Flight Model (FM) Developer's Notes Part 4:

Revealing the Dark Side of the F-16 - FLCS

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1 Introduction

Because the F-16 model with the Advanced Flight Model (AFM) code now reacted very closely to the real thing, it was impossible to fly it without developing the real, full and detailed F-16's Flight Control System.

Most people refer to "Limiters" when they talk about F-16 FLCS, but this is a very "simple" approach to the real FLCS. This is just scratching the surface; the terms of "limiters" are the main visible consequences of the FLCS but it does not explain why and how.

This note proposes to you a journey into the F-16 FLCS universe. I will try to explain you as simply as possible what were the challenges of the F-16 development, and the way the real engineers (and consequently BMS) have developed and improved the FLCS.

Be aware that most of the flying reflexes and knowledge that you acquired with the MPS simulator was wrong and some new training will be necessary.

Remember that MPS/Falcon 4 was considered by professional F-16 pilots as giving them "negative training" for their real flying. After the reading of this note, you will understand why.

Don't be afraid of all the graphs and schemes, everything will be explained clearly and no technical knowledge will be necessary to enjoy your journey.

Please note that this developer note is mostly based on the NASA Technical Paper 1538 (TP 1538) "Simulator Study of Stall / Post Stall Characteristics of a Fighter Airplane with Relaxed Longitudinal Static Stability".

2 F-16 Stability Characteristics

2.1 Longitudinal characteristics

It is generally well known that the F-16 has been one of the first produced aircraft to benefit from the concept of RSS (Relaxed Static Stability) in which the basic airframe is designed to have a very low or slightly negative static stability. The main advantage of this configuration is to allow a better maneuverability. The F-16 nominally operates at a very moderated level of negative static margin at low subsonic speeds.

Definition: Longitudinal Static Stability: it is the natural tendency to come back in the original flying situation after a perturbation in the pitch axis. For instance, from a trimmed situation, an aircraft that has a static stability will naturally pitch down after an AOA increase to come back to a lower AOA. On the contrary, from a trimmed situation, an aircraft without static stability will have a tendency to pitch up after an AOA increase; therefore will not come back to its original flying state.

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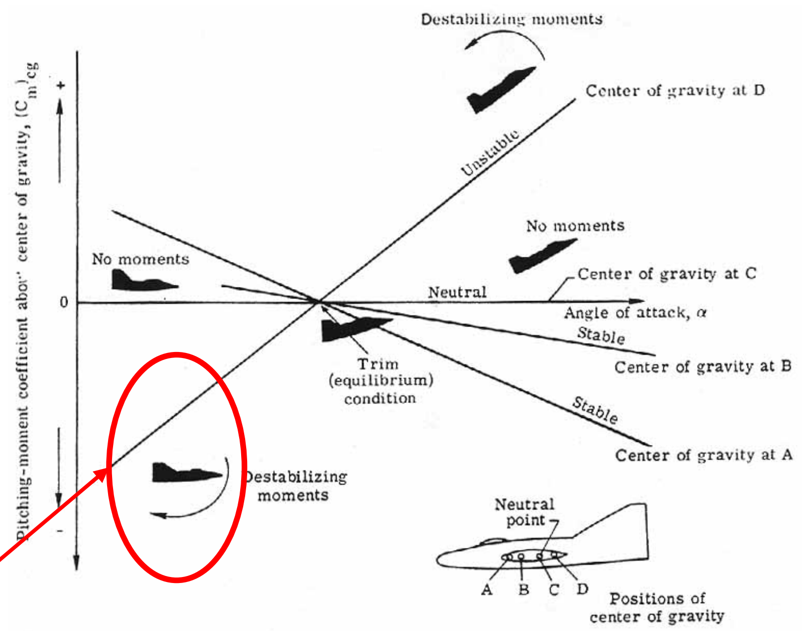

Figure 0: Pitching Moment (Cm) vs Angle of Attack. Conditions of stability (Credits: NASA)

Negative Static Margin

The Pitching moment (Cm) curve of the F-16 for low speed is described below. The pitching moment is the moment that is applied to the aircraft in the pitch axis, positive means the aircraft will pitch up, negative means that the aircraft will pitch down.

In the following graphs δh = Elevator deflection, +25deg means full deflection up (pitch down Cm<0 is expected), -25 deg means full deflection down (pitch up: Cm >0 is expected).

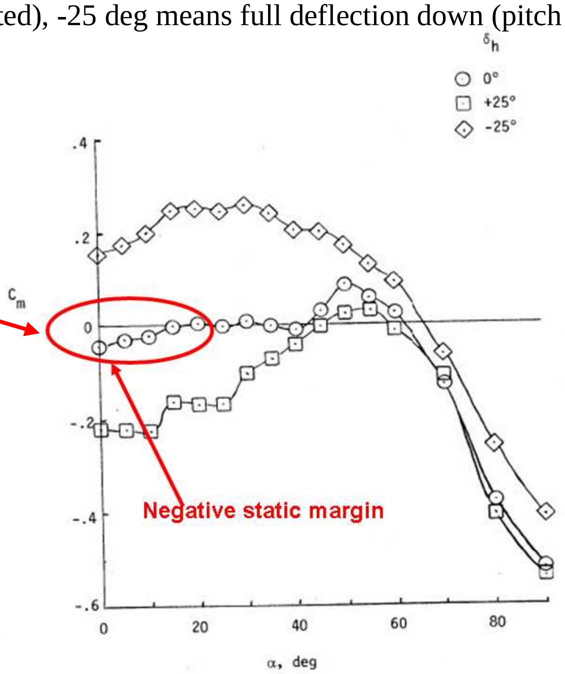

Figure 1: Pitch Momentum (Cm) vs AOA at low speed: static margin

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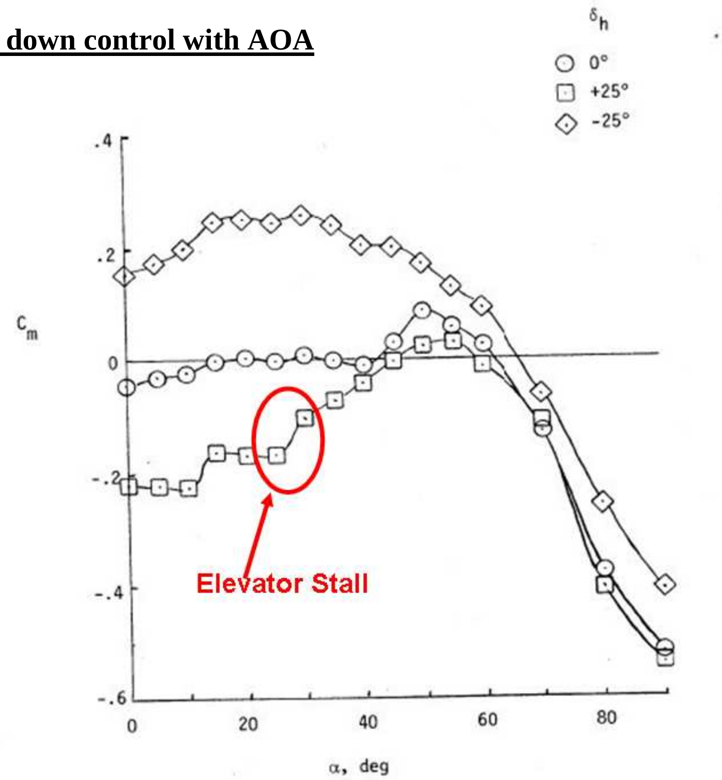
As shown on Figure 1 above, the F-16 has a negative static margin at low AOA, low speed that makes it unstable. The static margin is close to zero or even positive above 15 deg AOA making the Aircraft unstable in this area as well.

As a consequence, the FLCS pitch module will have to include an AOA feedback to create artificial pitch stability.

Loss of nose down control with AOA



At 25 deg AOA, the elevator in full deflection up has a local AOA of 50° and stalls. This stall leads to a loss of efficiency of the elevator and therefore a loss in nose down control effectiveness.

This loss in nose down control is particularly critical as the alpha limiter relies on the available nose down control momentum to prevent alpha from exceeding 25° (understand that above 25° AOA, the elevator have much difficulty in countering any pitch up situations).

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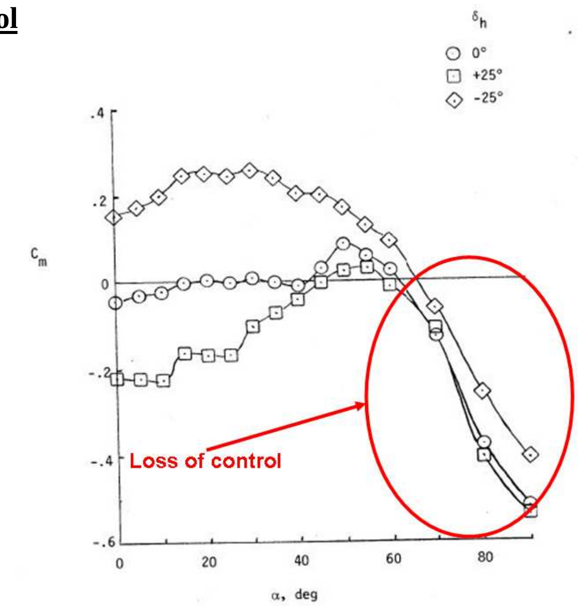
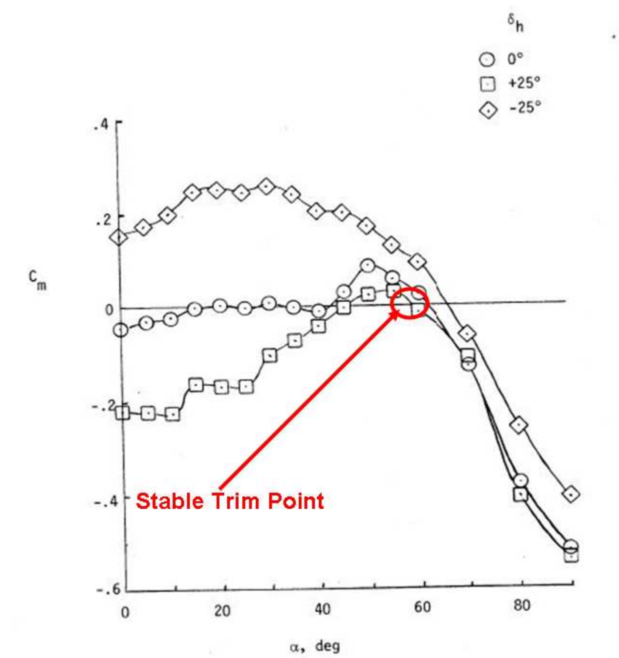
Loss of pitch up control



Above 60° AOA, whatever the elevator position, the Pitch momentum (Cm) becomes negative, therefore the aircraft becomes out of control in pitch. This area must be avoided.

