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An Investigation of the Effects of Flaperon Actuator Failure on Flight Maneuvers of a Supersonic Aircraft

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Abstract

The improvements in high performance and agility of modern fighter aircraft have led to improvements in survivability as well. Related to these performance increases are rapid response and adequate deflection of the control surfaces. Most control surface failures result from the failure of the actuator. Therefore, the failure and behavior of the actuators are essential to both combat aircraft survivability and maneuverability. In this study, we investigate the effects of flaperon actuator failure on flight maneuvers of a supersonic aircraft. The flight maneuvers were analyzed using six degrees of freedom (6DOF) simulations. This research will contribute to improvements in the reconfiguration of control surfaces and control allocation in flight control algorithms. This paper compares the results of these 6DOF simulations with the horizontal tail actuator failures analyzed previously.

Key Words : Flaperon, Actuator failure, Flight maneuver, Supersonic aircraft , Combat aircraft

1. Introduction

In the past, combat aircraft were designed using the concept of static stability for safety. However, as the technologies of aircraft developed and the appearance of digital fly-by-wire helped modern combat aircraft to relax this requirement. As a result, the digital fly-by-wire system allows the flight control computer to stabilize relaxed static stability aircraft (unstable characteristics) and the pilot to perform missions without excessive workload via improved maneuverability and performance [1],[2].

Flight control surfaces are either primary or secondary. Primary control surfaces are continuous activated. Secondary control surfaces are activated only for specific flight phases. Primary control surfaces are generally built into the aircraft wings and empennage. Typical primary controls include elevators on the horizontal tail, rudder on the vertical tail, and ailerons on the wings [3]. The leading and trailing edge flaps are used as secondary control surfaces and scheduled with angle of attack and Mach number to provide directional stability augmentation and maximum lift to drag ratio during high angle of attack. The ailerons (or flaperons), elevators (or horizontal tails), and rudders, the primary control surfaces, are controlled by pitch, roll, or yaw commands and not scheduled. In this paper, actuator failure analysis on a flaperon, a primary controls surface, is performed.

The aircraft's actuated primary control surfaces consist of ailerons, rudders, and horizontal tails. The T-50 also features flaperons which combine aileron and flap functionality. T-50 roll command input produces flaperons and horizontal tails deflections

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during normal operation. Previous research investigated the failure of the horizontal tail because its primary function is longitudinal stability and aircraft's maneuverability. This paper investigates the flaperons because its primary function is roll maneuverability.

According to the International Air Transport Association (IATA) report, the loss of control during flight is the top cause of fatal accidents from 2010 to 2014. An aircraft experiencing loss of control is in a critical situation. The simulation of aircraft control surface actuator failures is very important because actuation failure can cause aircraft loss of control [4].

There are a few papers that show the effects of flaperon actuator failure during subsonic flight. However, there is little research on the effects of maneuvers in the subsonic, transonic, and supersonic regimes with a modern military aircraft. This research presents the simulation results for the design of a control system with an optimized actuator and supports verifying actuator hinge moments for the new military aircraft.

This research can support the design of a control allocation algorithm that uses arbitrary redundant actuation to improve maneuvering. In addition, this study can also help design a reconfiguration algorithm that allows the control system to compensate for the failed actuation system using the remaining working actuation systems.

During failure states, failed surfaces hinge moments and aircraft maneuverability limits are reduced in the aircraft's flight envelope. Additionally, the handling qualities are calculated for the forward and aft C.G. locations of the supersonic aircraft and analyzed from the perspective of actuator failure. The effects of flight maneuvers on loading a variety of weapons with actuator failure are analyzed.

