was not designed for this negative departure situation at the time of analysis, this can affect flight safety during combat maneuver as well as flight tests.

The implemented limiters such as positive AoA limiter in pitch axis, rudder fader and RCL in lateral-directional axes are not good to prevent departure of aircraft against negative pilots' symmetric full input in negative high AoA's. A limiter increasing the negative departure resistance against pilots' negative symmetric input was designed and implemented.

Flight test for air-to-air tracking maneuver

The T-50 was designed to have capability of the combat tasks such as air-to-air tracking and air-to-ground maneuver. Consequently, flight tests for combined air-to-air tracking maneuvers have been performed to evaluate the tracking performance using the F-16 target aircraft in F0 configuration. It evaluates gross acquisition and fine tracking performance of an aircraft. The test items of gross acquisition evaluate initial capture performance and fine tracking evaluate precise tracking toward target aircraft.

Figure 8 shows the flight test result of 3-g wind-up turn varying side stick modes such active and passive to compare the stick effects. In active mode, the motors are active, providing programmed force-versus-displacement characteristics, as well as force feel linkage between the two stick units. In passive mode, the motors are not energized. The stick force-versus-displacement characteristics are determined by the mechanical feel spring cartridges. The result shows that the pilot uses the pitch correction more frequently and the amplitudes of pilots' pitch command is relatively large in active stick mode comparing to in passive stick mode.

This characteristic degrades the handling quality of aircraft during fine tracking.

Figure 9 shows the flight test result of the combined air-to-air tracking maneuver with active control stick in 350 knots, 20kft, UA, F0 configuration. This result shows the gross acquisition and fine tracking region. The pilot initially compensates the pitch response with large input to catch up with the target aircraft in gross acquisition stage. And, the pilot continuously compensates the pitch input to track the target aircraft in fine tracking stage. But the amplitude of pilots' pitch command looks relatively large and pitch command to correct the pitch response requires frequent the pilot inputs in fine tracking stage. This type of pilots' commands generate pitch bobble phenomenon and the pilot has difficulty to track the target due to pitch bobble. Test pilots comment that the gross acquisition is good in initial tracking, but fine tracking is not good because of pitch bobble. Also pilots comment that the pitch bobble occurred in active stick mode saying active stick characteristics affects, and this problem degrades the level of fine tracking performance.

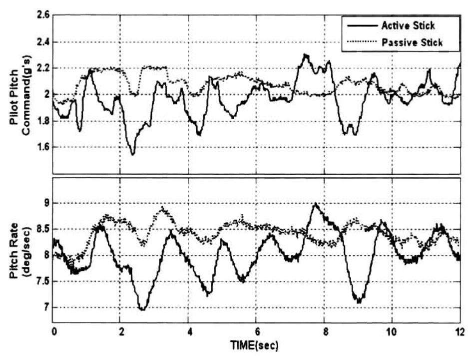

Fig. 8. Flight test of 3-g wind-up turn maneuver with active and passive control stick in 350 knots, 20kft, UA and F0 configuration

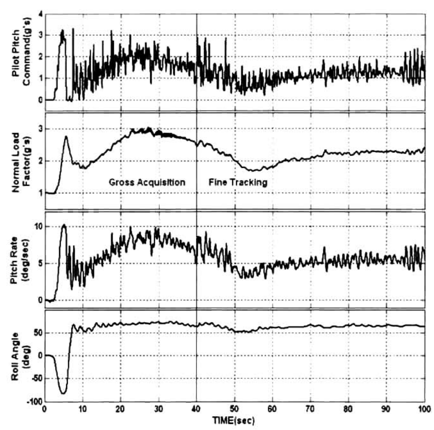

Fig. 9. Flight test of 3-g air-to-air tracking maneuver with active control stick in 350knots, 20kft, UA and F0 configuration

