A Study on Longitudinal Phugoid Mode Affected by Application of Nonlinear Control Laws

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Abstract

Relaxed Static Stability (RSS) concept has been applied to improve aerodynamic performance of modern version supersonic jet fighter aircraft. The T-50 advanced supersonic trainer employs the RSS concept in order to improve the aerodynamic performance. And the flight control system stabilizes the unstable aircraft and provides adequate handling qualities. The T-50 longitudinal control laws employ a proportional-plus-integral type controller based on a dynamic inversion method. The longitudinal dynamic modes consist of short period with high frequency and phugoid mode with low frequency. The design goal of longitudinal control law is optimization of short period damping ratio and frequency using Lower Order Equivalent System (LOES) complying the requirement of MIL-F-8785C. This paper addresses phugoid mode characteristics such as damping ratio and natural frequency that is affected by the nonlinear control laws such as angle of attack limiter, auto pitch attitude command system and autopilot of pitch attitude hold.

Key Word : Relaxed static stability, Digital fly-by-wire flight control system, Phugoid mode, Angle-of-attack limiter, Auto pitch attitude control law, Pitch attitude autopilot mode

Introduction

Recently, the high performance military aircrafts employ the relaxed static stability (RSS) concept to achieve performance enhancements. A digital fly-by-wire (DFBW) flight control system (FLCS) using modern digital control technology is adapted to stabilize an unstable aircraft and attain the 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 in T-50 supersonic advanced trainer. [1-4]

Figure 1 shows the feature of T-50 under flight tests. The T-50 employs the RSS concept to improve the aerodynamic performance and the DFBW FLCS to augment the stability and handling qualities. 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 than that of conventional aircraft was good enough for required lift for maneuvers with less drag. 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 implemented. Excellent flying qualities can be attributed to the DFBW FLCS feature of all time command and stability augmentation system in all three axes.

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Fig. 1. T-50 advanced supersonic jet trainer

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 flaperons 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 types of control surfaces minimizes the variation in roll power for flight conditions. A conventional rudder provides yaw control.

The longitudinal dynamic motion consists of two oscillatory terms; one is a highly damped with high frequency oscillation, the other is a very slowly damped with low frequency oscillation. The first is called the short period mode and the second is called the phugoid mode of motion. This paper addresses the result of linear and nonlinear analysis of phugoid mode characteristics using T-50 database. The linear analysis is conducted to analyze damping ratio and frequency with/without linear model of Angle of Attack (AoA) limiter by eigenvalues using Higher Order System (HOS). And the nonlinear analysis is conducted to analyze what is affected by nonlinear control laws such as AoA limiter, auto pitch attitude trim command system and autopilot mode of pitch attitude hold using an in-house simulation software.

Flight Control Law

Longitudinal flight control law

Figure 2 shows the basic structure of longitudinal control law of T-50. 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 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, command load factor 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 an aircraft.

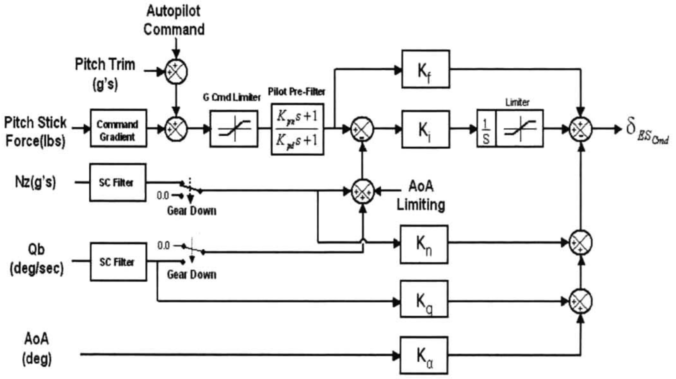

Fig. 2. Longitudinal control law

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. Then the pitch rate command is limited to preventing departure and 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.

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.

AoA Limiter

The T-50 uses the control law of AoA limiter to allow maneuvering up to whole usable AoA from the minimum to maximum. This control law is provided to prevent aircraft from departure at high AoA region. Figure 3 and 4 show the control law of AoA limiter and the schedule of AoA limiter function in UA mode.