2. Aircraft Equations of Motion and Aircraft Model

The following equations are the classical aircraft equations of motion [5].

$$m(\dot{U} - VP + WQ) = -mg\sin\Theta + F_{A_x} + F_{T_x}$$

$$m(\dot{U} - VR + WQ) = -mg\sin\Theta + F_{A_x} + F_{T_x}$$

$$m(\dot{W} - UQ + VP) = mg\cos\Phi\cos\Theta + F_{A_z} + F_{T_z}$$

$$I_{xx}\dot{P} - I_{xz}\dot{R} - I_{xz}PQ + (I_{zz} - I_{yy})QR = L_A + L_T$$

$$I_{yy}\dot{Q} + (I_{xx} - I_{zz})PR + I_{xz}(P^2 - R^2) = M_A + M_T$$

$$I_{zz}\dot{R} - I_{xz}\dot{P} + (I_{yy} - I_{xx})PQ + I_{xz}QR = N_A + N_T$$

The following variables are used:
m for mass
U, V, W for components of $\vec{V}$ along XYZ
P, Q, R for angular velocity components about XYZ
I_{xx} I_{yy}, I_{zz} for moments of inertia about XYZ
I_{xz} for products of inertia about XYZ
F_A for Aerodynamic force
F_T for Aerodynamic moment
L_A M_A, N_A Aerodynamic moment components
Θ for pitch attitude angle, Φ for bank angle

The T-50 Golden Eagle supersonic trainer was selected to investigate the current methodology used in a six degrees of freedom (6DOF) simulation for this research (Figure 1). The T-50 has a single engine producing 18,000 lbs of thrust. It was manufactured by Korea Aerospace Industries (KAI) for the Republic of Korea Air Force (ROKAF). It has a length of 43.1 ft (13.14 m), a height of 15.8 ft (4.82 m) and a wing span of 30.0 ft (9.45 m). Its maximum takeoff weight is around 27,000 lbs and can reach Mach 1.5. It has a maximum thrust to weight ratio of 1.0 [6].

The store loading has Air-to-Ground and Air-to-Air configurations. Air-to-Ground for subsonic conditions and Air-to-Air for transonic conditions were analyzed. The investigation of loading and unloading conditions in three different flight conditions is very important to pilots and engineers. If store loading degrades aircraft performance, the pilot should jettison stores in an emergency in pursuit of better performance.

Fig. 1 Aircraft Model: T-50 aircraft

3. Simulation Results of Actuator Failure and No Failure

3.1. Subsonic Maneuver without Store Loading at 20,000 ft

Figure 2 show the simulation of a T-50 without a store loading in subsonic flight at 20,000 ft and a control stick input with ±10 lbs to a 360º roll. One of the most important combat maneuvers is commanding a roll rate (pb). Maximum roll rate without actuator failure is 114 deg/sec while the loss of control to the left horizontal failure reduces this to 69 deg/sec. The bank angle (ϕ) requires 7 seconds to complete a 360º roll with left horizontal tail failure compared to 5.4 seconds nominally. The side slip angle (β) showed a difference of less than one degree. As shown in Figure 2, when the actuator of the left flaperon failed, it automatically changed to a damped bypass mode and the hinge moment moved to zero.

