Air Force Institute of Technology

AFIT Scholar

Theses and Dissertations

Student Graduate Works

3-1996

An Investigation into the Effects of Lateral Aerodynamic Asymmetries, Lateral Weight Asymmetries, and Differential Stabilator Bias on the F-15 Directional Flight Characteristics at High Angles of Attack

David R. Evans

Follow this and additional works at: https://scholar.afit.edu/etd

Part of the Aerodynamics and Fluid Mechanics Commons

Recommended Citation

Evans, David R., "An Investigation into the Effects of Lateral Aerodynamic Asymmetries, Lateral Weight Asymmetries, and Differential Stabilator Bias on the F-15 Directional Flight Characteristics at High Angles of Attack" (1996). *Theses and Dissertations*. 6115.
https://scholar.afit.edu/etd/6115

This Thesis is brought to you for free and open access by the Student Graduate Works at AFIT Scholar. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of AFIT Scholar. For more information, please contact AFIT.ENWL.Repository@us.af.mil.

AFIT/GAE/ENY/96M-1

AN INVESTIGATION INTO THE EFFECTS OF LATERAL AERODYNAMIC ASYMMETRIES, LATERAL WEIGHT ASYMMETRIES, AND DIFFERENTIAL STABILATOR BIAS ON THE F-15 DIRECTIONAL FLIGHT CHARACTERISTICS AT HIGH ANGLES OF ATTACK

THESIS

David R. Evans, Captain, USAF

AFIT/GAE/ENY/96M-1

Approved for public release; distribution unlimited

19961220 077

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

AFIT/GAE/ENY/96M-1

AN INVESTIGATION INTO THE EFFECTS OF LATERAL AERODYNAMIC ASYMMETRIES, LATERAL WEIGHT ASYMMETRIES, AND DIFFERENTIAL STABILATOR BIAS ON THE F-15 DIRECTIONAL FLIGHT CHARACTERISTICS AT HIGH ANGLES OF ATTACK

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air Education and Training Command
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Aeronautical Engineering

David R. Evans, B.S.

Captain, USAF

March 1996

Approved for public release; distribution unlimited

Preface

This research investigates the feasibility of quantifying the effects of lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias on the F-15 directional flight characteristics at high angles-of-attack (AOA). This research first provides the engineering background and methodology to quantify these effects using net yaw acceleration as a metric. Next, this research conducts experimental flight test to quantify the asymmetries and verify engineering background and methodology. The results of this research are then used to identify an aerodynamically symmetric F-15 configuration at high AOA. An aerodynamically symmetric F-15 configuration has the potential of reducing F-15 aircraft mishaps due to out of control or departure from controlled flight. Also, an aerodynamically symmetric configuration has the potential of increasing F-15 maneuverability at high AOA.

In performing the analysis and writing of this thesis, I have had a great deal of help from others. First and foremost, I would like to thank my wife Windy and daughter Casey for putting up with a dysfunctional husband and father for the past 33 months. It was their support and sacrifice that made this all possible. I wish to thank my advisor Dr. Brian Jones for supporting this unusual research request. I wish to thank my committee Dr. David Walker and Dr. Brad Liebst for their support. I would like to thank Mr. Stephen Herlt and Mr. Larry Walker for their expert guidance throughout this thesis. I would also like to thank Mr. Jeff Priem and the F-15 Systems Program Office for their sponsorship of this research. I would like to thank Mr. David Potts for his outstanding support in simulation. Finally, thanks go out to all the individuals of the HAVE LIST flight test team including the F-15 Eagle Logistics Flight who made the flight test all possible.

David R. Evans

Table of Contents

Page

List of Figures

Figure | Page

Figure | Page

Abstract:

The F-15 is a stable aircraft throughout most of its flight envelope. However, it still exhibits an uncommanded yawing and rolling tendency at true angles-of-attack (AOA) greater than 30 degrees. These uncommanded yawing and rolling tendencies are normally to the right and can lead to departure from controlled flight. Identified influencing factors of this uncommanded yawing and rolling motion are lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias. Previous research into the effects of these influencing factors has been mostly qualitative. This thesis is an attempt to quantify the effects of these influencing factors and then identify a symmetric F-15 configuration. The quantifying metric presented is net yaw acceleration. This thesis used both computer simulation and experimental flight test to investigate the ability to quantify these influencing factors. Thesis results indicate that each influencing factor can be quantified using net yaw acceleration. A discussion of the effects of each influencing factor on the F-15B high AOA net yaw acceleration is presented. Lateral weight asymmetries are shown to cause yaw acceleration away from the weight asymmetry at high AOA. Small changes in differential stabilator bias are shown to have little influence on net yaw acceleration at high AOA. Considering these discussions, the baseline F-15B is identified as the symmetric F-15B configuration. Finally, this thesis identifies two possible causes for F-15 departures. The two causes identified are transient net yaw acceleration and combined sense of yaw and roll rate. The understandings of these possible causes on F-15 departures are just beginning to be evaluated.

AN INVESTIGATION INTO THE EFFECTS OF LATERAL AERODYNAMIC ASYMMETRIES, LATERAL WEIGHT ASYMMETRIES, AND DIFFERENTIAL STABILATOR BIAS ON THE F-15 DIRECTIONAL FLIGHT CHARACTERISTICS AT HIGH ANGLES OF ATTACK

1. Introduction

With today's uncertain economy and shrinking defense budgets, the Air Force is having to find new ways of accomplishing their continuing mission with existing systems and hardware. For example, the procurement of the F-22 air superiority fighter was delayed due to program budget reductions. These delays in procurement of the F-22 are placing greater emphasis on extending the service life of existing F-15 air superiority aircraft. Efforts to extend the service life of the F-15 aircraft are taking many forms. This thesis will investigate one form of extending the F-15 aircraft service life by quantifying the effects of various F-15 lateral asymmetries. This quantification will allow the F-15 community to make more informed decisions about how to configure and rig the F-15 fleet. This informed decision on how to configure and rig the F-15 will result in a more aerodynamically symmetric F-15 configuration. An aerodynamically symmetric configuration will potentially extend the F-15 aircraft service life by reducing loss of F-15 aircraft from out of control or departure from controlled flight mishaps. This aerodynamically symmetric configuration will be comparable to equalizing the weight and aerodynamic asymmetries of the F-15. This weight and aerodynamic equalization will place the operational F-15 in the departure resistant zone as defined by T.O. 1F-15A-1 (1:6-6).

The F-15 is a stable aircraft throughout most of its flight envelope. However, it still exhibits an uncommanded yawing and rolling tendency at true angles-of-attack (AOA) greater then 30 degrees (2:31). This greater then 30 degrees true AOA is defined high AOA for this research. The uncommanded yawing and rolling are normally to the right and can lead to departure from controlled flight.

Nelson and Flynn (3:17) identified some influencing factors of this uncommanded yawing and rolling motion as lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias. Nelson and Flynn (3) showed through qualitative evaluation how these influencing factors effect the F-15 uncommanded yawing and rolling motion at high AOA. However, a quantitative relationship between each influencing factor and uncommanded F-15 yawing and rolling motion at high AOA was not established.

Previous work conducted on analyzing the effects of lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias came from flight test of partially instrumented F-15 aircraft. These partially instrumented F-15 aircraft were tested in a non-standard operational training configuration. The standard operational training configuration for the 1st Fighter Wing, Langley AFB, Virginia is a 20 mm gun, wing pylons and missile launchers, a single AIM-9 practice training missile, and centerline fuel tank. This training configuration is considered typical for most operational F-15 wings.

In 1993, a yaw sensitivity investigation was conducted by the Israeli Air Force (IAF) and McDonnell Douglas Aerospace Corporation (3:2). The investigation was conducted because of an increased yaw sensitivity observed in some of the IAF F-15D aircraft. This investigation included stalls of F-15D aircraft in various configurations, including centerline fuel tank. An outcome of this investigation was the gun gas exhaust louvers affect the F-15 uncommanded yawing and rolling motion at high AOA. As a result, the gun louvers were covered for the IAF F-15D fleet and an improved resistance to uncommanded yawing and rolling motions were perceived by test pilots.

In 1994, Snyder (4) reported on an investigation of F-15 differential stabilator bias. Snyder (4) used both open loop (i.e., no pilot inputs) and closed loop (i.e., pilot in the loop) aft stick stall flight test techniques (FTT). The open loop FTT consisted of a 1 g deceleration making no rudder input during the stall and measuring heading change over a period of time (4:2). The closed loop technique involved a 1 g deceleration controlling yaw rate with rudder during the stall (4:2). The F-15 configurations flown were various differential stabilator biases at 20,000 and 30,000 feet (6,096 and 9,144 meters) pressure altitude (PA) (4:2). Prior to Snyders report (4), F-15 Technical Order procedures used a left leading edge down (LLED) rigging for the stabilators. However, Snyders report (4) suggested a significant decrease in uncommanded yaw rate could be obtained during the stall with 0.8-inch (20.2-millimeters) right leading edge down (RLED) differential stabilator riggings. Snyders report (4) resulted in the F-15 maintenance technical order differential stabilator bias being changed. The new differential stabilator bias is from 0.2-inch (5.1-millimeter) to 0.4-inch (10.1-millimeter) left leading edge up (LLEU) and 0.2-inch (5.1-millimeter) to 0.4-inch (10.1-millimeter) RLED for a net bias of 0.4-inch (10.1-millimeter) to 0.8-inch (20.2 millimeters) RLED (5:7-36B). However, to date, no test has used a fully instrumented F-15 aircraft nor has any test attempted to rigorously quantify the effects of each influencing factor.

Snyder (4) gathered test pilot comments, estimated rudder pedal displacement, and video recordings on the effects of some of these influencing factors. Test pilot opinions need to be substantiated with engineering F-15 flight simulations and instrumented flight tests of standard operational training configured F-15 aircraft (6:6). This research will accomplish the needed requirement by rigorously quantifying and correlating the effects of lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias on the uncommanded yawing and rolling motion of the F-15 at high AOA as stated in the following objectives.

The general objective of this research will be to quantitatively investigate the correlation between lateral aerodynamic asymmetry, lateral weight asymmetry, and differential stabilator bias upon the directional flight characteristics of the F-15 at high AOA. More specifically this research will:

1. Determine the relationship between lateral center-of-gravity (c.g.) shifts and uncommanded yaw accelerations for 1 g flight above 35 cockpit units AOA at full aft stick.

2. Determine the relationship between differential stabilator biases and uncommanded yaw accelerations for 1 g flight above 35 cockpit units AOA at full aft stick.

3. Determine the relationship between AIM-9 missile location on Stations 2A and 8B and uncommanded yaw accelerations for 1 g flight above 35 cockpit units AOA at full aft stick.

4. Compare flight test results, from objectives one through three, with F-15 six degree-of-freedom (6-DOF) simulator predictions.

5. Use the results from objectives one through three to identify a symmetric F-15 configuration for 1 g flight above 35 cockpit units AOA at full aft stick.

To accomplish these objectives, this research will present a method of quantifying the effects of each influencing factor by examining how each influencing factor effects the slope of the F-15s steady state yaw rate curve. Lateral wing fuel asymmetries, AIM-9 missile location, and differential stabilator bias will be examined.

Each asymmetric contributor will be examined with the use of a 6-DOF F-15 engineering simulation and a fully instrumented F-15B aircraft. The 6-DOF F-15 engineering simulation will be modified to allow an asymmetric AIM-9 carriage, a preset differential stabilator bias, and the inclusion of an asymmetric aerodynamic force at high AOA. The simulation runs will be used to predict the net yaw acceleration for each F-15 configuration. The net yaw acceleration magnitudes for each influencing factor will then be compared with each other to quantitatively identify the relative effects of each influencing factor and to identify an aerodynamically symmetric F-15 configuration.

Finally, the 6-DOF simulation runs were used as engineering background to develop F-15B flight test points and profiles (7:1). Flight testing was directed by the Commandant, USAF Test Pilot School (TPS) and was conducted at the Air Force Flight Test Center (AFFTC), Edwards AFB, California (7). Twelve F-15B sorties totaling 14.4 hours were flown by a group of students from USAF TPS Class 95A. The sorties were flown between 27 September 1995 and 26 October 1995. The flight test results will be used to quantitatively correlate each asymmetric influencing factors effects on net yaw acceleration. These flight test results will provide operational F-15 wings more information on how to configure their aircraft for day to day training flights, and also to validate and improve 6-DOF, F-15 simulator predictions.

2. Background

2.1 General:

This chapter identifies F-15 external Station location, defines aircraft coordinate system, and discuses research specific terminology. Station locations are alpha-numeric identifiers used to locate various external store locations on the F-15 airframe. AIM-9 missiles, external fuel tanks, and wing mounted pylons are a few external stores that can be mounted on these Stations (1:5-14). The aircraft coordinate system defines positive directions for distances, angles, forces, and moments. These distances, angles, forces, and moments include lateral c.g. shifts, side forces, and yawing moments. Finally, research specific terminology are terms that have a specific meaning to this research. These research specific terms include lateral aerodynamic asymmetry, lateral weight asymmetry, and differential stabilator bias.

2.2 F-15 External Station Locations:

In Figure 2-1, the various F-15 external Station locations discussed in this research are identified. In Figure 2-1, Station' 2A and 2B are the left outboard and left

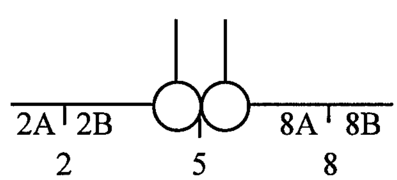
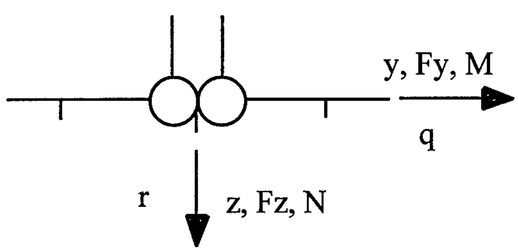


Figure 2-1. F-15 external Station locations, aft view.

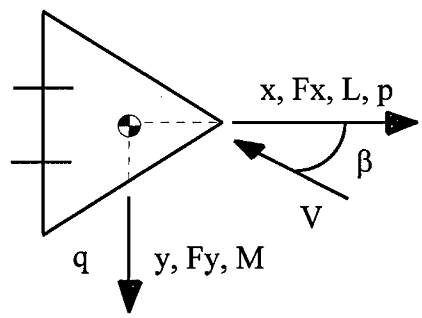
inboard wing pylon missile launchers respectively. Station 2 is the left wing pylon location. Station 5 is the centerline pylon location. Stations' 8A and 8B are the right inboard and right outboard wing pylon missile launchers respectively. Finally, Station 8 is the right wing pylon location.

2.3 F-15 Coordinate System:

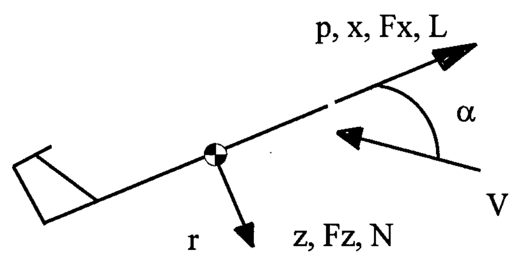
Figure 2-2 is the right-handed body axis coordinate system used in this research. The axis are fixed to the aircraft centerline and the longitudinal c.g. location. All directions are positive unless stated otherwise. In Figure 2-2, x, y, and z are distances



a. Aft view.



b. Top view.



c. Side View.

Figure 2-2. Right-handed coordinate System.

along each axis; α is angle of attack; β is side slip; Fx, Fy, and Fz are forces acting on the aircraft in the respective direction; L, M, and N are rolling, pitching, and yawing moments respectively; p, q, and r are roll, pitch, and yaw rates respectively; and V is the free stream velocity.

2.4 Asymmetry:

Most aircraft have a x-z plane of symmetry. In Figure 2-3, the baseline F-15 appears symmetric about the x-z plane (i.e., it appears that everything located to the left

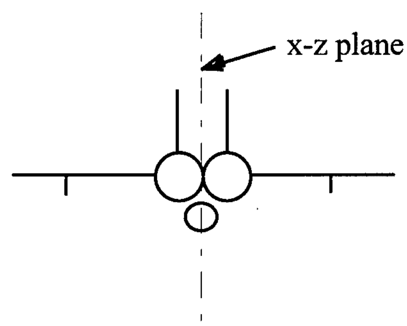


Figure 2-3. x-z plane of symmetry.

of the x-z plane is also located to the right of the x-z plane). However, due to different aerodynamic characteristics (gun exhaust vents) and different internal mass distribution (right side gun location), the baseline F-15 is not considered symmetric about the x-z plane. The gun exhaust vents and right side gun location are just two reasons for asymmetry about the x-z plane. Other reasons for asymmetry about the x-z plane are wing fuel imbalance and odd external store carriage. This research examines the effects of asymmetries on the F-15 directional flight characteristics at high AOA. High AOA for this research is defined as AOA above 30 degrees true AOA. Specifically, the asymmetries examined are lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias.

2.5 Lateral Aerodynamic Asymmetry:

Lateral aerodynamic asymmetry is any unbalanced lateral aerodynamic force acting on the aircraft about the aircraft's c.g.. This unbalanced lateral force causes the aircraft to yaw and then roll. There are two primary causes of F-15 lateral aerodynamic asymmetry, 20 mm gun gas exhaust vent effects and asymmetric AIM-9 carriage.

First, the gun gas exhaust vent location shown in Figure 2-4, takes high pressure air from the bottom of the aircraft, passes it through the gun bay, and exhausts it upwards and slightly aft (8:238). Walker (8:243) reports that this venting causes distortion of high AOA nose vortices which in turn causes a right yaw bias at high AOA.

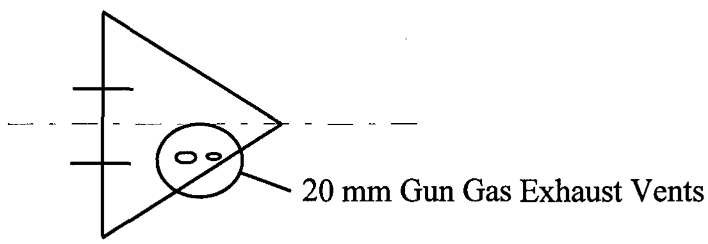
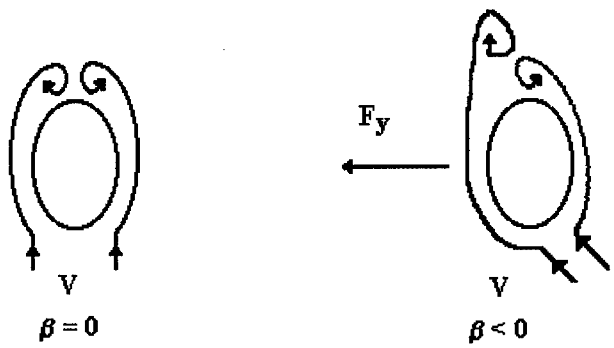


Figure 2-4. 20 mm gun gas exhaust vent location.

The F-15 sheds nose or forebody vortices at high AOA (8:243). Depending on how the gun vent system distorts these forebody vortices an asymmetric side force (F_y) develops. Also, if the aircraft is subjected to a sideslip angle (β), the forebody vortices tend to overlap each other. This overlapping of vortices creates an asymmetric side force (F_y) as shown in Figure 2-5. Blake and Barnhart (9:1) demonstrated the effects of side slip (β) on forebody vortices. However, the effect of gun gas exhaust venting on the forebody vortices is still not well defined. These gun gas exhaust effects tend to have significant influences at Mach numbers greater than 0.4 (0.5 at 30,000 feet {9,144 meters}pressure altitude {PA}) and AOA between 28 and 34 CPU AOA (10:7).



a. Relative wind zero sideslip.   b. Relative wind negative sideslip.

Figure 2-5. Forebody vortex flows over an aircraft nose shape at high AOA.

This gun gas venting asymmetry first surfaced in 1990 as an uncommanded yawing and rolling motion on a F-15C at Bitburg AB, GE (2:31). The Bitburg F-15C developed an uncommanded yaw and roll while configured with no external stores or pylons. This uncommanded yaw and roll was named the Bitburg roll (2:30). A characteristic of the Bitburg roll is up to 60 degrees per second right roll rate (8:2). At higher altitudes, the Bitburg roll is primarily a yawing motion (2:32). Furthermore, the Bitburg roll normally occurs only when the AOA is between 32 to 35 CPU AOA and the airspeed is between 250 to 350 knots (129 to 180 meters/second) calibrated airspeed (KCAS) (6:2).

Until recently, the causes of the Bitburg roll were unknown. Walker (11:4) has shown a relation between the 20 mm gun gas venting system, gun port opening, and Bitburg roll. However, the Bitburg roll and its lateral aerodynamic asymmetric effects are still not fully understood.

Second, the F-15 is configured for everyday operational training flights with two wing pylons on Stations 2 and 8, an asymmetric AIM-9 missile, on either Station 2A or 2B, and a centerline fuel tank on Station 5 as shown in Figure 2-6.

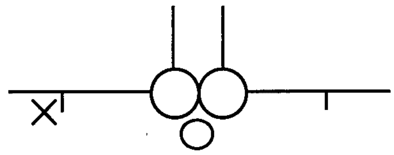
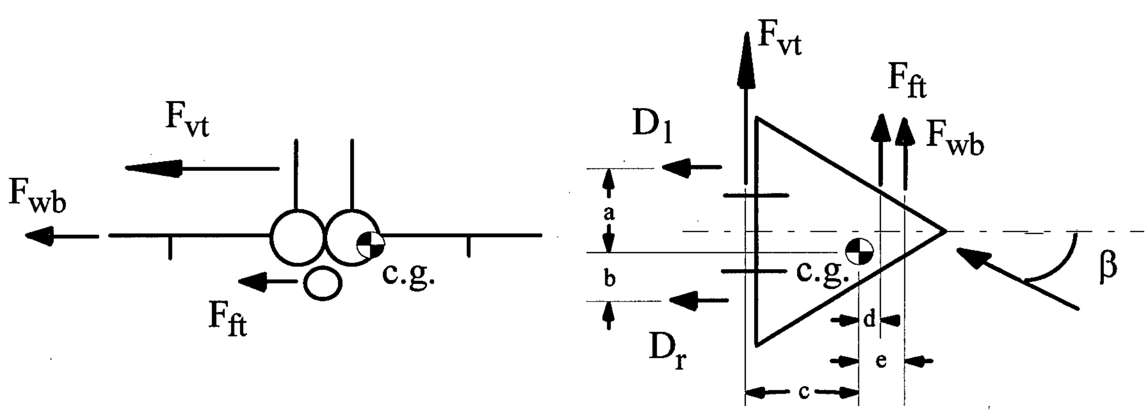


Figure 2-6. Standard operational training configuration, aft view.

The asymmetric external carriage of an AIM-9 missile at all AOA causes an increase in net aerodynamic drag on the respective side of the aircraft (1:B1-4). For the F-15 shown in Figure 2-6, this increase in aerodynamic drag causes the aircraft to yaw left and then roll left into the missile. The aircraft yaw is caused by an increase in aerodynamic drag due to the missile on the left side of the aircraft. The aircraft roll is caused by positive dihedral effect. Dihedral effect is the change in rolling moment (L) due to a unit sideslip (β) and is written in stability derivative form as C_{l_β} (12:139). Positive dihedral effect is when an aircraft subjected to a positive sideslip angle rolls away from that sideslip angle. For example, assume an F-15 with positive dihedral effect is flying at a positive sideslip angle. The positive dihedral effect causes the F-15 to roll left away from the positive sideslip angle. Returning to the standard operational training configuration as shown in Figure 2-6, the F-15 loaded with an asymmetric AIM-9 on the left yaws and then rolls to the left into the asymmetric AIM-9 missile.

2.6 Lateral Weight Asymmetry:

Lateral weight asymmetry is any uneven weight distribution about the aircraft x-z plane. The F-15 has a built in lateral weight asymmetry of 1,700 foot-pound (2,305 Newton-meter) right wing heavy due to the right side gun location (1:6-6). This uneven lateral weight distribution causes the aircraft to yaw and roll away from the heavy wing at high AOA as stated in the T.O. 1F-15A-1 (1:6-5). This is explained by variations in the aircraft's directional stability at high AOA. Directional stability or weathercock stability is the change in yawing moment (N) due to a unit sideslip (β) and is written in stability derivative form as $C_{n\beta}$ (12:156). An aircraft is said to have positive directional stability if when subjected to a positive sideslip angle, the aircraft develops a positive yawing moment (12:156). This positive yawing moment reduces the positive sideslip angle. When the F-15 stalls, the airflow across the vertical stabilizers is greatly reduced (1:6-2). This reduction in airflow across the vertical stabilizers reduces the effectiveness of the vertical stabilizers and therefore, reduces the F-15's directional stability at high AOA (1:6-2). The centerline fuel tank further reduces directional stability of the F-15 (1:6-3). The centerline fuel tank like the fuselage produces a side force (F_{ft} and F_{wb} respectively) forward of the aircraft's c.g.. Therefore, when the aircraft is subjected to a sideslip (β), the fuel tank and fuselage side forces increase the sideslip angle (see Figure 2-7). This increasing sideslip is negative directional stability. In Figure 2-7 if



a. Aft view. b. Top view.