In the UA mode, one of three limiters can be selected by using a store configuration switch for the positive AoA limiter. The FLCS limits the normal load factor to 8 g's maximum for AoA less than 15 degrees. Above 15 degrees of 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 AoA limit of 25 degrees is allowed for 1g flight in CAT I store configuration. When CAT II store configuration is selected, the 1g AoA limit becomes 22 degrees, and with CAT III selection, the limit is further reduced to 19 degrees.

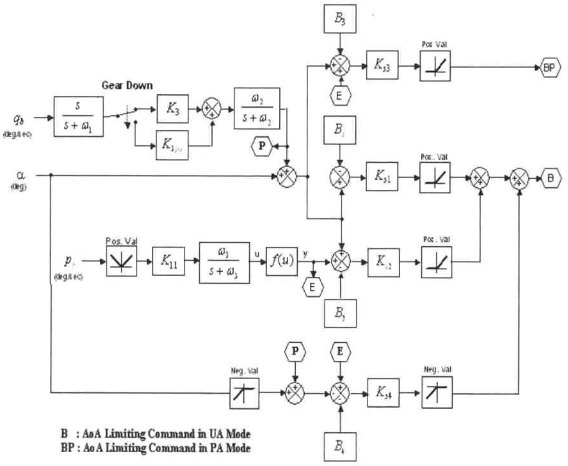

Fig. 3. Control law of AoA Limiter

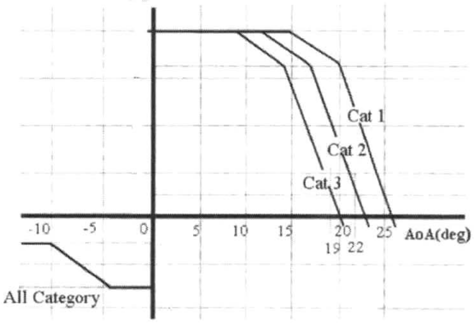

Fig. 4. Schedule of AoA Limiter in UA mode

The negative AoA limiter control law is adapted to improve the characteristic of negative departure resistance in longitudinal control law in UA mode. The negative AoA limier is independent of the store configuration switch positions and scheduled only by AoA. The FLCS limits the normal load factor to -3 g's minimum for AoA less than -4 degrees. Below -4 degrees of AoA, minimum g's increase as a function of AoA with -1 g's occurred at -10 degree AoA.

In the PA mode, the positive AoA limiter is independent of the store configuration switch positions. The positive AoA limiter allows 14 deg/sec of pitch rate capability up to 13 degrees of AoA. Above 13 degrees of AoA, strong positive AoA limiter command is introduced to create positive speed stability.

Auto pitch attitude trim command system

The lift force of wing equivalent to the component of cosine term in gravity is necessary to climb and descent with constant velocity. Equation (1) shows this relation;

$$W\cos\theta = L \tag{1}$$

Approximately, the term of normal acceleration is expressed by $\cos \Theta$ and for smaller than 1-g flight condition of aircraft; we get equation (2)

$$\cos\theta = \frac{L}{W} \simeq N_z \leq 1 \tag{2}$$

The normal acceleration is used as feedback variable in longitudinal control law of UA mode. The control laws generate nose up command to sustaining the 1-g condition, and we get equation (3)

$$\Delta_{cmd} = 1 - \frac{L}{W} = 1 - \cos\theta \tag{3}$$

Therefore, the pilot necessary the nose down command to maintain the attitude during climb or descent, and we get equation (4). Therefore, auto pitch attitude trim command system is employed to compensate for nose down command corresponding to nose up command of control law. This control law is applied to path of pilot pitch command in pitch axis

$$\Delta_{Trim} = -\Delta_{cmd} = \cos\theta - 1 \tag{4}$$

This auto pitch attitude trim command reduces the pilot workload during climb and descent with uniform velocity. Also, this control law improves the phugoid characteristics during level flight.

Autopilot control law in pitch axis

The T-50 control law provides autopilot modes in pitch and roll axes. The altitude and pitch attitude hold modes are employed in pitch axis. And the roll attitude hold, heading select and steering select modes are employed in roll axis. The altitude hold mode maintains a captured aircraft altitude and the pitch attitude hold mode maintains a captured aircraft pitch attitude. The roll attitude hold mode maintains a captured aircraft roll attitude, the heading select steers the aircraft to a heading selected on the Horizontal Situation Indicator (HSI) and steering select mode steers the aircraft to a selected way point.