Deep Stall



When the AOA becomes >25°, the FLCS will command full pitch down, i.e. elevator +25° to push the nose down. However, around 60 deg AOA, we can see on the graph here above that the elevator +25deg curve cross the Cm = 0. Therefore there is here a **stable trim point** where the aircraft may potentially stay at 60 deg AOA (if AOA increases, aircraft will pitch down naturally, if AOA decreases it will pitch up naturally).

This particular point is well known for the F-16 and is characteristic of the "Deep Stall (DS)".

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Loss of nose down control with side slip

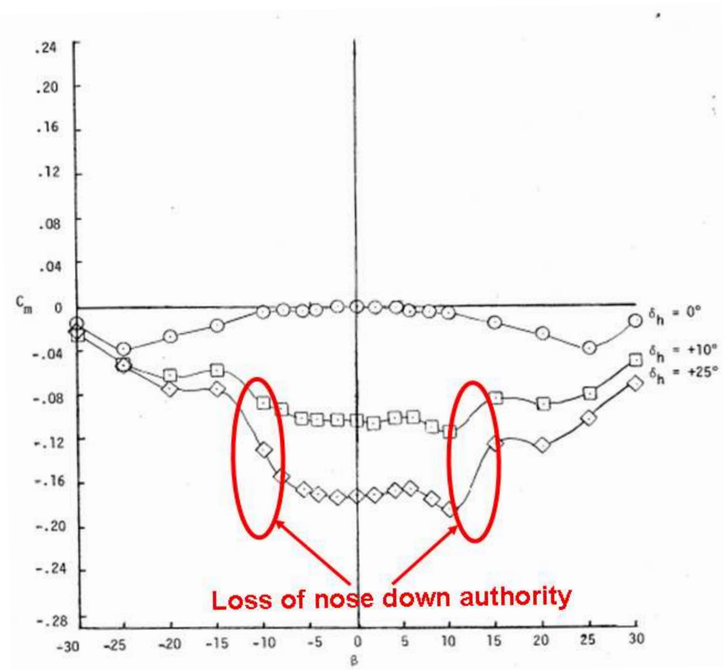

Figure 2: Pitch Momentum (Cm) vs Beta (side slip) at 25° AOA

At 25° AOA, the efficiency of the elevator for nose down control is sharply decreased with side slip (Beta) magnitude greater than 10°. Thus if a departure involving large sideslip excursions should occur, the effectiveness of the angle of attack limiter system to maintain alpha at or below 25° will be further degraded by the reduction in available nose down control moment.

For all those reasons; to inhibit inadvertent excursions to these extremes angle of attack (> 60 °) the pitch control system incorporates an angle of attack / normal-acceleration limiting system (CAT system) which drives the elevators in an attempt to limit the angle of attack to below 25°.

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2.2 Directional & Lateral Stability

In this chapter we will enter into the very interesting area of lateral and roll stability and control. It will explain one of the main purpose of the ARI (Aileron–Rudder Interconnect), and the Yaw SAS (Stability Augmentation System)

AILERON ADVERSE YAW

Definition: Cn : Yawing momentum , if Cn>0 nose slices to the right, Cn< 0 nose slices to the left.
Cn,β , means dependence of the yawing momentum with side slip angle (β)
Cn,α means dependence of the yawing momentum with AOA (α)

Definition: Cl : Rolling momentum , if Cl>0 Aircraft rolls to the right, Cl< 0 aircraft rolls to the left.
Cl,β , means dependence of the rolling momentum with side slip angle (β).
Cl,α means dependence of the rolling momentum with AOA (α)

Definitions:
δr = Rudder deflection
δa = Aileron deflection

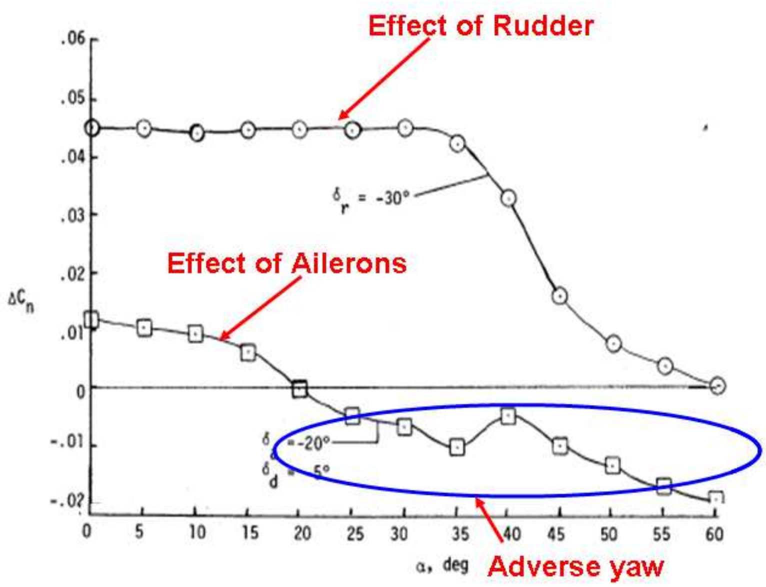

Figure 3: Dependence of Cn with AOA(α) for full deflection of Rudder/Aileron

As shown on Figure 3 above, the rudder effectiveness is high and essentially constant over the operational range of angle of attack (AOA<25°). The adverse yaw produced by the aileron above 20° AOA is small in comparison with moments produced by the rudder.

Therefore a proper coordination between Aileron and rudder (ARI) should be able to suppress the roll – control adverse yaw and minimize side slip in the normal flight AOA conditions.

It is very interesting to note that at 60 deg AOA, the rudder has absolutely no effectiveness on yaw…therefore the rudder effectiveness in the case of a spin stall is very limited. On the contrary, the adverse yaw produced by the ailerons at 60° AOA is important and will play a significant role to control a spin stall.

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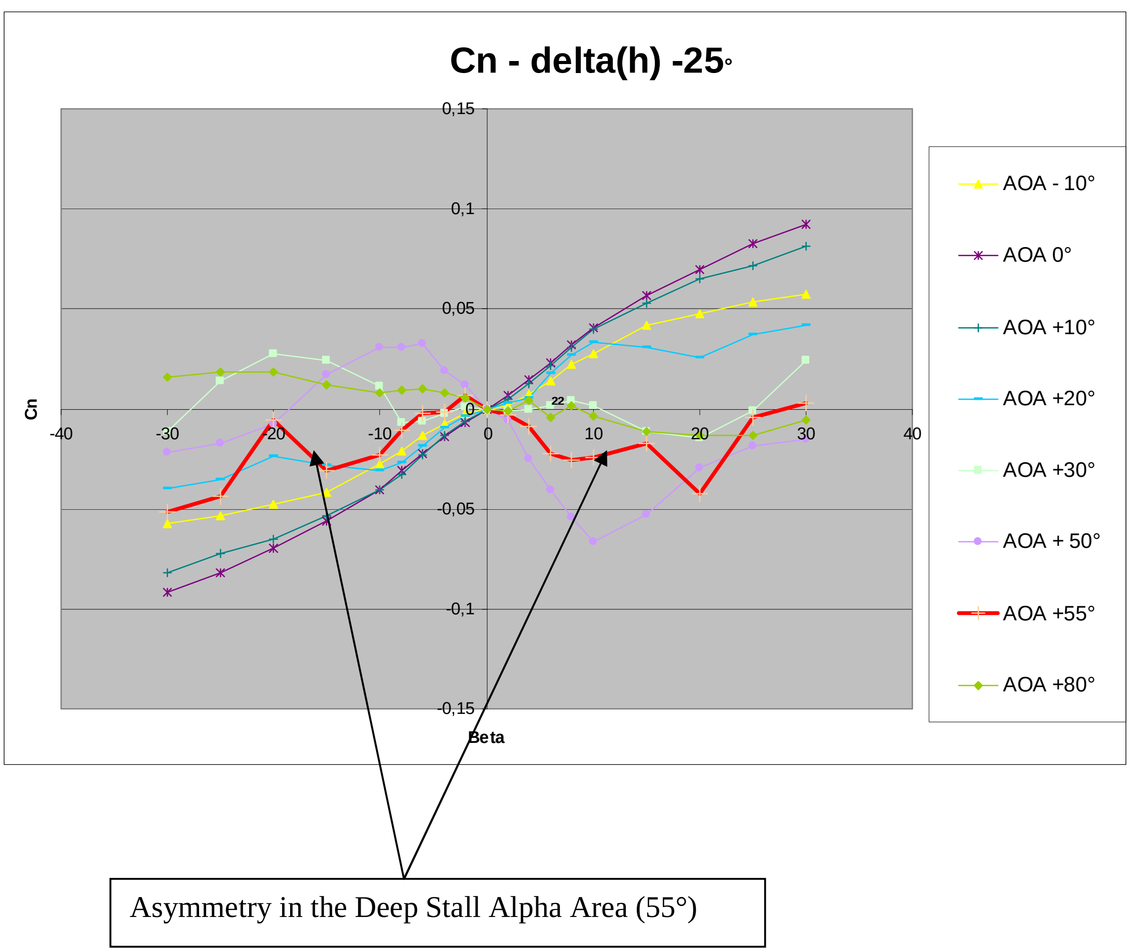
AERODYNAMIC ASYMMETRIES

At that point we should talk about an important airframe characteristic for the F-16 that has been highlighted by the NASA TP1538 study: **the aerodynamic asymmetries.**

The model was initially tested without any aerodynamic asymmetries; that is, the aerodynamic coefficients CY, Cl, Cn were 0 for Beta = 0° and neutral lateral – direction controls. In the normal angle of attack flight envelope of current fighter aircraft this modeling assumption was been found to be generally valid; in the wind tunnel measured asymmetries are normally insignificantly small. However, experience has shown that, in many configurations, these asymmetries can reach significant magnitude at post stall alpha (AOA). The data confirms that within the normal alpha flight envelope, these asymmetries are small enough to be ignored. However, they rapidly increase in magnitude for alpha >30°, particularly, yawing moment asymmetry reaches its maximum value in the alpha region of the Deep Stall Trim point.