Control Law Design and Flight Test Result

Blended roll system in lateral-direction flight control law

The roll rate feedback gain (Kr2a) is small comparing to pilot roll command gain (Kr1a) in beta-betadot feedback system. Thus, the dynamic roll stability decreases during symmetric maneuver in asymmetric loading configurations because of differential lifting force distributions. The roll rate feedback gain should be increased to augment the roll stability against external turbulence or pilots' symmetric input. To increase the roll rate feedback gain, the lateral control laws adapt the simple roll rate feedback system like F-16's structure. The structure of directional control law is not changed. Figure 10 shows the pilot roll command and roll rate feedback gains in beta-betadot feedback and simple roll rate feedback system. The roll rate feedback gain (Kr_simple) increases in simple roll rate feedback system comparing to beta-betadot feedback system. And, the Kr_simple uses the pilot roll command and roll rate feedback gains at once instead of Kr1a and Kr2a in simple roll rate feedback system

The flight test of maximum 360-degree roll maneuver is performed with simple roll rate feedback system to check the maximum roll performance. Figure 11 shows the flight test result of maximum 360-degree left roll release in 300 knots, 20kft, UA and F10 configuration. As a result, the wing pitching moment increases when the pilots release the roll stick after 360-degree roll. In other words, the flaperon deflection increases when the pilots release the roll stick because of the augmentation of the roll stability caused by increasing the roll rate feedback gain. This problem affects the structural margin of the aircraft.

In order to solve this problem, the lateral-directional control law structure adapts the blended roll system between the beta-betadot feedback systems for large pilot roll command/roll rate and the simple roll rate feedback system for small pilot roll command/roll rate as in Figure 12. The concept of this control law is that the pilots' roll command and roll rate are small during symmetric maneuver. Therefore, if the pilots' roll command is below 5 lbs or the roll rate is below 20 deg/sec, lateral-directional control laws employ the simple roll rate feedback system. Also, if the pilots' roll command is larger than 9 lbs or the roll rate is larger than 40 deg/sec, lateral-directional control laws employ the beta-betadot feedback system. For the roll command between 5 and 9 lbs or the roll rate between 20 and 40 deg/sec, lateral-directional control laws employ the blended roll system. This control law does not affect the characteristic of roll maneuver, but the roll stability is increased when the aircraft are doing level flight or symmetric maneuver requiring small amount of roll input.

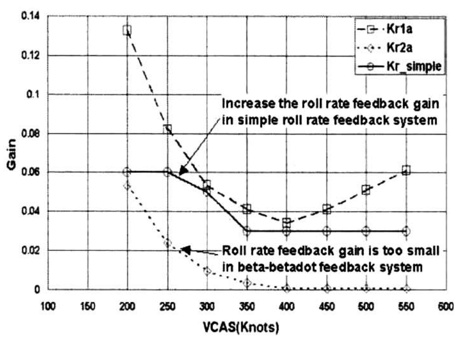

Fig. 10. Roll command and roll arte feedback gain in beta-beatdot and simple roll rate feedback system

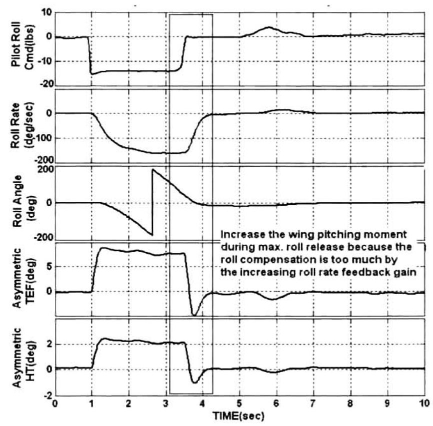

Fig. 11. Flight test of maximum 360 deg roll maneuver with simple roll rate feedback system in 300knots, 20kft, UA, 1g and F10 configuration

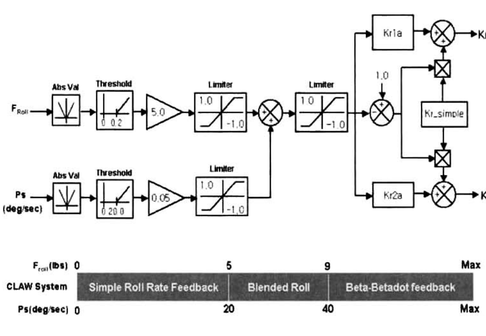

Fig. 12. Control law of blended roll system in lateral control law

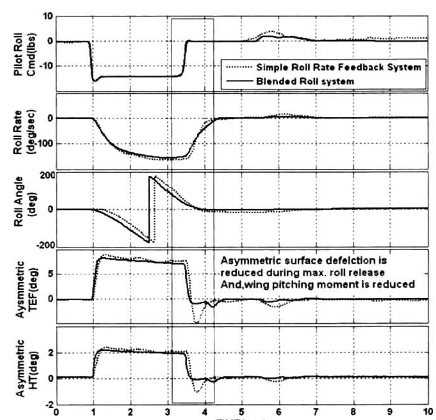

Fig. 13. Flight test of maximum 360 deg roll maneuver with blended roll system in 300knots, 20kft, UA, 1g and F10 configuration