Figure 5 shows the control law of autopilot mode in pitch axis. The variables of pitch attitude, altitude and vertical velocity are used in autopilot modes in pitch axis. A complementary filters are added on to the altitude input and vertical velocity path. These filters will attenuate the noise by Integrated Multi-Function Probe (IMFP) in the altitude feedback while not adding time delay to the feedback signal. The result will be a smoother autopilot ride. The cos and cos function are used in autopilot of pitch attitude and altitude hold modes. This function helps the autopilot to maintain constant pitch attitude and altitude during bank angle change.

The autopilot command is used in conjunction with the primary mode of operation by sending pitch and roll command inputs into the primary control paths. During pitch and roll autopilot operation, the control stick steering (i.e., a pilot command inputs will temporarily disconnect the autopilot) is available. The autopilot can be engaged only in the UA mode of operation.

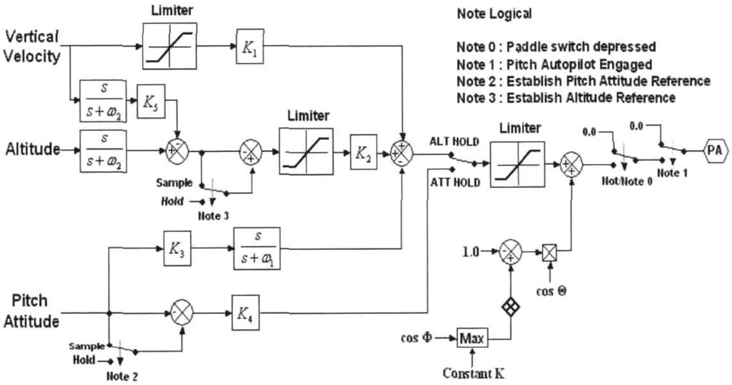

Fig. 5. Autopilot control law in pitch axis

Analysis and Result

Definition of aircraft configurations and test points

Figure 6 shows the loading configurations of T-50 advanced supersonic trainer. T-50 has several loading configurations to support combat/training missions. The F0 symmetric loading configuration is representative form of CAT I, the aircraft carries a launcher at wing-tips (station 1 and 7). The F10 configuration is a representative form of CAT II, the aircraft carries AIM-9's at wing-tips and 150 lbs fuel tank at station 4. The F12 configuration is a representative form of CAT III, the aircraft carries AIM-9's at wing-tips, 150 lbs fuel tank at station 3, 5 and SUU-20 at station 4.

Figure 7 shows the test points of linear and nonlinear analysis. Linear analysis is conducted by eigenvalue method using an in-house software. Also, nonlinear analysis is conducted for pitch motion characteristics affected by nonlinear control laws such as AoA limiter, auto pitch attitude trim command system and autopilot mode using a nonlinear simulation software.

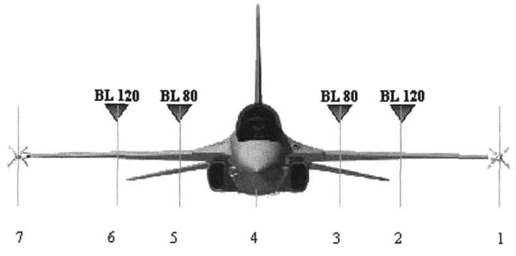

Fig. 6. Aircraft loading configurations

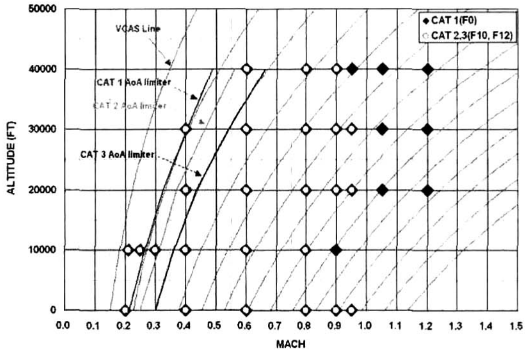

Fig. 7. Test points

Requirements

In this paper, the evaluation reference of phugoid mode is MIL-F-8785C requirements [5,6]. This requirement describes the phugoid motion (i.e., long-period airspeed oscillations), which occur when the airplane seeks a stabilized airspeed following a disturbance. The aircraft shall meet this requirement.