Figure 2-7. Side forces acting on F-15 during a wings level lateral weight asymmetry.

the assumption is made that right side drag (D_r) is approximately equal to left side drag (D_l) and that the aircraft is flying wings level, then the F-15 must fly at a sideslip angle (β) into the heavy wing to balance the forces about the c.g. as shown in Equation (2-1),

$$\Sigma M_{c.g.} = -D_l*a + D_r*b + F_{vt}*c - F_{ft}*d - F_{wb}*e = 0. \qquad (2\text{-}1)$$

In Equation (2-1) $M_{c.g.}$ is the moment about the c.g.; D_l is the left side drag force; D_r is the right side drag force; F_{vt} is side force due to the vertical tails and rudders; F_{wb} is side force due to wing and aircraft body; F_{ft} is side force due to the centerline fuel tank; and a,b,c,d, and e are perpendicular distances from the c.g. to the respective force. Equation (2-1) is satisfied only if the F-15 is flying in a sideslip. If the sideslip is zero, then the three side forces F_{vt}, F_{ft}, and F_{wb} are all zero. With these side forces zero, Equation (2-1) simplifies to Equation (2-2),

$$\Sigma M_{c.g.} = -D_l*a + D_r*b \neq 0. \qquad (2\text{-}2)$$

Equation (2-2) is not equal to zero since the assumption was made that D_r equals D_l and distance 'a' is larger then distance 'b'. Because the F-15 must fly at a sideslip angle with a lateral weight asymmetry, the effects of reduced directional stability at high AOA are seen.

As the AOA increases the F-15 directional stability is decreased (7:-2). In Figure 2-7, when the F-15 is flying with a lateral weight asymmetry and wings level it must fly with a sideslip angle on the aircraft. Therefore as the AOA increases, the F-15 directional stability decreases and sidesilp increases (aircraft yaws) to balance Equation (2-1). As sideslip increases, the F-15's positive dihedral effect rolls the aircraft away from the sideslip. Thus, the reduced directional stability coupled with positive dihedral effect cause the F-15 to yaw and roll away from the heavy wing at high AOA.

Returning to the standard operational training configuration shown in Figure 2-6, the single AIM-9 on the left side creates a lateral weight asymmetry of 2,126 foot-pound

(2,882 Newton-meter) left wing heavy (1:6-7). The F-15 also has the built in lateral weight asymmetry of 1,700 foot-pound (2,305 Newton-meter) right wing heavy due to the right side gun location (1:6-6) These two asymmetries combine for a total weight asymmetry of 426 foot-pound (577 Newton-meter) left wing heavy. Because of the built in gun weight asymmetry, the F-15 Flight Manual provides a preferred asymmetric AIM-9 loading (1:5-14). The preferred asymmetric AIM-9 loading is load the extra missile on the left side of the aircraft on either Stations 2A or 2B as shown in Figure 2-6.

Snyder, et al, (8:7) reports this guidance may not be the best way to load a F-15 for everyday operational training flights. Snyder, et al, (8:239) reports that a F-15 configured with an AIM-9 on Station 2B and without a 20 mm gun may actually yaw and roll right at high AOA. Although Snyder, et al, (8) reported results were conducted on a F-15 without a gun, they still demonstrate the need to accurately determine the effects of weight asymmetry on aircraft directional flight characteristics at high AOA.

2.7 Differential Stabilator Bias:

Differential stabilator bias is the difference between the leading edges of the right and left stabilator from a known reference mark on the aircraft (5:7-36B). Maintenance rigs the differential stabilator bias based on Technical Order (T.O.) guidance and the results of two functional checks performed during a F-15 Functional Check Flight (FCF) (13: 1-14). Current maintenance T.O. guidance suggests a differential stabilator rigging of 0.4-inches (10.1-millimeters) right leading edge down (RLED) and 0.4-inches (10.1-millimeters) left leading edge up (LLEU) for a net 0.8-inch (20.2-millimeters) difference (5:7-36B). This stabilator bias is fixed and does not washout with increased AOA. Snyders results (4) prompted this recent change in the F-15 stabilator rigging from 0.5-inch (12.7-millimeters) left leading edge down (LLED) or -0.5-inch (-12.7-millimeters) difference to the current 0.8-inch (20.2-millimeters) difference discussed above (5:7-36B). The negative sign in the stabilator difference is a sign convention used in this research and has no other significant meaning. The negative sign means the net differential stabilators are biased to cause a left roll at low AOA while a positive difference causes a right roll at low AOA. Low AOA is defined as true AOA below 20 degrees. Snyder (4) demonstrates a left rolling stabilator bias increases the F-15's apparent nose right yaw and roll at high AOA while the right rolling stabilator bias reduces the apparent nose right yaw and roll at high AOA. The changes in yaw and roll rates at high AOA are due to adverse yaw produced by differential stabilators (14:258).

Although numerous flight tests were conducted on similar topics, no rigorous quantitative data has been gathered about the effects of lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias on the F-15s directional flight characteristics at high AOA. This research will quantify these effects.

3. Approach

3.1 General:

This research is broken into two phases, simulation and flight test. Phase I is the modification of an existing F-15 engineering simulator. The simulator results are used to predict the quantitative effects of lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator biases on the F-15s AOA directional flight characteristics. The quantifying metric is a comparison of the net yaw acceleration for each asymmetric configuration. The net yaw acceleration is defined as the mean slope of the steady state yaw rate curve. These simulations provide the engineering background used to develop the Phase II flight test profiles.

Phase II consists of a 12 flight, 14.4 hour, F-15B flight test program called HAVE LIST (7). Data gathered during the flight test are used to quantify the effects of lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator biases upon the F-15Bs high AOA directional flight characteristics. Finally, the flight test is used to validate the F-15 six degree of freedom (6-DOF) simulator predictions.

3.2 Phase I, Engineering Analysis:

Over 88 computer simulations were conducted to predict the quantitative effects of lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias upon the directional flight characteristics of the F-15 at high AOA. The simulations were conducted using a modified 6-DOF, F-15E computer engineering simulator.

3.2.1 Simulator Description:

The simulator was developed jointly by 88th Communications Group / Science and Engineering (CG/SCES) and the F-15 Systems Program Office (SPO) at Wright-Patterson AFB, Ohio (15). The computer model is written in ADSIM computer language using non-linear aircraft equations of motion (15). The computer simulation is run on a real-time station computer system based on a VME multi-processor from Applied Dynamics, Ann Arbor, Michigan (15).

The computer model is set by internal switches to aerodynamically duplicate a F-15A and therefore, provide accurate F-15A aerodynamic properties (15). The F-15A was simulated because, at the time of simulation, Summer and Fall of 1994, the F-15A was the aircraft selected for the HAVE LIST flight test program flown in the Fall of 1995. Although the simulator aerodynamically duplicates the F-15A, it uses the pre Version 8, F-15E flight control system (15).

The pre Version 8 F-15E flight control system like the F-15A flight control system does not allow for side acceleration (n_y) and side-slip rate ($\dot{\beta}$) feedback nor does it allow for direct control of the differential stabilators through rudder pedal movement at high AOA (15). Consequently, the primary difference between the F-15E pre Version 8 flight control system and the F-15A flight control system is the F-15E uses a digital flight control system and the F-15A uses an analog flight control system (15). No significant differences in flight control movement or placement occur between the two systems during the stalls (16:11). Therefore, the pre Version 8, F-15E flight control system is considered representative of the F-15A flight control system for the flight regime of interest.

During phase I, the computer simulation was modified to better predict F-15A high AOA directional flight characteristics. These modifications accounted for lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias at high AOA.

The first modification accounted for the aerodynamic asymmetry of a single AIM-9 missile loaded on either Station 2A or 8B and the unknown aerodynamic asymmetry of the gun vent system at high AOA. An asymmetric aerodynamic model of a single AIM-9 missile was developed using existing AERO-TAB-5 aerodynamic data for symmetric AIM-9 missile (17). To account for a single AIM-9 on either Station 2A or 8B, the aerodynamic data was divided by the number of missiles for which it was gathered and then multiplied by the appropriate flight parameters to determine the lift and drag forces for a single AIM-9. Next, the forces and the moments created by the single AIM-9 were included in the appropriate aircraft equations-of-motion (EOM). For example, if the symmetric AIM-9 aerodynamic data was gathered for four missiles, the computer simulation divides this data by four. Next, the simulation multiplies the data by the appropriate flight parameters to determine the lift, drag, and moment forces produced by the single AIM-9. Finally, these forces and moments were included in the simulation EOM. This asymmetric aerodynamic model of a single AIM-9 was considered representative of the simulated lateral asymmetric aerodynamic effects of the single AIM-9.

The remaining lateral aerodynamic asymmetric effects were simulated by using a mixture of AERO-TAB-5 and AERO-TAB-6 (18) aerodynamic data. AERO-TAB-5 and AERO-TAB-6 aerodynamic data includes two lateral aerodynamic asymmetric coefficients termed $C_{N_{RB}}$ and $C_{Y_{RB}}$. These two coefficients are asymmetric yawing and asymmetric side force coefficients respectively. However, the AERO-TAB-5 aerodynamic data base is limited above 30 degrees true AOA (14:255). AERO-TAB-6 aerodynamic data is developed using static, forced oscillation, rotary balance, and free spin wind tunnels (14:255). These wind tunnels are used to expand the AERO-TAB-5 aerodynamic data base above the 30 degree true AOA region (14:255). Further, AERO-TAB-6 is a rotational aerodynamic data set (i.e., the data contains and uses angular velocities of the aircraft as another variable in look-up tables). Implementation of the full aerodynamic data set would have required extensive modification to the present simulation routine that was not practical for this research. Consequently, only the AERO-TAB-6 $C_{N_{RB}}$ and $C_{Y_{RB}}$ coefficients were used. The rotational aerodynamic effects were removed by setting the angular velocity in the table look-up to zero.

Finally, in order to use the AERO-TAB-6 $C_{N_{RB}}$ and $C_{Y_{RB}}$ coefficients, an additional term called Offset was added to the simulation look up tables. Wood (19) describes the Offset term as an aerodynamic asymmetry scaling factor derived from test pilot opinion of how strong the aerodynamic asymmetries are perceived in a given flight regime. The Offset term is a multiplier of the $C_{N_{RB}}$ and $C_{Y_{RB}}$ coefficients (15).

The second modification to the simulation allowed the existence of a lateral weight asymmetry. The lateral weight asymmetries simulated were a single AIM-9 configuration as well as an asymmetric fuel loading. The single AIM-9 configuration and asymmetric fuel loading were handled by simply inputting the correct moments of inertia and aircraft c.g. locations directly into the simulation start-up routine. The aircraft inertia and c.g. locations for each lateral weight asymmetry are calculated as shown in the F-15 Stability Derivatives Mass and Inertia Characteristics Manual, McDonnell Douglas Corporation (20).

The final modification to the simulation was an adjustable differential stabilator bias. The differential stabilator bias was introduced as a constant bias added to the F-15 mechanical control system. This modification added a summer to the F-15 control system just after the Pitch Roll Channel Assembly (PRCA), as shown in Figure 3-1. In Figure 3-1 the modifications net effect was to add one-half bias to the left stabilator and subtract one-half bias from the right stabilator.

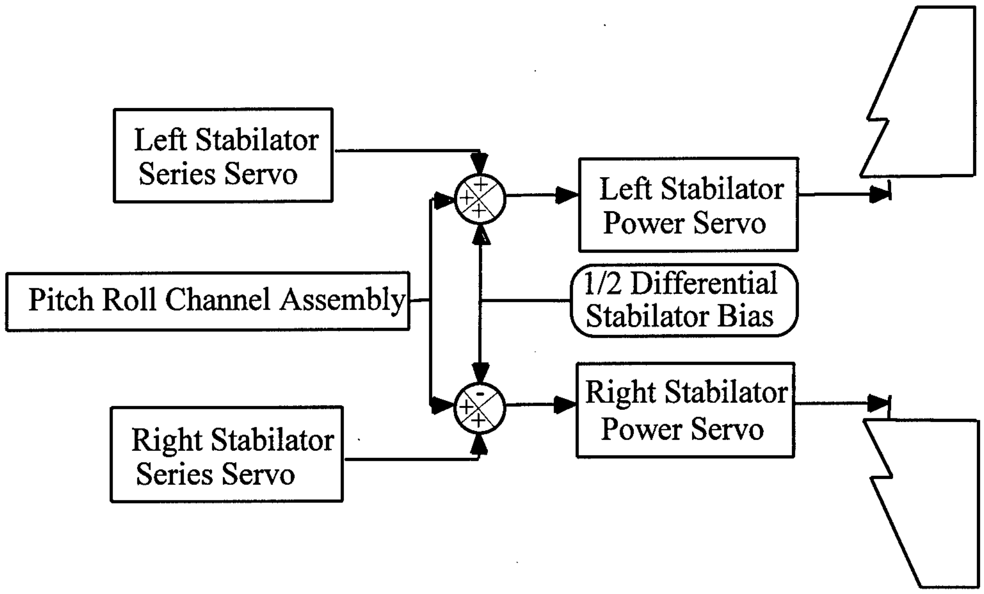


Figure 3-1. Differential stabilator bias implementation.

Lastly, the simulator initial trim routine was examined to ensure it did not affect the differential stabilator bias in a way unlike the aircraft. The simulators initial trim routine trimmed the flight control surfaces to maintain the desired initialized unaccelerated flight condition (15). The simulator trimmed the aircraft using the trim button on the control stick. Therefore, flight control surfaces were positioned to a trimmed position by the flight control system and not by an arbitrary simulator control input. The importance of trimming in this manner was the differential stabilator biases evaluated are small and any abnormal adjustment made to the differential stabilator bias by the simulator effects the analysis.

3.2.2 Simulator Test Procedures:

Simulation was conducted in four phases, each at a different stabilator bias. The baseline F-15A simulated was configured with 2 wing pylons on Stations 2 and 8, 4 LAU-114 launchers mounted on the wing pylons, 20 mm gun, centerline fuel tank, and 50 percent internal fuel. The four differential stabilator bias settings simulated were: 1) a 0.25-inch (6.4-millimeter) right leading edge up (RLEU) with 0.25-inch (6.4-millimeter) left leading edge down (LLED) for a -0.5-inch (-12.7-millimeter) difference; 2) a symmetric case ; 3) a 0.25-inch (6.4-millimeter) right leading edge down (RLED) with 0.25-inch (6.4-millimeter) left leading edge up (LLEU) for a 0.5-inch (12.7-millimeter) difference; and 4) a 0.5-inch (12.7-millimeter) RLED with 0.5-inch (12.7-millimeter) LLEU for a 1.0-inch (25.4-millimeter) difference. The minus sign above indicates the differential stabilator bias causes a left rolling tendency at low AOA while a positive difference causes a right rolling tendency at low AOA. Simulations during each of the four phases included asymmetric fuel loads ranging from 1,000 pounds (4,448 Newtons) left wing heavy to 1,280 pounds (5,694 Newtons) right wing heavy and simulations of AIM-9 asymmetries loaded on either Station 2A or 8B. Data were gathered using a full aft stick stall flight test technique (FTT). The FTT is described in subsequent paragraphs. Simulations were accomplished in the cruise configuration (i.e., gear, flaps, and speedbrake retracted) at 32,000 and 15,000 feet (9,754 and 4,572 meters) PA.

The FTT was a full aft stick stall. The aircraft was initialized in a trimmed wings level flight attitude at 200 knots (103 meters/second) calibrated airspeed (KCAS) for the 15,000 foot (4,572 meter) PA stall and at 250 KCAS (129 meters/second) for the 32,000 foot (9,754 meter) PA stall. Trim power was used throughout the stall. Five seconds after the simulation run began, a 27.2 pound (121 Newton) aft stick input was made. The aft stick input was applied linearly over a 5 second time period. The 27.2 pound (121 Newton) aft stick input was equivalent to full aft stick. This full aft stick input was characterized by a nominal stabilator deflection of 28 degrees and a true AOA of 36 to 38 degrees. No lateral stick inputs were made during the maneuver.

3.2.3 Simulator Data Reduction:

The first step in data reduction is the development of a metric to identify and quantify the effects of each of the various asymmetric influencing factors. Since the effect of each asymmetric influencing factor on the directional flight characteristics of the F-15 is a research objective, it is logical to use a directional flight parameter as a quantifying metric. This research hypothesized that the net yaw acceleration can be used as the quantifying metric. The net yaw acceleration metric for this research is calculated by taking the mean slope of the steady state yaw rate curve. The results of these net yaw accelerations are presented in Appendix B, Figures B1 - B4. For example, Figure 3-2 is a plot of yaw rate versus time. In Figure 3-2 the baseline F-15 at 15,000 feet (4,572 meters) PA is rigged with a symmetric stabilator. In Figure 3-2 the yaw rate is assumed steady state at 40 seconds. Also, the yaw rate curve at times greater than 40 seconds is

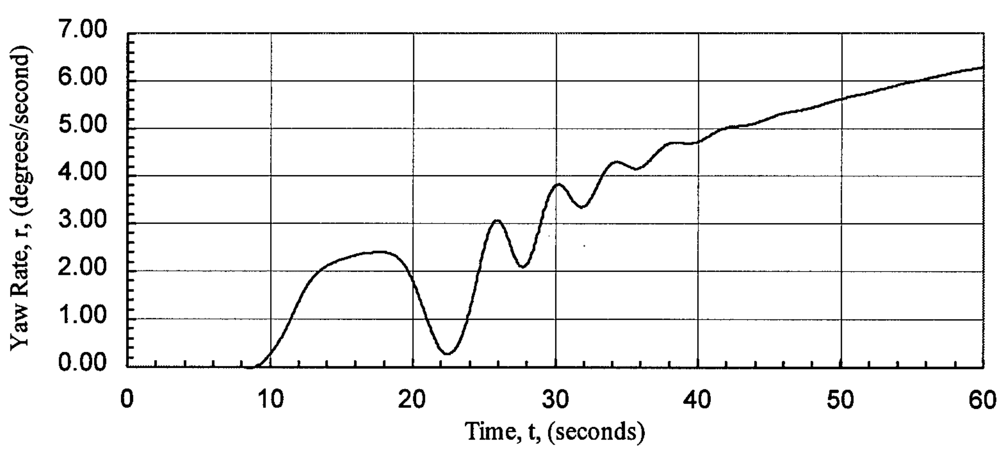


Figure 3-2. Baseline F-15A simulator yaw rate prediction at 15,000 feet (4,572 meters) PA, with symmetric stabilators.

assumed linear. Therefore, the net yaw acceleration is constant since the net yaw acceleration is the slope of the linear steady state yaw rate curve. When net yaw acceleration is zero the aircraft is considered symmetric.

3.3 Phase II, F-15B Flight Test:

A 12 flight, 14.4 hour, F-15B flight test program was flown at the Air Force Flight Test Center, Edwards AFB, California (7). Over 150 full aft stick stalls were flown. The stalls were used to quantitatively analyze the effects of lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator biases on the F-15B high AOA directional flight characteristics.

3.3.1 F-15B Test Aircraft Description:

The F-15B was manufactured by the McDonnell Douglas Corporation. It was a tandem, two-seat aircraft powered by two Pratt & Whitney F100-PW-100 engines. The engines were augmented with afterburners and produce approximately 25,000 pounds (111,205 Newtons) thrust each. The aircraft had high-mounted swept back wings, variable geometry inlets and twin vertical tails. The irreversible, hydraulic flight control system had a Control Augmentation System (CAS) in the roll, pitch, and yaw axes. Flight control surfaces on the test aircraft included ailerons for roll, differential stabilators for roll and pitch, and twin rudder surfaces, one mounted on each vertical tail, for directional control (1:1-1).

The test aircraft was a production F-15B, S/N 76-0130. The baseline test aircraft was flown with a centerline fuel tank, two wing pylons on stations 2 and 8, 4 LAU-114 launcher rails, 20 mm gun, and gun exhaust louvers open. This was considered a standard operational training configuration. The gun bay ammo drum and feed chute were removed and replaced with instrumentation (21). The test aircraft was modified with an electronic data acquisition system (DAS), a C-band beacon for range tracking, and a wing fuel transfer pump control panel for controlling internal wing fuel asymmetries (22). The parameters recorded by the DAS are shown in Appendix A,

Table A1. The wing transfer pump panel was located in the front cockpit and includes two switches, one for each wing fuel transfer pump. Turning off the transfer pump allowed a wing fuel imbalance to occur due to unequal transferring of the internal wing tank fuel. These modifications did not significantly alter the aerodynamic or mass and inertia characteristics of the test aircraft. Therefore, the test aircraft was considered both operationally and production representative.

Prior to testing, the F-15B S/N 76-0130 was checked for wing twist, stabilator hysteresis and lateral c.g. position. The results of the wing twist survey were the right wing leading edge was 3.35-inches (85.1-millimeters) down while the left wing leading edge was 3.42-inches (86.9-millimeters) down. This twist was within F-15 Technical Order limits. The stabilator hysteresis check resulted in right stabilator hysteresis of 0.375-inches (9.525-millimeters) and left stabilator hysteresis of 0.1875-inches (4.763-millimeters). The lateral c.g. check resulted in a zero fuel weight lateral c.g. of 0.55-inches (13.97-millimeters) right of aircraft centerline. These measurements are considered typical of an operationally representative F-15B.

3.3.2 Flight Test Procedures:

The test was flown in two phases. Each phase concentrated on a separate differential stabilator bias. The two differential stabilator bias settings flown were: 1) 0.4-inch (10.1-millimeter) right leading edge down (RLED) with 0.4-inch (10.1-millimeter) left leading edge up (LLEU) for a 0.8-inch (20.2-millimeter) difference; and 2) 0.2-inch (5.1-millimeter) right leading edge up (RLEU) with 0.0-inch (0.0-millimeter) left bias for a -0.2-inch (-5.1-millimeter) difference. All flight tests were monitored in the telemetry control room, real time. Data were gathered using the full aft stick stall FTT described in subsequent paragraphs. The test used a build-up approach in both asymmetry and altitude. A build-up approach was an approach that first examined a nominal configuration and than progressed to the abnormal configurations. An example of a build-up approach for weight asymmetry was first testing at zero weight asymmetry followed by testing at increasingly heavier weight asymmetries. All testing was accomplished in the cruise configuration (i.e., gear, flaps, and speedbrake retracted) at 32,000 and 15,000 feet (9,754 and 4,572 meters) PA.

The FTT was a 1 g full aft stick stall. The data band was ±2,000 feet (± 610 meters). The data band is the range of altitude where data is collected. Aircraft fuel was recorded from a 250 KIAS (129 meters/second) trim shot held for a minimum of 30 seconds to reduce fuel indication errors due to fuel slosh. A trim shot is an open loop unaccelerating trimmed flight condition. The aircraft was then slowed to a 180 KIAS (92.7 meters/second) trim shot at the top of the data band and the maneuver begun. Next, idle power was selected prior to 25 cockpit units (CPU) AOA, and a 1 g deceleration, without use of speed brake, was performed. During the deceleration through 35 CPU AOA, the wings were kept level with lateral stick inputs. Above 35 CPU AOA, the control stick was kept centered and no attempt was made to counter wing rock. As a reference during the deceleration the pilot observed the heads up display (HUD) to keep the flight path marker on the horizon until 25 CPU AOA. At 25 CPU AOA, the pilot smoothly increased the aft stick movement attempting to maintain level flight until reaching the aft stick position. Lateral stick remained centered with maximum longitudinal deflection throughout the maneuver.

To aid in keeping the stick centered at the aft stop, the seat and stick were marked in both cockpits with three parallel lines as shown in Figure 3-3. When the lines were aligned, the stick was in a repeatable, pilot to pilot, stall to stall, centered aft position. During the stall, the rear cockpit crew member monitored lateral stick position, altitude, engines, and bank angle. Recovery from the stall was initiated at the first of the following: bottom of data band, yaw rate exceeding 25 degrees per second in the control room or 30 degrees per second (departure warning tone) in the aircraft, bank angle above

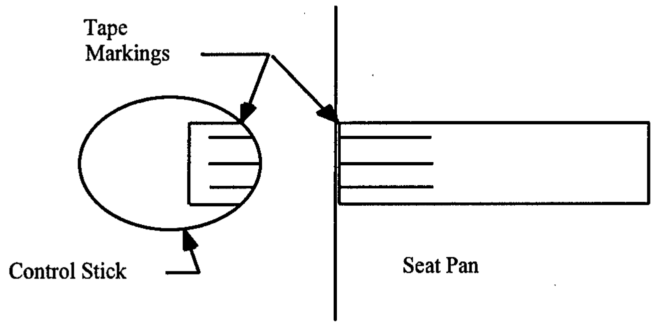


Figure 3-3. F-15B stick centering markings.