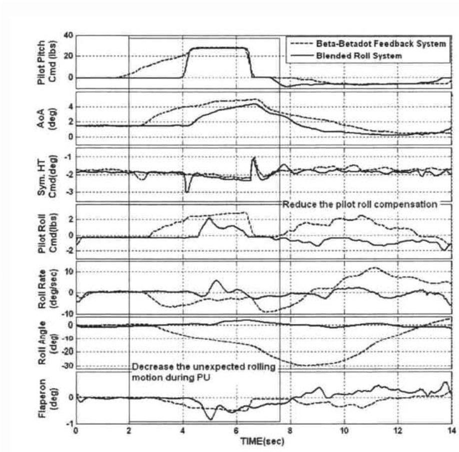

Fig. 14. Flight test of pull up maneuver with blended roll system in M0.8, 20kft, UA, 1g and F11D1 configuration

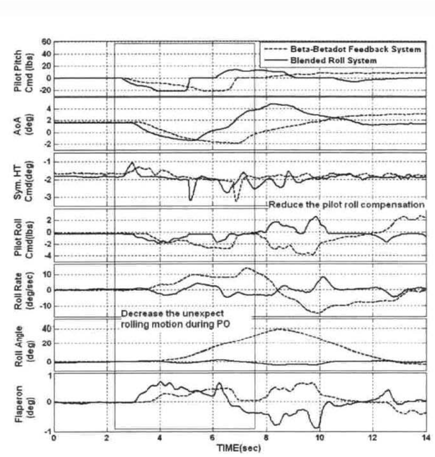

Fig. 15. Flight test of pull over maneuver with blended roll system in M0.8, 20kft, UA, and F11D1 configuration

Figure 13 shows the flight test result of maximum 360-degree left roll maneuver with only the simple roll rate feedback and with blended roll system in 300 knots, 20kft, UA and F10 configuration. The results show the wing pitching moment decreases in blended roll system without degrading maximum roll performance.

Figure 14 and Figure 15 shows the PU and PO (Push Over) maneuver with only the beta-betadot feedback and with blended roll system in M0.8, 20kft, UA and F11D1 asymmetric loading configuration. The roll-off tendency decreases during symmetric maneuver in blended roll system. Based on the flight test results, the blended roll system effectively decreases the roll-off tendency without degrading the maximum roll performance in asymmetric loading configurations.

Negative AoA limiter

Currently, the positive AoA limiter control law is provided in longitudinal control laws. This control law is to prevent aircraft departure during positive pitch maneuvering. With the aid of the limiter, the aircraft does not enter into departure during positive pitch maneuvers in high AoA flight regime.