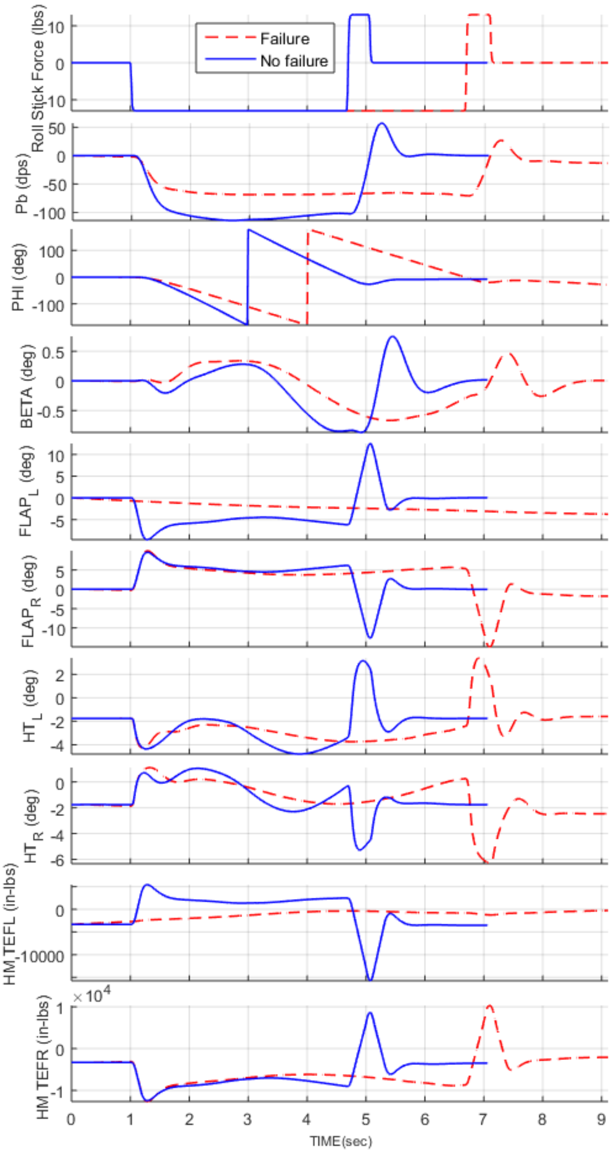

Fig. 2 Simulation results without store loading (20,000ft, Mach 0.547): roll stick force, Pb (roll rate), BETA (bank angle), β (side slip), FLAPL (left Flaperon), FLAPR (right Flaperon), HTL (left horizontal tail), HTR (right horizontal tail), HM TEFL (Hinge Moment of the left flaperon), and HM TEFR (Hinge Moment of the right flaperon) between no failure and failure.

The concept for the damped bypass mode is described as follows. To control primary control surfaces during normal operation, a Main Control Valve is opened by an electrical signal from the Actuator Control System, allowing hydraulic pressure to flow. The hydraulic fluid flows into the actuator cylinder, as the hydraulic pressure pushes the ram, the primary control surfaces are driven. On the T-50 aircraft, when there is a dual failure state in the electrical system or a Main Control Valve failure, the hydraulic system switches to a failure state. A failed control surface will block the main control valve of the hydraulic actuator. The shut off valve to control hydraulic fluid is also closed. In the actuator cylinder, the hydraulic fluid flows slowly and freely through th e orifice between the actuator chambers. This failure mode is called damped bypass mode or surface reco nfiguration mode. The control surface in failure mode will move according to outside aerodynamic forces and will not follow the command from the flight contr ol system any more.

Table 1 Maximum roll rate of flaperon and horizontal tail in subsonic maneuver without store loading

Control Surface	Roll rate (deg/sec)	
	No failure	Failure
Flaperon	**114**	**69**
Horizontal tail [7]	**114**	**70**

As shown in Table 1, a maximum roll rate of 70deg/sec with horizontal tail failure in subsonic conditions without store loading was found in a previous study. The difference of roll rate between flaperon and horizontal tail failure is minimal.

3.2 Subsonic Maneuver with Store Loading at 20,000 ft

Figure 3 shows the simulation of a T-50 with stores in subsonic flight at 20,000 ft and a control stick input of ±10 lbs to a 360º roll. The aircraft roll rate (pb) response with and without the stores were similar. The nominal roll rate including stores is 116.6 deg/sec reduced to 72.18 deg/sec in the event of actuation failure. The bank angle (ϕ) required 7.4 seconds to perform a 360º roll with a left flaperon failure, compared to 6.5 seconds nominally. The side slip angle (β) showed a difference of less than one degree. As shown in Figure 3, when the left flaperon

(FLAPL) actuator failed, it automatically changed to damped bypass mode and the hinge moment moved to zero.

