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POST STALL CHARACTERISTICS OF HIGHLY AUGMENTED FIGHTER AIRCRAFT

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Abstract

The deep stall phenomenon and related post stall characteristics are described in considerable detail, including the various stages of departure from controlled flight. The problematics of deep stall characteristics in view of ever changing operational requirements and aircraft modifications are presented. The development of corresponding flight control laws in highly augmented fighter aircraft (General Dynamics F-16 and Israel Aircraft Industries LAVI) is outlined. Results of 6DOF digital simulations and flight test data (accumulated in recent IAF high AOA test program) of deep stalls and post departure phenomena are presented. The impact of configuration changes, pilot input coordination, and selected flight control system modifications are shown and discussed.

I. Introduction

The advent of Control Configured Vehicle (CCV) concepts which permitted operation of aerodynamically unstable aircraft, introduced a hitherto unknown phenomenon, the deep stall.

A deep stall is a condition of uncontrolled flight in which the aircraft is locked in a high AOA (> 60 DEG) attitude and a nose down command cannot be effected with available control power. Deep stalls are characterized by very low velocity flight ($V \sim 0$) accompanied by a rapid rate of descent (1000 nds of ft/min) and low frequency oscillations around all three axis.

Advanced flight control systems as implemented in the F-16 and the LAVI combat aircraft are designed to provide exceptional flying qualities and theoretically departure proof flight . Extensive flight and operational experience have proven however, that the flight control system limiters which operate to keep the aircraft within the controlled flight envelope, can be broken, and departures from controlled flight may occur.

The operation of aircraft in a bewildering array of configurations at varying external aerodynamics, weights, moments of inertia, and center of gravity locations further complicates the issue and increases the likelihood of encountering departure/post departure conditions with unacceptable characteristics.

This mounts a particular challenge for the Air Force which has to certify new operational configurations for which the aircraft's flight control system was not originally designed.

Considerable efforts have been expended in the last decade by manufacturers and operators alike to recognize and understand the deep stall phenomenon and develop concepts and associated control laws for recovery. These efforts were hampered by the fundamentally different approaches chosen by pilots and engineers respectively. While engineers pushed towards fully automatic recovery control systems (pilot out of the loop), pilots insisted on devices facilitating deep stall recognition and effective manual recovery modes like Manual Pitch Override (MPO).

This paper describes the fundamentals of the deep stall phenomenon and the evolution of those control laws of the F-16 and LAVI aircraft that were designed to deal with out of control flight conditions. Early FCS versions that treated the problem with Anti Spin Modes and MPO are shown and current and future models that cope with considerable variations in aircraft configurations, are presented.

The different stages of development of control laws are illustrated using flight test data, handling quality simulators, and digital computer simulations.

II. The Deep Stall Phenomenon

Operation of statically unstable aircraft (center of gravity behind the neutral point) became possible through the advent of Fly By Wire flight control systems. The main insentive for the introduction of static instability was increased performance achieved through the utilization of positive lift on the tail surfaces (see Fig. 1) as well as the provision of a wider range of C.G. positions to accommodate multiple configurations.

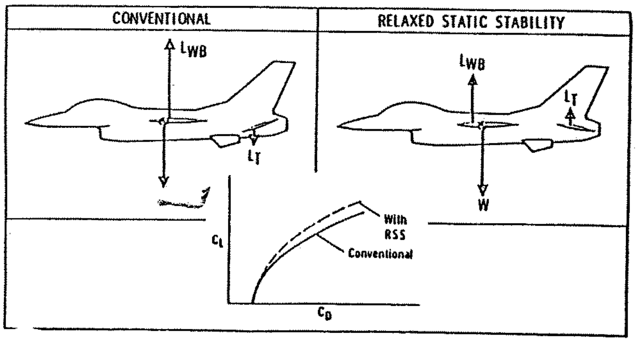


Figure 1: Relaxed Static Stability

The Cm vs. Cl graph for statically unstable aircraft indicates a trim condition at a high AOA, beyond AOA stall as illustrated in Fig. 2. Note that such a trim point does not exist on the corresponding Cm vs. Cl graph for statically stable aircraft. This post stall trim condition is called deep stall.