120 degrees, or unexpected motion such as nose slices. The recovery technique was to smoothly bring the control stick to neutral preventing the coupling of yaw with roll and pitch. At 180 KIAS (92.7 meters/second), the aircraft was rolled to the nearest horizon and recovered to level flight.

3.3.3 Flight Test Data Reduction:

Just as simulation, the flight test net yaw acceleration is assumed constant and is the primary dependent variable of interest. Yaw rate during the test point was recorded on DAS. However, unlike the smooth simulation steady state yaw rate curves, the flight test steady state yaw rate curves are oscillatory. The yaw rate oscillation is primarily due to the F-15 wing rock at high AOA that was not simulated. Therefore, a Microsoft EXCEL for Windows^{TM} Version 5.0 least squares linear curve fit of yaw rate is used to obtain net yaw acceleration (23:352). A sample plot of yaw rate data and a respective linear curve fit is presented in Figure 3-4.

This linear function is then differentiated to obtain net yaw acceleration. For example, the net yaw acceleration for the sample data shown in Figure 3-4 is

0.44 degrees/second^2. The net yaw acceleration results as a function of lateral c.g. position for the F-15B flight test are presented in Appendix B, Figures B1 to B4.

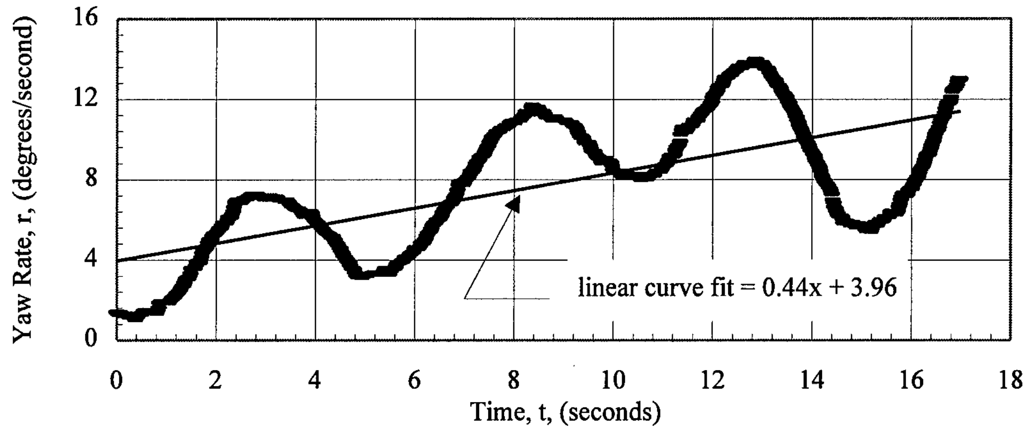


Figure 3-4. F-15B yaw rate at 32,000 feet (9,754 meters) PA for zero fuel asymmetry with 0.4 inch (10.1 millimeter) LLEU and 0.4 inch (10.1 millimeter) RLED.

Net yaw acceleration is plotted versus lateral c.g. position to eliminate effects of gross weight, and to normalize weight asymmetry so test results could be applied to other aircraft and compared to simulation results. These lateral c.g. (y_{cg}) shifts in inches are calculated using Equation (3-1),

$$y_{cg} = \frac{(15833.9 + 90.5 * \Delta W_f)}{(29011 + W_f)} \tag{3-1}$$

where ΔW_f is the wing fuel asymmetry in pounds and W_f is the total fuel in pounds. Equation (3-1) is an empirical relationship for lateral c.g. position. Equation (3-1) is based on the test aircraft empty weight lateral c.g. position (7:19). Using Equation (3-1), a lateral c.g. shift of 1-inch (25.4-millimeter) is equivalent to a 213 pound (947 Newton) wing fuel asymmetry for the test aircraft loaded with 6,086 pounds (27,073 Newtons) or

50 percent internal fuel. The same data reduction procedure is applied for flights conducted with different missile loading, and different differential stabilator biases.

3.4 Simulation and Flight Test Differences:

The simulation and flight test differs in three ways. First, a F-15A was simulated and a F-15B flight tested. Second, the full aft stick stall FTT used for simulation was not the same as the FTT used for flight test. Third, the simulation used a thrust for level flight power setting while the flight test used idle power throughout the aft stick stall.

At the time of simulation, Summer and Fall 1994, the F-15A was scheduled for the Fall 1995, flight test. However, due to F-15A unavailability, the F-15B was used. The difference between the F-15A and F-15B is the F-15Bs larger two place canopy. The two place canopy is directionally de-stabilizing at high AOA (1:6-8). Therefore, some error is expected between the F-15A simulation predictions and the F-15B flight test results. Although some error is induced by the two place canopy, F-15A simulation trends are considered valid.

Another error source was the different FTT used during simulation. The simulation used a much faster aft stick input than the flight test. Also, the simulation maneuver was begun from a higher trim airspeed than the flight test. The different stall entry used during simulation introduces an unknown error. An attempt to reduce this unknown error is made by taking net yaw acceleration data only after the F-15 aircraft response is steady state.

Finally, the simulation FTT used the trim thrust for level flight power setting throughout the stall: the flight test used idle power. This difference between simulated and flight tested power setting causes another unknown error due to engine gyroscopic effects. The simulation does not include coefficients that account for engine gyroscopic effects (15). Therefore, the gyroscopic effects associated with simulation power setting do not effect the magnitude of simulated net yaw acceleration. However, the flight test is affected by engine gyroscopic effects. The magnitude of this gyroscopic effect is unknown. An attempt to reduce this engine gyroscopic error is made by using idle power throughout the flight test stalls.

These differences introduce errors into the simulation and flight test comparisons. Consequently, only trends from the 6-DOF simulator are used for comparison to flight test.

4. Results and Discussion

4.1. Introduction:

This chapter will quantify how each asymmetric influencing factor discussed in Chapter 2 effects the value of net yaw acceleration. As noted earlier in Sections 3.2 and 3.3, the simulation and flight test concentrate on two F-15 differential stabilator biases. Research results presented in this chapter indicate the trends for both differential stabilator biases are similar. Therefore, this chapter will use a single differential stabilator bias as an example to demonstrate how a change in lateral weight asymmetry, differential stabilator bias, and lateral aerodynamic asymmetry affect the value of net yaw acceleration at high AOA. The example presented is the 0.4-inch (10.2-millimeter) RLED with 0.4-inch (10.2-millimeter) LLEU differential stabilator bias at 32,000 feet (9,754 meters) PA. This example will be compared to the simulated 0.5-inch (12.7-millimeter) RLED with 0.5-inch (12.7-millimeter) LLEU differential stabilator bias for simulation flight test comparison. The flight test differential stabilator bias differs slightly from the simulated differential stabilator bias because of the inability to adjust the test aircraft differential stabilator bias in a continuous fashion (3:11). The test aircraft differential stabilator bias is adjusted in finite increments (3:11). Therefore, not all stabilator biases are achievable in the aircraft.

This chapter first presents how flight test net yaw acceleration data are analyzed. Using this analysis combined with 6-DOF F-15 simulation predictions, each of the various asymmetric influencing factors effects on net yaw acceleration are evaluated. Based on this evaluation, differences between simulator and flight test results along with differences between this research and previous research results are discussed. Also, based on this evaluation, a symmetric F-15 is identified. Furthermore, numerous lessons learned about the F-15 and F-15 high AOA flight characteristics are presented.

4.2. Quantifying the Asymmetric Influencing Factors:

Lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias are quantified using net yaw acceleration as a metric. Simulation results are presented in Figures B1-B4 and B11-B14 while flight test results are presented in Figures B1-B10 and B15-B16. Due to the random nature of flight test net yaw acceleration, the flight test data presented in Figures B1-B4 are fit with a least squares linear curve fit that includes 68 percent confidence boundaries for the linear predictions. Jones (25:1-43) defines this confidence interval as a range of values that have a chosen probability of containing the true hypothesized quantity. For this research the chosen probability is 68 percent. This research also uses the 68 percent confidence interval as the definition for a small change in net yaw acceleration. For example, if a change in an asymmetric influencing factor causes the change in net yaw acceleration to remain within the 68 percent confidence interval than that change in net yaw acceleration is considered small. Figure 4-1 is a plot of the random flight test net yaw acceleration data versus

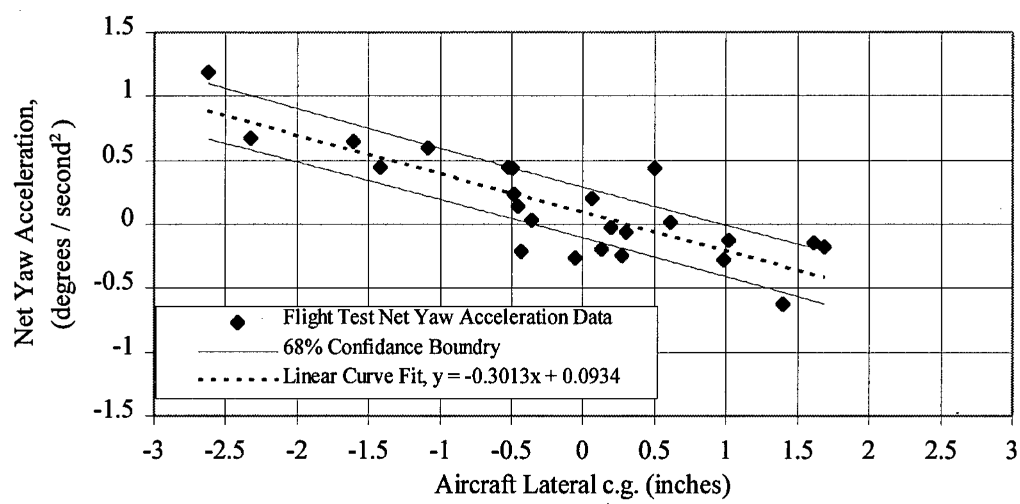


Figure 4-1. F-15B net yaw acceleration at 32,000 feet (9,754 meters) PA, with 0.4-inch (10.1-millimeter) RLED and 0.4-inch (10.1-millimeter) LLEU.

lateral c.g. position for the example F-15B. The confidence boundaries shown in Figure 4-1 are calculated using the MATLAB™ 'polyconf' function in the Statistics Toolbox (25:2-80). The flight test net yaw acceleration data are assumed to have an independent normal distribution. This assumption is necessary when using the 'polyconf' function. As a check of this assumption the flight test net yaw acceleration data are analyzed using MATLAB™ 'normplot' (25:2-70). 'Normplot' is a normal probability plot for graphical normality testing (25:2-70). If net yaw acceleration is normally distributed, the plot of normal probability versus net yaw acceleration resulting from 'normplot' will be linear (25:2-70). Figure 4-2 is a sample normal probability plot of net yaw acceleration for the example F-15B. In Figure 4-2 the net yaw acceleration data are considered linear

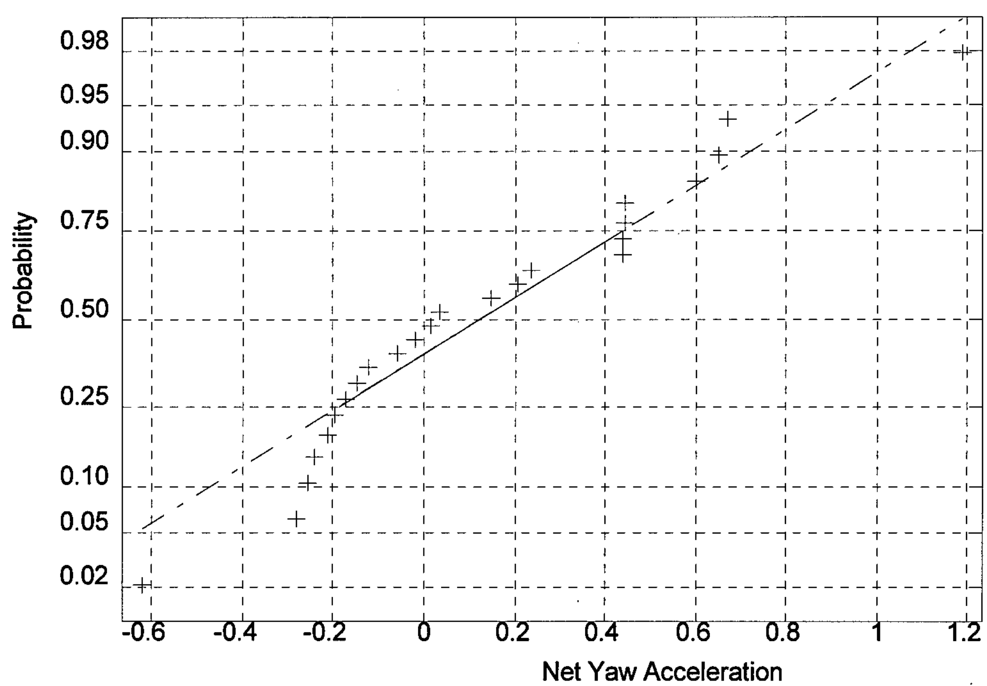


Figure 4.2. Normal probability plot of net yaw acceleration data for example F-15B.

supporting the normal distribution assumption. Therefore, the MATLAB™ 'polyconf' confidence boundaries are considered valid. The following analysis will use the flight test linear curve fit and 68 percent confidence bounds curves for comparison. The simulation results will be presented as a curve or point where appropriate.

4.3. Lateral Weight Asymmetries:

The effects of lateral c.g. shifts ranging from 2.8 inches (71.1 millimeters) left of aircraft centerline to 2.6 inches (66.0 millimeters) right of aircraft centerline on net yaw acceleration are tested. These c.g. shifts are equivalent to a 8,152 foot-pound (11,052 Newton-meter) left wing heavy asymmetry and 7,569 foot-pound (10,262 Newton-meter) right wing heavy asymmetry for the test aircraft with a 50 percent internal fuel load. Lateral c.g is adjusted in flight by use of the wing fuel transfer pump control switches. The fuel transfer pump control switches are turned on and off to allow a lateral wing fuel imbalance or a lateral c.g. shift to occur. Simulation and flight test results for net yaw acceleration as a function of lateral c.g. are presented in Figures B1 to B4. Figure 4-3, is a plot of simulator predictions and flight test linear curve fit along with

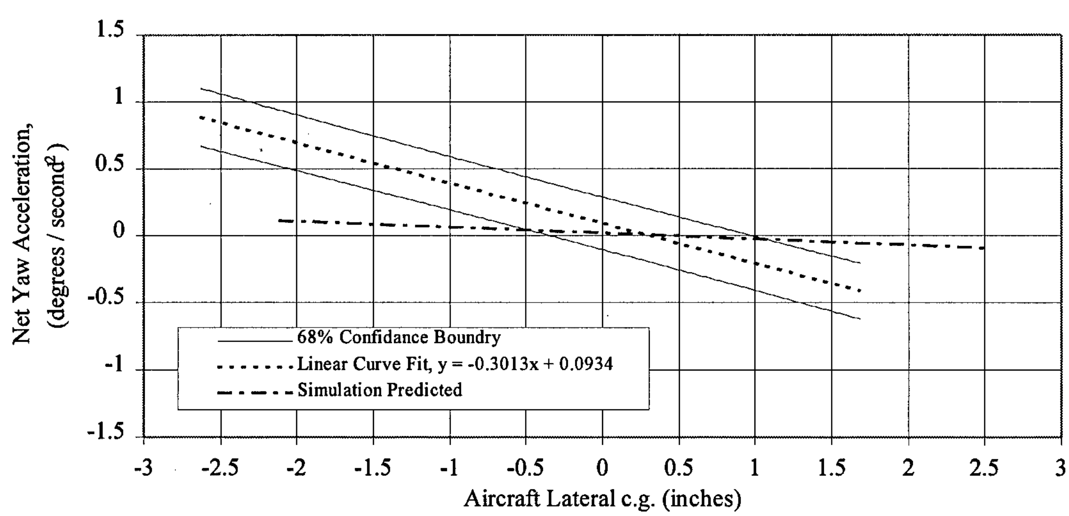


Figure 4-3. Simulation and flight test comparison of F-15 net yaw acceleration at 32,000 feet (9,754 meters) PA, with 0.4-inch (10.1-millimeter) RLED and 0.4-inch (10.1-millimeter) LLEU.

the 68 percent confidence boundaries for the example F-15 configuration. As shown in Figure 4-3, the simulation and flight test curves have a slope of same sense for lateral weight asymmetry. Therefore, Figure 4-3 indicates as lateral c.g. shifts to the left of aircraft centerline (negative) the aircraft yaws right (positive net yaw acceleration) at high AOA, and as lateral c.g. shifts to the right of aircraft centerline (positive) the aircraft yaws left (negative net yaw acceleration) at high AOA. This yawing away from an offset lateral c.g. agrees with Snyder, et al, (8:242) for the reasons given in Section 2.6. These same trends as shown in Figure 4-3 are valid for all data presented in Figures B1-B4. Although the slopes are of same sense, the magnitudes of simulator predicted net yaw acceleration are smaller than flight test net yaw acceleration. Therefore, flight test results should be used to update the F-15 simulator aerodynamic model. This updated aerodynamic model can than be used to more accurately model F-15 directional flight characteristics at high AOA.

A possible starting point for the updates is implementing the entire AERO-TAB-6 data set and analyzing the magnitude and true effects of the Offset scaling factor. The Offset term as explained earlier in Section 3.2.1, is a scaling factor used to scale the asymmetric yawing and side force coefficients $C_{N_{RB}}$ and $C_{Y_{RB}}$ respectively. The Offset term is based on test pilot comments of how the aircraft reacts in the flight regime of interest (19). Either of these starting points may result in a better model of F-15 high AOA aerodynamics and therefore, result in better simulator predictions.

Operational F-15s shift lateral c.g. for numerous reasons. These reasons include asymmetric external stores (e.g., asymmetric AIM-9 loading), asymmetric wing fuel tank feeding, and right side 20 mm gun location. Therefore, based on the results of this research, the weight asymmetry due to the 20 mm gun causes the F-15B to yaw away from the gun at high AOA.

4.4. Differential Stabilator Bias:

Two separate differential stabilator biases, 0.5-inch RLED (12.7-millimeter) with 0.5-inch (12.7-millimeter) LLEU (1.0 rig) and symmetric (0.0 rig) are simulated to investigate the effects of small changes in differential stabilator bias on aircraft net yaw acceleration during full aft stick stalls. Both differential stabilator biases are tested at various lateral c.g. locations. Both differential stabilator biases indicate the same trends, (i.e., right lateral c.g. shift causes a negative net yaw acceleration, and left lateral c.g. shift causes a positive net yaw acceleration) as presented in Figures B1-B4.

Comparison of 1.0 rig and 0.0 rig net yaw acceleration at 32,000 feet (9,754 meters) PA is presented in Figure 4-4. Figure 4-4 predicts that a small change to a right rolling differential stabilator produces a downward shift in the net yaw acceleration curve. This downward shift in net yaw acceleration is towards the zero net yaw acceleration axis. This type of shift toward the zero net yaw acceleration axis is desired since a zero net yaw acceleration value corresponds to a symmetric F-15 (see Section 4-6). Therefore, the simulation results support Snyder (4) flight test results.

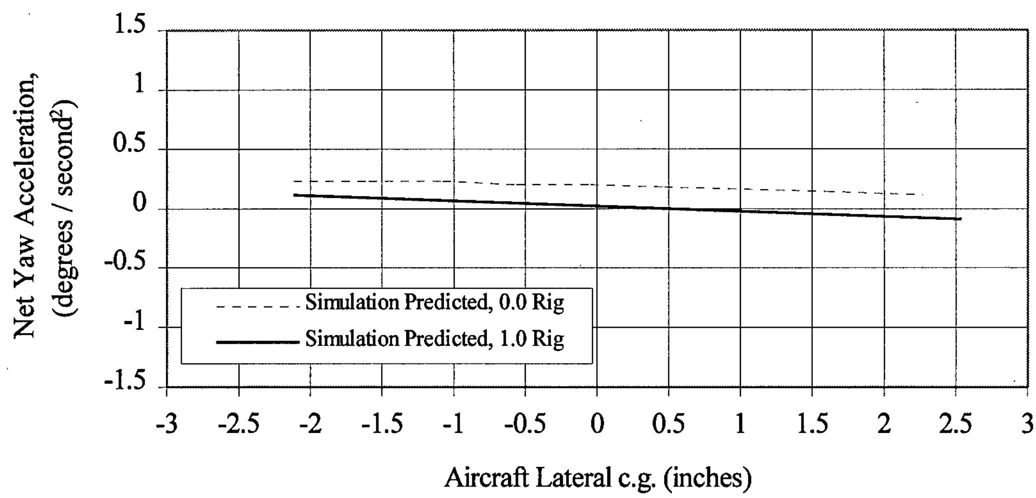


Figure 4-4. Simulator predicted effects of changing differential stabilator bias at 32,000 feet (9,754 meters) PA.

However, the flight test results presented next will indicate that small changes in differential stabilator bias cause only a small change in net yaw acceleration at high AOA. These small changes in net yaw acceleration do not support Snyders (4) conclusions.

Two separate differential stabilator biases, 0.4-inch RLED (10.2-millimeter) with 0.4-inch (10.2-millimeter) LLEU (0.8 rig) and 0.2-inch (5.1-millimeter) RLEU with 0.0-inch (0.0-millimeter) LLEU (-0.2 rig) are flight tested to investigate the effects of changing differential stabilator bias on aircraft net yaw acceleration during 1 g full aft stick stalls. Both differential stabilator biases are tested at various lateral c.g. locations. Both differential stabilator biases indicated the same trends, (i.e., right lateral c.g. shift causes a negative net yaw acceleration, and left lateral c.g. shift causes a positive net yaw acceleration) as presented in Figures B1-B4 and Figures B9-B10.

Comparison of the -0.2 rig with the example 0.8 rig net yaw acceleration at 32,000 feet (9,754 meters) PA is presented in Figure 4-5. Figure 4-5 indicates that the effects on net yaw acceleration of changing differential stabilator bias from the example

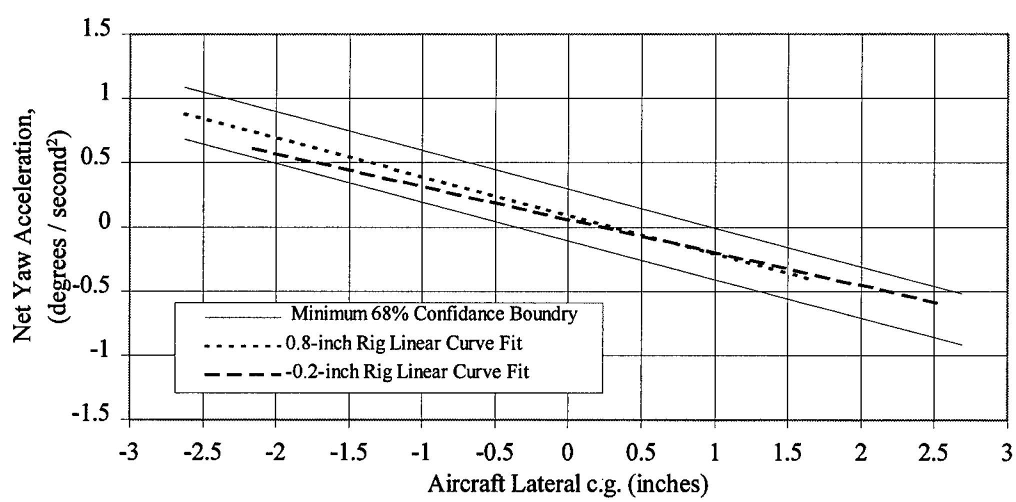


Figure 4-5. F-15B flight test effects of changing differential stabilator at 32,000 feet (9,754 meters) PA.

0.8 rig to the -0.2 rig stabilator bias is small. Therefore, based on this small difference in flight test results, small changes in differential stabilator bias cause small changes in net yaw acceleration at high AOA.