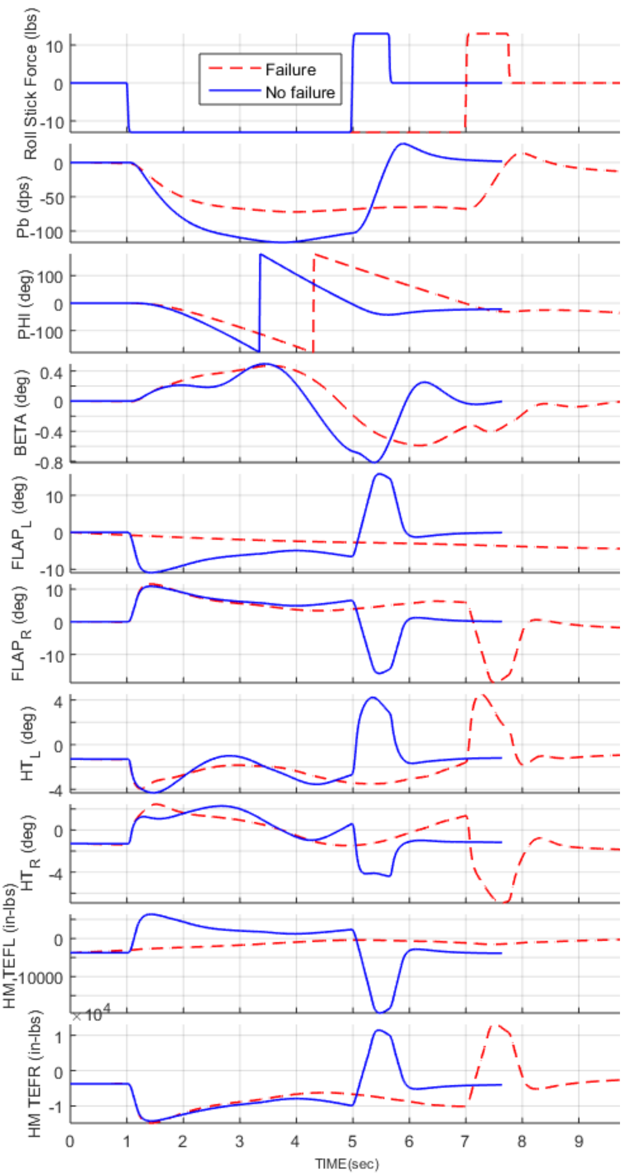

Fig. 3 Simulation results with store loading (20,000ft, Mach 0.547): roll stick force, Pb, BETA, β, FLAPL, FLAPR, HTL, HTR, HM TEFL, and HM TEFR between no failure and failure

Table 2 Maximum roll rate of flaperon and horizontal tail in subsonic maneuver with store loading

Control Surface	Roll rate (deg/sec)	
	No failure	Failure
Flaperon	116.6	72.07
Horizontal tail [7]	116.6	72.18

As shown in Table 2, a maximum roll rate of 72.18 deg/sec with horizontal tail failure in subsonic conditions without store loading was found in a previous study. The difference of roll rate between flaperon and horizontal tail failure is minimal.