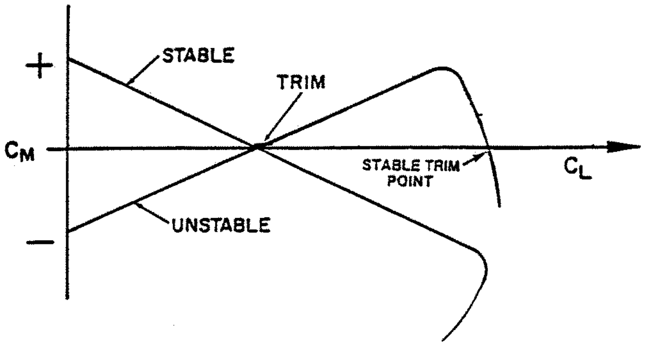


Figure 2: Cm vs. Cl

Typical Cm vs. AOA graphs drawn for varying elevator positions at two c.g. locations (case 1 and case 2) are illustrated in Fig. 3.

For both cases post stall trim conditions exist. For case 1 (forward c.g.) a maximum nose down command will recover the aircraft from the deep stall condition while in case 2 (aft c.g.) this command will not suffice and the aircraft will hang in the deep stall. Incidentally, a deep stall may be upright or inverted, depending on the entry conditions.

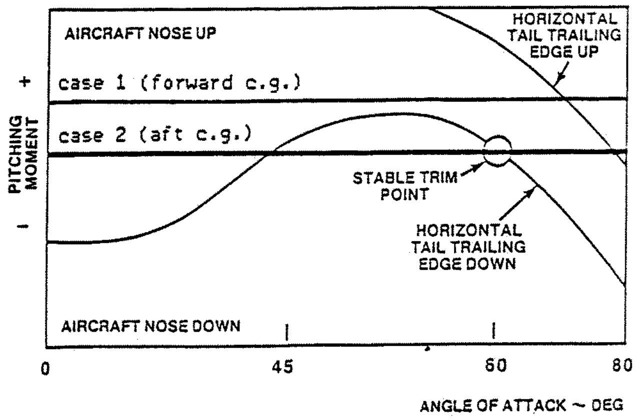


Figure 3: Deep Stall

Naturally, aircraft manufacturers will aim to design aircraft which are not susceptible to deep stalls. However , the desire to fulfil the above goal will usually penalize the potential gains that can be obtained through statically unstable operation (aft c.g. locations, lower trim drag). In addition, low control surface efficiencies at high AOA/low velocity make deep stall recovery by direct push down command unlikely. As a result, advanced control augmented fighter aircraft can be flown into a deep stall condition.

The manufacturers approach the solution to the deep stall problem on two levels:

1. Development of control laws to prevent departures into deep stall.
2. Development of recovery concepts, once a deep stall has occurred.

III. Post Stall Control Laws

Control treatment of the post stall regime as implemented in the F-16 and LAVI fighter aircraft consists of the following stages:

1. Departure recognition and engagement of relevant control laws.
2. Operation of control surfaces throughout the departure, until recovery.
3. Recognition of recovery and reengagement of regular control laws.

Stage 1 - Engagement

Departure recognition is achieved through measurements of flight parameters (AOA, velocity). Post stall control laws are engaged at a preset threshold (see Fig. 4,5).

A typical characteristic of this stage is the loss of command by the pilot as the FCS flies the aircraft.

Stage 2 - Deep Stall

Control laws throughout the departure deal with two different aspects - spin prevention and the longitudinal recovery concept. Spin prevention is achieved by measuring yaw rates and engaging all available control surfaces (rudder, flaperons, and differential elevator) to counteract any developing spin . Figure 4 shows the anti-spin mode of the F-16 aircraft. A similar concept is implemented in the LAVI FCS where rudder and ailerons counteract the yaw rate.