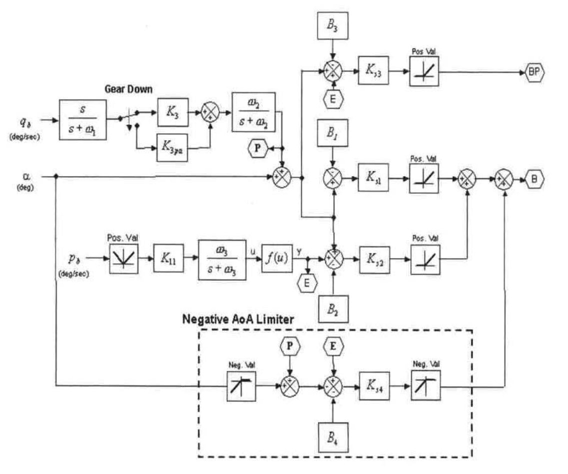

Fig. 16. Control law of negative AoA limiter

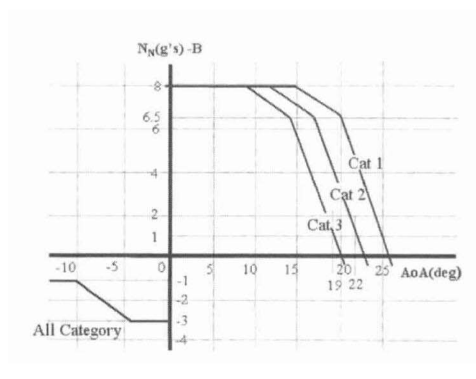

Fig. 17. Schedule of AoA limiter

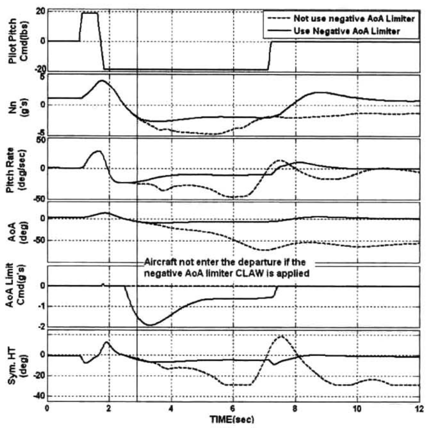

Fig. 18. Non-real time simulation of departure resistance with negative AoA limiter in 300knots, 35kft, UA, c.g 41.1% MAC and F11 configuration

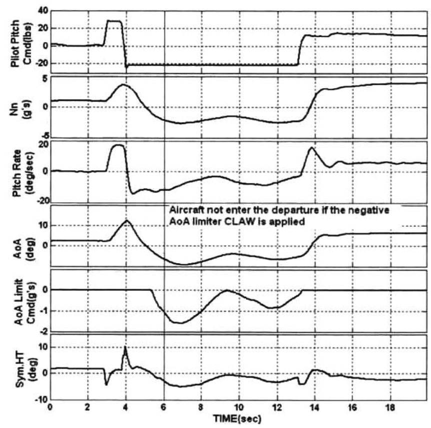

Fig. 19. Flight test of departure resistance with negative AoA limiter in 300knots, 35kft, UA, c.g 41.1% MAC and F11 configuration

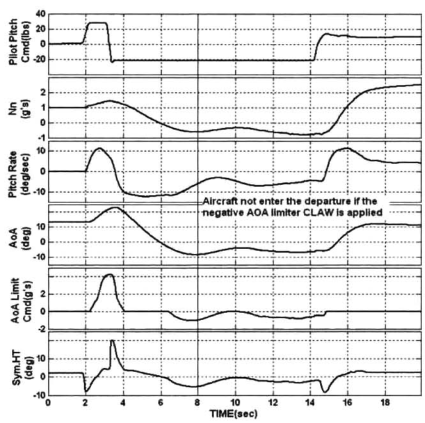

Fig. 20. Flight test of departure resistance with negative AoA limiter in 150knots, 35kft, UA, c.g 41.1% MAC and F11 configuration

The result of the non-real time simulation reveals that the aircraft could enter the departure during the aggressive negative pitch maneuver. This problem affects the flight safety during aggressive pilots' symmetric maneuver. Therefore, the negative AoA limiter control law is designed to improve the characteristic of negative departure resistance in longitudinal control law. Figure 16 and 17 show the control law of AoA limiter and the schedule of positive and negative AoA limiter function in UA mode. The negative AoA limiter is independent of the store configuration switch position and scheduled only by AoA. The FLCS limits the normal load factor to -3 g's minimum for AoA lower than -4 degree. Below -4 degree AoA, minimum g limit varies as a function of AoA with -1 g's occurred at -10 degree AoA.

The negative AoA limiter control law affects the handling qualities such as negative pitch capture maneuver in low speed area. Therefore, the HQS pilot simulation is performed to evaluate the handling qualities in pitch axis. Handling quality test items are smooth and aggressive pitch captures. The criteria of handling quality tests are the Cooper Harper Rating (CHR) and Pilot Induced Oscillation (PIO). After conducting the HQS pilot simulation, pilots comment that handling qualities are not degraded in high-speed flight regime but the aircraft shows pitch up tendency in low speed flight regime. The pitch up tendency occurs by negative AoA limiter command because the variation of AoA is little bit large during aggressive pitch capture maneuver in the low speed regime. But, the aircraft can be stabilized by pilot's pitch correction without degrading handling qualities.