3.3 Transonic Maneuver without Store Loading at 20,000 ft

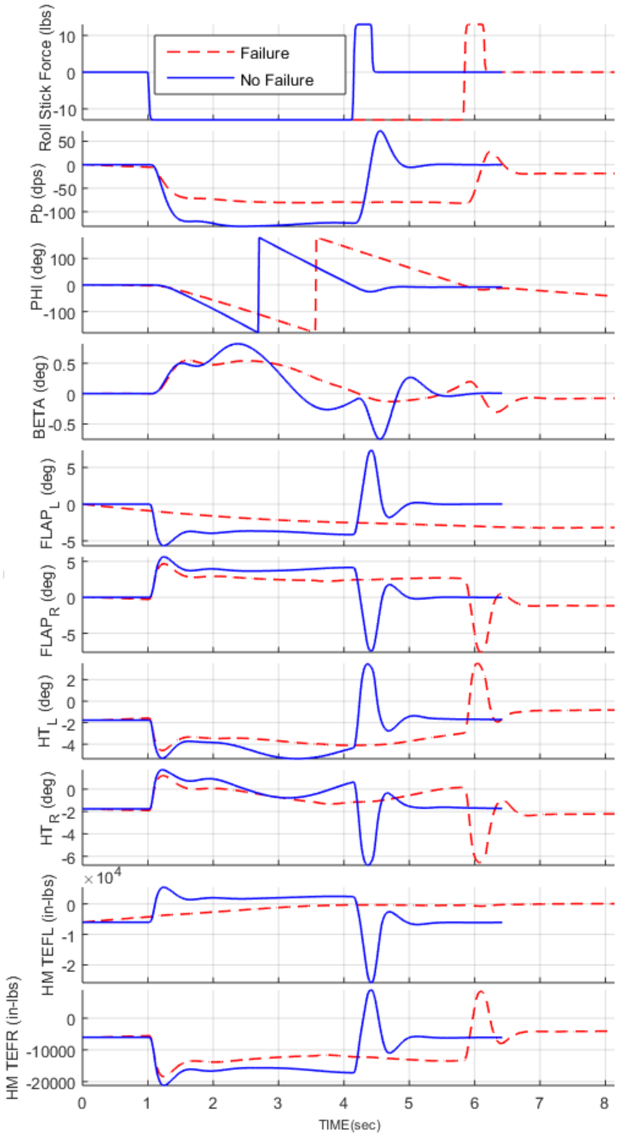

Fig. 4 Simulation results without store loading (20,000 ft, Mach 0.8): roll stick force, Pb, BETA, β, FLAPL, FLAPR, HTL, HTR, HM TEFL, and HM TEFR between no failure and failure

Figure 4 shows the T-50 simulation without stores in transonic flight at 20,000 ft and a control stick input of ±10 lbs to a 360º roll. The transonic roll rate during normal operation increases to 131.2 deg/sec which reduces to 80.76 deg/sec in the case of actuation loss on the left flaperon. The bank angle (ϕ) required 6.4 seconds to perform a 360º roll affected by the left flaperon failure compared to 5 seconds nominally. The side slip angle (β) is a difference of less than one degree. As shown in Figure 4, when the actuator of the left flaperon

(FLAPL) failed, it again automatically changed to a damped bypass mode and the hinge moment of the left flaperon tail again moved to zero.

The effect of actuator failure on the case without store loading increased the maximum hinge-moment from approximately 8,887 in-lbs (nominal operation) to 8,497 in-lbs (failed actuation). The effect of the store loading results in a decrease in the maximum flaperon hinge moment (from approximately 8,497 in-lbs without stores to 7,996 in-lbs with stores) during the worst case of actuator failure.

Table 3 Maximum roll rate of flaperon and horizontal tail in transonic maneuver without store loading

Control Surface	Roll rate (deg/sec)	
	No failure	Failure
Flaperon	**131.2**	**80.76**
Horizontal tail [7]	**131.2**	**68.13**

As shown in Table 3, a maximum roll rate of 68.13 deg/sec with horizontal tail failure in subsonic conditions without store loading was found in a previous study. The difference of roll rate between flaperon and horizontal tail failure is 12.63 deg/sec.

3.4 Transonic Maneuver with Store Loading at 20,000 ft

Fig. 5 show the simulation of T-50 with store loading in transonic flight at 20,000 ft and a control stick input with ±10 lbs to a 360º roll.

The transonic roll rate (pb) responses with and without actuation failure and including a store loading are similar to the roll rates without the store loading. The nominal, transonic roll rate is ~129 deg/sec while the case with actuator failure reduced the roll rate to ~78.93 deg/sec. In the bank angle (ϕ) of the left flaperon (FLAPL) failure, it takes about 7.5 seconds to perform a 360º roll. In the bank angle (ϕ) of no failure (normal), it takes about 5.9 seconds to perform a 360º roll. The side slip angle (β) is a small difference of less than one degree.

As shown in Figure 5, when the actuator of the left flaperon (FLAPL) fails, it automatically changes to a damped bypass mode and the hinge moment of the left flaperon tail moves to zero.

The maximum hinge moment of the left flaperon under failure with a store loading is about twice the hinge moment of the same left flaperon case without store loading.