Comparing Figures 4-4 with 4-5 notice the flight test does not indicate the same shift down toward the zero net yaw acceleration value as did the simulation predictions. Furthermore, from Figure 4-6 which is a comparison of -0.2 rig and 0.8 rig net yaw

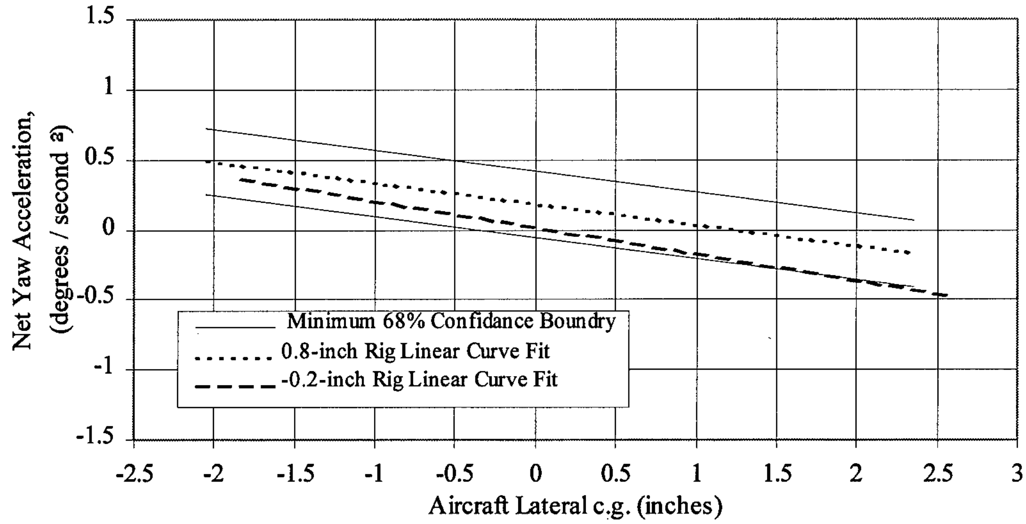


Figure 4-6. F-15B flight test effects of changing differential stabilator at 15,000 feet (4,572 meters) PA.

acceleration at 15,000 feet (4,572 meters) PA notice the small change to a right rolling differential stabilator bias produces an upward shift in the net yaw acceleration curve. Although the net yaw acceleration curve shifts up for the change in differential stabilator bias, the shift is considered small in terms of effects on net yaw acceleration. As discussed in Section 4.2, the shift is considered small because the majority of the net yaw acceleration linear curve fits lie within the 68 percent confidence interval. Therefore, the flight test indicated small change in net yaw acceleration for a small change in differential stabilator bias do not support the Snyder (4) and Snyder, et al, (8) conclusion of a significant effect on uncommanded yaw rate at high AOA is achievable by a small change in differential stabilator bias.

As discussed in Chapter 1, Snyders report (4) resulted in changes to the current F-15 maintenance guidance on differential stabilator bias. One of these changes for setting differential stabilator bias is given in TO 1F-15A-2-27JG-40-1 (5:7-36B). The job guide states, "normal stabilator rig position is 0.2 to 0.4-inch (5.1 to 10.2-millimeter) left LE (leading edge) up and 0.2 to 0.4-inch (5.1 to 10.2-millimeter) right LE (leading edge) down from the reference mark as entered in AFTO Form 781F" (5:7-37B). Therefore, the F-15 maintenance community must rig the differential stabilators in the range of a 0.4 to a 0.8-inch (10.2 to 20.4-millimeter) rig. On the basis of the small effects on net yaw acceleration for small changes in differential stabilator bias, this research does not support the use of such a limited differential stabilator bias range. Finally, because there is only a small difference noted between the 0.8 rig and the -0.2 rig at either altitude tested, the high AOA rig check used to determine the effectiveness of the differential stabilator rigging needs to be re-addressed. The FCF high AOA lateral rig check is discussed further in Section 4.7.3.

4.5. Lateral Aerodynamic Asymmetries:

Lateral aerodynamic asymmetries of an asymmetric AIM-9 missile loading are quantified. The asymmetric missile effect on aircraft net yaw acceleration at high AOA is divided into an aerodynamic and weight effect. The aerodynamic effect is a result of an increase in aerodynamic drag. The increase in aerodynamic drag is from the external mounting of the AIM-9. The increase in aerodynamic drag causes the aircraft to yaw into the missile as described in Section 2.5. The weight effect is a result of missile weight shifting lateral c.g. position. The shift in lateral c.g. causes the aircraft to yaw away from the missile at high AOA as presented in Section 2.6. In order to analyze the aerodynamic effects of the asymmetric AIM-9, the weight of the AIM-9 missile is analytically accounted for in the data analysis. To analytically account for the weight of the asymmetric AIM-9, the F-15 net yaw acceleration is analyzed at the c.g. location which includes the AIM-9 missile weight. The net yaw acceleration at this c.g. location allows the aerodynamic effects of the asymmetric AIM-9 to be analyzed. The results of this analysis are presented in Figures B11-B14 and Figure 4-7. Figure 4-7 is a plot of

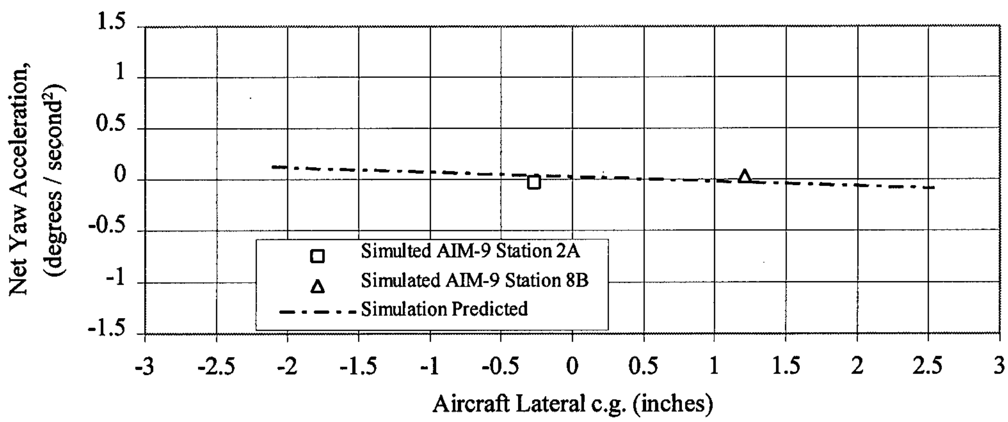


Figure 4-7. F-15 simulation net yaw acceleration predictions at 32,000 feet (9,754 meters) PA with 0.5-inch (12.7-millimeter) RLED and 0.5-inch (12.7-millimeter) LLEU.

simulator predicted net yaw acceleration versus lateral c.g. for the example F-15 configuration to include AIM-9 loadings. In Figure 4-7, the simulation results show at high AOA the AIM-9 missile aerodynamic effects lie near the simulator predicted lateral c.g. net yaw acceleration curve. Because the AIM-9 points lie near the lateral c.g. curve, the associated net yaw accelerations due to missile aerodynamic effects are considered small. This simulator predicted AIM-9 aerodynamic effect is supported by flight test data.

Returning to the example F-15B configuration, Figure 4-8 is plot of the linear curve fit net yaw acceleration versus lateral c.g. shift with flight test AIM-9 net yaw acceleration data over plotted. Figure 4-8 is for the example F-15B. Other AIM-9 missile data are presented in Figures B5-B8.

In Figure 4-8, the missile lateral aerodynamic asymmetric net yaw acceleration points lie within the data scatter of the raw baseline aircraft net yaw acceleration points.

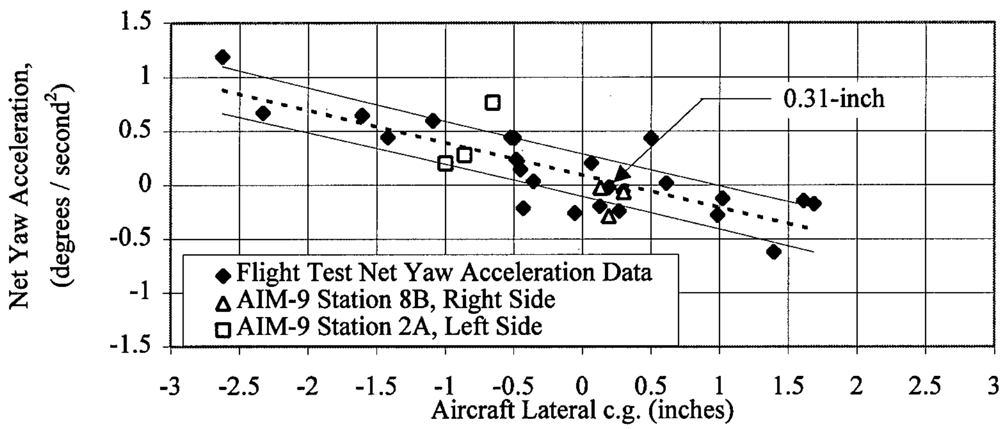


Figure 4-8. Sample AIM-9 missile effects on example F-15B.

Therefore, based on these flight test results, the missile aerodynamic effects are considered small which agrees with simulation predictions.

4.6. Identifying a Symmetric F-15:

Identification of a symmetric F-15 consists of finding the balance point for the aerodynamic asymmetries, weight asymmetries and differential stabilator biases. The symmetric F-15 is determined by identifying the F-15 configuration that results in a zero net yaw acceleration at high AOA. Returning to the simulation predicted differential stabilator bias effects shown in Figure 4-4, the F-15 configuration that results in zero net yaw acceleration is the baseline F-15 with the differential stabilators biased to 0.5-inch

(12.7-millimeter) RLED with 0.5-inch (12.7-millimeter) LLEU. This agrees with Snyder, et al, (8). However, as discussed in Section 4.4, flight test indicates that small changes in differential stabilator bias have only small effects on the value of net yaw acceleration. Therefore, flight test results do not associate a small differential stabilator bias with a symmetric F-15B configuration.

From Figures B1-B4, the flight tested F-15 configuration that results in zero yaw acceleration is the baseline F-15 independent of differential stabilator bias tested. From Figures B1-B4, the linear fit curve of net yaw acceleration crosses the zero net yaw acceleration at lateral c.g. values ranging from 0.1-inch (2.54-millimeter) to 1.1-inch (27.9-millimeter) right of aircraft centerline. However three out of four configurations flight tested indicate a right lateral c.g. shift of 0.1 to 0.35-inch (2.54 to 8.9-millimeter) is a symmetric F-15B configuration. The example F-15 linear curve fit of yaw acceleration presented in Figure 4-8 crosses the zero net yaw acceleration at 0.31-inch (7.9-millimeter). This lateral c.g. shift is similar to the lateral c.g. shift due to the right side location of the 20 mm gun. The right lateral c.g. shift due to the 20 mm gun weight is 0.35 to 0.55-inch (8.9 to 14-millimeter) for the baseline aircraft depending on total fuel remaining. Therefore, the data presented in Figures B1-B4 do not support modifications to the F-15 that change the lateral aerodynamic characteristics at high AOA. The data also does not support the use of a small differential stabilator bias setting to achieve a symmetric F-15 configuration at high AOA. The previous analysis was for a F-15 without any asymmetric external stores and as discussed in Chapter 1, the F-15 normally flies with a single AIM-9 practice training missile.

The F-15 fleet often uses one AIM-9 missile on either Station 2A or 8B for training missions with the preferred asymmetric AIM-9 missile loaded on Station 2A (1:5-14). The lateral c.g. shift due to a single AIM-9 loaded on either Station 2A or 8B at 50 percent internal fuel load is -0.29-inch (-7.4-millimeter) or 1.19-inch (30.2-millimeter) respectively. Simulation and flight test results are shown in Figures 4-4 and 4-5. Both simulation and flight test results indicate this c.g. shift results in approximately the same magnitude net yaw acceleration right (positive) or left (negative) depending on where the asymmetric AIM-9 is loaded. Therefore, this research does not support a preferred AIM-9 loading.

4.7. Lessons Learned:

This section discusses findings that were not specific research objectives. Nonetheless, these research findings are of importance to further understand the F-15 high AOA lateral-directional flying characteristics. The areas discussed are departure susceptibility, F-15 production fuel indications, FCF high AOA lateral rig checks, and altitude effects.

4.7.1. Departure Susceptibility:

At the beginning of this research it was believed simply changing differential stabilator bias could have an influence on improving departure resistance (8:245). The initial simulation results presented in Section 4.4 support that claim. Figure 4-9, is a plot of simulator predicted differential stabilator bias versus net yaw acceleration. In Figure 4-9, the differential stabilator bias sign convention is the same as described in Section 4.4. A positive bias causes the F-15 to roll right at low AOA and a negative bias causes the F-15 to roll left at low AOA. From Figure 4-9, the 1.0-inch rig results in a zero net yaw acceleration. The zero net yaw acceleration is assumed to be the symmetric aircraft. Therefore, the simulation supports changing the F-15 differential stabilator bias to a right roll bias at low AOA. However, flight test results indicate small differential stabilator bias changes have only a small effect on net yaw acceleration as presented in Section 4.4. Not only does flight test conclude small changes in differential stabilator

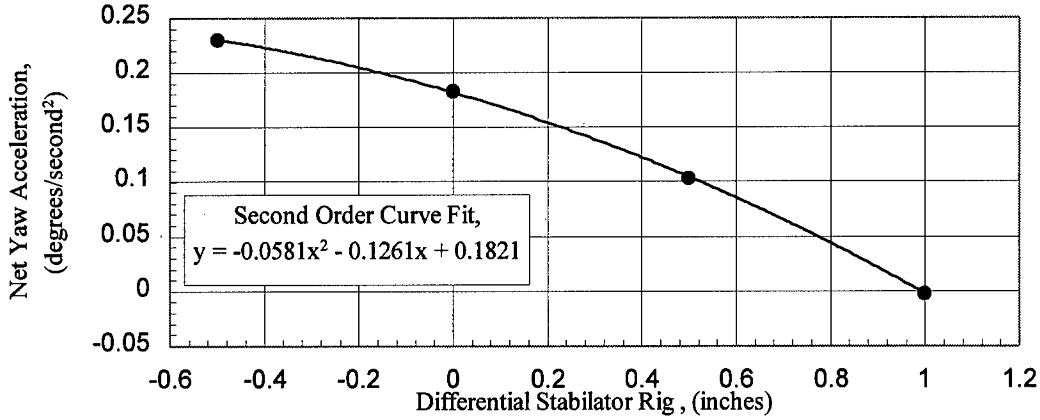


Figure 4-9. Simulator predicted net yaw acceleration for various differential stabilator rigs at 32,000 feet (9,754 meters) PA and with a 0.471-inch (12.0-millimeters) lateral c.g. shift.

bias cause small changes in net yaw acceleration but test pilot comments suggest the transitory yaw accelerations due to the oscillatory nature of the F-15 wing rock influence the aircrafts departure susceptibility (7). This conflicts with Snyder, et al, (8). Snyder, et al, (8) reports that small changes in differential stabilator may increase departure resistance, however, the results of this research de-emphasize the ability of small changes in differential stabilator bias to reduce F-15 departure susceptibility.

Departures in this research are defined as an uncommanded motion that requires the pilot to take corrective action to recover the aircraft. This definition does not include the case of first indication of the departure warning tone as stated in the F-15 flight manual (1:6-7). The departure warning tone simply indicates to the pilot that excessive yaw rates are developing not of an impending departure. During the flight test, numerous full aft stick stall test maneuvers were terminated for excessive yaw rate (7). However, only two true departures occurred.

Each departure is characterized by an uncommanded roll rate and a self sustained yaw rate in excess of 30 degrees/second. Both departures occurred with lateral fuel imbalances. The first departure was a 1,000 pound (4,448 Newton) left wing heavy fuel asymmetry and the second departure a 750 pound (3,336 Newton) left wing heavy asymmetry. The first departure occurred with the 0.8-inch (20.4-millimeter) rig at 15,000 feet (4,572 meter) PA and the second with the -0.2-inch (-5.1-millimeter) rig at 32,000 feet (9,754 meter) PA. The first departure resulted in a 630 degree right rotation. The second departure resulted in 360 degree right rotation. Both departures required the pilot to take corrective action to recover the aircraft. The 750 pound (3,336 Newton) left wing heavy asymmetry was flown numerous times, however, only one departure resulted. An in-depth analysis of the reasons why an F-15B departs one time and not the other is beyond the scope of this research. However, if these departure reasons are identified a decision can be made on whether to eliminate the cause or provide a more meaningful departure warning system to the pilot.

Two of the many possible causes for these departures are transient yaw acceleration and combined yaw and roll rate sense. Figure 4-10 is a plot of typical flight test yaw rate. In Figure 4-10, the transient yaw acceleration is shown as the mean slope of the oscillatory portion of the yaw rate curve. For this sample yaw rate data the

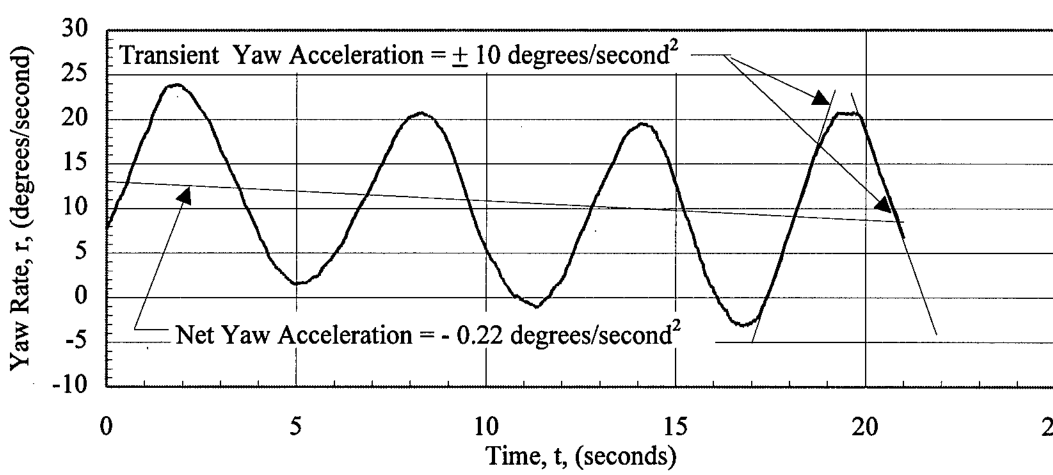


Figure 4-10. Transient yaw acceleration for sample flight test F-15B data.

transient yaw acceleration is $\pm$ 10 degrees/second^2. The plus-minus is a result of the oscillations. Also in Figure 4-10, the net yaw acceleration is shown to be - 0.22 degrees/second^2. The transient yaw acceleration is 46 times greater magnitude than the net yaw acceleration value. It is the large magnitude of these transient yaw accelerations that may be influencing the F-15s departure susceptibility. Test pilot comments indicate these large transient yaw oscillations are unaffected by small changes in differential stabilator (7). The F-15E Version 8 flight control enhancements use side acceleration (n_y) and side-slip rate ($\dot{\beta}$) feedback to greatly reduces the magnitude of wing rock at high AOA (14:260). The reduction in wing rock may reduce the magnitude of the transitory yaw acceleration by reducing the yaw oscillations due to wing rock. The reduction in magnitude of transitory yaw acceleration may increase departure resistance. Therefore, if this flight control system is implemented in the F-15A/B/C/D, the departure resistance at high AOA may increase. The F-15E Version 8 flight control enhancements also allow for direct control of differential stabilator through the rudder pedal movement. The use of differential stabilator for directional control at high AOA has improved the F-15E high AOA handling characteristics (14:260). The difference between this active use of differential stabilator and the ground adjusted differential stabilator is the magnitude of the differential stabilator used. The active differential stabilator is using inches of differential stabilator for directional control at high AOA while the ground adjusted differential stabilator uses less then an inch of differential stabilator (14). This difference in differential stabilator usage allows the active flight control system to use large amounts of differential stabilator control power to maneuver the F-15E at high AOA (14). The less then an inch of ground adjusted differential stabilator use was shown in Section 4.4, to be insignificant in affecting the F-15B high AOA directional flight characteristics. Besides the transitory net yaw acceleration, the combined yaw and roll rate sense is a possible influence of F-15 departures.

Figures 4-11a and 4-11b are typical flight test yaw and roll rate traces. In Figure 4-11a the yaw and roll rates are of opposite sense. Opposite sense means if the yaw rate is increasing the roll rate is decreasing. However, during another full aft stick stall, the yaw and roll rates are of like sense as shown in Figure 4-11b. Like sense means

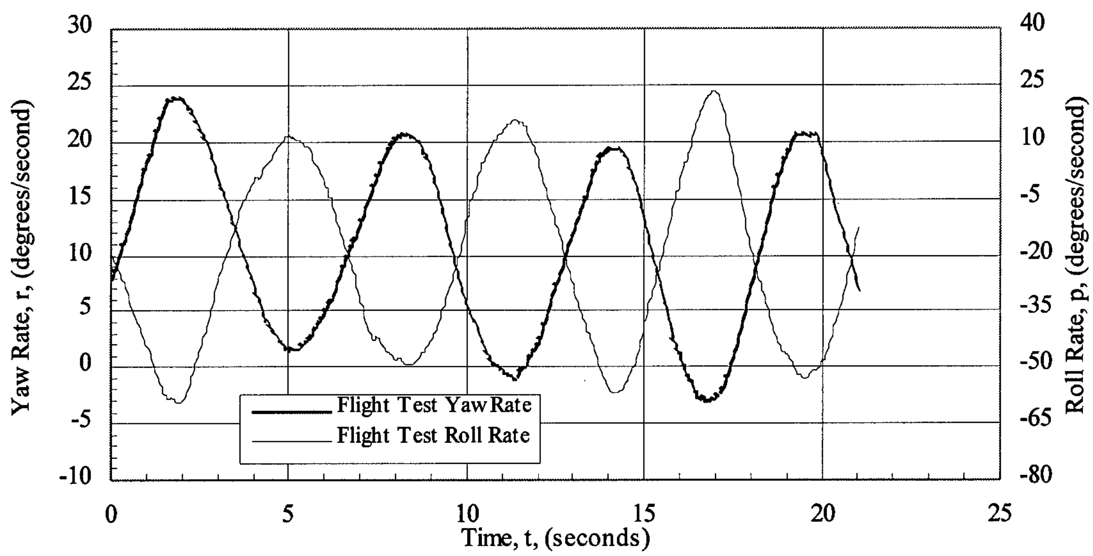


Figure 4-11a. F-15B opposite sense yaw and roll rates.

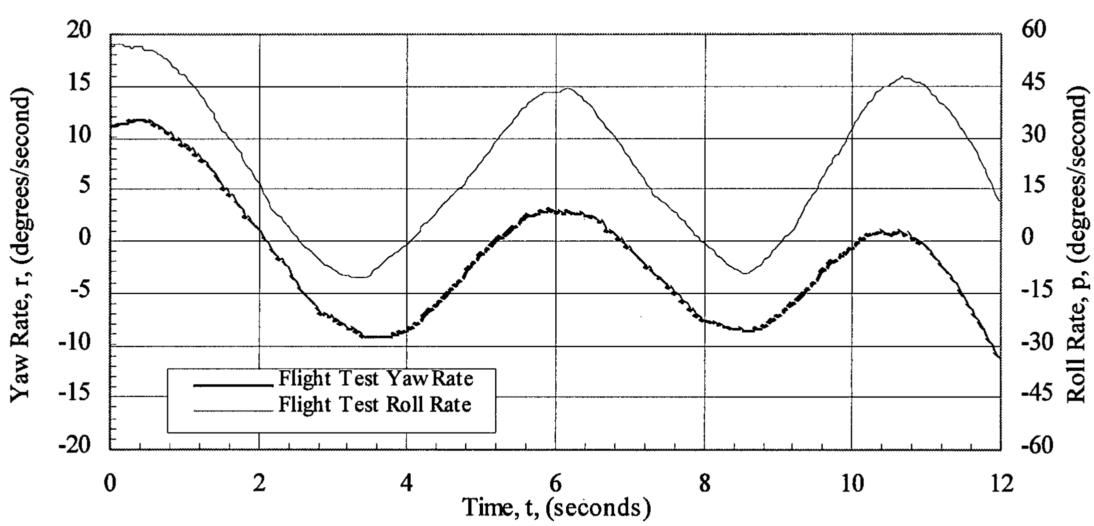


Figure 4-11b. F-15B same sense yaw and roll rates.

if the yaw rate is increasing the roll rate is increasing. Sixty stalls are sampled varying differential stabilator bias, AIM-9 missile location, and altitudes. Out of the 60 stalls sampled, 25 have yaw and roll rates of same sense. Both of the departures previously discussed occurred when yaw and roll rates are of same sense. There is no present explanation for why some stalls have yaw and roll rates of same sense and other stalls have opposite sense. Also the consequences of yaw and roll rate sense on departure is unknown. Continued research in this area may provide answers to these unknowns.