The MIL-F-8785C requirement is as follows;

Level 1	ζ_p at least 0.04
Level 2	ζ_p at least 0
Level 3	Time to double amplitude at least 55 seconds

Note that level 1 is satisfactory, level 2 is acceptable and Level 3 is controllable.

Linear analysis

Algorithm of linear analysis

The longitudinal dynamic oscillatory motions consist of short period mode, generally with frequencies from 0.01 to 10 rad/sec and the phugoid mode with frequencies from 0.01 to 1 rad/sec. [7] The phugoid mode is low frequency motion in which forward speed and altitude are interchanged. The resulting oscillations are in pitch attitude, airspeed, altitude and flight path angle, while the AoA remains constant.

Figure 8 shows analysis process of phugoid mode by eigenvalue method using HOS. This process is divided into three parts depending upon pole locations. First case is that complex poles are not existed within frequency 1 rad/sec. If the poles exist in right plane and maximum real part of pole is larger than 0.001 rad/sec, damping ratio and frequency of phugoid mode are calculated

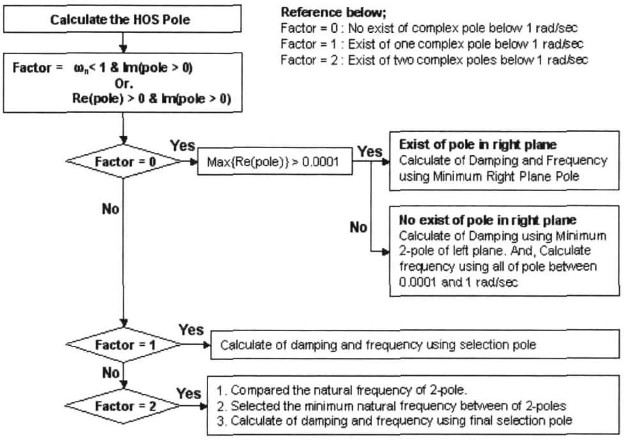

Fig. 8. Algorithm of phugoid mode calculation

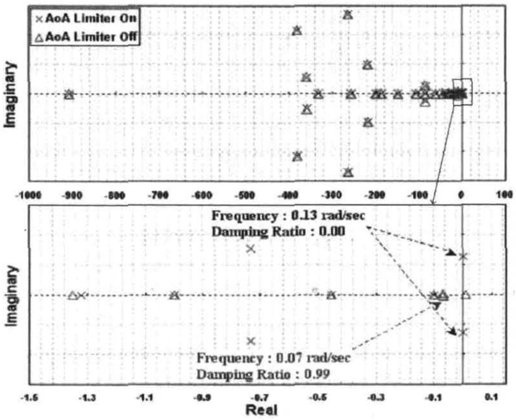

Fig. 9. Location of closed-loop pole
(M0.3@10kft, UA, F10, CAT 2)

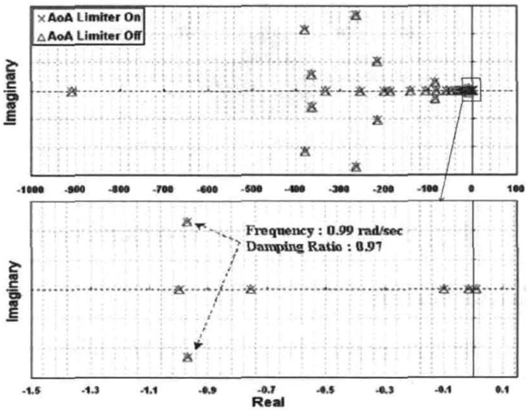

Fig. 10. Location of closed-loop pole
(M0.4@10kft, UA, F10, CAT 2)

by minimum pole in right plane. If the poles doesn't exist in right plane, damping ratio is calculated by smallest two poles in left plane and frequency is calculated by poles within frequency 1 rad/sec. Second case is that one complex pole is existed within frequency 1 rad/sec. In this case, damping ratio and frequency are calculated by complex pole. Third case is that two complex poles are existed within frequency 1 rad/sec. In this case, damping ratio and frequency are calculated by pole with smallest natural frequency compare between two poles.