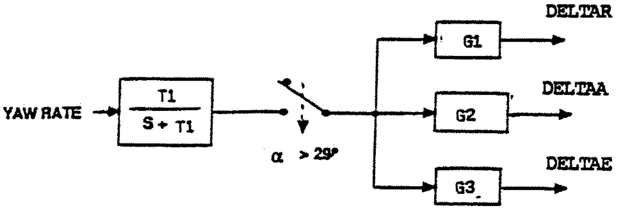


Figure 4: F-16 Anti-Spin mode

Longitudinally, the FCS will command maximum nose down at AOA above the threshold. If control power at the specific aircraft c.g. is sufficient, safe recovery will be achieved. If not, the aircraft will hang in a deep stall. For this particular situation, the FCS has a provision for direct pilot intervention achieved via the Manual Pitch Override (MPO) switch installed in the cockpit. The F-16 FCS control laws, while in the MPO mode, are illustrated in Fig. 5. To effect recovery, the pilot has to manually operate the longitudinal control surfaces (F-16 - elevator, LAVI - canard and elevons) in phase with the natural pitch oscillations until sufficient nose down attitude is attained and recovery is achieved.

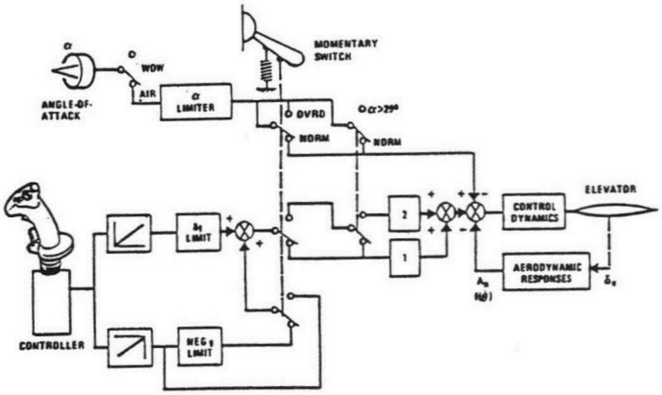


Figure 5: F-16 MPO mode

Stage 3 - Recovery

This stage is a mirror reflection of stage 1. Nominal FCS control laws will hold the aircraft within the controlled flight envelope (AOA < threshold) after recovery has been achieved. The pilot will once again be in full command of the aircraft.

F-16 flight test data of a typical complete deep stall cycle are presented in Fig. 6. Operation of the anti-spin mode is shown by rudder deflections in reponse to yaw rate development (max. yaw rate 20 Deg/sec). The pitch rocking recovery concept is illustrated by the in-phase pilot commands while in the MPO mode.

IV. Technical Discussion

The major effects contributing to post stall aircraft characteristics encountered during operational experience and recent investigations (6DOF simulations, handling qualities simulators and flight tests) are discussed and illustrated in the following paragraph. The discussion will be divided into three sections, each dealing with one stage of the deep stall.

1. Engagement Stage

One of the central topics during the engagement stage of the post stall control laws is the definition of the threshold parameters and the determination of their value. At the threshold values the FCS will switch from nominal to post stall control laws. It is evident that there is a tradeoff between early and late engagement.

Early engagement facilitates recovery since the departure is likely not to be fully developed at the time the post stall control laws cut in. At the same time, for a given maneuver early engagement can cause departure since the post stall control laws (anti-spin mode) may limit the pitch authority of the elevator (F-16) or elevons (LAVI).

Late engagement retains a larger envelope with nominal control laws but may result in difficult departure entry conditions (high AOA, angle of sideslip and yaw rates)