4.7.2. Cockpit Fuel Indication Errors:

Lateral c.g. shifts are achieved using the wing fuel transfer pump modification to create a lateral wing fuel imbalance (22). The magnitude of the lateral wing fuel asymmetry is determined using the DAS fuel indicating system. The magnitude of lateral wing fuel asymmetry is determined by subtracting the right wing fuel quantity from the left wing fuel quantity. The lateral wing fuel imbalances are defined positive for right wing heavy fuel asymmetries and negative for left wing heavy fuel asymmetries. DAS fuel indications are used over the production cockpit indications since the production cockpit wing fuel indicators are only accurate to ± 200 pounds (±890 Newtons) (1:1-16). Therefore, the possible fuel asymmetry error based on cockpit fuel indications is ± 400 pounds (±1,780 Newtons). The ± 400 pound (±1,780 Newtons) fuel asymmetry error is too large for this research. That large of a lateral fuel asymmetry error can effect the F-15 flight characteristics at high AOA. However, DAS fuel readings are achieved independently without use of the cockpit fuel indication system. Peavy (24) reports a DAS lateral fuel asymmetry error of ± 100 pounds (±445 Newtons) as determined by a two point volumetric calibration. Therefore, the calibrated DAS lateral fuel asymmetry indication is used as the truth source for this research. DAS lateral fuel indications are also used to verify the flight manual accuracy of the front cockpit fuel indicator. The verification of cockpit indicated lateral fuel asymmetry inaccuracy is discussed in the following paragraphs.

Figure 4-12 is a plot of fuel asymmetry error (Δw_{fe}) versus front cockpit total fuel weight for F-15B S/N 76-0130. Data are recorded both electronically on DAS and

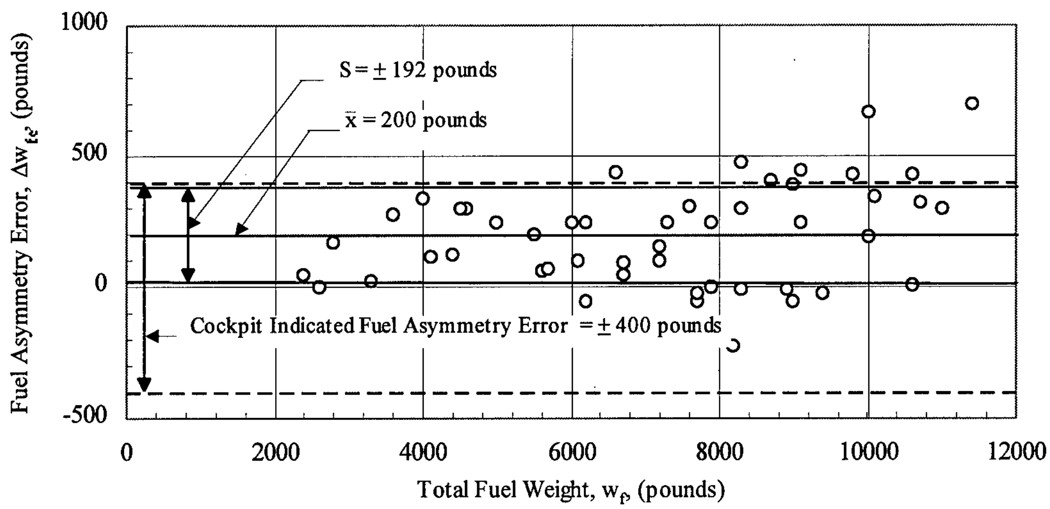


Figure 4-12. F-15B S/N 76-0130 lateral fuel asymmetry error, front cockpit indicator.

handheld in the cockpit. Lateral fuel asymmetry error (Δw_{fe}) is given by Equation (4-1a) and (4-1b) and indicated by an 'o' in Figure 4-12.

$$\Delta w_{fe} = \Delta w_{fdas} - \Delta w_{fcp}: \qquad \Delta w_{fdas} > 0 \tag{4-1a}$$

$$\Delta w_{fe} = \Delta w_{fcp} - \Delta w_{fdas}: \qquad \Delta w_{fdas} < 0 \tag{4-1b}$$

where Δw_{fdas} is the DAS indicated lateral fuel asymmetry and Δw_{fcp} is the front cockpit indicated fuel asymmetry. The reason for two equations is to keep the errors of too small an asymmetry (positive errors) or too large an asymmetry (negative errors) correct. The sign of fuel asymmetry changes when looking at right versus left fuel asymmetries. Too small a fuel asymmetry means fuel needs to be added to the heavy wing, and too large a fuel asymmetry means fuel needs to be subtracted from the heavy wing. In Figure 4-12, the average fuel asymmetry reading error is positive. Positive cockpit indicated fuel asymmetry error means the cockpit indicated fuel asymmetry is indicating less than the actual lateral fuel asymmetry. The sample mean ($\overline{x}$) and sample standard deviation (S) for the data presented in Figure 4-12 are calculated using Equations (4-2) and (4-3) and presented in Figure 4-12.

$$\overline{x} = \frac{1}{N}\sum x_i \tag{4-2}$$

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2} \tag{4-3}$$

where N is the number of samples and x_i is the sample value. The sample mean and sample standard deviation indicate to one sample standard deviation that this aircraft averages a 200 pound $\pm$ 192 pound (890 Newton $\pm$ 854 Newton) less lateral fuel asymmetry than actually present. This error is within the $\pm$ 400 pound ($\pm$ 1,780 Newton) flight manual predicted cockpit indicated fuel gauge accuracy's for calculating lateral fuel asymmetries (1:1-16). The magnitude of this lateral fuel asymmetry error demonstrates the inability of the production fuel gauge to accurately define the actual aircraft lateral fuel asymmetry.

Finally, as a check of DAS versus cockpit indicated lateral fuel asymmetry, a comparison of aircraft response at high AOA to both DAS and cockpit fuel asymmetry indications is accomplished. Overall aircraft lateral-directional response as described in T.O. 1F-15A-1 (1:6-5) of yawing and rolling away from a heavy wing at high AOA more closely matches the aircraft response expected due to the DAS indicated lateral fuel asymmetry. For example, Table 4-1 contains three sample lateral fuel asymmetries and their corresponding net yaw accelerations. Looking at the second entry, the cockpit indicated lateral fuel weight asymmetry is 100 pounds (445 Newtons) right wing heavy

Table 4-1. Comparison of DAS and cockpit lateral fuel asymmetries to F-15B response.

Cockpit Indicated Lateral Fuel Asymmetry (pounds)	DAS Indicated Lateral Fuel Asymmetry (pounds)	Net Yaw Acceleration (degrees/second^2)
400 right wing heavy	50 left wing heavy	-0.0582
100 right wing heavy	330 left wing heavy	0.6581
375 left wing heavy	850 left wing heavy	1.4792

while the DAS asymmetry is 330 pounds (1,468 Newtons) left wing heavy. The cockpit indicated fuel asymmetry according to the T.O. 1F-15A-1 should cause the aircraft to yaw and roll left away from the heavy wing at high AOA. However, the aircraft actually yaws right. The right yaw agrees with DAS indicated 330 pound (1,468 Newtons) left wing heavy asymmetry. The other two entries in Table 4-1 also show aircraft response more closely matches the aircraft response expected for the DAS indicated lateral fuel asymmetries. Entry one is an almost neutral yaw acceleration that agrees with the small 50 pound (222 Newton) DAS indicated fuel asymmetry. Entry three is a relatively large yaw acceleration that again agrees with the large 850 pound (3,781 Newton) DAS indicated fuel asymmetry. Again based on the response of the aircraft, the production fuel gauges are shown to be inaccurate. The fuel gauge inaccuracies can lead to an unknown error due to a possible unknown fuel asymmetry in high AOA lateral asymmetry testing to include the FCF high AOA lateral rig check.

4.7.3. FCF High AOA Lateral Rig Check:

As discussed in Section 4.4, there is only a small difference noted between the 0.8 rig and the -0.2 rig. Because of this small difference, the FCF high AOA lateral rig check used to determine the effectiveness of the differential stabilator rigging needs to be re-addressed. A high AOA rig check is performed on the F-15 FCF (13). This rig check is used to determine if the F-15 stabilator bias is correct (13). The high AOA rig check attempts to determine a differential stabilator bias setting for the F-15 that produces symmetric directional flight characteristics at high AOA (13:1-14). However, there are two major sources of error that can influence the outcome of the high AOA rig check. The two error sources are the ability to carefully maintain the control stick in the aft centered position and the ability to accurately measure lateral weight asymmetry. Both of these errors can lead to an unnecessary re-rigging of the differential stabilators. Also, the baseline F-15B flight tested was shown in Section 4.4 to have a small change in net yaw acceleration due to a small change in differential stabilator bias. These error sources and the small differences between the two stabilator biases demonstrate the need to re-evaluate the usefulness of the high AOA rig check.

If the control stick is not carefully maintained in the aft centered position, the differential stabilator deflection does not represent the true maintenance set differential stabilator bias. This change in differential stabilator deflection is due to changing differential stabilator deflection with changing lateral control stick position. Figure 4-13 is a plot of ground measured differential stabilator change versus lateral control stick position for the test F-15B aircraft. The change in differential stabilator deflection is measured with the control stick in the full aft position. A measurement is taken from a reference mark on the side of the aircraft to a reference mark on the stabilator leading edge. The control stick is then moved laterally in 0.25-inch (6.4-millimeter) increments.

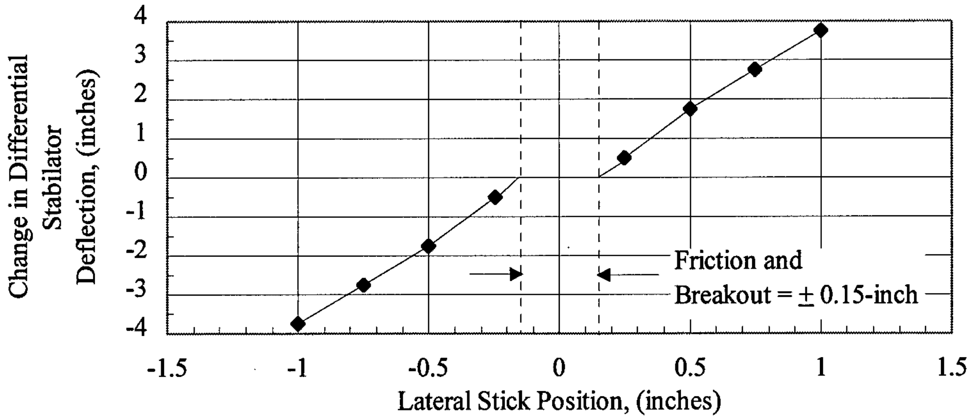


Figure 4-13. Lateral stick position effects on F-15B S/N 76-0130 differential stabilator deflection.

The change in distance between the aircraft and stabilator reference marks is recorded. This procedure is done for both stabilators. The changes are then added to get the total change in differential stabilator deflection for a given change in lateral stick position.

In Figure 4-13, if the FCF pilot moves the control stick laterally as little as 0.25-inch (6.4-millimeter) the differential stabilator position changes by 0.5-inch (12.7-millimeter) from the maintenance set differential stabilator bias. Therefore, to maintain the desired differential stabilator deflection, the FCF pilot must keep the stick centered ± 0.15-inch (± 3.8-millimeter) throughout the high AOA rig check. Also, if a change is made to the differential stabilator bias based on this FCF high AOA rig check another FCF high AOA rig check is flown. The second FCF is flown to verify the differential stabilator bias change is correct. However from Figure 4-13, without an instrumented control stick position indicator there is no guarantee that the FCF pilot will place the stick in the same aft centered position as on the first flight. Therefore, there is no guarantee that the correct change in differential stabilator bias is being evaluated. Again this difficulty of testing correct differential stabilator bias on subsequent FCF flights is seen in Figure 4-13. Assume a FCF pilot on the second stabilator bias verification FCF flight misplaces the control stick laterally by 0.5-inch (12.7-millimeter) from the first FCF flight. This lack of exact lateral control stick placement changes the differential stabilator deflection by 1.75-inches (44.5-millimeters). This change of differential stabilator deflection causes the FCF pilot to evaluate a totally different differential stabilator than intended. This research uses an instrumented F-15B and a calibrated control stick to ensure consistent aft centered stick position stall to stall. Therefore, the instrumented aircraft allows the true effects of differential stabilator bias to be evaluated.

The second major error source in the high AOA rig check is inaccurate lateral weight asymmetry indications as discussed previously in Section 4.7.2. Aircraft lateral weight asymmetry is caused by two primary sources asymmetric configuration such as a single AIM-9 missile and lateral wing fuel imbalance. The lateral asymmetry due to asymmetric configuration is well known and presented in T.O.1F-15A-1 (1:6-7). However, the lateral fuel imbalance indicator (cockpit fuel indicator) is not accurate enough for use as a measure of lateral fuel imbalance in flight test. Therefore, the inaccuracies of cockpit fuel indications combined with the high AOA lateral rig check allowable fuel asymmetry of $\pm$ 150 pounds ($\pm$ 667 Newtons) causes an unknown magnitude lateral c.g. shift. This unknown lateral c.g. shift may cause the F-15 to yaw at high AOA. If the yaw is significant enough, the F-15 stabilator bias will be unnecessarily re-rigged because of the unknown lateral c.g. shift and not because of incorrect differential stabilator bias.

4.7.4. Altitude Effects:

The effects of altitude on net yaw acceleration are presented in Figures B15 and B16. These two figures are comparisons of lateral c.g. shift versus net yaw acceleration for both 15,000 and 32,000 feet (4,572 and 9,754 meters) PA. In Figures B15-B16, the change in linear curve fits for both yaw accelerations are small. The only notable difference between the two altitudes shown in Figures B15-B16 is the slope of the linear fit net yaw acceleration. The slope for the linear fit net yaw acceleration at low altitude is slightly shallower than the higher altitude. This shallower net yaw acceleration slope is due to the increased directional stability of the F-15 at lower pressure altitudes (1:6-6).

4.8. Summary:

This chapter presented a method of quantifying lateral asymmetries using net yaw acceleration as a metric. Simulation analysis was shown to be a useful tool in identifying trends of lateral asymmetry effects on F-15 high AOA flight characteristics. Differences between the simulation and flight test results along with differences between this research and previous research were discussed. Next, a symmetric F-15 was identified based on a F-15 configuration that resulted in a net yaw acceleration of zero. Finally, the combination of simulation and experimental flight test analysis identified two possible causes of F-15 departures at high angles of attack.

5. Conclusions and Recommendations:

5.1. Introduction:

This research has characterized the effects of lateral weight asymmetries, differential stabilator biases, and lateral aerodynamic asymmetries using net yaw acceleration as a metric. Both a modified 6 DOF F-15 simulator and a modified F-15B aircraft were used to gather data to characterize the effects of each asymmetric contributor. The gathered data was used to compare the predictions of the 6 DOF simulator with flight test results. The data were also used to quantify the effects of each of the lateral asymmetries and to identify a symmetric F-15 configuration. Finally, the simulation and flight test results led to many lessons learned about the F-15 high AOA flying characteristics.

5.2. 6 Degree-of-Freedom Simulator Comparison:

A 6 degree-of-freedom simulation was used as basis for the flight test. The simulation predicted correct trends and accurate lateral aerodynamic asymmetric missile effects. Although the simulator predicted correct net yaw acceleration versus lateral c.g. position curve slope sense, the simulation underestimated the magnitude of net yaw acceleration for lateral weight asymmetries or lateral c.g. shifts. However, the simulation did agree with flight test results for missile aerodynamic effects on net yaw acceleration. The simulation predicted the missiles to have a small effect on net yaw acceleration and flight test results confirmed the small aerodynamic effects.

Recommendation 1: Use flight test results to update the simulator aerodynamic model of the F-15.

5.3. Lateral Weight Asymmetries:

This research indicated a correlation between lateral c.g. position and net yaw acceleration. Positive lateral c.g. positions of up to 2.6-inches (66.0-millimeters) resulted in a negative net yaw acceleration, while negative lateral c.g. positions of up to 2.8-inches (71.1-millimeters) resulted in positive net yaw acceleration. The operational F-15 is known to shift lateral c.g. for numerous reasons. Some of these reasons include asymmetric external stores, asymmetric wing fuel tank feeding, and the built-in positive lateral c.g. shift of the right side 20 mm gun location. This research concluded that the F-15B yaws away from the lateral c.g. shift. Hence, the lateral weight asymmetry due to the right side 20 mm gun location causes the aircraft to yaw away from the gun at high AOA.

5.4. Differential Stabilator Bias:

The simulation and flight test concentrated on two F-15 differential stabilator biases. The two biases were a symmetric bias and a right rolling stabilator bias. These biases were simulated and flight tested to investigate the effects of changing differential stabilator bias on aircraft net yaw acceleration during 1 g full aft stick stalls. Both simulated and flight tested differential stabilator biases were analyzed at various lateral c.g. locations. Both simulated and flight tested differential stabilator biases indicated the same trends of right lateral c.g. shift causing a negative net yaw acceleration, and left lateral c.g. shift causing a positive net yaw acceleration. The simulation predicted that a small change from the symmetric differential stabilator bias (0.0 rig) to the right rolling differential stabilator bias (1.0 rig) results in a reduction of net yaw acceleration. This reduction in net yaw acceleration agreed with Snyders (4) research results. Although simulation predictions agreed with Snyder (4) flight test did not.

The flight test results indicated small changes in differential stabilator bias from a near symmetric differential stabilator bias (-0.2 rig) to a right rolling differential stabilator bias (0.8 rig) have small effects on net yaw accelerations at high AOA. Therefore, the usefulness of adjusting the differential stabilator in small amounts to attain a symmetric F-15 configuration at high AOA was not supported. The differences between the results of this research and previous research were attributed to aircraft configuration, instrumentation, and flight test method discussed in Chapters 1 and 3. Because of the results of this research, current F-15 differential stabilator guidance brought about by the results of previous research need to be re-addressed.

Current F-15 maintenance guidance on setting differential stabilator bias is to rig the differential stabilators in the range of a 0.4 to a 0.8-inch (10.2 to 20.4-millimeter). The differential stabilator biases for flight test ranged from -0.2-inch (-5.1-millimeter) to 0.8-inch (10.2-millimeter). This range covers a full 1-inch (25.4-millimeter) difference in differential stabilator bias with only small effects on aircraft net yaw acceleration. Therefore, the flight tests do not support the use of such a limited differential stabilator bias range.

Finally, because there was only a small difference noted between the 0.8-rig (10.2-millimeter) and the -0.2 rig (-5.1-millimeter) at either altitude tested, the check for determining the effectiveness of the differential stabilator rigging needs to be re-evaluated. A high AOA rig check is performed on F-15 Functional Check Flights (FCF). The high AOA rig check attempts to determine a differential stabilator bias for the F-15 that produces symmetric directional flight characteristics at high AOA. However, two major sources of error were identified that can influence the outcome of this high AOA rig check.

The two error sources were the ability to carefully maintain the control stick in the aft centered position and the ability to accurately measure lateral weight asymmetry.

If the control stick was not carefully maintained in the aft centered position, the differential stabilator deflection would not represent the desired differential stabilator deflection. Therefore, without an instrumented control stick position indicator there was no guarantee that the FCF pilot would place the stick in the same aft centered position stall to stall and flight to flight. The second major error with the high AOA rig check was the inability to accurately measure lateral weight asymmetry. Both of these errors can lead to an unnecessary re-rigging of the differential stabilators.

Recommendation 2: Re-evaluate and determine the need to perform the Functional Check Flight high AOA lateral rig check.

5.5. Lateral Aerodynamic Asymmetries:

This research quantified the lateral aerodynamic asymmetries of an asymmetric AIM-9 missile configuration. Net yaw acceleration was the metric. Results indicated AIM-9 missile effects were predominately caused by the weight of the missile and not by the asymmetric aerodynamics of the external missile carriage.

5.6. Identifying a Symmetric F-15:

This research identified an aerodynamic symmetric F-15B configuration. Identification of a symmetric F-15 consisted of finding the balance point for the aerodynamic asymmetries, weight asymmetries and differential stabilator biases. The symmetric F-15 was determined by identifying the F-15 configuration that resulted in a zero net yaw acceleration at high AOA. The F-15 configuration that resulted in zero yaw acceleration was the baseline F-15 independent of differential stabilator bias tested. The baseline F-15B configuration consisted of a centerline fuel tank, two wing pylons on Stations 2 and 8, four LAU-114 launchers, and gun installed with gun exhaust system open. Therefore, the data presented did not support modifications to the F-15 to change the lateral aerodynamic characteristics of the F-15 at high AOA.

The F-15 fleet often uses one AIM-9 missile on either Station 2A or 8B for training missions with the preferred asymmetric AIM-9 missile loaded on Station 2A. The c.g. shift resulted in approximately the same magnitude net yaw acceleration, both right (positive) or left (negative) depending where the asymmetric AIM-9 was loaded. Therefore, the flight test data did not support a preferred AIM-9 loading.

5.7. Departure Susceptibility:

This research indicated small differential stabilator bias changes had a small effect on net yaw acceleration. Not only did this research indicate small changes in differential stabilator bias produce small changes in net yaw acceleration, but test pilot comments suggested the transitory yaw accelerations due to the oscillatory nature of the F-15 wing rock influenced the departure susceptibility of the F-15B at high AOA.

Departures in this research were defined as an uncommanded motion that required the pilot to take corrective action to recover the aircraft. Only two true departures as defined above occurred in flight test. Two of the many possible causes for these departures were transient yaw accelerations and combined yaw and roll rate sense. The transient yaw acceleration was the mean slope of the oscillatory portion of the yaw rate curve. This transient yaw acceleration was up to 46 times greater magnitude than the net yaw acceleration value. It was the large magnitude of these transient yaw accelerations that may be influencing the F-15s departure susceptibility. Another possible cause of F-15 departure was the combined sense of yaw and roll rates.

Twenty-five of sixty stalls sampled, had yaw and roll rates of same sense. Both of the departures previously discussed occurred when yaw and roll rates were of same sense. There was no explanation for why some stalls have yaw and roll rates of same sense and other stalls have opposite sense. Also, the consequences of yaw and roll rate sense on departure was unknown. Therefore, the effects, of yaw and roll rate sense on F-15 departure susceptibility is unknown.

Recommendation 3: Conduct follow-on research into the effects of transient net yaw acceleration and yaw and roll rate sense on F-15 departure susceptibility. Investigate the physical reasons for why yaw and roll rate sense is at times of like sense and at other times of opposite sense.

5.8. Cockpit Fuel Indication Errors:

The production cockpit fuel indicator which is the primary operational indicator of a lateral weight asymmetry was shown to be unreliable for lateral asymmetry flight test. The production cockpit wing fuel tank indicators were accurate to $\pm$ 200 pounds ($\pm$890 Newtons) each; therefore, the possible fuel asymmetry error was $\pm$ 400 pounds ($\pm$1,780 Newtons). The magnitude of this lateral fuel asymmetry error was large enough to adversely effect the F-15 high AOA directional flight characteristics, and characterizing the effects of a specific lateral wing fuel imbalance was difficult.

Recommendation 4: Investigate and determine if the production fuel quantity indication system can be updated to more accurately display actual fuel readings to the pilot.

5.9. Altitude Effects:

The change in linear curve fits for both yaw accelerations at the altitudes tested were small. The only notable difference between the two altitudes tested was the slope of the linear fit net yaw acceleration curves. The slope for the low altitude case were slightly shallower than the higher altitude.

5.10. Summary:

This research quantitatively investigated the correlation between lateral aerodynamic asymmetry, lateral weight asymmetry, and differential stabilator bias upon the directional flight characteristics of the F-15 at high AOA. Although, this research accomplished the needed requirement of rigorously quantifying and correlating the lateral asymmetries on the uncommanded yawing motion of the F-15 at high AOA other areas for further research were identified. The general areas for further research discussed were transient yaw acceleration, yaw and roll rate sense, and modification to the F-15 simulator aerodynamic model. The transient yaw acceleration and yaw and roll rate sense should be further investigated for their effects if any on F-15 departure susceptibility. The modification to the F-15 simulator aerodynamic model should be investigated to allow a better prediction of F-15 high AOA directional flight characteristics. Both of these areas for further research may result in a better understanding of F-15 high AOA lateral-directional flight characteristics.