Figure 18 and 19 show the result of non-real time simulation and flight test in the same flight condition of 300 knots, 35kft, UA and F11 with c.g 41.1% MAC. And, Figure 20 show the result of flight test in 150knots, 35kft, UA and F11 with c.g 41.1% MAC. As the result of flight test, the aircraft does not enter departure during the negative pitch maneuver if the negative AoA limiter control law is employed. Based on flight tests, this control law prevents aircraft from departure during negative pitch maneuver without degrading the handling qualities.

Pilot pre-filter scheduler

The longitudinal dynamic motions consist of two oscillatory terms: one is highly damped and high frequency oscillation, the other is very slowly damped and low frequency oscillation. The first is called the short period mode of motion while the second is called the phugoid mode of motion. Equation (1) shows the typical transfer function of the short period characteristics of pitch rate against the pilot pitch stick command.

$$\frac{q}{F_s} = \frac{K_\theta \left(T_{\theta 2} s + 1\right) e^{-T_{\theta 2} s}}{s^2 + 2\zeta \omega s + \omega^2} \tag{1}$$

Generally, the zeros of the system are decided by aerodynamic property of the aircrafts and this doesn't affect the feedback system. But, the location of zero affects the handling qualities of the aircraft. Therefore, the locations of zeros are considered in order to get good handling quality. If we apply the pole-zero cancellation method to equation (1), we get equation (2)

$$\frac{q_{DES}}{F_p} = \frac{T_{\theta 2}^{DES} s + 1}{T_{\theta 2} s + 1} \frac{q}{F_s} \tag{2}$$

The filter is designed in pilot pitch command loop in order to improve the flying quality using the equation (2), and we get equation (3)

$$\frac{K_{pn} s + 1}{K_{pd} s + 1} = \frac{T_{\theta 2}^{DES} s + 1}{T_{\theta 2} s + 1} \tag{3}$$

This filter is applied to pilot pitch command loop in PA and UA configurations. Equation (3) represents the pilot per-filter.

The gross acquisition system is the normal acceleration following system. This system is designed to get optimum response of normal acceleration. Therefore this system is generally employed in the UA mode requiring the fast aircraft response such as the air-to-air combat. But, the response of pitch rate shows poor transient response characteristics. The fine tracking system is the pitch rate following system. This system is designed to get optimum pitch rate response. Therefore this system is employed in the PA mode because the pilot can control the aircraft precisely in the approach and landing phase. But the response of aircraft can be too slow. Therefore these control systems should be adequately employed in FLCS to optimize the flight characteristics. The T-50 longitudinal control laws employ the normal acceleration following system in UA mode and the pitch rate following system in PA mode.

The fine tracking performance is degraded in flight test of combined air-to-air tracking because of active stick characteristics. To improve the fine tracking performance, the pilot pre-filter scheduler is proposed. The pilot pre-filter affects the handling qualities of aircraft so it should be designed carefully to improve the fine tracking performance without degrading the gross acquisition performance.

To verify and validate the pilot pre-filter, analysis and tests are conducted. First, the non-real time simulation is performed to analyze the pitch step response against variation of pilot pre-filter gain (K_{pn}) in M0.6, 20K, UA and F0 configuration. Figure 21 shows the simulation result of step response as variation of pilot pre-filter gain (100%, 60% and 40%) with 0.5 g displacement differential (G) breakpoint. As the pilot pre-filter gain is decreased, the aircraft transient response becomes shorter and better in the simulation result. In other words, pitch rate response gets more sensitive as pilot pre-filter gain is increased.