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Definition: LCDP : Lateral Control Divergence Parameter is often used to appraise the roll – control effectiveness at high angles of attack. Positive values of this parameter indicate a normal roll response, and a negative value indicates a reversed response.

How come the roll response could be reversed?

The answer to that question is not obvious. In fact, the Rolling Momentum Cl is dependant on the Side slip angle (β); this means that side slip induces a roll. For instance, a side slip to the right often induces a roll to the right. The magnitude of this dependence is one of the characteristic of the airframe. For the F-16 this dependence is included in the Cl,β curve that can be found in the charts page 83, 84 & 85 of the NASA Technical Paper 1538 (TP 1538).

So, reference is made to Figure 3: above 20 deg AOA, the use of aileron provokes an adverse yaw. That means that a **roll to the right** will induces a **side slip to the left**. There is a point where the roll to the left induced by the side slip to the left is higher than the original roll to the right due to aileron. When that point is reached, a deflection of the aileron to the right will create a roll to the left.

To prevent this phenomenon, one purpose of the ARI is to force the rudder to automatically compensate the adverse yaw induced by the aileron to minimize the side slip and therefore minimize the adverse induced roll.

Hereunder is the LCDP curve for the F-16 with or without ARI, you can notice that the LCDO allows full roll control with a comfortable margin for the whole flight envelope.

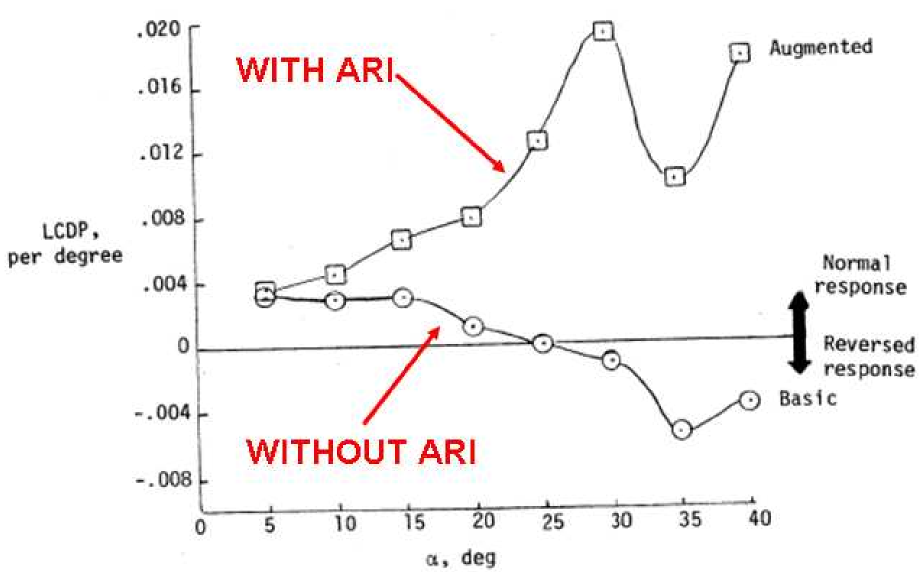

Figure 4: Dependence of LCDP with AOA(α) , with or without ARI

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THE YAW SAS

Classically, an aircraft has several oscillatory modes coupling roll and yaw that can endanger the normal flight regime.

- Dutch roll: This is an oscillatory combined roll and yaw motion. The Dutch roll may be described as a yaw and roll to the right, followed by a recovery towards the equilibrium condition, then an overshooting of this condition and a yaw and roll to the left, then back past the equilibrium attitude, and so on. The period is usually on the order of 3–15 seconds, but it can vary from a few seconds for light aircraft to a minute or more for airliners. Although usually stable in a normal aircraft, the motion may be so slightly damped that the effect is very unpleasant and undesirable. Some swept-wing aircraft have an unstable Dutch roll. If the Dutch roll is very lightly damped or unstable, the yaw damper becomes a safety requirement, rather than a pilot and passenger convenience.

- Roll mode: Roll subsidence mode is simply the damping of rolling motion. There is no direct aerodynamic moment created tending to directly restore wings-level, i.e. there is no returning "spring force/moment" proportional to roll angle. However, there is a damping moment (proportional to roll *rate*) created by the slewing-about of long wings. This prevents large roll rates from building up when roll-control inputs are made or it damps the roll *rate* (not the angle) to zero when there are no roll-control inputs (ref. Wikipedia)

- Spiral mode: if a spirally unstable aircraft, through the action of a gust or other disturbance, gets a small initial roll angle to the right, for example, a gentle sideslip to the right is produced. The sideslip causes a yawing moment to the right. If the dihedral stability is low, and yaw damping is small, the directional stability keeps turning the aircraft while the continuing bank angle maintains the sideslip and the yaw angle. This spiral gets continuously steeper and tighter until finally, if the motion is not checked a steep, high-speed, spiral dive results (ref Wikipedia)

The Stability Augmentation System of the F-16 (SAS) includes a feedback of yaw rate, pitch rate and alpha (r-p*α) and lateral Acceleration (ay) that enhances significantly the stability of both the Dutch roll and roll modes in the normal flight envelope (AOA<25°).

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2.3 Kinematic & Inertia–coupling Phenomena

KINEMATIC COUPLING

As indicated in Figure 5, a kinematic coupling between angle of attack and sideslip occurs when an airplane is rolled about its X-axis at high angles of attack. If the airplane is flying at an angle of attack with the wings level and the pilot initiates a pure rolling motion about its X-axis, all the initial angle of attack will have been converted into sideslip after 90° of roll. Because it is undesirable to generate large amounts of sideslips at high AOA from a roll performance, as well as a departure-susceptibility stand point, **most current fighters are designed to roll more nearly about the velocity vector than the body axis.** It is obvious that this conical rotation around Pstab vector motion eliminates the coupling between alpha and beta.

The ARI and SAS are design to attempt to make the airplane roll about its velocity vector.

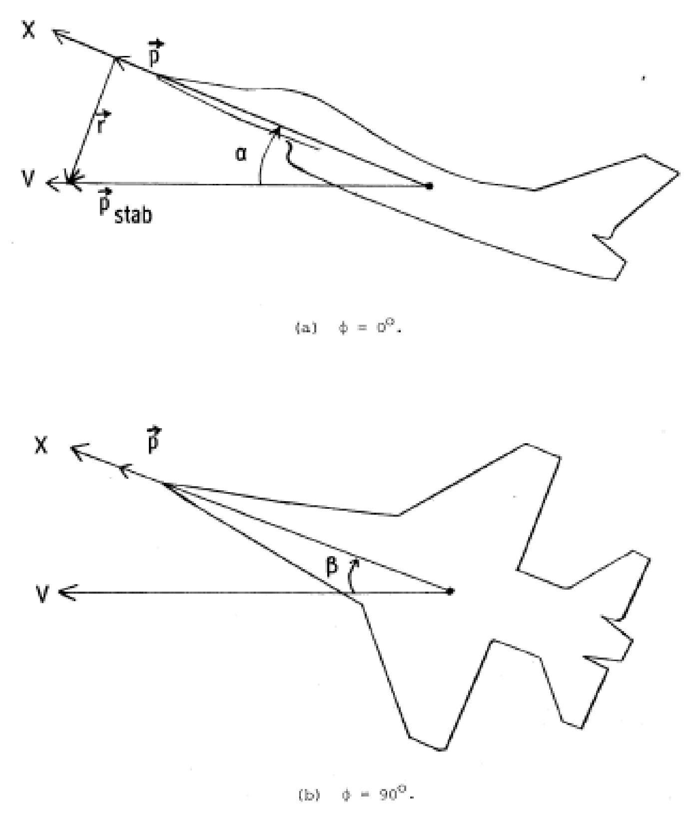

Figure 5: Conversion of AOA into Beta during roll around X-Axis.

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INERTIA COUPLING

A second form of coupling that is very important to the high angle of attack dynamics of the F-16 configuration **is due to inertial effects and is a consequence of the kinematic coupling control (see above).**

Figure 6 illustrates the inertial pitching moment that is produced when the airplane is rolled about its velocity vector. To visualize this effect, the fuselage-heavy mass distribution of the airplane is represented as a dumbbell, with the mass concentrated at the two ends. If the airplane is flying at some AOA and rolls about its velocity vector, the dumbbell will tend to pitch up to align itself perpendicular to the rotation vector.

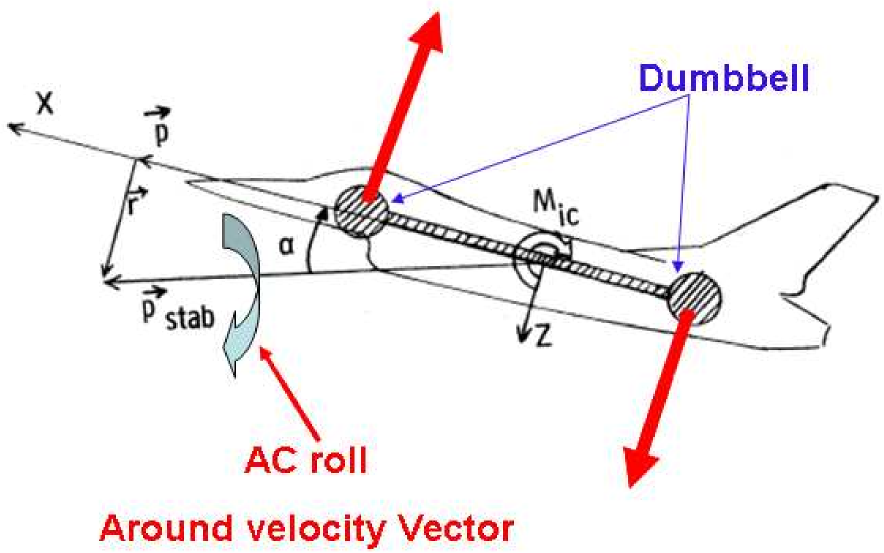

Figure 6: Illustration of inertia coupling

This nose-up pitching effect is very dependant on the roll rate and is very problematic for aircraft that employ relaxed pitch stability. This inertia coupling phenomenon is therefore the main driver of the roll rate limiter (detailed in the FLCS chapter).