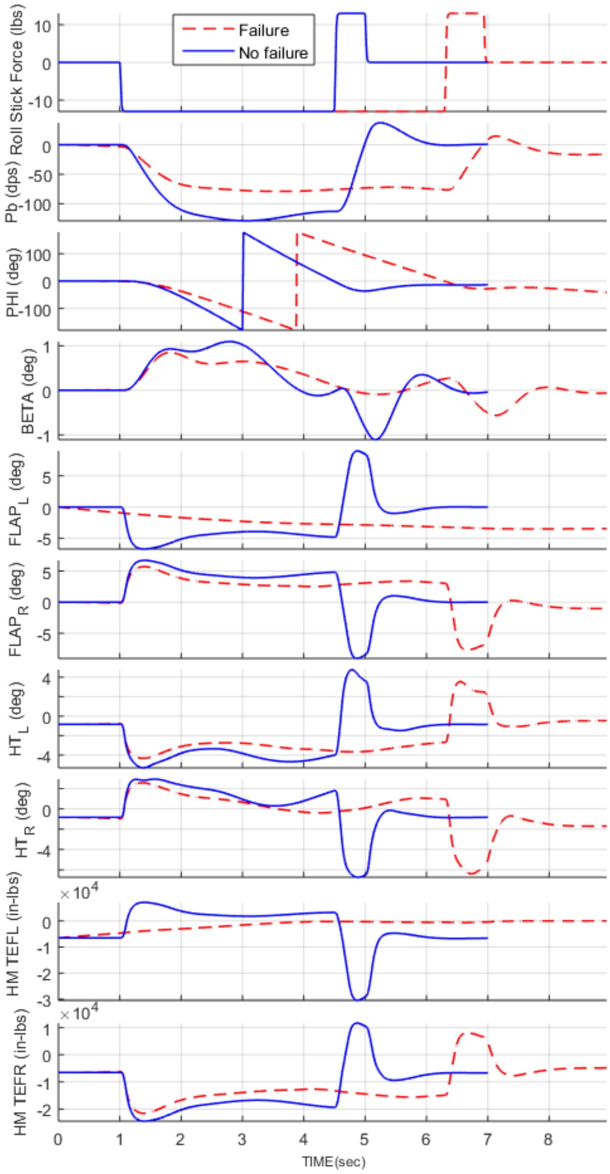

Fig. 5 Simulation results with store loading (20,000 ft, Mach 0.8): roll stick force, Pb, BETA, β, FLAPL, FLAPR, HTL, HTR, HM TEFL, and HM TEFR between no failure and failure

Table 4 Maximum roll rate of flaperon and horizontal tail in transonic maneuver with store loading

Control Surface	Roll rate (deg/sec)	
	No failure	Failure
Flaperon	**129**	**78.93**
Horizontal tail [7]	**129**	**63.2**

As shown in Table 4, a maximum roll rate of 63.2 deg/sec with horizontal tail failure in subsonic conditions without store loading was found in a previous study. The difference of roll rate between flaperon and horizontal tail failure is 15.73 deg/sec.