Figure 22 shows the scheme of pilot pre-filter gain scheduler. The pilot pre-filter scheduler is a function of displacement differential (G) between the pilot normal acceleration command and normal acceleration of the aircraft. If G is large, like transient stage, the pilot pre-filter gain is increased to optimize the gross acquisition performance. And if G is small like steady-state flight, the pilot pre-filter gain is decreased to optimize the fine tracking performance. This scheduler has three options, which are 100%, 60% with 0.5g and 1g-breakpoint multiplier. The Kpn_mult is multiplied to pilot pre-filter gain shown in figure 2 (K_{pn}). The pilot can select and operate the options using the flight control test panel (FCTP) option. In order to evaluate the gross acquisition and fine tracking performance with pilot pre-filter scheduler, the combined air-to-air tracking maneuver is performed in 350knots, 20K, UA and F0 configuration. Figure 23 shows the flight test result of the air-to-air tracking maneuver with the pilot pre-filter scheduler options. From the figure the magnitude of pilot command and pitch rate reduces if the pilot pre-filter scheduler uses 60%with 1.0g breakpoint. And the pitch bobble diminishes and the fine tracking performance improves without degrading the gross acquisition performance in combined air-to-air tracking maneuver. Also, the handling quality does not degrade like pitch capture maneuver in pitch axis. The pilot pre-filter logic in T-50 control laws improves the fine tracking performance without degrading the gross acquisition and handling qualities.

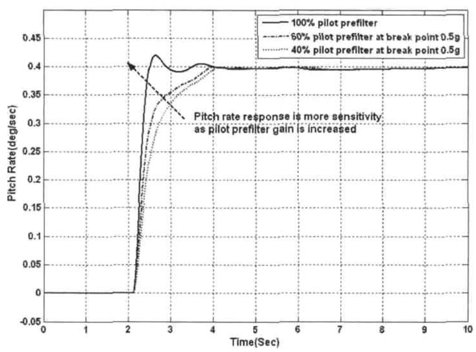

Fig. 21. Non-real time simulation of step response in M0.6, 20kft, UA and F0 configuration

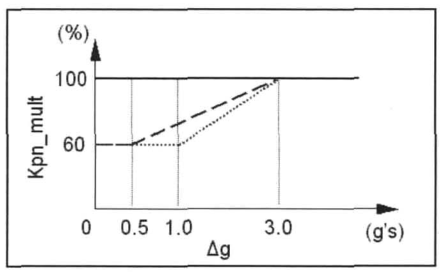

Fig. 22. Scheme of the pilot pre-filter scheduler

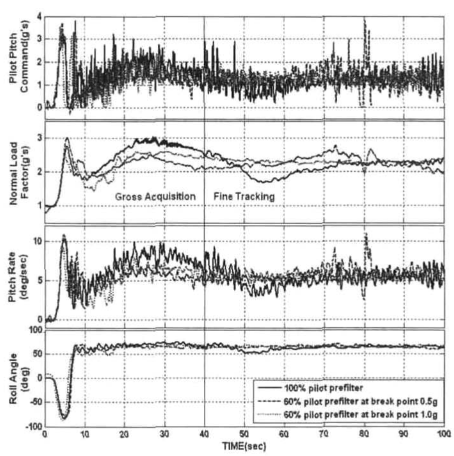

Fig. 23. Flight test result of 3-g air-to-air tracking with pilot pre-filter scheduler in 350knots, 20kft, UA and F0 configuration

Conclusions

High performance military aircraft T-50 employs the RSS concept to achieve performance enhancements. A DFBW FLCS is adapted to guarantee the stability of the statically unstable aircraft using the high degree of digital control technology. Consequently, the flight control laws in the DFBW FLCS augment the performance and the stability of the aircraft in all flight envelopes. These flight control laws are evaluated by flight tests and these results are fed back to improve the handling qualities and stability by updating flight control laws.

During the flight tests, problems degrading the handling qualities and stability of aircraft are found and solved by the design of nonlinear and linear control laws with less cost and time impact on the development. This paper proposed some concepts of flight control laws such as blended roll system in lateral axis, negative AoA limiter and the pilot pre-filter scheduler in pitch axis to solve the flight test issues. Flight test results performed with these control laws to verify the handling qualities and stability of aircraft are described. In summary, the control law of the blended roll system improves the roll-off tendency during the symmetric maneuver in asymmetric loading configurations without degrading maximum roll performance and the negative AoA limiter improves the negative g maneuverability and stability without degrading the handling quality in pitch axis. The control law of the pilot pre-filter scheduler improves the fine tracking performance without degrading gross acquisition in combined air-to-air tracking.

Handling qualities and stability of T-50 advanced supersonic jet trainer are improved by updating the control laws during FSD (Full-Scale Development) flight test. Also, the control laws will be updating to improve handling qualities of adequate for the light attack fighter by accomplishing the post FSD.

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