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3 FLCS

The FLCS system of the F-16 is a combination of three modules: a pitch FLCS, a roll FLCS and a yaw FLCS. The FLCS of the F-16 has three operational modes / laws that we call "Gains"

- Stand-by gains: not implemented in BMS
- Landing Gear (LG) gains
- Cruise gains: normal operation mode

The Cruise gains FLCS developed for the NASA Langley's simulator is based on the real F-16 and has been developed to improve roll departures and study the best solution to exit deep stalls. The real F-16 FLCS has been improved following this NASA study results.

The FLCS Cruise gains implemented in BMS are identical to the Langley's one. LG gains and Ground gains that were not described in the TP1538 have been developed using the Cruise gain as the base system and adding some modules to match the different description in the available F-16 documentation.

3.1 Cruise Gains

3.1.1 Pitch

The Pitch FLCS features:

- **A pilot input system**
- **A negative G limiter**
- **A roll departure prevention system**
- **An angle of attack / normal-acceleration limiting system (CAT limiter)**
- **An AOA feedback & PID**
- **A normal acceleration feedback**
- **A pitch rate feedback**
- **An elevator roll blending system**
- **A Manual Pitch Override system**

The main purpose of the Pitch FLCS is to control the instability in pitch of the F-16 by limiting the requested Gs to permitted Gs. It directly controls the elevator angles.

The available Gs are computed depending on the AOA (computed by the anti-roll departure system see § 3.1.2), the normal acceleration of the aircraft (an), the pitch rate (q) and the manual pitch trim.

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Pilot Input System

The Pitch FLCS in Cruise gains is basically based on G control. The input of the pilots is always "G", i.e., the pilot requires a certain amount of "Gs" and the system tries to give the requested Gs within the limits allowed and at the rate permitted.

As show in Figure 7 the pilot can command (request) between -4G and + 10G

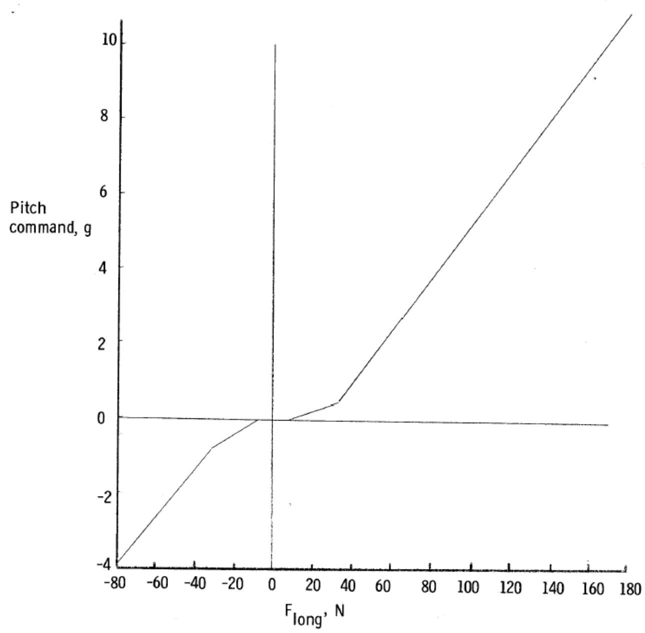

Figure 7: pilot input

However, the requested Gs are immediately limited in the input module at +8G independently of any other considerations.

In addition to the pilot requested Gs, the system always commands a permanent +1G on top of it - see "normal acceleration feedback".

As a conclusion, the pilot can request between -3 G and +9G.

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Negative G limiter

This module prevents negative G departures. At very low dynamic pressure (low speed/high altitude) and negative AOA, the elevators don't have much authority in nose up, therefore if too much negative Gs are requested in those situations, the FLCS would be unable to control the negative static margin and could enter in negative pitch departure.
At the very limit, the requested Gs can be limited down to -1G (read +0G – see normal acceleration feedback).

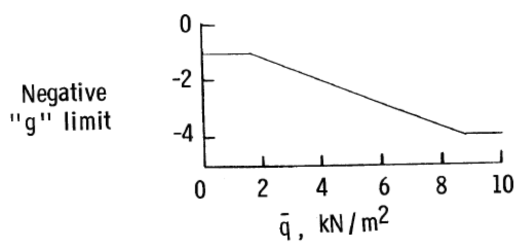

Figure 8: Neg G limiter

Roll departure prevention system

Due to Inertia coupling, pitch up was developed at high roll rate (see §2.3 – inertia coupling), provoking a departure called "roll departure". A roll departure prevention system has been studied by NASA in the TP1538 and included in the real F-16 FLCS. This "roll departure prevention system" has two major components, one in the pitch FLCS module, the other in the Roll FLCS module (see §3.1.2).

For the pitch module, the main idea is to make the system believe that at high roll rate, the AOA is higher than the real by adding a term: "Δαp". This will force the pitch system to "believe that the AOA is too high" and to apply some pitch down that will counter effect the inertia coupling. This "modified AOA" value is the one that is injected in the pitch FLCS CAT limiter.

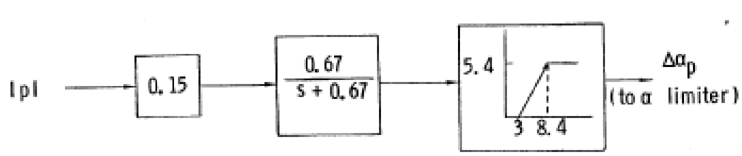

Figure 13: "Faked AOA" - Δαp-

As indicated in Figure 13, "p" being the pitch rate as input value,

- When pitch rate is lower than 20 deg/s, Δαp =0 and the real AOA is not modified
- When pitch rate is higher than 56 deg/s, Δαp =+5.4° and this additional value is added to the real AOA and injected in the pitch FLCS CAT limiter.

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Angle of attack / normal-acceleration limiting system (CAT limiter)

This module is well known from F-16 drivers and the "Dash One". It lowers the available Gs depending on the AOA and the position of the CAT limiter.

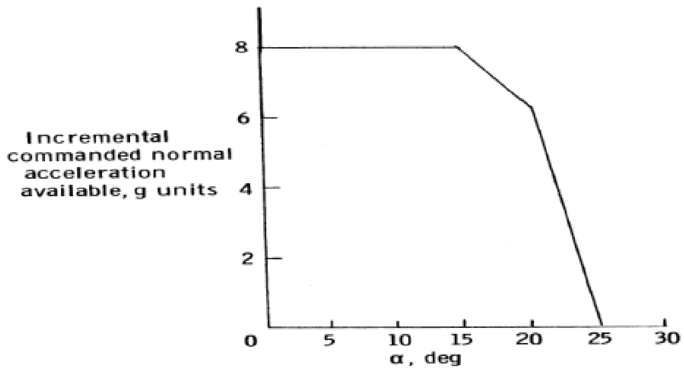

Figure 9: CAT1 limiter (from TP1538)

For example, below 15° AOA, the systems allows +8G (read +9G…. remember ;)), at 20° AOA , the systems allows +6.3G (read +7.3G) and at 25° AOA the systems allows only 0G (read +1G) i.e. level flight.

The CAT3 system was not described in the Langley's NASA simulator; however the full CAT3 system has been implemented in BMS from the "Dash One". See Figure 10.

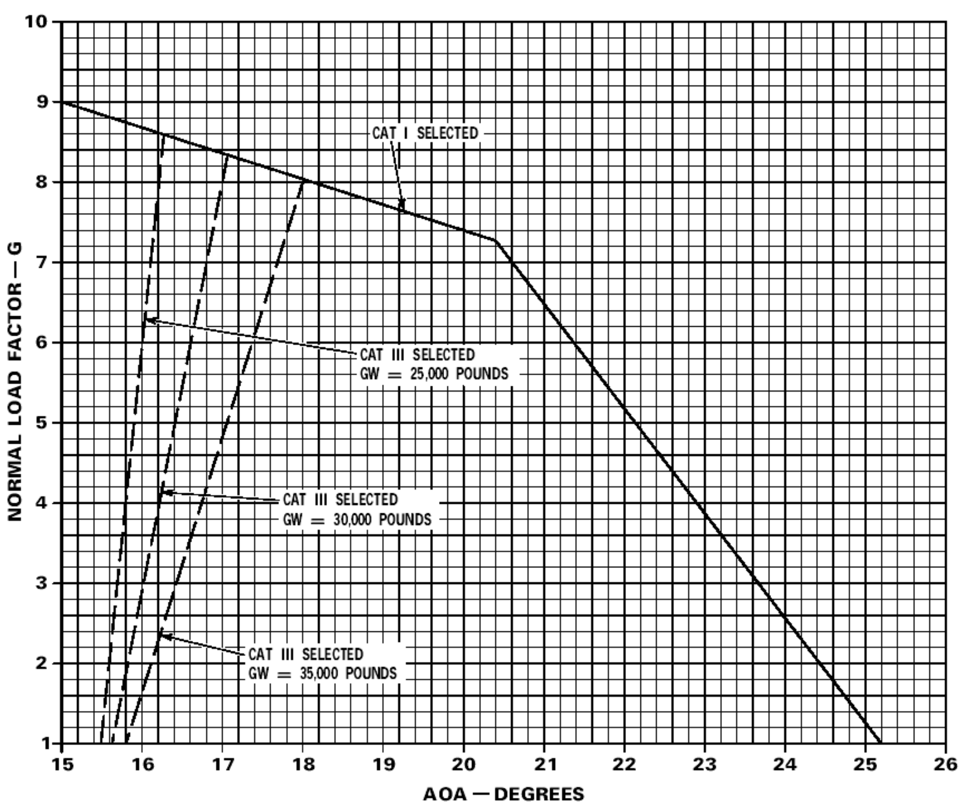

Figure 10: CAT1 & CAT3 limiter (from Dash 1)

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Figure 10 is not easy to understand for the CAT3 limiter. Basically in CAT3, the AOA is limited between 15.5° and 15.8° whatever the Gs conditions. That means that when the airframe is able to pull 9G at low AOA (at high speed for instance), the CAT3 limiter will not limit the Gs… but as soon as the AOA reaches 15.5° (intersection between the dash lines and the CAT1 curve), the CAT3 limiter will limit the AOA at this value, therefore the available Gs will be automatically reduced following the dash line.
The indication of weight is confusing. It does not mean that the CAT3 limiter has a different action with weight …it just means that for a given AOA (15.5°) and speed, the airframe is able to pull Gs depending on its weight (that is basic physics).
For instance:

- At 25,000 lbs : ~Mach 0.8 : 15.5° AOA = 8.6g
- At 30,000 lbs : ~Mach 0.8 : 15.5° AOA = 8.3g
- At 35,000 lbs : ~Mach 0.8 : 15.5° AOA = 8g

The reducing of the Available Gs in CAT3 configuration was necessary to prevent pitch departures with particular loadout configurations.