Figure 9 and 10 show the example of eigenvalue method for analysis of phugoid mode in F10 configuration. Figure 9 shows the result of linear analysis with/without linear model of AoA limiter in M0.3, 10kft, UA and F10 configuration. If linear model of AoA limiter is applied to linear system, two pair of complex poles exist within frequency 1 rad/sec. And, frequency and damping ratio of phugoid mode are calculated by pole with smallest natural frequency compared between two poles. Figure 9 shows frequency is 0.13 rad/sec and damping ratio is almost zero.

Consequently, handling quality of phugoid mode is level 2 with AoA limiter in this point. The AoA is 12.3 degrees in this test point and AoA limiter function of CAT II is operated in this AoA region. If linear model of AoA limiter is not applied to linear system, phugoid mode characteristic comes to be improved with level 1 handling quality, frequency of 0.07 rad/sec and damping ratio of 0.99. Figure 10 shows the result of linear analysis with/without linear model of the AoA limiter in M0.4, 10kft, UA and F10 configuration. The AoA is 10.4 degrees in this test point and AoA limiter of CAT II does not affect to this test point. One pair of complex poles exist within frequency 1 rad/sec but, phugoid mode not exists in this test point with frequency 0.99 rad/sec and the damping ratio 0.97.

Result of linear analysis

Frequency and damping ratio of phugoid mode are calculated by eigenvalue method in HOS. Linear analysis was performed with 2 options with/without the linear model of AoA limiter to analysis of phugoid mode effect by AoA limiter function.

Figure 11 to 16 show the result of phugoid mode with/without linear model of AoA limiter in each loading configurations. Blue dotted lines represent Mil-F-8785C's requirements in the figures. The result of the linear analysis, phugoid mode seems to appear at some of low speed flight conditions such as operating region of AoA limiter as shown in Table 1. The phugoid mode appears at M0.2, @S.L(Sea Level) and M0.21, M0.24@10kft in F0 loading configuration. And, handling quality of phugoid mode complies level 1 requirement in these test points. If AoA limiter is not applied to HOS, phugoid mode comes to be improved as shown in Figure 12. The phugoid mode appear at M0.2@S.L, M0.21, M0.25 and M0.3@10kft in F10 configuration. And, handling quality of phugoid mode complies the level 1 requirement except M0.3@10kft. The phugoid mode appears at M0.2@SL, M0.22, M0.25, M0.3@10kft, M0.4@20kft, M0.4@30kft and M0.6@40kft in F12 configuration. And, handling quality of phugoid mode also complies the level 1 requirement except M0.6@40kft.