3.5 Supersonic Maneuver without Store Loading at 20,000 ft

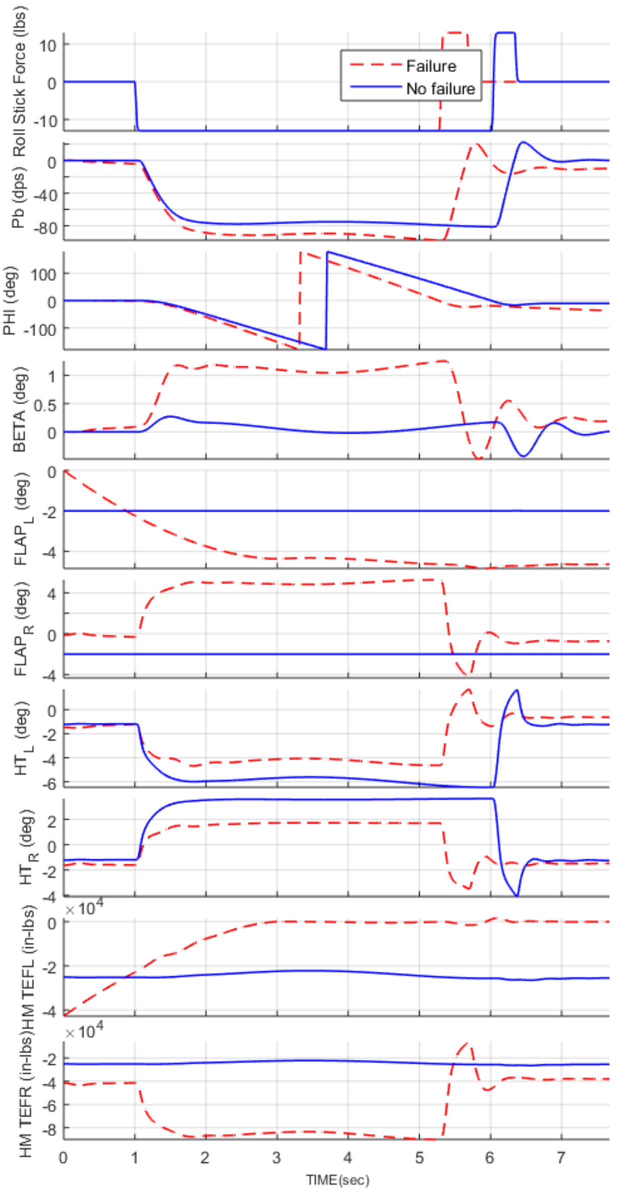

Fig. 6 Simulation results with store loading (20,000 ft, Mach 1.2): roll stick force, Pb, BETA, β, FLAPL, FLAPR, HTL, HTR, HM TEFL, and HM TEFR between no failure and failure

Figure 6 shows the T-50 simulation without stores in supersonic flight (Mach 1.2) at 20,000 ft and a control stick input of ±10 lbs commanding a 360º roll. The supersonic roll rate during normal operation is ~77.77 deg/sec. However, this increases to ~121.2 deg/sec in the case of actuation loss on the left flaperon.

The bank angle (ϕ) required just 5.1 seconds to perform a 360º roll with the left flaperon failure, however, without the failure, the same maneuver required 6.7 seconds. In this case (the supersonic flight regime), roll rate was greater with an actuator failure than in normal operation because the side slip angle (β) with a failure was larger (around 1 deg) compared to normal operation (less than 0.25 deg). Therefore, the time to perform a 360º roll with an actuator failure is faster than under normal operation. In the supersonic regime, small perturbations of side slip angle (β) increase the roll rate thereby reducing the time necessary to perform a 360º roll maneuver. The right flaperon during no failure is fixed during the simulation in Fig.6. This is an expected response of the flaperon at this flight condition.

As in the earlier subsonic and transonic cases, when the left flaperon (FLAPL) actuator failed, it automatically changed to a damped bypass mode and the left flaperon hinge moment moved to zero. The effect of actuator failure on the case with a store loading increased the maximum hinge-moment from approximately 20,000 in-lbs (nominal operation) to 90,000 in-lbs (failed actuation), well within actuator hinge moment capability.

Table 5 Maximum roll rate of flaperon and horizontal tail in supersonic maneuver without store loading

Control Surface	Roll rate (deg/sec)	
	No failure	Failure
Flaperon	77.77	97.64
Horizontal tail [7]	77.77	121.2

As shown in Table 5, a maximum roll rate of 121.2 deg/sec with horizontal tail failure in subsonic conditions without store loading was found in a previous study. The difference of roll rate between flaperon and horizontal tail failure is 23.56 deg/sec.

3.6 Handling Qualities with most forward CG, nominal CG, and most aft CG

Lastly, Figure 7 shows the T-50 simulation without stores in transonic flight at 20,000 ft and a control stick input of ±10 lbs commanding a 360º roll. Regarding normal acceleration (Nn), handling qualities degrade at the most-aft CG condition. As shown in pitch rate (Qb) of Figure 7, the actuator failure at the most-aft CG condition also degrades aircraft performance. This aircraft performance degradation increases the pilot's workload.