AOA feedback & PID

This system allows controlling the negative static stability of the aircraft (see §2.1).

Elevator roll blending system

This system mixes the angle of the elevator coming from the pitch FLCS module with the differential angle coming from the roll FLCS module.

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Deep Stall & Manual Pitch override system

This system has been created following the NASA Technical Paper 1538 (TP 1538) and it basically allows overriding the pitch FLCS system and gives direct control of the elevators to the pilot.

As seen in the chapter 2.1, there is a stable trim point around 60° of AOA, which allows the aircraft to enter in a Deep Stall. In this configuration, the FLCS system will always command elevator maximum pitch down angle: +25°; as seen previously, in this configuration, the aircraft will remain in deep stall.

When in a departure, overshoot values of alpha is in most of the cases too much above the trim point, resulting in a generation during the downswing of sufficient nose-down pitch rate to drive the airframe nose down over the Cm>0 hump and result in recovery.

Generally the airplane does not constantly drop into the deep stall trim point if its initial peak of alpha was greater than 75°. It is not common even after a departure to enter into a deep stall.

However, experience in flight and NASA testing demonstrated that it was possible in very rare cases to enter a deep stall.

It has been demonstrated that without aerodynamic asymmetry, the build up yaw rate was null, and the deployment of speed brakes and TEF were sufficient to quickly enter a recovery.

A quite different result was obtained with aerodynamic asymmetry (see §2.2); in that case, the asymmetry could cause a yaw rate of ~20°/s to the left that the FLCS was unable to compensate. After entering into spin stall, deployment of speed brakes and TEF was not sufficient to recover. Additional nose up inertia coupling moment caused by the angular rate was sufficient to negate the relatively small amount of nose down moment generated by the speed brakes and flap changes.

Generally, it was found that recovery to normal flight conditions could not be attainted with deployment of speed brakes and TEF unless the pilot deployed them early in the entry while there were still large oscillations in the motion. Obviously this was difficult to do and in the majority of the cases, recovery was not obtained.

The solution proposed by NASA was to manually override the FLCS and allow the pilot to command full pitch up. In that situation, the pitch up momentum was sufficient enough to increase AOA above +60 deg where the natural pitch down effect was sufficient to by pass the deep stall stable trim point. This technique was named "pitch rocking" and is illustrated in Figure 11.

Different GC position and/or weapon asymmetry can modify the response of the aircraft in terms of departure/deep stall and recovery.

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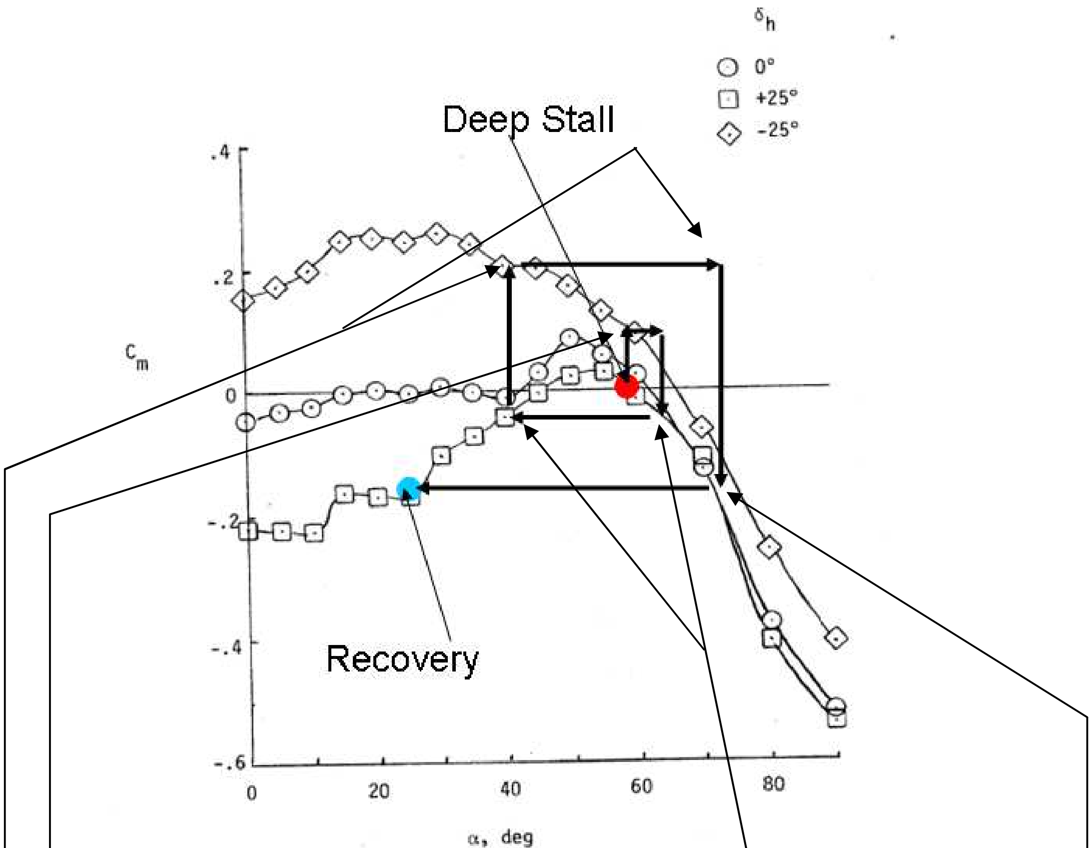


Figure 11: MPO: Rocking technique

From a DS situation, AOA 60°, the pilot enters in MPO

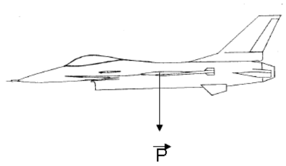
- Pilot commands full pitch up, the elevators have sufficient authority to pitch up and increase AOA around 63°.
- Pilot commands pitch down, elevators here have some small nose down authority at 63° AOA, therefore the aircraft pitches down and AOA is reduced to 40°.
- Pilot commands pitch up again , at 40° AOA, the elevators have a strong pitch up authority, the AOA is then increased to 70°
- Pilots then commands pitch down in this area, and the elevators have a strong pitch down authority, the aircraft pitches down and reaches 25° AOA => Recovery!

Revealing the Dark Side of the F-16 - FLCS

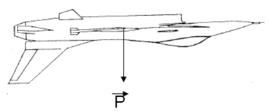
Normal acceleration feedback

Definition: The normal acceleration: "an" is the acceleration in "g" of the aircraft positive along the Z axis **including gravity (and other pitch/roll rate effects)**

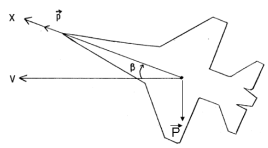
Examples assuming a straight flight, no turn:



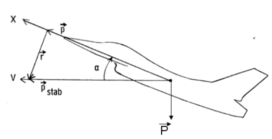
an = 1g



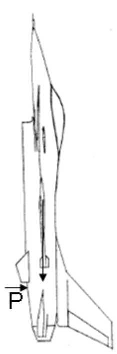
an = -1g



an = 0 g



an = g*cos(45) =0.7g



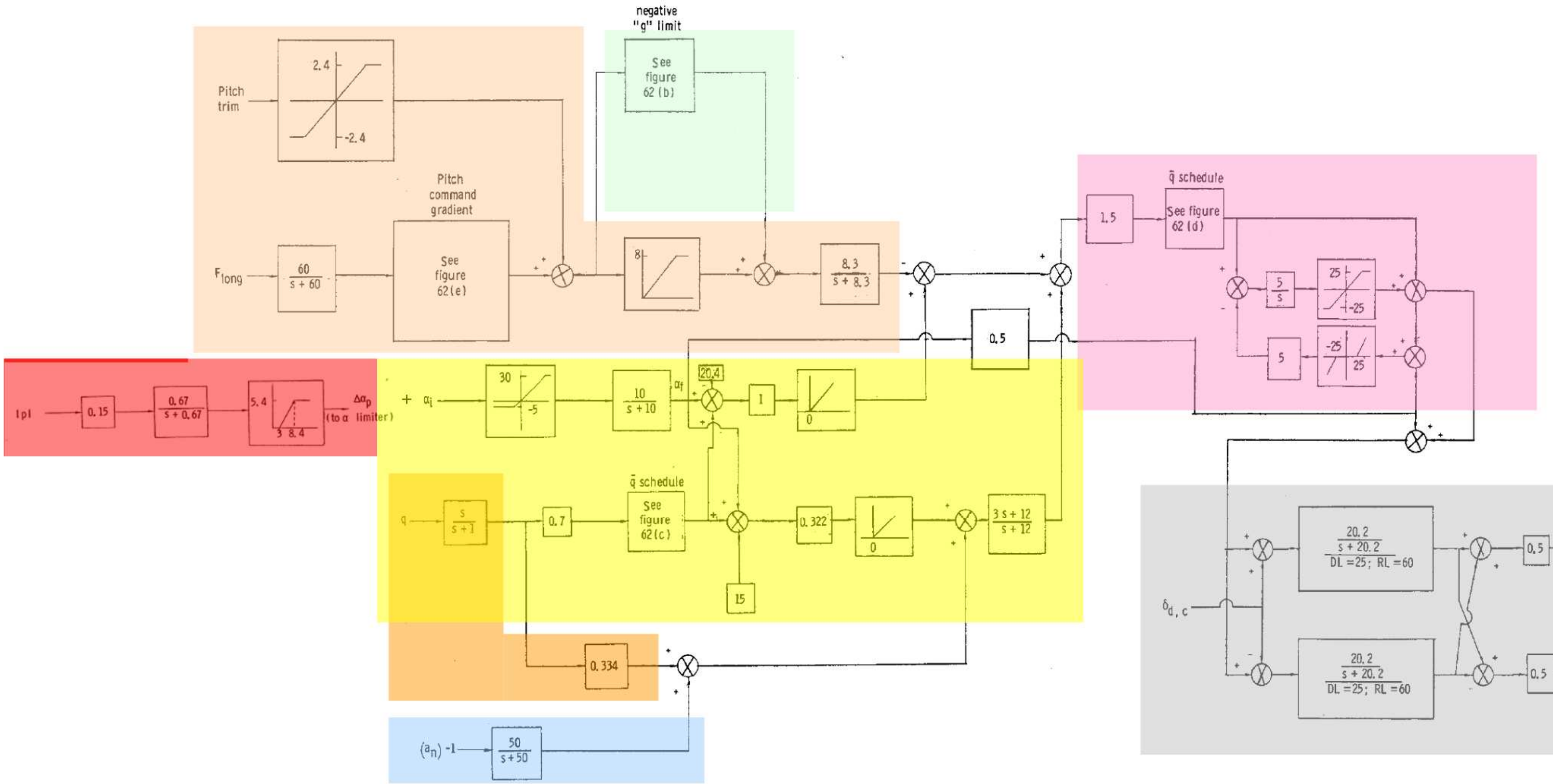
an = 0g

The normal acceleration feedback injects the term "+ (1-an)*g" in the FLCS pitch command.

This Feedback has therefore two purposes:

- It controls indirectly the pitch rate that will be applied (for 9g commanded, going from 1g to 5g will be much quicker than going from 8g to 9g). It means that it controls the speed/rate of the g evolution. (quicker at low g, slower at higher g).
- **Without pilot input, this acceleration feedback commands a permanent normal acceleration of +1g.**

OVERALL SCHEMATIC OF THE PITCH SYSTEM



- Pilot Input system
- Negative G limiter
- CAT Limiter
- Pitch rate feedback
- Normal acceleration feedback
- AOA feedback & PID
- Elevator roll blending
- Roll Departure prevention

Revealing the Dark Side of the F-16 - FLCS

3.1.2 Roll

The Roll FLCS features:

- **A pilot input system**
- **A roll departure prevention system**
- **A Roll rate feedback and command system (PID)**
- **An automatic departure/spin prevention**
- **An elevator / aileron mixing system**

The main purpose of the roll FLCS is to limit the roll rate to acceptable values to avoid too much inertia coupling that could provoke an excessive and uncontrollable pitch up and a departure (see §2.3 – inertia coupling). This kind of departure is called a "roll departure" and is the most common way to make the F-16 depart.

Pilot input system

Originally, the pilot was able to request 308 deg/s without any restrictions: **max requested roll.**

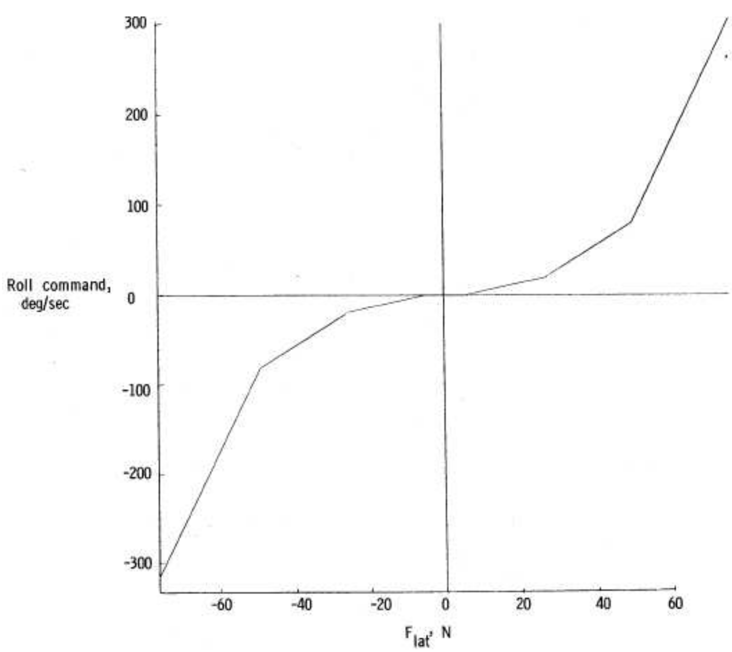


Figure 12: Roll rate commanded.

In some flight conditions, this was leading to major roll departures coming from excessive inertia coupling. One of the purposes of the NASA TP1538 was to propose a system to prevent a roll departure.

Revealing the Dark Side of the F-16 - FLCS

Roll departure prevention

This roll departure prevention system has two major components, one in the pitch FLCS module (see §3.1.2) and the other in the Roll FLCS module.

Basically, four parameters are playing a major role in a roll departure:

- The AOA (the higher the more critical – already close to pitch departure)
- The dynamic pressure –qbar- (the lower the more critical – loss of elevators effectiveness)
- The elevators position (the higher the more critical – less control angle available)
- The rudder position commanded by yaw FLCS module (for Digital FLCS only)

The idea was to reduce the available roll rate taking into account those three factors and to allow a **max commanded roll rate: (Pcom)max.**

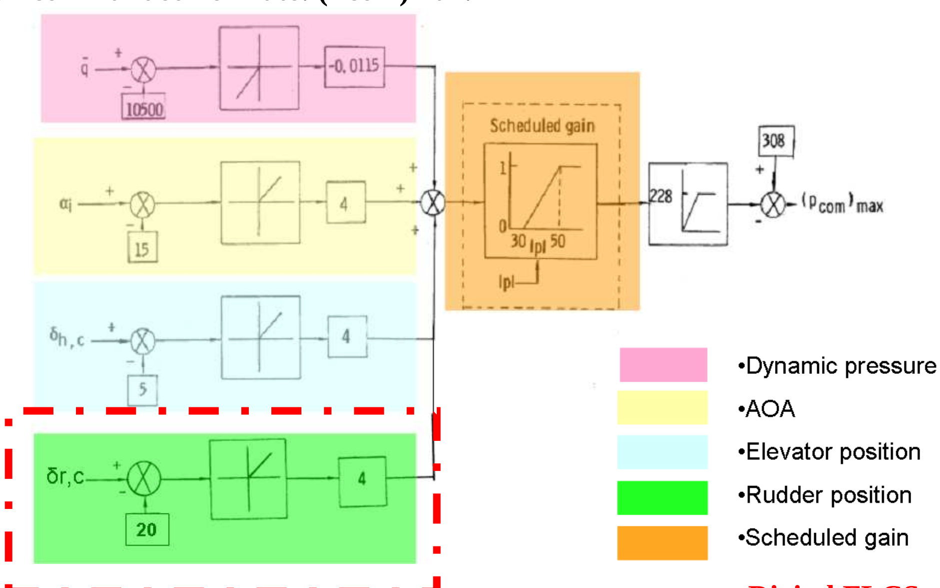


Figure 13: Roll departure prevention

We can see in Figure 13 that the system is not active under 30deg/s of roll rate and is fully active for roll rate above 50 deg/s (see scheduled gain).

The maximum reduction of roll rate is 228 deg/s which means that in the worst case scenario, the maximum allowed roll rate will be 308 – 228 = 80 deg/s.

The worst case scenario is low speed, high altitude, high AOA and pitch up command which is basically a barrel roll at high AOA – this is what we call an "assault on two limiters": roll rate and pitch.

Revealing the Dark Side of the F-16 - FLCS

The values of max *requested* roll rate and max *commanded* roll rate have slightly evolved in the real F-16 FLCS compared with the NASA TP 1538 (that had too large of a safety margin). Real values have been implemented and allow higher max roll rate (max 360 deg/s).

In case of FLCS failure, this roll rate limiting system may be damaged.

Be careful when executing a barrel roll at low speed/high alt. You are playing with the limits of the system.

In the CAT3 configuration, the aircraft is less resistant to roll departure due to increased weight, increased inertia and gravity center displacement. In order to reduce the roll departure risk, the max commanded roll rate in CAT3 is approximately reduced by 40% of the max commanded roll rate of the CAT1 configuration.

Roll rate feedback and command system (PID)

It allows achieving the requested / commanded roll rate with smooth roll rate accelerations and decelerations. It allows as well as maintains stable flight without pilot roll input.

Without this PID system, the roll would have been extremely violent and uncontrollable.

This roll rate command system loses its efficiency at low speed/high altitude (low qbar) where the elevators loose their aerodynamic efficiency.

Typically, at low speed, coming from max roll rate and releasing the stick, the aircraft will continue to roll a few degrees. To make it stop quicker, an opposite stick pressure is required.

This behavior is well described in the F-16 -1. I don't know why the engineers did not include a qbar feedback in this roll rate command system that could have improved the crispness of roll at low speed / high altitude. Nevertheless, BMS strictly simulates the real system here.