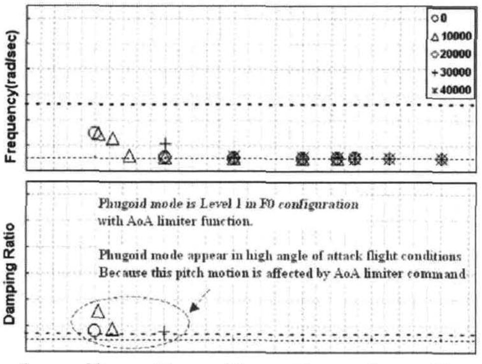

Fig. 11. Result of phugoid mode analysis of F0 configuration with AoA Limiter

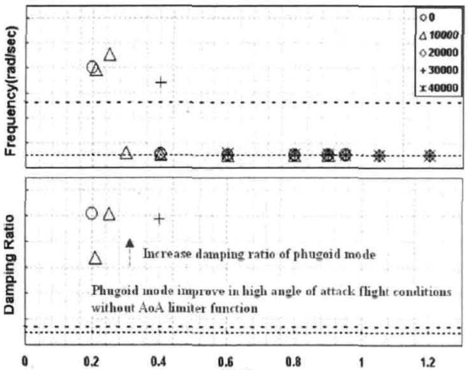

Fig. 12. Result of phugoid mode analysis of F0 configuration without AoA Limiter

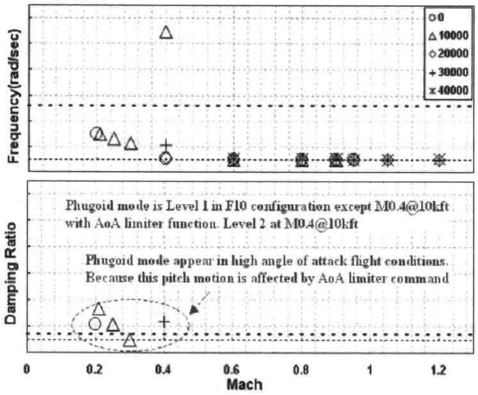

Fig. 13. Result of phugoid mode analysis of F10 configuration with AoA Limiter

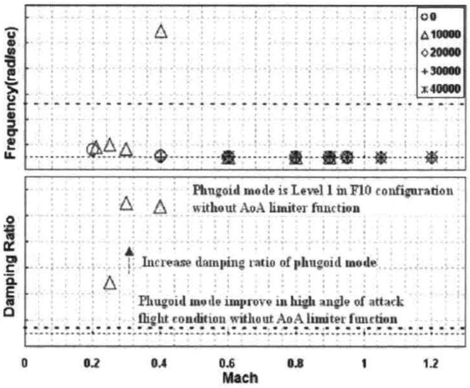

Fig. 14. Result of phugoid mode analysis of F10 configuration without AoA Limiter

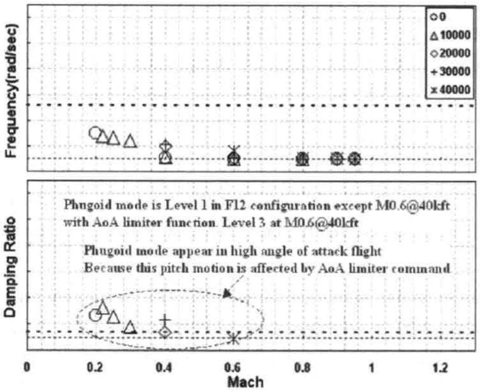

Fig. 15. Result of phugoid mode analysis of F12 configuration with AoA Limiter

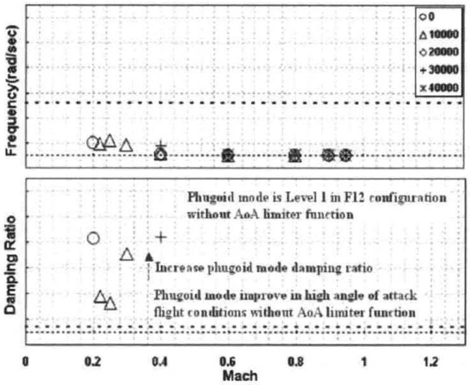

Fig. 16. Result of phugoid mode analysis of F12 configuration without AoA Limiter

Table 1. Result of linear analysis

Aircraft Configuration	Alt (kft)	Mach	Frequency (rad/sec)	Damping Ratio	HQ Level
F0	0	0.2	0.19	0.06	1
	10	0.21	0.19	0.22	1
		0.25	0.16	0.08	1
F10	0	0.2	0.20	0.12	1
	10	0.21	0.20	0.23	1
		0.25	0.16	0.11	1
		0.3	**0.13**	**0.00**	**2**
F12	SL	0.2	0.20	0.16	1
	10	0.22	0.17	0.22	1
		0.25	0.16	0.15	1
		0.3	0.14	0.08	1
	20	0.4	0.10	0.04	1
	30	0.4	0.11	0.13	1
	40	**0.6**	**0.07**	**-0.01**	**2**

The results of the linear analysis reveal that the phugoid mode appears at low speed and high AoA flight condition with linear model of AoA limiter function but, phugoid motion is improved if AoA limiter function is not applied to HOS. The AoA limiter function is operating in some of these test points. And, the aircraft is not maintain trim position without pilot pitch or trim command because AoA limiter function is operating. Therefore, these test points are not considered analysis points because the AoA limiter command is affecting phugoid mode. Also, it is expected that the pilot will not operate the aircraft at these low speeds for an extended length of time without pilot command. And, the pilot cannot notice the lightly damped phugoid mode since the period of oscillation is long enough around 50 seconds.

Non-linear analysis

The AoA limiter function has been designed to guarantee the aircraft safety by preventing the aircraft departure at high AoA flight conditions. But it has been found that this control law degrades the handling quality of phugoid mode at high AoA flight conditions. The auto pitch attitude trim command system is adapted to reduce the pilot workload during descent or climb with uniform velocity. Also autopilot system is adapted to pitch and roll control law in normal operational mode. In this section, nonlinear analysis is performed to analyze phugoid mode effect with/without nonlinear control laws such as AoA limiter, auto pitch attitude trim command system and autopilot mode. Non-real time simulation is performed with four conditions using non-real time simulation software. Simulation process is that the aircraft is trimmed at a specified flight condition, and the pilot pitch command is applied during short time(i.e., impulse type). Finally, motion of phugoid mode is monitored for an extended length of time without pilot command.