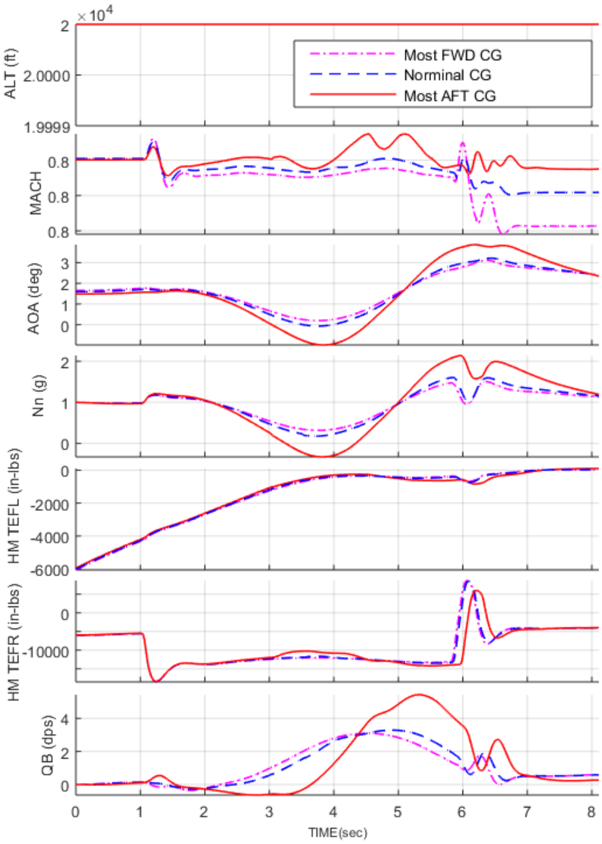

Fig. 7 Simulation results without store loading: Alt, Mach number, α, Nz, HTR, HM HTL, HM HTR, and QB (pitch rate) at Most Forward CG, Nominal CG and Most Aft CG

Table 6 Ranges of Nn, Qb, and AOA of separate flaperon and horizontal tail failures in transonic maneuvers without store loading

Control Surface		Nn (g)	Qb (deg/s)	AOA (deg)
		Failure		
Flaperon	Min	-0.440	-0.602	-0.979
	Max	+2.143	+5.425	+3.866
Horizontal tail [7]	Min	-1.294	-2.766	-2.614
	Max	+2.431	+8.544	+4.259

As shown in Table 6, the maximum Nn, Qb, and AOA of horizontal tail of the failure condition in subsonic maneuver without store loading was analyzed in the previous study. Nn, Qb, and AOA in the condition of the horizontal tail failure are higher than the flaperon failure.

4. Conclusions

This paper has presented the effects of flight maneuvers on a T-50 aircraft with flaperon actuator failure. Under subsonic condition, the effects of flight maneuvers with flaperon actuator failure on the T-50 aircraft are similar to the effects of flight maneuvers with horizontal tail actuator failure. Under subsonic and transonic conditions, the effects of flight maneuvers with flaperon actuator failure on the T-50 aircraft were analyzed. In this study, the effects of representative store loadings with flaperon actuator failure were simulated. Roll rates of the aircraft with or without store loading were similar. Even though the hinge moments with flaperon actuator failure is bigger than hinge moments with normal flaperon actuator, the hinge moments with flaperon actuator failure does not exceed the maximum hinge moment of the flaperon actuator. Time to bank, a function of roll rate is one of top requirements in aircraft performance. From Sec. 3.1 to Sec. 3.4, time to bank with store loading is longer than time to bank without store loading. Longer time to bank is a major disadvantage for a pilot. Therefore, with flaperon actuator failure, a pilot needs to jettison external stores based on roll performance degradation. Under supersonic condition, the roll rates of the aircraft with flaperon actuator failure are bigger than a normal flaperon actuator. Unexpected or uncomfortable roll rates with flaperon actuator failure may cause a pilot to control aircraft with higher workload than normal condition. Therefore, the pilot should return to transonic region to relieve workload.

Under transonic condition, the roll rate of the failure of the left flaperon actuator is faster than the failure of the left horizontal tail actuator. Under supersonic condition, the roll rate of the failure of the left flaperon actuator is slower than the failure of the left horizontal tail actuator. The simulation results showed that at the most-aft CG condition, the aircraft's handling qualities of both left flaperon and horizontal tail actuator failure were significantly degraded more than the most-forward and nominal CG conditions. During a failure in the supersonic regime, the roll rate responses of both left flaperon and horizontal tail actuator failure were larger than in normal operation due to small perturbations of side slip angle (β) increasing the roll rate. In regard to the aircraft handling qualities, the flaperon actuation failure understandably degrades the aircraft's performance and capability. In the aircraft handling qualities, the case of the horizontal tail actuator failure was worse than the flaperon actuator failure.

Future Work

In this study, the effects of representative store loadings with flaperon actuator failure were simulated. Next, handling qualities with most forward CG, nominal CG, and most aft CG will be investigated in subsonic and supersonic conditions. Then all store configurations will be accomplished simulating a flaperon actuator failure. In addition, the effects of flight maneuvers with rudder actuator failure on the T-50 aircraft will be analyzed.

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