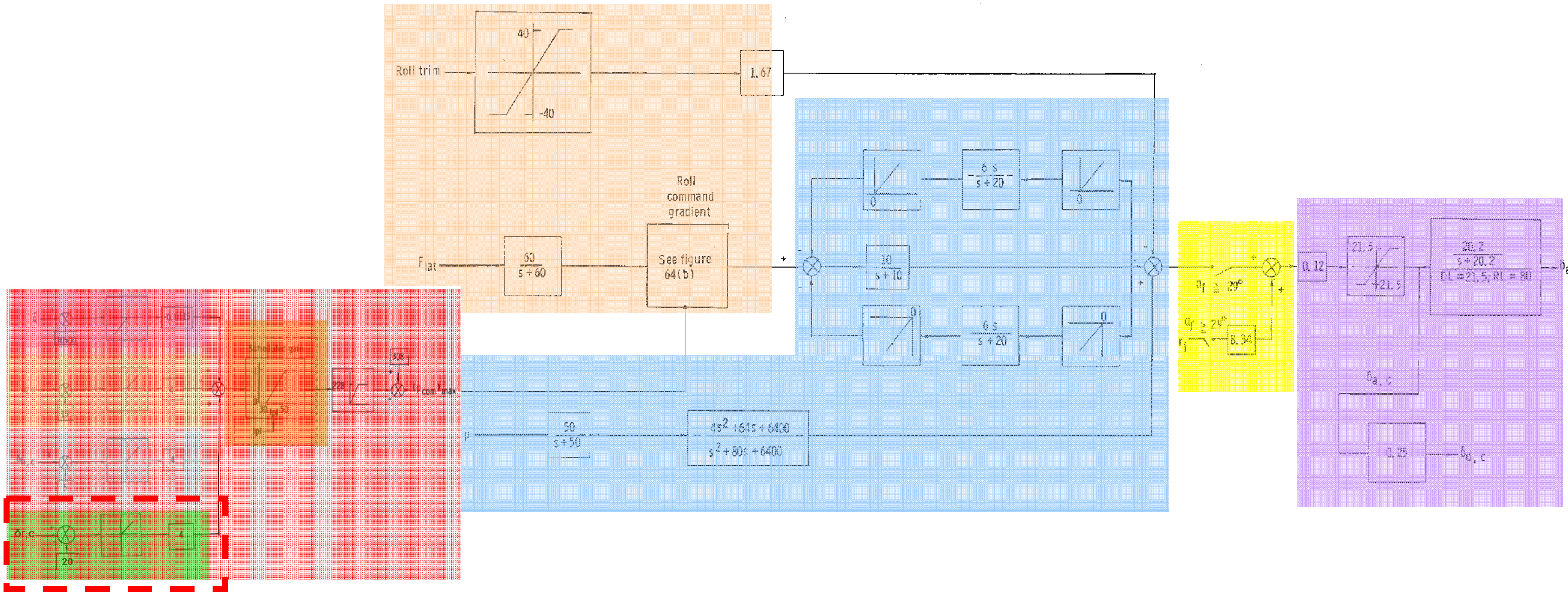
Automatic departure/spin prevention

As seen in the § 2.2 Figure 3, at high AOA, the rudder has a very small effect on yaw whereas the ailerons have a very good yaw control. Therefore, to prevent spins, above AOA 35°, an automatic departure – spin prevention system is activated which uses a yaw-rate feedback to drive the roll control surfaces to oppose any yaw rate buildup. Pilot roll commands are cut out only when MPO is engaged.

Elevator / aileron mixing system

For the F-16, roll is controlled both by elevator differential angle and ailerons. Basically, the elevator angle is computed by the Roll FLCS and the law for the aileron is derived from it: Angle (aileron) = 0.25 * Angle (elevator).

OVERALL SCHEMATIC OF THE ROLL SYSTEM



- •Pilot input system
- •Automatic departure / Spin prevention
- •Roll departure prevention
- •Elevator / aileron mixing
- •Roll rate feedback and command
- Digital FLCS

Revealing the Dark Side of the F-16 - FLCS

3.1.3 Yaw

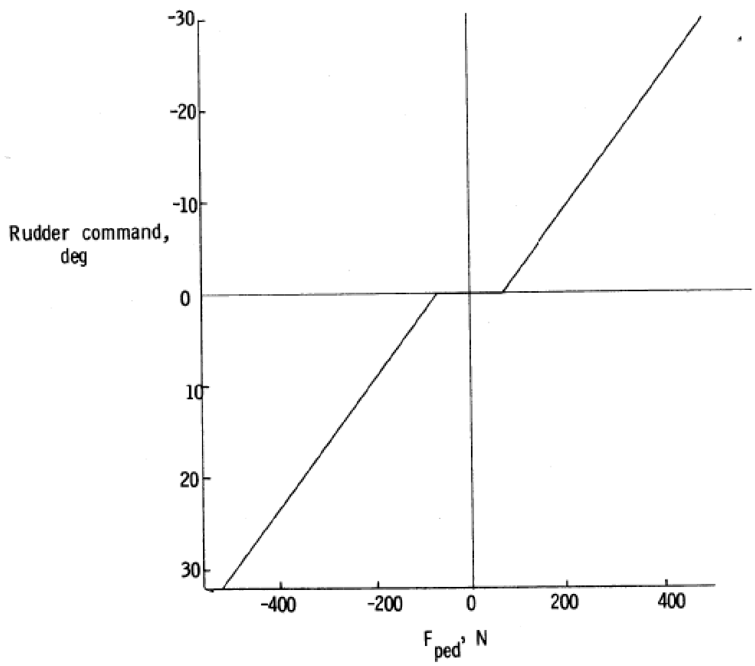
The Yaw FLCS features:

- **A pilot input system**
- **A Stability Augmentation System (SAS)**
- **An Aileron Rudder Interconnect (ARI)**
- **A departure / spin prevention system**

The main purpose of the yaw FLCS is to minimize the side slip angle during aircraft evolution, in particular coordinated turns, avoid any roll reverse behavior and ensure aircraft rolls about its velocity vector.

Pilot input system

The pilot can request between -30 and + 30 degrees of rudder deflection.



However, the rudder is completely controlled by the FLCS to perfectly coordinate turns and avoid any side slip angle.

Revealing the Dark Side of the F-16 - FLCS

In theory the pilot should never apply any rudder input. In particular, at high AOA, the precise control of the rudder is so important that any input from the pilot in those situations could trigger a departure. To prevent those situations, the FLCS reduces the effectiveness of the pilot input:

CAT1: max deflection reduced above 14° AOA down to zero at 26°AOA
CAT3: max reduced above 3° AOA down to zero at 15°AOA

Another reflex from most of traditional pilots is to put some rudder in order to accelerate the roll rate. The yaw FLCS of the F-16 already controls the rudder to provide the requested roll rate, and a pilot input of the rudder does not improve the roll rate and could lead to negative effect. In order to prevent the pilot to input some rudder, the yaw FLCS also includes a limiter with the roll rate (Figure 15)

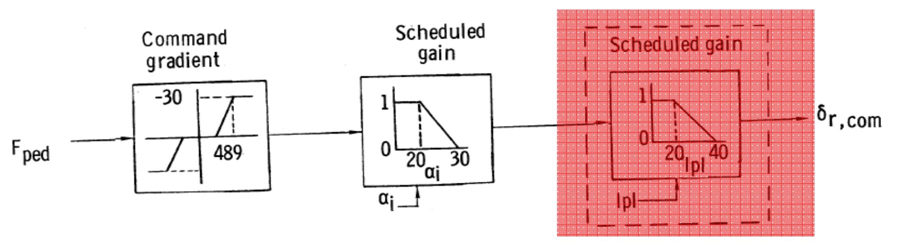


Figure 15: Rudder pilot input roll rate & AOA limiter

Above a roll rate of 20°/s the rudder pilot input is minimized down to 0 above 40°/s.

Pilot rudder input is useless on the F-16 and could eventually worsen the flight and roll capacities of the aircraft or increase departure risk. In most cases, the pilot rarely needs to have any control of the rudder.

Stability augmentation system

This system takes as input the roll rate, yaw rate and AOA and acts on the rudder to dampen the adverse effects of yaw/roll coupling (see § 2.2 YAW SAS).

ARI

As described in the §2.2, the ARI makes the rudder compensate the yaw effect coming from the aileron. This prevents any reverse roll behavior.

However, there is a situation where the ARI can be very dangerous for the aircraft. Indeed, on ground, in case of a crosswind, the pilot has to put rudder and aileron in the same direction (into the wind) to steer. If the ARI were activated, an input on the aileron would have made the rudder turn in the opposite direction which could lead to loss of control of the aircraft. To prevent this situation, the ARI is disconnected when the main gear speed is greater than 60 knots or if AOA exceeds 35 degs.

ARI is activated within two seconds after the LG handle is raised (spin down braking system). If the LG handle remains down, 10-20 seconds are required. ARI can kick in faster if you apply braking force while in the air.