1) With AoA limiter function and auto pitch attitude trim command system.
2) Without AoA limiter function and with auto pitch attitude trim command system.
3) With AoA limiter function and without auto pitch attitude trim command system.
4) With auto pitch attitude trim command system, AoA limiter function and autopilot modes of pitch attitude hold.

Figure 17 and 18 show the result of non-real time simulation for each case at M0.3, 10kft, UA, F10 and M0.6, 40kft, UA, F12 loading configurations. In the first case, phugoid mode appears with frequency of 0.129 rad/sec and magnitude of pitch attitude of 0.23 degree. The magnitude of pitch attitude is slightly divergent from 0.23 to 0.24 deg after 200 sec in M0.3, 10kft, UA and F10. And, phugoid mode appears with frequency of 0.069 rad/sec and magnitude of pitch attitude of 0.19

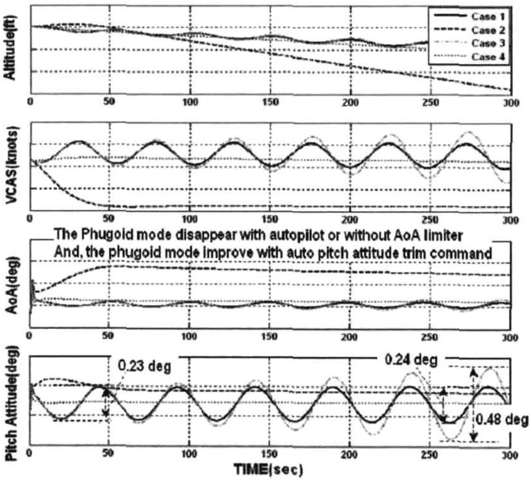

Fig. 17. Result of non-real time simulation of F10 configuration

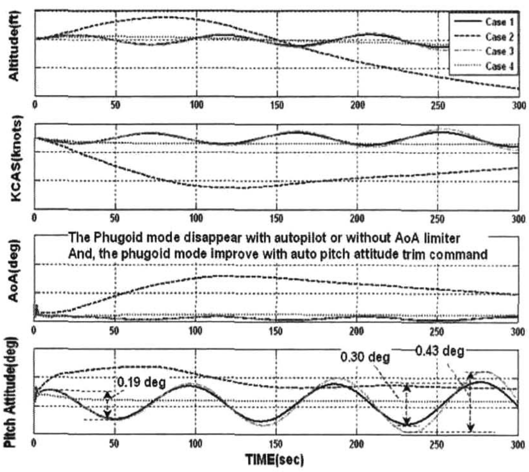

Fig. 18. Result of non-real time simulation of F12 configuration

degree. The magnitude of pitch attitude is slightly divergent from 0.19 to 0.30 deg after 200 sec in M0.6, 40kft, UA and F12. In the second case, phugoid mode disappears with constant pitch attitude and AoA. Therefore, phugoid mode is affected by AoA limiter function similar to result of linear analysis. In the third case, phugoid mode appears and magnitude of pitch attitude is slightly divergent from 0.23 to0.48 deg in M0.3, 10kft, UA, F10 and from 0.19 to 0.43 deg in M0.6, 40kft, UA, F12 after 200 sec. From the results of case 2 and 3, auto pitch attitude trim command system improves phugoid mode characteristics. In the fourth case, phugoid mode disappears when autopilot mode of pitch attitude hold is engaged.

The results of the nonlinear analysis reveal that AoA limiter function degrades the phugoid mode characteristics but, characteristics of phugoid mode is improved by auto pitch attitude trim command system and autopilot mode of pitch attitude hold mode. And, the pilot would not notice this phugoid mode because magnitude of pitch attitude is too small and frequency is too slow. The non-real time simulation result shows that phugoid mode disappears if AoA limiter is not used. Obviously, phugoid mode is impacted by AoA limiter command. Although AoA limiter degrades phugoid mode, this control law is functioning in pitch axis because this control law is very useful to improve aircraft safety by preventing departure in high AoA conditions.