APPENDIX A

INSTRUMENTATION

Table A1: F-15B Instrumentation Resolutions and Sampling Rates

PARAMETER NAME	SOURCE	RANGE	RESOLUTION	SAMPLES PER SECOND
Left Aileron Position	Transducer	±20deg	0.05deg	53.33
Right Aileron Position	Transducer	±20deg	0.05deg	53.33
Left Stabilator Position	Bus - 16 Bit	- 30deg to 15deg	0.006deg	26.66
Right Stabilator Position	Bus - 16 Bit	- 15deg to 30deg	0.006deg	26.66
Left Rudder Position	Transducer	±30deg	0.04deg	53.33
Right Rudder Position	Transducer	±30deg	0.04deg	53.33
Speed Brake Position	Transducer	0deg to 45deg	0.03deg	53.33
Longitudinal Stick Force	Transducer	±25 lbs	0.04 lbs	53.33
Lateral Stick Force	Transducer	±20 lbs	0.05 lbs	53.33
Longitudinal Stick Position	Transducer	-3 to 6 in	0.008 in	53.33
Lateral Stick Position	Transducer	±4 in	0.007 in	53.33
Right Rudder Pedal Force	Transducer	±200 lbs	0.3 lbs	53.33
Left Rudder Pedal Force	Transducer	±200 lbs	0.3 lbs	53.33
Right Rudder Pedal Position	Transducer	±4 in	0.02 in	53.33
Left Rudder Pedal Position	Transducer	±4 in	0.02 in	53.33
Right Power Lever Angle	Transducer	0deg to 130deg	0.09deg	6.66
Left Power Lever Angle	Transducer	0deg to 130deg	0.09deg	6.66
Left Fuel Flow	Transducer	0 to 100,000 lbs/hr	0.025 lbs/hr	6.66
Right Fuel Flow	Transducer	0 to 100,000 lbs/hr	0.025 lbs/hr	6.66
Left Engine Nozzle Area	Transducer	2.5 to 65. ft^2	0.022 ft^2	6.66
Right Engine Nozzle Area	Transducer	2.5 to 65. ft^2	0.022 ft^2	6.66
Left Core Speed (N2)	Production System	0 to 110 %	0.2 %	53.33
Right Core Speed (N2)	Production System	0 to 110 %	0.2 %	53.33
Pressure Altitude	Bus - 16 Bit	-1,560 to 80,337 ft	1.25 ft	26.66

Table A1: F-15B Instrumentation Resolutions, and Sampling Rates (concluded).

PARAMETER NAME	SOURCE	RANGE	RESOLUTION	SAMPLES PER SECOND
ψ - Heading Angle	Bus	±180deg	0.4deg	26.66
θ - Pitch Angle	Bus	±180deg	0.09deg	26.66
ϕ - Roll Angle	Bus	±180deg	0.09deg	26.66
Left Fuel Quantity	Production System	0-3200 lbs	2.5 lbs	53.33
Right Fuel Quantity	Production System	0-3200 lbs	2.5 lbs	53.33
Mach	Bus - 15 Bit	0.0985 to 3.0195	0.0002	26.66
V_T - True Airspeed	Bus - 15 Bit	60 to 1710 kt	0.125 kt	26.66
Indicated Airspeed	Bus - 15 Bit	14.12 to 999.9 kt	0.625 kt	26.66
Total Fuel Quantity	Bus - 16 Bit	0 to 25,600 lbs	2 lbs	26.66
p - Roll Rate	Transducer	±120deg/sec	0.1deg/sec	53.33
q - Pitch Rate	Transducer	±60deg/sec	0.1deg/sec	53.33
r - Yaw Rate	Transducer	±60deg/sec	0.1deg/sec	53.33
n_z - g's Coarse	Transducer	-10 to 10 g	0.02 g	53.33
n_z - g's Fine	Transducer	±3 g	0.004 g	53.33
n_y - Lateral g	Transducer	±2 g	0.004 g	53.33
n_x - Longitudinal g	Transducer	±2 g	0.003 g	53.33
Normal Accel	Bus - 16 Bit	±16 g	0.0005 g	26.66
α - Angle of Attack - True	Bus	-5deg to 35deg	0.05deg	53.33
β- Angle of Sideslip - Fine	Transducer	±30deg	0.025deg	53.33
Total Temp	Production	-50 to 150deg F	0.5deg F	53.33
Event Marker	Transducer		Discrete	53.33
IRIG Time				53.33
Voice				2666.66

* Not listed are a number of seldom used navigation, weapons, and radar parameters

APPENDIX B

DATA PLOTS

Data Basis: Flight Test
Test Aircraft: F-15B S/N 76-0130
Test Dates: Sept 95 - Oct 95
Flight Test Technique: Full Aft Stick Stall, Engines IDLE

Configuration: Cruise (gear, flaps, and speed brake retracted)
Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8
Engines: F100-PW-100 Fuel: JP-8
Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

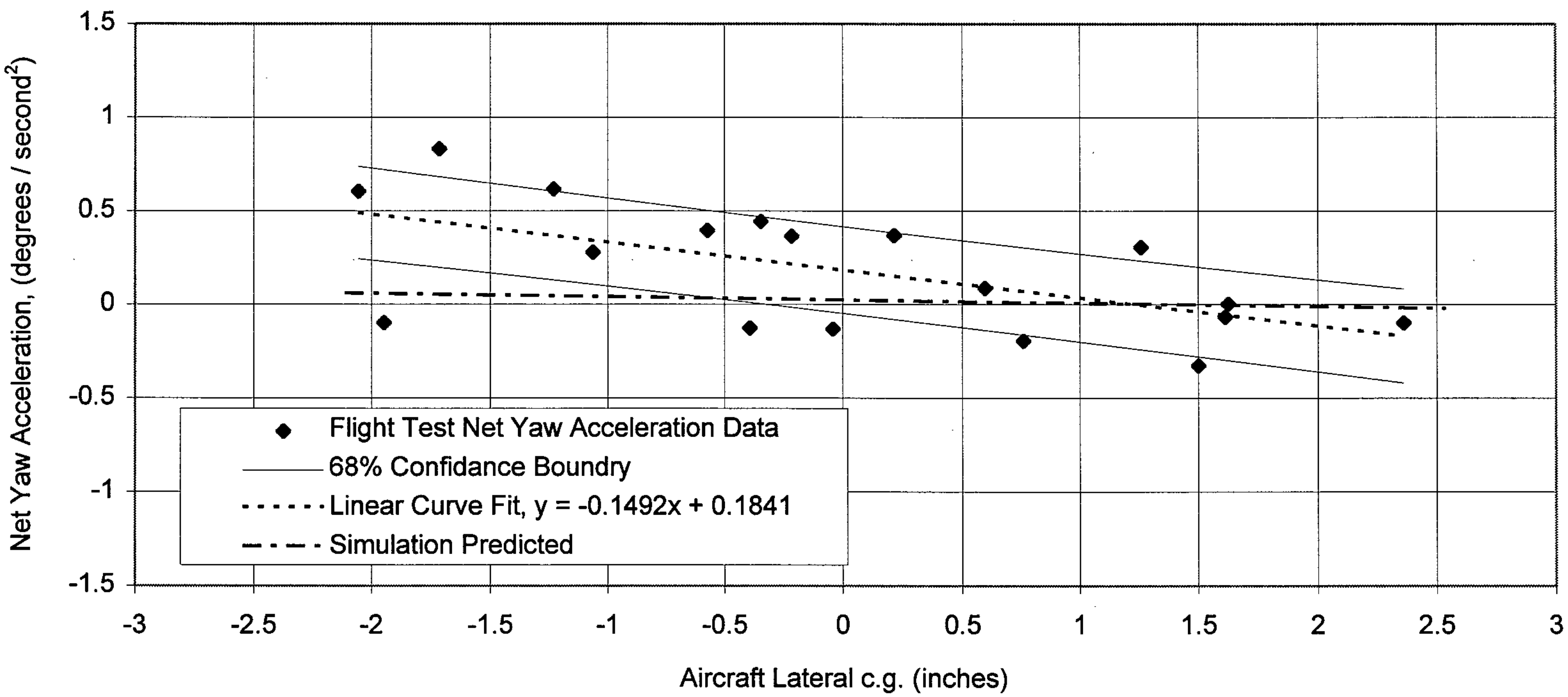


Figure B1. F-15B Net Yaw Acceleration at 15,000 feet PA, With 0.4-inch LLEU and 0.4-inch RLED

Data Basis: Flight Test
Test Aircraft: F-15B S/N 76-0130
Test Dates: Sept 95 - Oct 95
Flight Test Technique: Full Aft Stick Stall, Engines IDLE

Configuration: Cruise (gear, flaps, and speed brake retracted)
Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8
Engines: F100-PW-100 Fuel: JP-8
Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

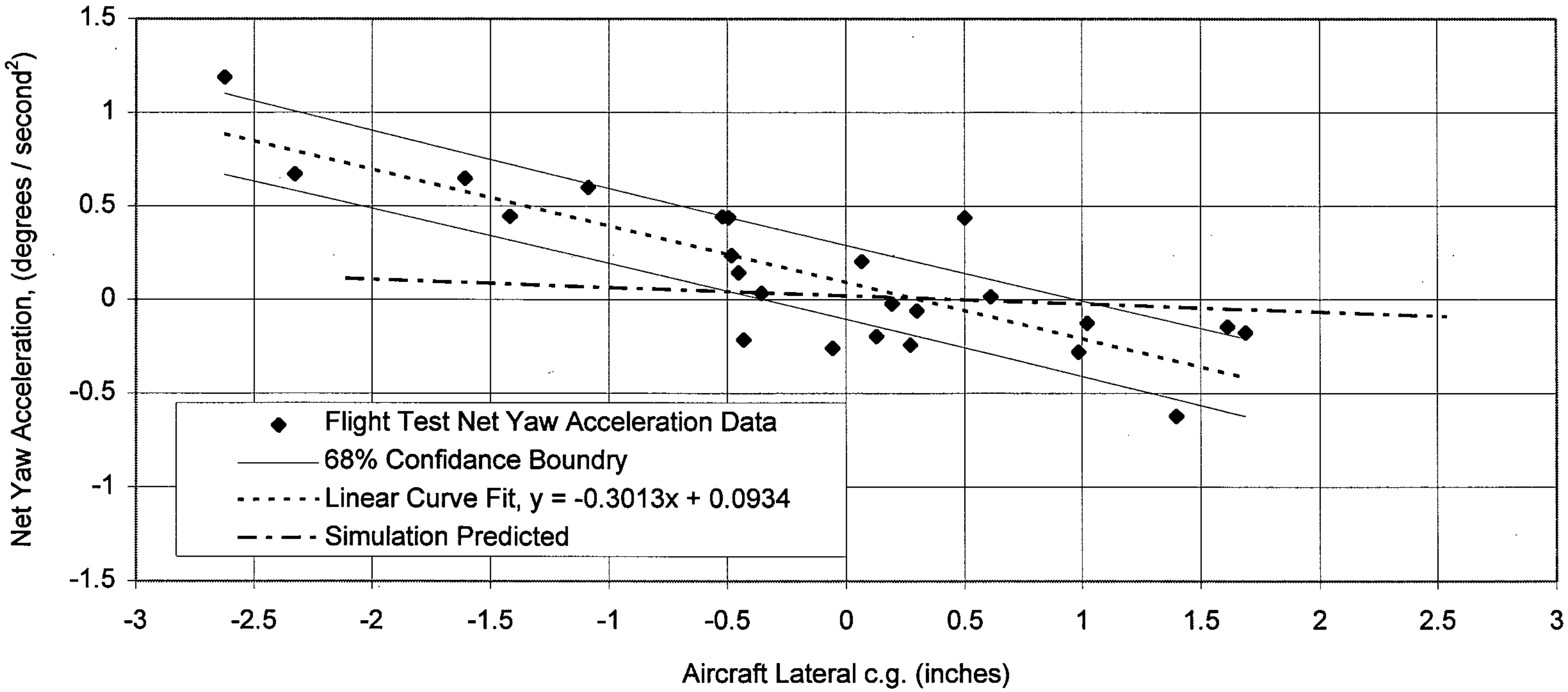


Figure B2. F-15B Net Yaw Acceleration at 32,000 feet PA, With 0.4-inch LLEU and 0.4-inch RLED

Data Basis: Flight Test Test Aircraft: F-15B S/N 76-0130 Test Dates: Sept 95 - Oct 95 Flight Test Technique: Full Aft Stick Stall, Engines IDLE	Configuration: Cruise (gear, flaps, and speed brake retracted) Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8 Engines: F100-PW-100 Fuel: JP-8 Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

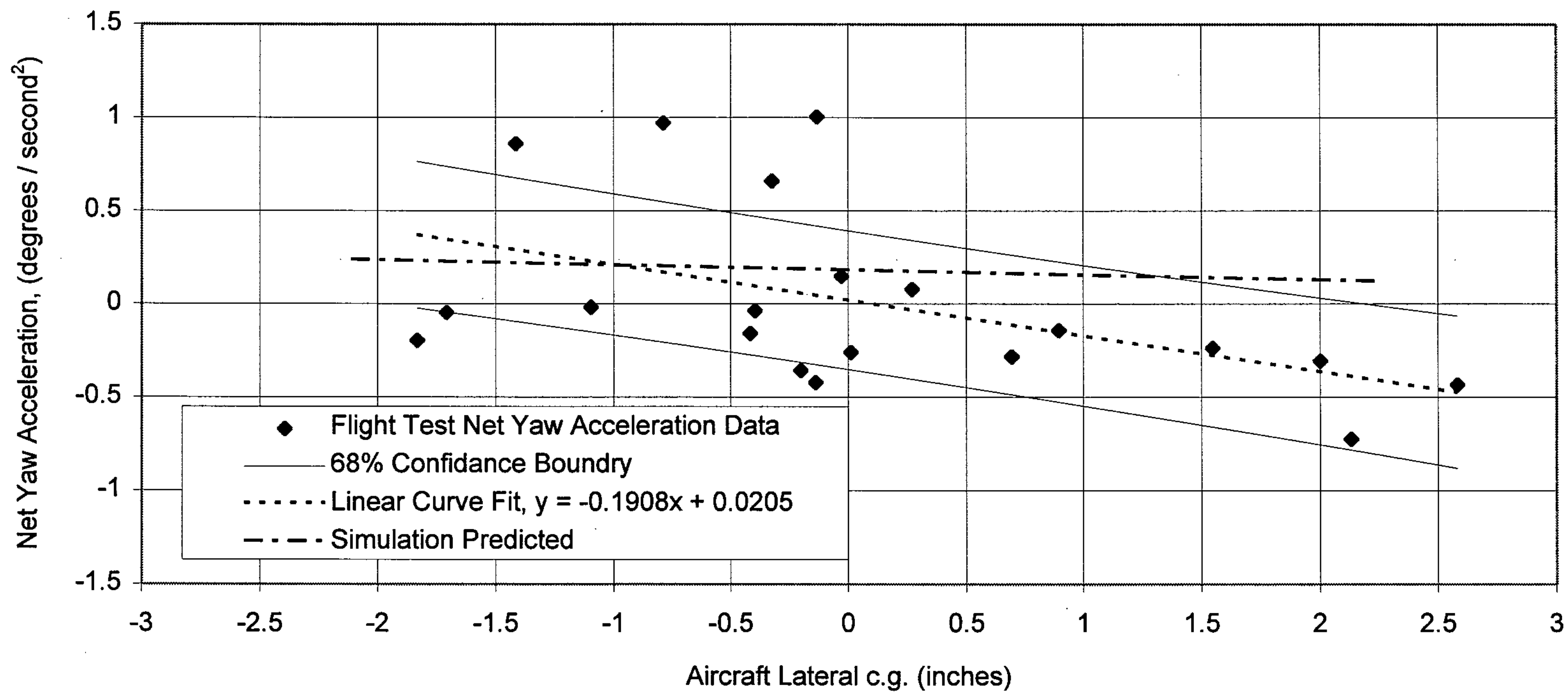


Figure B3. F-15B Net Yaw Acceleration at 15,000 feet PA , With 0.0-inch LLEU and 0.2-inch RLEU

Data Basis: Flight Test Test Aircraft: F-15B S/N 76-0130 Test Dates: Sept 95 - Oct 95 Flight Test Technique: Full Aft Stick Stall, Engines IDLE	Configuration: Cruise (gear, flaps, and speed brake retracted) Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8 Engines: F100-PW-100 Fuel: JP-8 Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

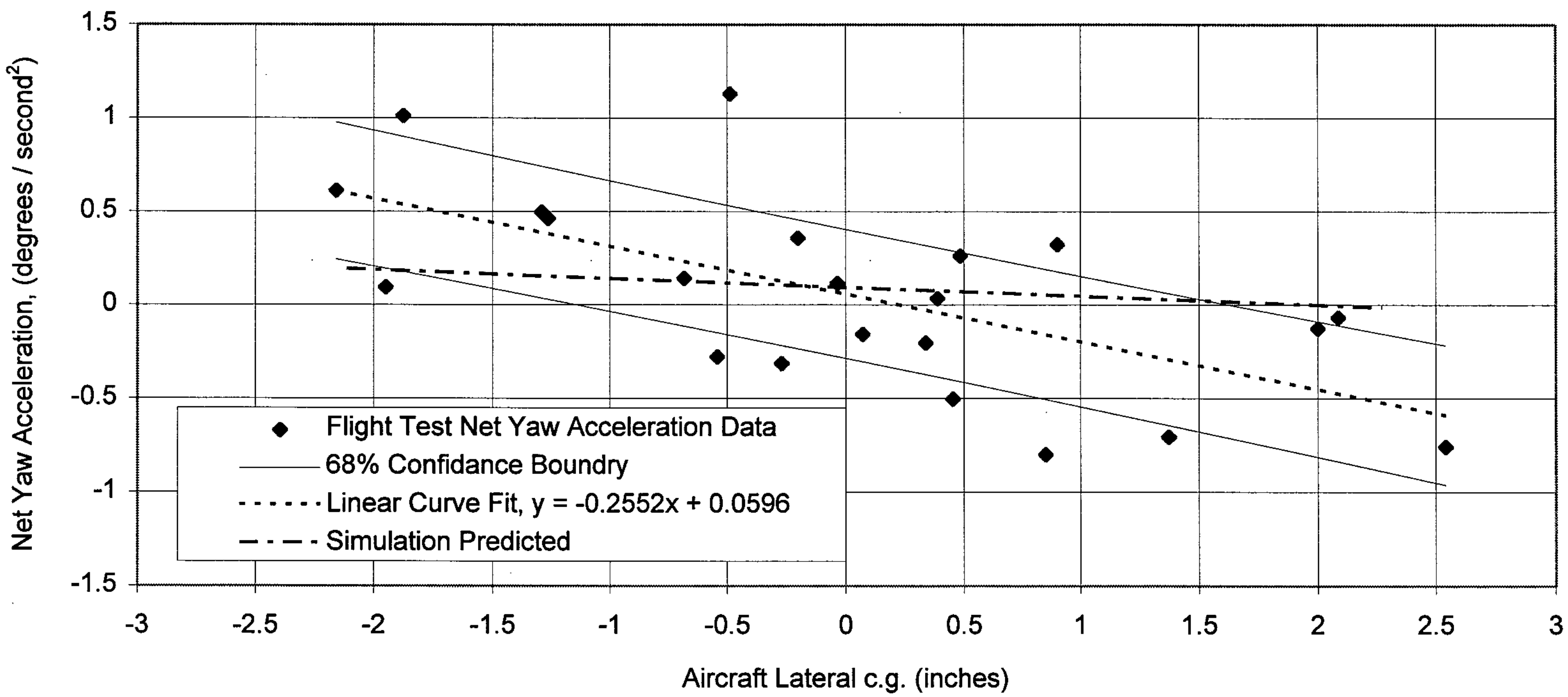


Figure B4. F-15B Net Yaw Acceleration at 32,000 feet PA, With 0.0-inch LLEU and 0.2-inch RLEU

Data Basis: Flight Test
Test Aircraft: F-15B S/N 76-0130
Test Dates: Sept 95 - Oct 95
Flight Test Technique: Full Aft Stick Stall, Engines IDLE

Configuration: Cruise (gear, flaps, and speed brake retracted)
Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8
Engines: F100-PW-100 Fuel: JP-8
Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up   RLED/U - Right Leading Edge Down/Up

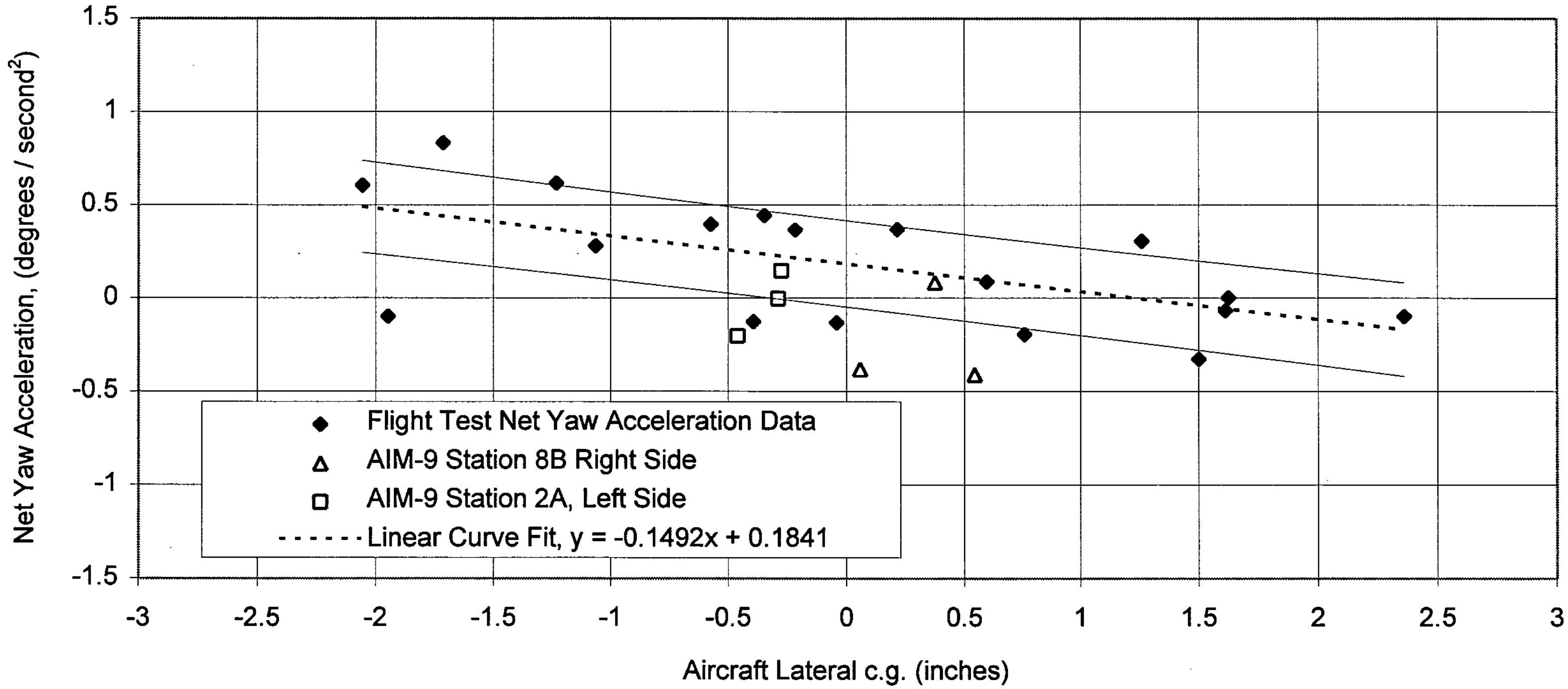


Figure B5. F-15B Net Yaw Acceleration Missile Effects at 15,000 feet PA, With 0.4-inch LLEU and 0.4-inch RLED.