Revealing the Dark Side of the F-16 - FLCS

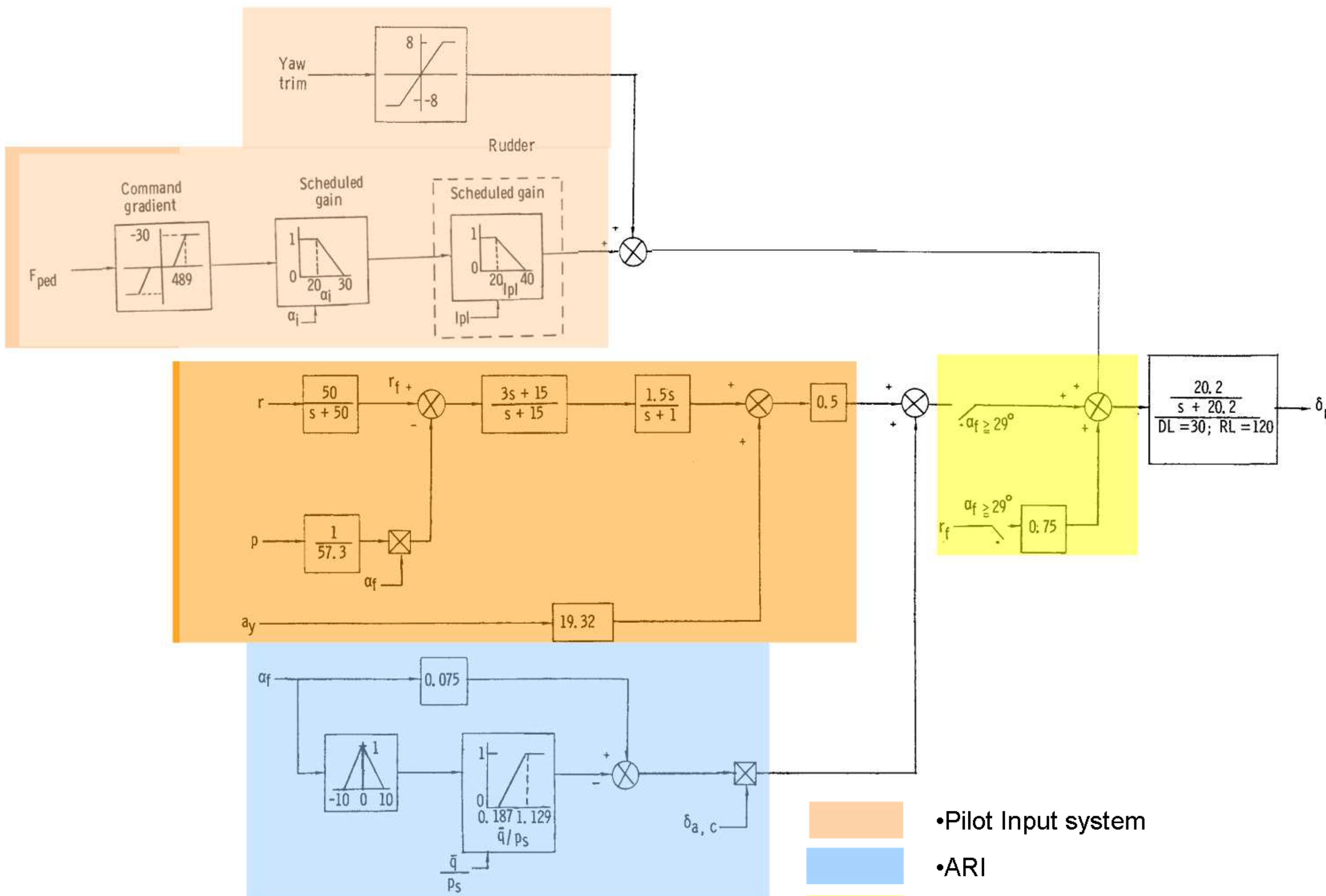
Departure / spin prevention system

As in the roll axis, above 35° AOA, a departure spin-prevention mode is activated which drives the rudder to oppose any yaw rate buildup.

Pilot rudder commands are cut out only when MPO is engaged (however above 26°, rudder input are zeroed).

For digital FLCS systems, below -5° AOA and 170 kts, the FLCS system provides an anti-spin rudder input.

OVERALL SCHEMATIC OF THE YAW SYSTEM



- •Pilot Input system
- •ARI
- •Spin / departure prevention system
- •Stability Augmentation system

Revealing the Dark Side of the F-16 - FLCS

3.2 Landing Gear (LG) Gains

The FLCS is in takeoff and landing gains with the LG handle in the down position, the ALT FLAPS switch is in extend below 400 kts, or the air refuel switch is in open (below 400 kts).

Pitch FLCS

In LG gains, the pitch FLCS operates as a pitch rate command system until 10° AOA. That means **that the pilot commands a pitch rate and no longer a g value**. Consequently , when no input is requested, the system commands 0° pitch rate, therefore whatever the conditions, the nose will stay steady and the FPM will move up and down depending on the AOA/speed.

After 10° AOA, the system is a blended pitch rate and AOA command. That means that AOA feedback is injected in the pitch rate command to command a nose down. This blended system has been created in order to give more feedback to the pilot while landing. Indeed, with this system, after 10° AOA, the pilot will have to apply a constant pull pressure on the stick to avoid the nose going down. This gives the pilot the feedback of a classic NFBW airplane during landing.

Roll FLCS

In LG gains, the roll rate is limited to half of the value of the cruise gains value and is independent of AOA, airspeed or horizontal tail position.

3.3 LEF & TEF Scheduling

LEF and TEF now have a real impact in the motion behavior of the F-16. A locked LEF or TEF could result in considerably reduced/degraded handling of the aircraft.

LEF

Leading edge flaps are controlled by the FLCS and the deflection is scheduled with angle of attach and mach. When supersonic, the LEFs are 2 degrees up.

Exceptions cases are:

- When WoW on main gear, the LEFs are 2 degrees up
- LEF asymmetry brakes are locked

TEF

The TEF are controlled as a function of the LG handle position, the ALT FLAPS switch and airspeed.

ALT FLAPS switch to EXTEND or LG handle to DN:

- Speed < 240 kt : TEFs position is 20 degrees down
- Speed >240 : TEFs reduces deflection as a function of airspeed until fully retracted at 370 kt

Revealing the Dark Side of the F-16 - FLCS

3.4 Gun Compensation

The gun of the F-16 is mounted off center from the fuselage axis, resulting in a yaw momentum when firing.

A gun compensation system has been developed in order to minimize the yaw momentum and to stabilize aiming.

The first compensation is done with the rudder. During firing, the rudder is angled to compensate from the yaw induced. Lateral acceleration feedback of the yaw system is deactivated during gun firing.

At the same time as the rudder is angled, it induces some roll; therefore the roll system also includes an independent compensator that zeroes the induced roll during firing.

Be aware that gun compensation is optimized for 0.7 – 0.9 mach range, therefore all excursions may not be eliminated if the gun is fired out of that range.

BMS models the real gun compensation system. In case of FLCS failure; the gun compensation system may be damaged resulting in very less precise (nearly impossible) gun firing.

4 The Asymmetry Problem

Asymmetry along the X axis (roll asymmetry)

Most of people believe that the F-16 FLCS includes a system to trim any asymmetry on the roll axis. This idea is wrong.

The F-16 does not include a roll trim system and the pilot has to constantly manage the roll trim in case of asymmetry.

Most people believe that the asymmetry is just an additional weight on one wing that makes one wing heavier and makes the aircraft roll toward the heaviest wing.

Some people claimed a bug during beta testing, because if not trimmed, the aircraft performed infinite rolls toward the heaviest wing. They, as well as most of the people that believed the above statement, also believed that once the aircraft was banked 90° toward the heaviest wing, it was in a stable position and the aircraft should stop rolling.

This intuitive physics effect is completely wrong and this should be explained here in order to understand all the implications of such an asymmetry for the pilot. Basically, the mistake that most people make comes from the confusion between Mass and Weight.

Revealing the Dark Side of the F-16 - FLCS

Mass is the quantity of material that constitutes an object and it is measured in Kg. The repartition of that mass defines the Gravity Center.

Weight is the force coming from gravity that is proportional to the mass. The weight force is applied on the Gravity Center and is measured in Newton (N).

In Newton physics, mass is an independent value whereas weight depends on the planet you are on.

A solid object rotates around its center of inertia. For a solid object, the center of inertia is superposed with the Gravity Center (GC) (or Center of Gravity – CG).

Therefore, a solid object rotates around its gravity center and the weight is applied at this gravity center.

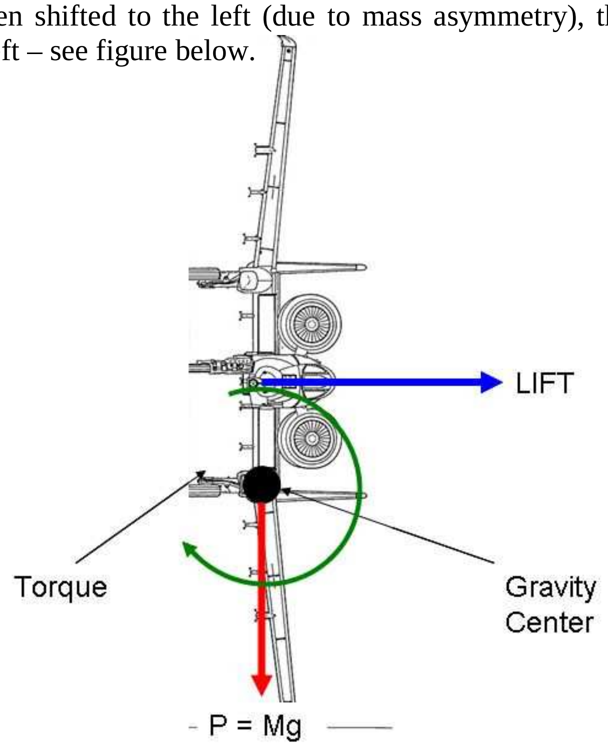
When you drop a bomb, your mass reparation is moving so your gravity center is moving – let's say to the left for example.

As the weight force applies on the gravity center, if no other forces are applied, no rotation is expected! The weight does not produce any torque.

To be clear, it is NEVER THE WEIGHT that makes the aircraft roll in case of asymmetry. In other words, the phenomenon is INDEPENDENT from aircraft attitude in the earth system.

So in the air, what makes the aircraft roll in case of asymmetry?

Well the resultant **lifting force is applied to the center of the a/c** (aero center).Therefore as the gravity center has been shifted to the left (due to mass asymmetry), the lifting force is creating a Torque to the left – see figure below.



Revealing the Dark Side of the F-16 - FLCS

If the lift force was null – there would be no torque, and then no rotation. But for the F-16, the **FLCS is always seeking 1G**, which means that there is always a lifting force applied. Therefore, whatever the aircraft's attitude in the earth system, in case of asymmetry, the aircraft will keep rolling and rolling and rolling.

The only way to stop it:

* Push on your stick to force 0G: then you will notice that whatever the amount of asymmetry you have, at 0G the aircraft will stop rolling.

* Trim to create a counter torque.

Now you understand that when you trim for 1G, the counter torque is compensating the LIFT (1G) / GC torque. But when you pull 4-5 Gs, then the generated torque is 4-5X greater, therefore the initial trim is not sufficient enough. The aircraft will start rolling again when you pull. **You will have to compensate for it during your pull.**

Asymmetry along the Z axis (yaw asymmetry)

One critical asymmetry induced by an asymmetrical weapon load out is the asymmetry along the Z axis.

This creates a torque that generates a side slip angle. As we saw, side slip angles must be avoided at all costs because they can trigger departures.

As a consequence, it is generally requested to trim the rudder in order to reach zero side slip and avoid yaw departures.

Of course, trimming the rudder will induce roll; therefore the procedure for trimming asymmetrical configurations is:

- Trim rudder to reach zero side slip angle.
- Trim Ailerons to reach zero roll rate.

In case of asymmetrical configuration, the aircraft must be trimmed prior to takeoff and the trim amount is dependant on the takeoff speed and amount of asymmetry. Failure to properly trim could result in a wing strike or even a crash during takeoff.