Flight test result

The flight tests are performed to analysis of flight characteristics in high AoA flight conditions with operating AoA limiter function. The initial flight condition is 180 knots, 10kft, UA, F10 and 240 knots, 32kft, UA, F12 loading configurations. And, the aircraft reduce airspeed to 150 and 160 knots with 1-g level flight.

Figure 19 and 20 show flight test results of 1-g level deceleration in each flight conditions. The AoA limiter operates above 12 degree AoA in CAT II and 9 degree AoA in CAT III loading configurations. And, the pilot uses the pitch command to maintain 1-g level flight above 12 degree AoA in CAT II and 9 degree AoA in CAT III. The magnitude of pitch rate is more increased in AoA limiter operating regions compared to normal operational flight regions. But, this tendency occurred when the pilot continuously compensates pitch control to maintain 1-g level flight. Also, the pilot comments that response of pitch motion is acceptable because magnitude of pitch rate is less than 1.2 deg/sec.

Finally, AoA limiter function affects to pitch motion and these motions are generated by the pilot pitch command to maintain 1-g level flight. But, test pilots comment that these motions do not affect to the handling quality of phugoid mode because magnitude of pitch rate is too small.

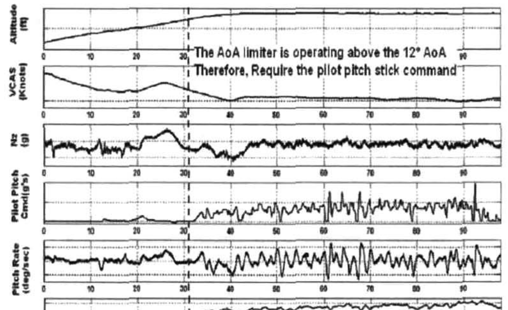

Fig. 19. Result of flight test of level deceleration of F10 configuration

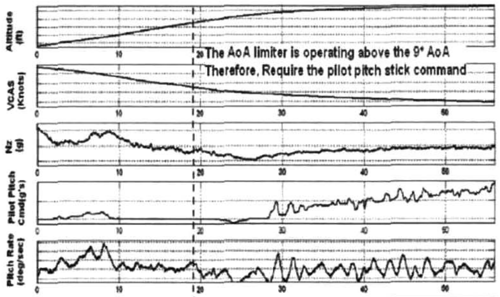

Fig. 20. Result of flight test of level deceleration of F10 configuration

Also, the pilot does not feel these motions because the pilot compensates pitch attitude continuously corresponding to AoA limiter command.

Conclusions

High performance military aircraft employs the RSS concept to achieve performance enhancements. A DFBW FLCS is adapted to guarantee stability of the statically unstable aircraft using the high degree of digital control technology. Consequently, flight control laws in the DFBW FLCS augment the performance and the stability of the aircraft in all flight envelopes. Generally, the goal of longitudinal control laws optimize of the short period mode characteristics because the modern supersonic jet fighters are required to have high aerodynamic performance. The control laws are designed to improve aircraft safety and reduce the pilot workload in longitudinal axis. The AoA limiter function is designed to prevent aircraft departure in high AoA flight conditions by the symmetric pilot command. The auto pitch attitude trim command system and autopilot mode are designed to reduce the pilot workload during 1-g level flight conditions.

In this paper, the analysis of phugoid mode was performed using linear analysis with HOS, nonlinear analysis and flight tests in each loading configurations. The result of linear analysis, T-50 has phugoid mode in low speed flight conditions and level 1 requirement are not satisfied at some of these points. This result is effected by AoA limiter function but, requirement of phugoid mode satisfy level 1 if AoA limiter is removed in pitch axis control law. The results of nonlinear analysis show auto pitch attitude trim command system improves phugoid mode and autopilot mode of pitch attitude hold removes phugoid mode. Finally, phugoid mode of T-50 appears at low speed and high AoA flight conditions and the characteristics do not comply level 1 requirement at some of these points because AoA limiter affects phugoid mode. But, phugoid mode is improved or disappeared if nonlinear control laws such as pitch attitude trim command system and autopilot mode are applied to pitch axis control law. As a result, phugoid mode of T-50 complies the level 1 requirement in all flight envelope and configurations except high AoA regions with operating AoA limiter.

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