Data Basis: Flight Test Test Aircraft: F-15B S/N 76-0130 Test Dates: Sept 95 - Oct 95 Flight Test Technique: Full Aft Stick Stall, Engines IDLE	Configuration: Cruise (gear, flaps, and speed brake retracted) Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8 Engines: F100-PW-100 Fuel: JP-8 Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up   RLED/U - Right Leading Edge Down/Up

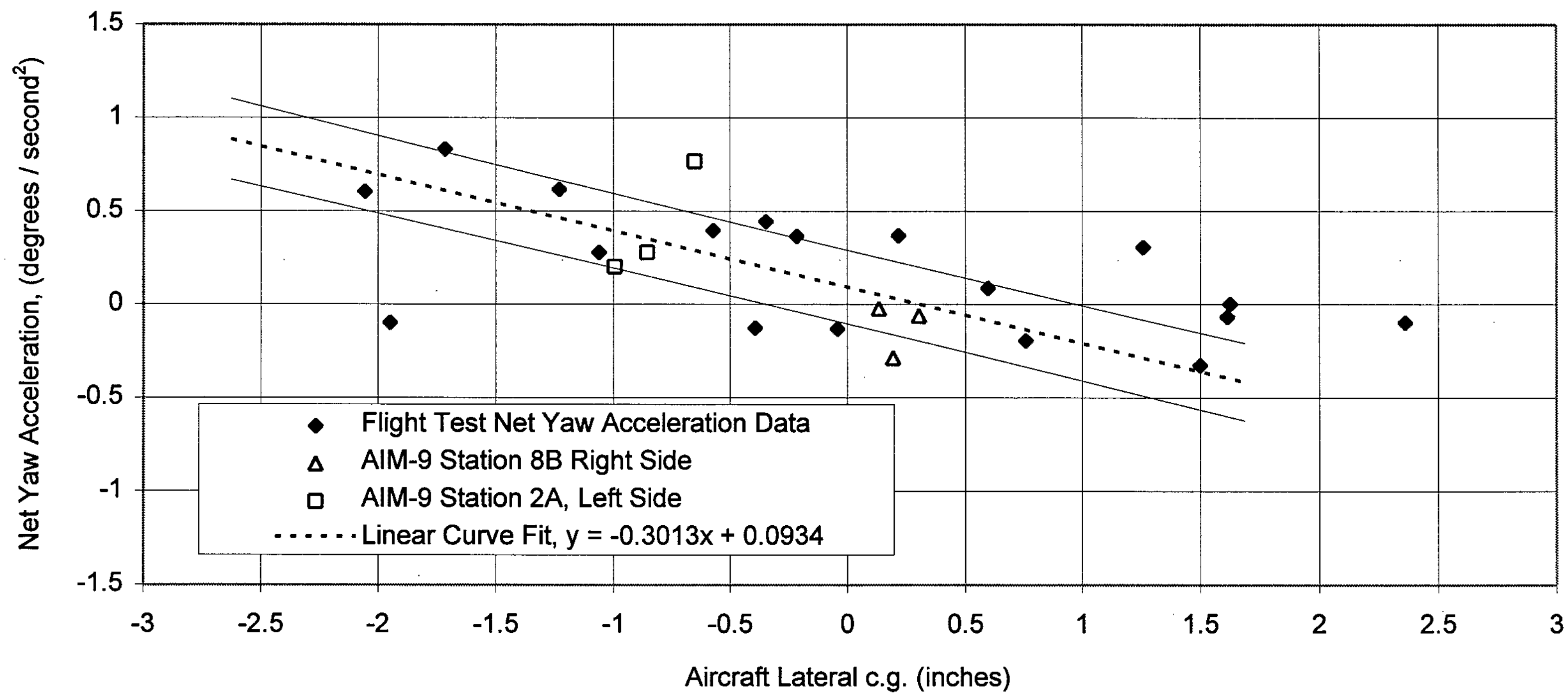


Figure B6. F-15B Net Yaw Acceleration Missile Effects at 32,000 feet PA, With 0.4-inch LLEU and 0.4-inch RLED

Data Basis: Flight Test
Test Aircraft: F-15B S/N 76-0130
Test Dates: Sept 95 - Oct 95
Flight Test Technique: Full Aft Stick Stall, Engines IDLE

Configuration: Cruise (gear, flaps, and speed brake retracted)
Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8
Engines: F100-PW-100 Fuel: JP-8
Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up

RLED/U - Right Leading Edge Down/Up

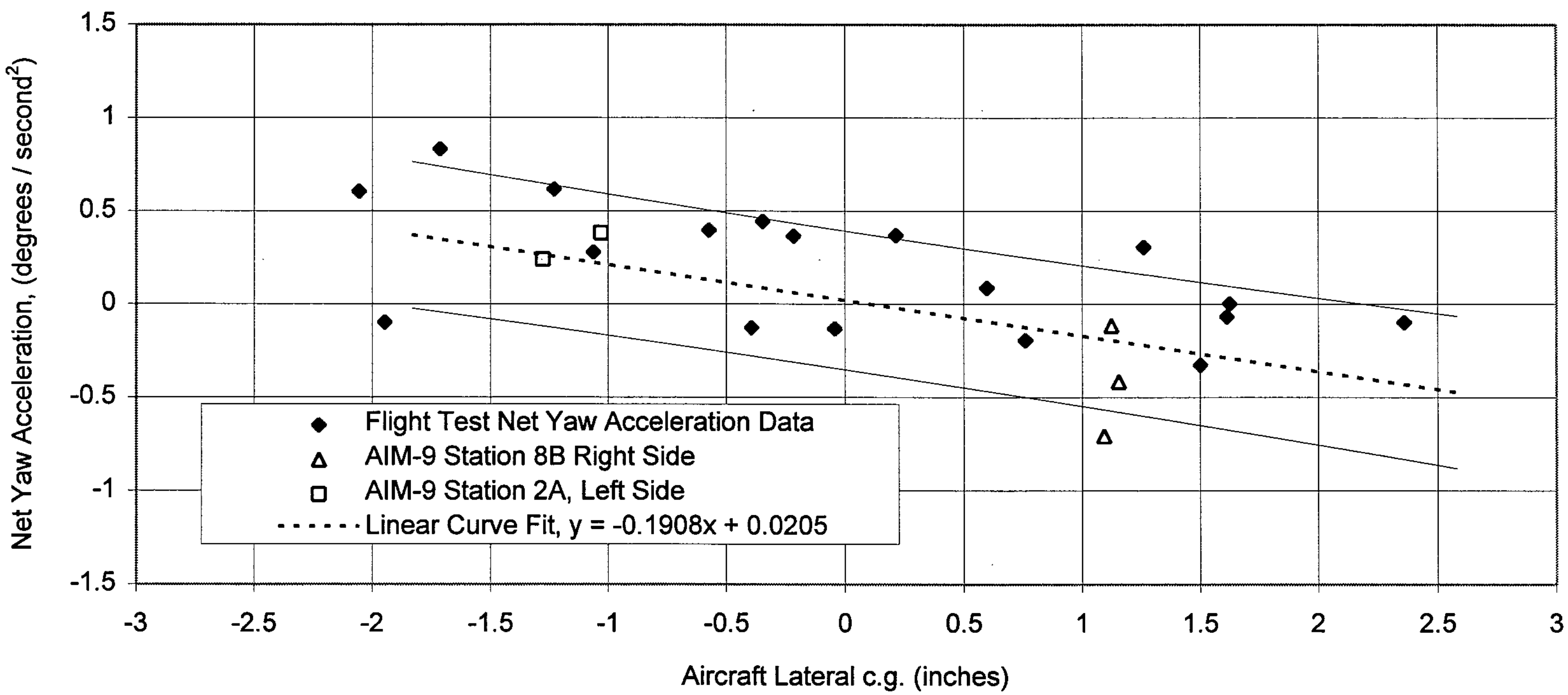


Figure B7. F-15B Net Yaw Acceleration Missile Effects at 15,000 feet PA, With 0.0-inch LLEU and 0.2-inch RLEU

Data Basis: Flight Test Test Aircraft: F-15B S/N 76-0130 Test Dates: Sept 95 - Oct 95 Flight Test Technique: Full Aft Stick Stall, Engines IDLE	Configuration: Cruise (gear, flaps, and speed brake retracted) Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8 Engines: F100-PW-100 Fuel: JP-8 Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

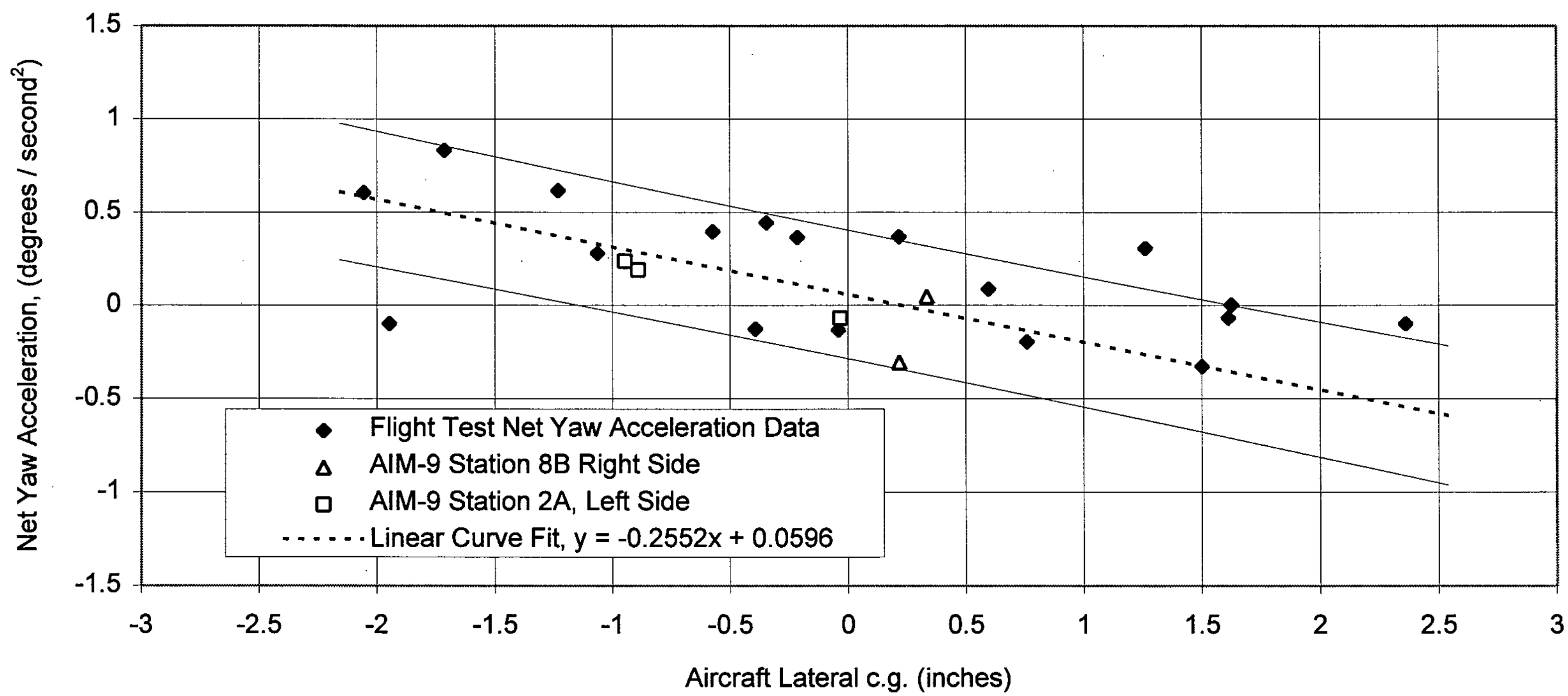


Figure B8. F-15B Net Yaw Acceleration Missile Effects at 32,000 feet PA, With 0.0-inch LLEU and 0.2-inch RLEU

Data Basis: Flight Test Test Aircraft: F-15B S/N 76-0130 Test Dates: Sept 95 - Oct 95 Flight Test Technique: Full Aft Stick Stall, Engines IDLE	Configuration: Cruise (gear, flaps, and speed brake retracted) Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8 Engines: F100-PW-100 Fuel: JP-8 Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

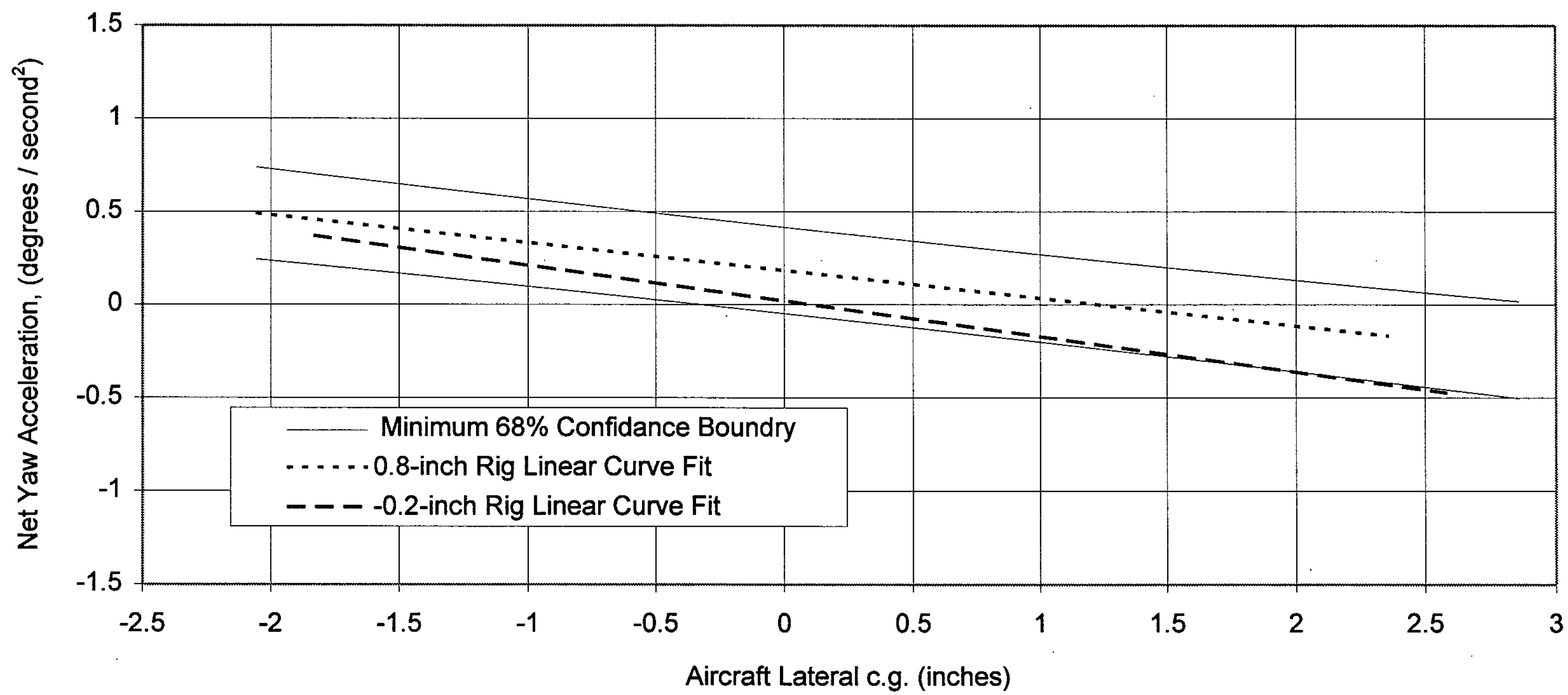


Figure B9. F-15B Differential Stabilator Bias Effects at 15,000 feet PA.

Data Basis: Flight Test
Test Aircraft: F-15B S/N 76-0130
Test Dates: Sept 95 - Oct 95
Flight Test Technique: Full Aft Stick Stall, Engines IDLE

Configuration: Cruise (gear, flaps, and speed brake retracted)
Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8
Engines: F100-PW-100 Fuel: JP-8
Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

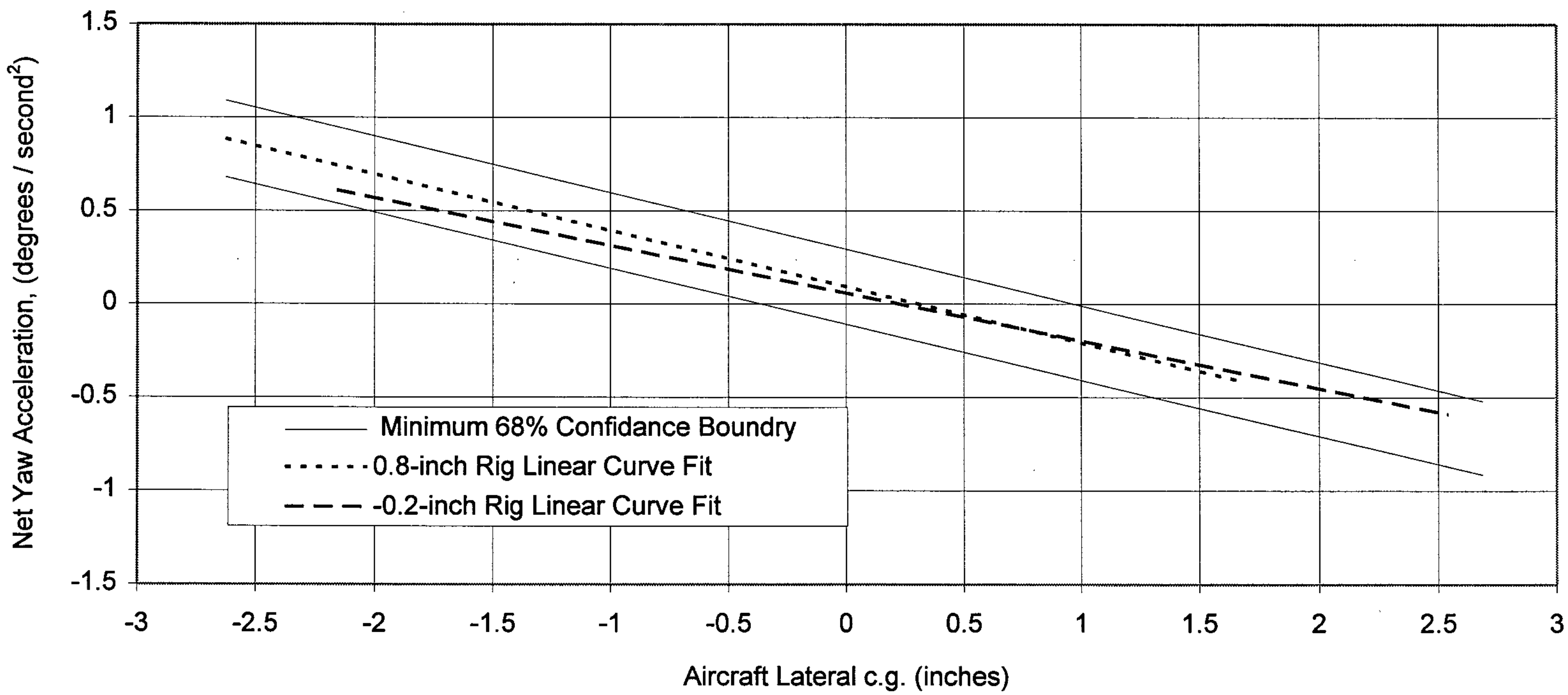


Figure B10. F-15B Differential Stabilator Bias Effects at 32,000 feet PA.

Data Basis: Simulation Test Aircraft: F-15A Input: 5 seconds Full Aft Stick Stall at 200 knots Data Source: AERO-TAB-5 and AERO-TAB-6, F-15 aerodynamic data	Configuration: Cruise (gear , flaps & speed brake retracted) Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8 Engines: F100-PW-100

LLEU - Left Leading Edge Up

RLED/U - Right Leading Edge Down/Up

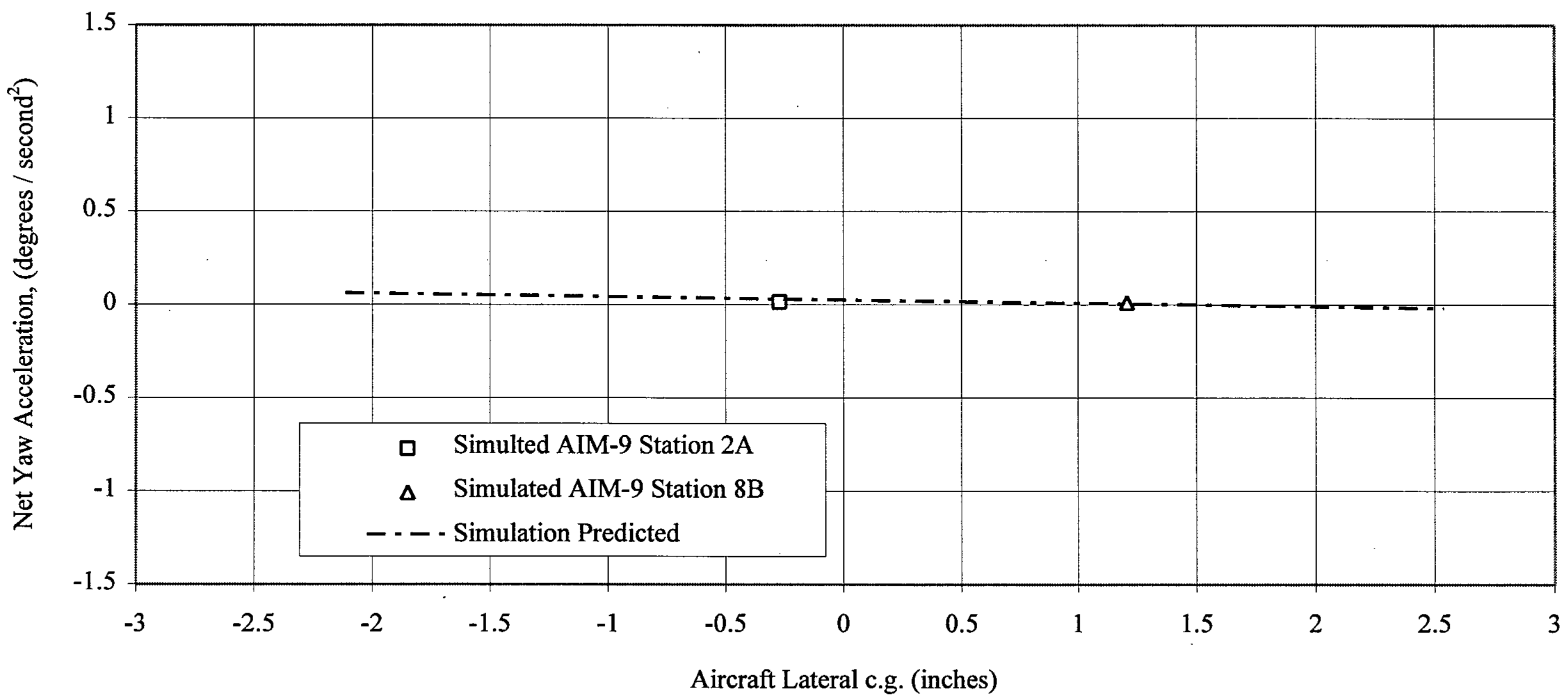


Figure B11. Simulator Predicted Net Yaw Acceleration at 15,000 feet PA, With 0.4-inch LLEU and 0.4-inch RLED

Data Basis: Simulation
Test Aircraft: F-15A
Input: 5 seconds Full Aft Stick Stall
at 250 knots
Data Source: AERO-TAB-5
and AERO-TAB-6, F-15 aerodynamic data

Configuration: Cruise (gear , flaps & speed brake retracted)
Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on
Stations 2 and 8
Engines: F100-PW-100

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

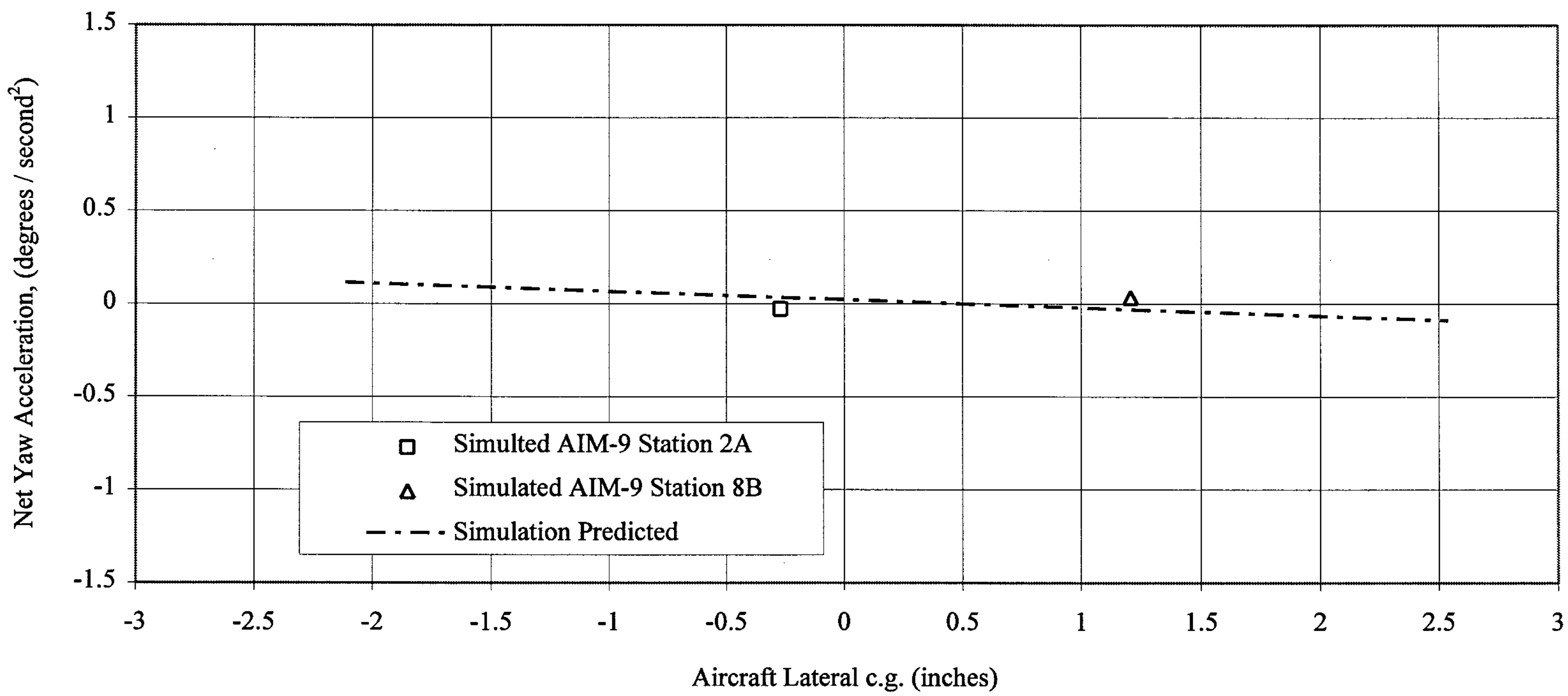


Figure B12. Simulator Predicted Net Yaw Acceleration at 32,000 feet PA, With 0.4-inch LLEU and 0.4-inch RLED

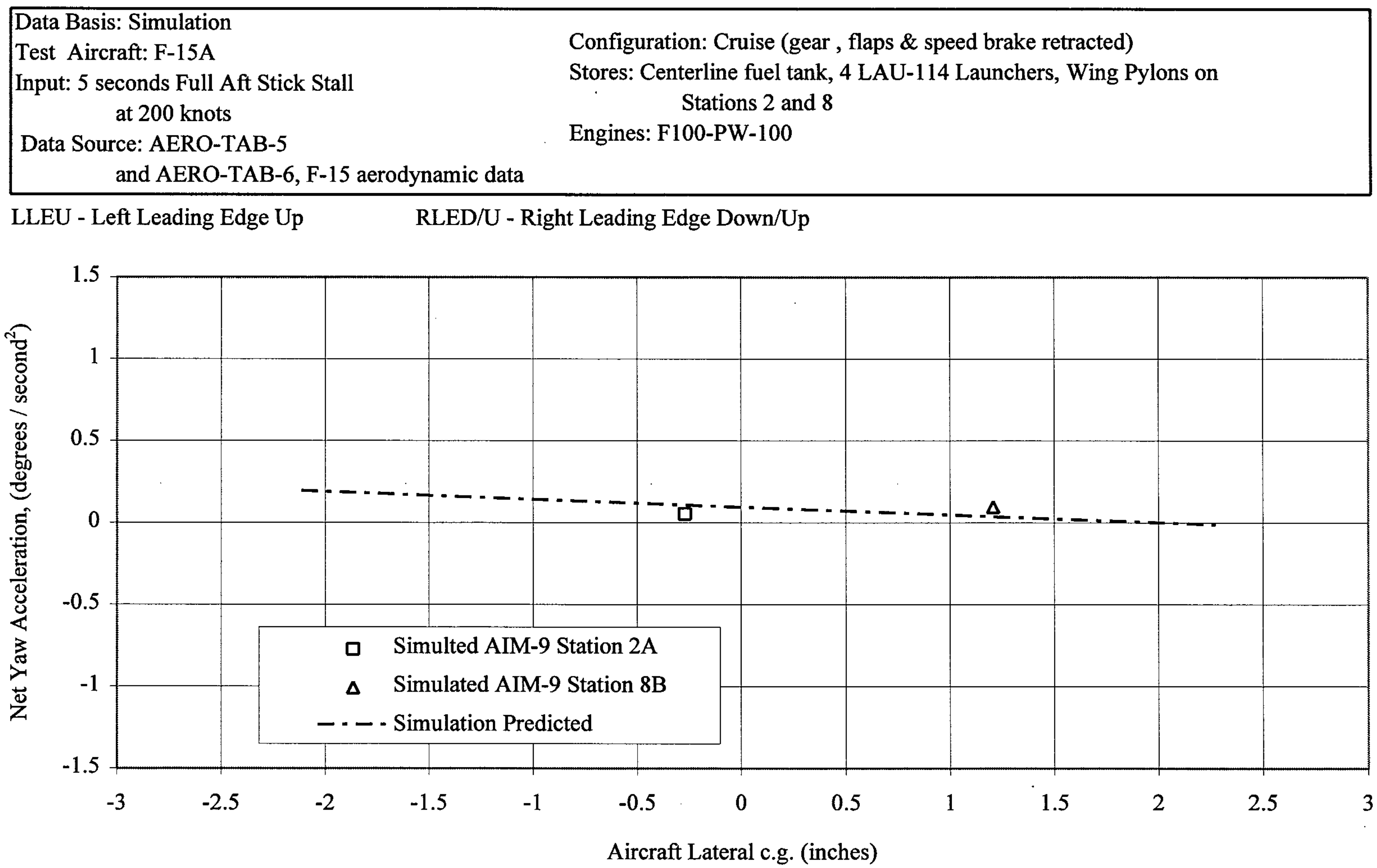


Figure B13. Simulator Predicted Net Yaw Acceleration at 15,000 feet PA, With Symmetric Stabilator.

Data Basis: Simulation Test Aircraft: F-15A Input: 5 seconds Full Aft Stick Stall at 250 knots Data Source: AERO-TAB-5 and AERO-TAB-6, F-15 aerodynamic data	Configuration: Cruise (gear , flaps & speed brake retracted) Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8 Engines: F100-PW-100

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

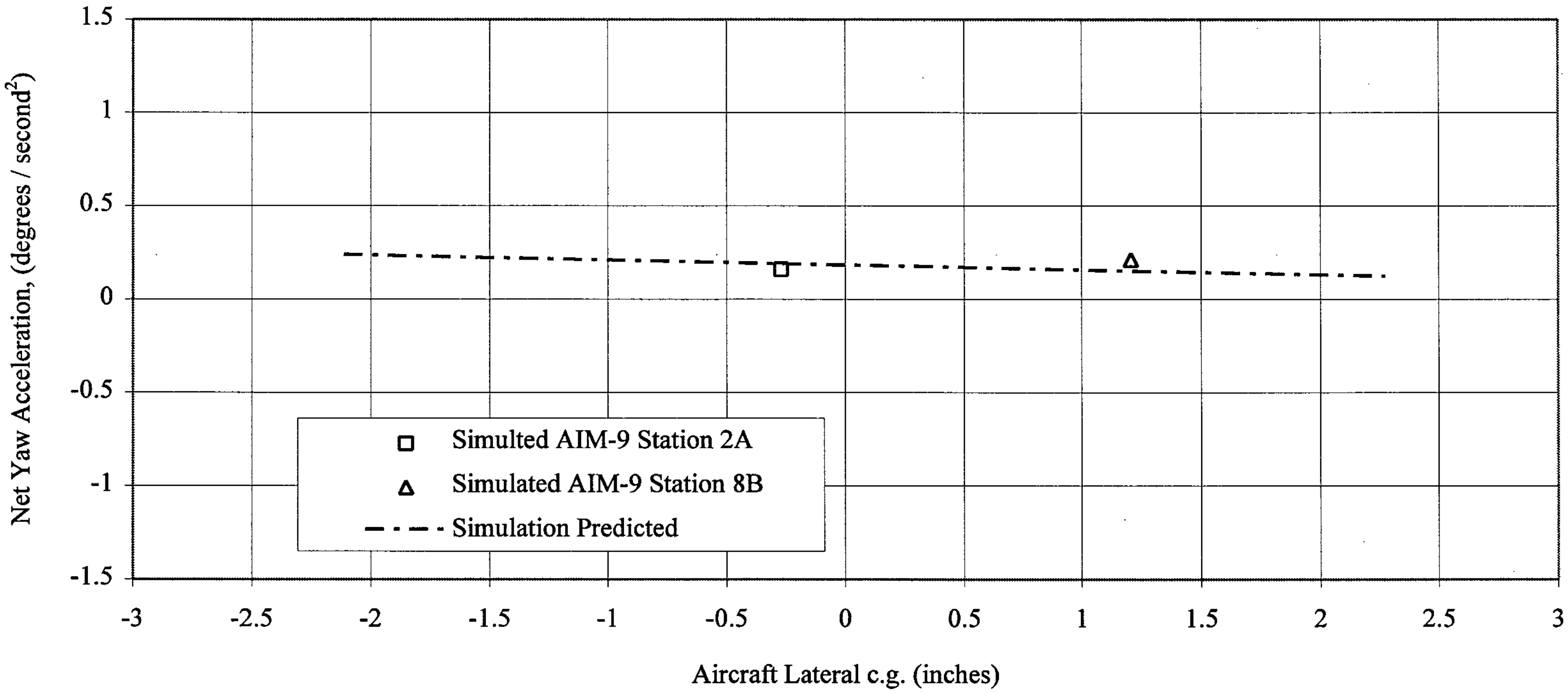


Figure B14. Simulator Predicted Net Yaw Acceleration at 32,000 feet PA, With Symmetric Stabilator.

Data Basis: Flight Test Test Aircraft: F-15B S/N 76-0130 Test Dates: Sept 95 - Oct 95 Flight Test Technique: Full Aft Stick Stall, Engines IDLE	Configuration: Cruise (gear, flaps, and speed brake retracted) Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8 Engines: F100-PW-100 Fuel: JP-8 Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

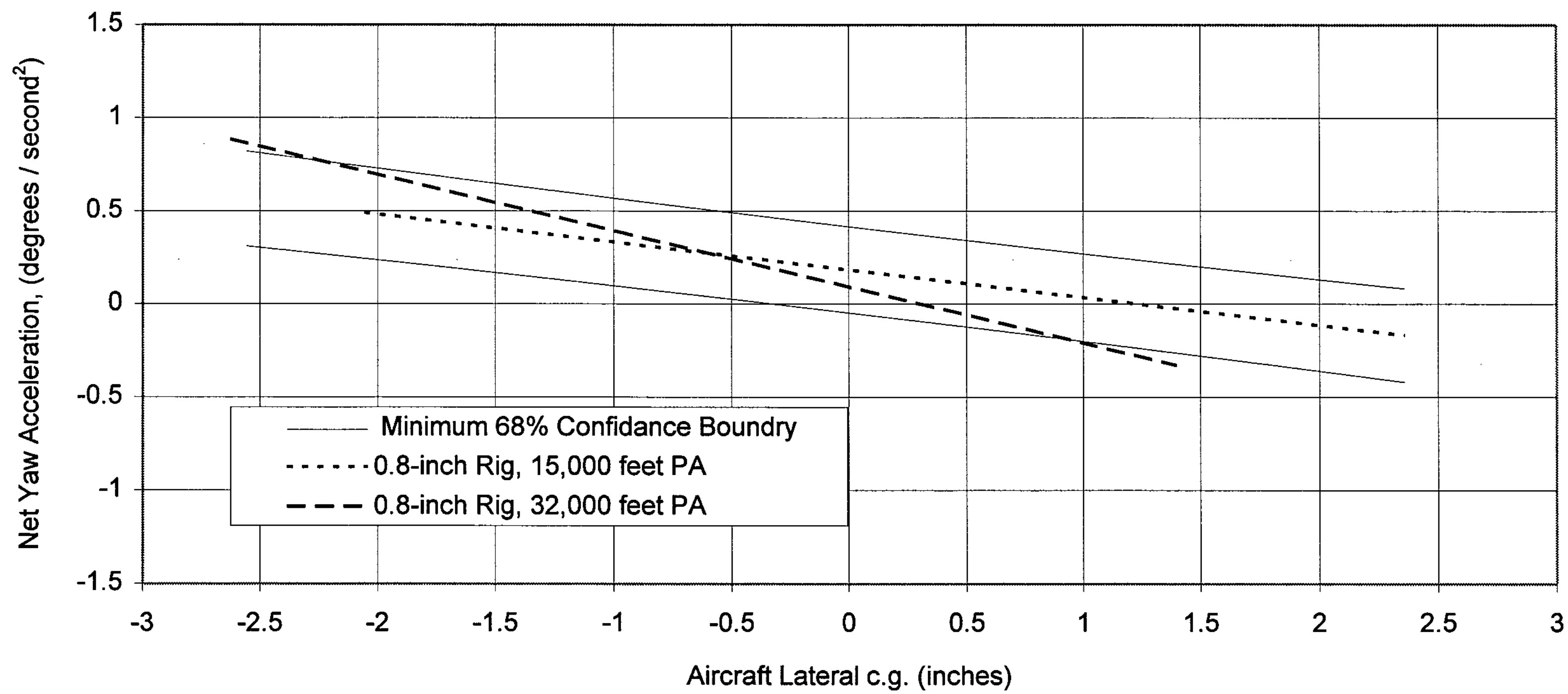


Figure B15. F-15B Altitude Effects on Net Yaw Acceleration for 0.4 LLEU and 0.4 RLED.

Data Basis: Flight Test	
Test Aircraft: F-15B S/N 76-0130	Configuration: Cruise (gear, flaps, and speed brake retracted)
Test Dates: Sept 95 - Oct 95	Stores: Centerline fuel tank, 4 LAU-114 Launchers, Wing Pylons on Stations 2 and 8
Flight Test Technique: Full Aft Stick Stall, Engines IDLE	Engines: F100-PW-100 Fuel: JP-8
	Data Source: Data Acquisition System (DAS)

LLEU - Left Leading Edge Up RLED/U - Right Leading Edge Down/Up

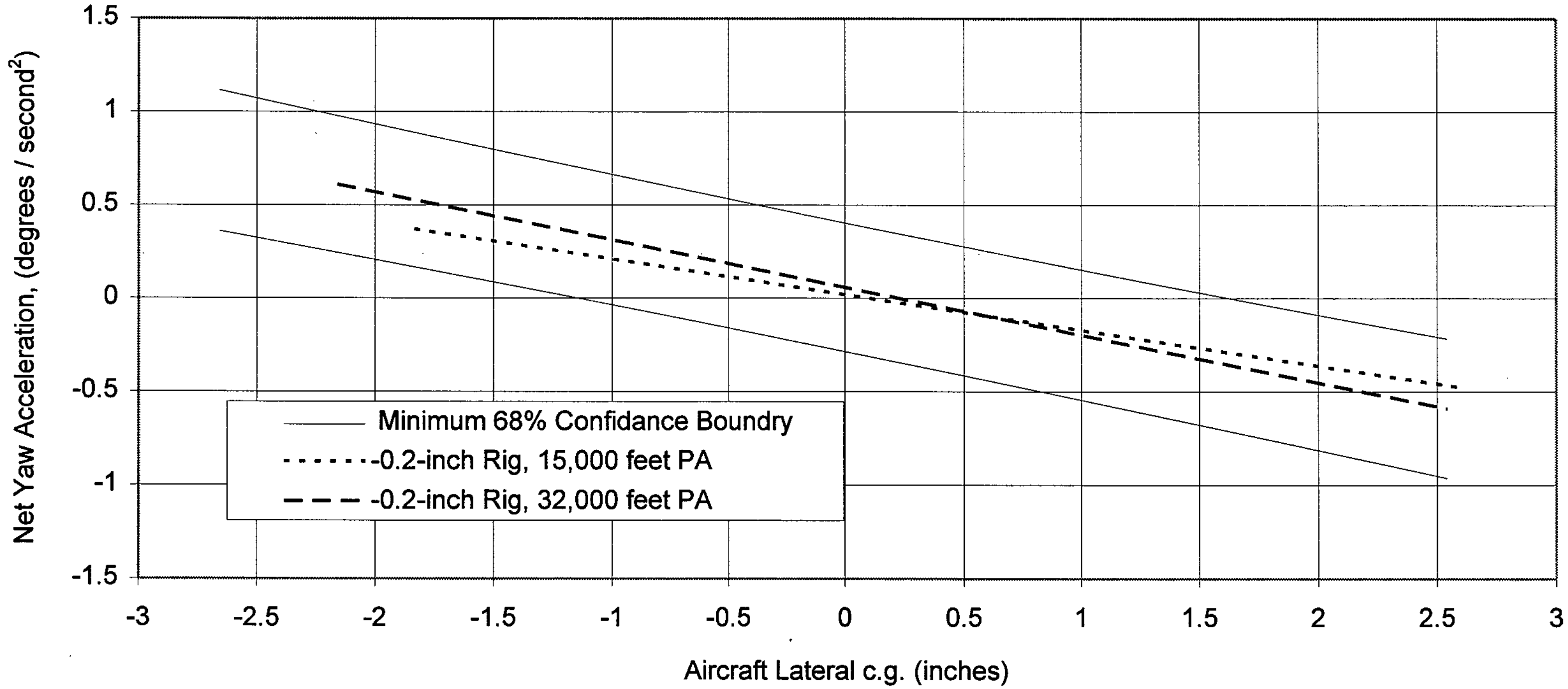


Figure B16. F-15B Altitude Effects on Net Yaw Acceleration for 0.0 LLEU and 0.2 RLEU.

Bibliography

1. Department of the Air Force, Flight Manual, USAF Series Aircraft, F-15, Technical Order 1F-15A-1, Change 9, WR-ALC/LZDT, Robins AFB GA, 1 July 1989.

2. Herlt, S., " The Bitburg Maneuver and Other Handling Quarks," Aerospace Digest: 30-33 October-December 1992.

3. Nelson, B. G. and Flynn, J. F., "F-15 High AOA Yaw Sensitivity Investigation," Flight Test Results Memorandum 26 July to 12 August 93: FTRM No. F-15-03-111.

4. Snyder, B. D, " F-15 Stabilator Rigging Test," AFDTC Letter Report 94-02: 46th TW Air Force Development Test Center, Eglin AFB FL, July 1994, (AD B0187426).

5. Department of the Air Force, Technical Manual, Job Guide, USAF Series Aircraft, F-15, Technical Order 1F-15A-2-27JG-40-1, Change 29 ,WR-ALC/LZDT, Robins AFB GA, 01 February 1995.

6. Crawford, W. N. and Hollingsworth, W. B., " Bitburg Roll Summary Report," Mini-Task 91-21: Contract F09603-90-6-00122-0025.

7. Evans, D. R., Refaely, I., Tanner, R. J., Wenger, L., and Zimmerman, D. L., " A Limited Investigation of Lateral Asymmetry and Differential Stabilator Bias on the F-15B at Moderate-to-High Angles-of-Attack (HAVE LIST)," AFFTC-TR-95-75: December 1995.

8. Snyder, B., Watrous, D, and Walker, L. A., "Operational Improvements to the Eagle's High Angle of Attack Handling Qualities," Thirty-eighth SETP Symposium Proceedings, Beverly Hills CA, September 1994.

9. Blake, W. B. and Barnhart, B. P., "Rotational Aerodynamics of Elliptic Bodies at High Angles of Attack," AIAA-90-0068: 28th Aerospace Sciences Meeting, Reno NV, January 8-11, 1990.

10. Webster, F., "F-15 CTF Bitburg Eval Results," F-15 Keep Eagle TCM No. 4: McDonnell Douglas, Saint Louis MO, December 14-15, 1993.

11. Walker, L., "Why The F-15 Rolls right at High Angles of Attack," Aerospace Digest: 1-5 December 1993.

12. Roskam, J., Airplane Flight Dynamics and Automatic Flight Controls, The University of Kansas, Lawrence KA,1979.

13. Department of the Air Force, Technical Manual, Acceptance and Functional Check Flight Procedures, USAF Series, F-15A/B/C/D Aircraft, Technical Order 1F-15A-6CF-1, Change 2, WR-ALC/LZDT, Robins AFB GA, 15 September 1994.

14. Felock, J., Habig, C., and Herlt, S., "Enhanced High AOA Capabilities for the F-15E," Thirty-eighth SETP Symposium Proceedings, Beverly Hills CA, September 1994.

15. Potts, D., F-15E 6-DOF Simulator Notes, 88th CG/SCES, Wright-Patterson AFB OH, August 1994.

16. Bennett, R. L., Analysis of the Effects of Removing Nose Ballast From the F-15 Eagle, MS Thesis, AFIT/GA/ENY/91D-1, School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, December 1991, (AD A244044).

17. McDonnell Douglas Aircraft Co., F15_AERO_5_WORK, Working Papers, McDonnell Douglas Co., Saint Louis MO, Febuary 1992.

18. McDonnell Douglas Aircraft Co., F15_AERO_6_WORK, Working Papers, McDonnell Douglas Co., Saint Louis MO, Febuary 1994.

19. Wood, R., Aerodynamisist, McDonnell Douglas Co, Saint Louis MO, Telephone interview, 25 August 1994.

20. McDonnell Douglas Corporation, "F-15 Stability Derivatives Mass and Inertia Characteristics, Part I," Report Number MDC A4172, USAF Series Manual A-11-2-2-1-1, Aero / Inertia, Saint Louis MO, August 1, 1976.

21. Department of the Air Force, USAF Test Pilot School Instrumentation Handbook, USAF Test Pilot School, Edwards AFB CA, January 1995.

22. Department of the Air Force, Modification Operational Supplement, USAF Series Aircraft, F-15, USAF S/N 76-0130, AFFTC, Edwards AFB CA, 21 August 1995.

23. Microsoft, User's Guide Volume 1, Microsoft EXCEL for Windows™ Version 5.0: Microsoft Corporation, Cambridge MA, 1993.

24. Peavy, B., F-15B S/N 76-0130, HAVE LIST Fuel Calibration Notes, USAF TPS/TSF, Edwards AFB CA, September 1995.

25. Jones, B., Statistics Toolbox User's Guide, Math Works Inc., Natick MA, December 1991.

Vita

Captain David R. Evans [redacted], [redacted] He graduated from The Wilkes-Barre Area Vocational Technical School and James M. Coughlin High School in 1980. He completed a Bachelor of Science in Aerospace Engineering at The Pennsylvania State University in 1986. In May 1986, he was commissioned through the Air Force ROTC program. Captain Evans began active duty in October of 1986 attending Undergraduate Pilot Training at Vance AFB, Oklahoma. Upon graduation, he was assigned as an F-15 aircraft commander to the 1st Fighter Wing, Langley AFB, Virginia. While at Langley, Captain Evans participated in Operations DESERT SHIELD and DESERT STORM. He was then selected to attend the Air Force Institute of Technology (AFIT) / USAF Test Pilot School courses. In July 1993, Captain Evans entered the School of Engineering at AFIT Wright Patterson AFB, Ohio. In January 1995, he entered the USAF Test Pilot School, Edwards AFB, California. Upon completion of the experimental test pilot curriculum, he was assigned to the 40th Flight Test Squadron, Eglin AFB, Florida as an F-15 Experimental Test Pilot. Prior to departing for Eglin, Captain Evans completed his AFIT degree of Master of Science in Aeronautical Engineering.

[redacted]

[redacted]

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1996	Master's Thesis

4. TITLE AND SUBTITLE
AN INVESTIGATION INTO THE EFFECTS OF LATERAL AERODYNAMIC ASYMMETRIES, LATERAL WEIGHT ASYMMETRIES, AND DIFFERENTIAL STABILATOR BIAS ON THE F-15 DIRECTIONAL FLIGHT CHARACTERISTICS AT HIGH ANGLES OF ATTACK

5. FUNDING NUMBERS

6. AUTHOR(S)
Evans, David R., Captain, USAF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Institute of Technology, Wright-Patterson AFB, Ohio 45433-6583

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/GAE/ENY/96M-1

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Jeffrey S. Priem, Team Leader, F-15 System Program Office
Building 32
2300 D Street
Wright-Patterson AFB, Ohio 45433-7245

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE
A

13. ABSTRACT
The F-15 is a stable aircraft throughout most of its flight envelope. However, it still exhibits an uncommanded yawing and rolling tendency at high angles-of-attack. Identified influencing factors of this uncommanded motion are lateral aerodynamic asymmetries, lateral weight asymmetries, and differential stabilator bias. Previous research into the effects of these influencing factors has been qualitative. This thesis quantifies the effects and then identifies a symmetric F-15 configuration. The quantifying metric presented is net yaw acceleration. This thesis used both computer simulation and experimental flight test to quantify these effects. A discussion of each influencing factors effects on the F-15B high AOA net yaw acceleration is presented. Aerodynamic asymmetries of the baseline F-15B are shown to cause a right yaw. Lateral weight asymmetries are shown to cause yaw acceleration away from the weight asymmetry. And, small changes in differential stabilator bias are shown to have little influence on net yaw acceleration. Considering these discussions, the baseline F-15B is identified as the symmetric F-15B. Finally, this thesis identifies two possible causes for F-15 departures, transient net yaw acceleration and combined sense of yaw and roll rate. The understandings of these possible causes on F-15 departures are just beginning to be evaluated.

14. SUBJECT TERMS

F-15 aircraft	stall	stability and control	high angle-of-attack
fighter aircraft	flight simulation	asymmetric loading	stabilator
AIM-9	directional stability		

15. NUMBER OF PAGES
95

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-010280-5500
Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102