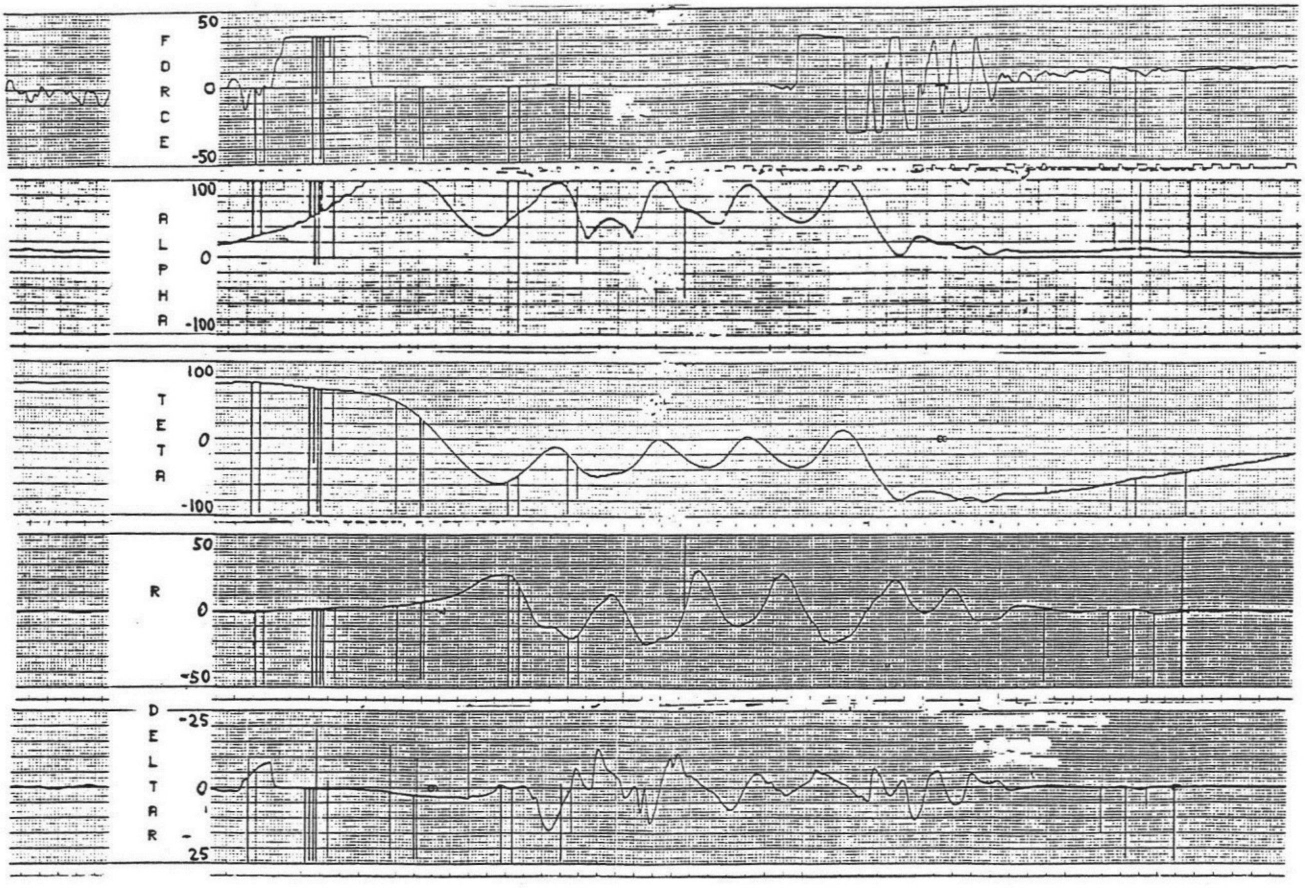


Figure 6: Complete Deep Stall Cycle - Flight Test

2. Deep Stall Stage

This stage is characterized by oscillations around all three axis while the aircraft rapidly loses altitude at airspeeds close to zero.

Configuration Effect

The frequency and amplitude of the oscillations, particularly in the lateral/directional plane, are highly sensitive to the aircraft configuration. Recent models of the F-16 aircraft with modified aerodynamics and increased inertia/mass exhibited deep stalls with lower frequencies and higher amplitudes causing unacceptable recovery characteristics in loadings with centerline stores.

A comparison between the deep stall characteristics of recent configuration and an earlier production F-16 is shown in Fig. 8. The considerable amplitudes of the yaw/roll oscillations in the newer aircraft require substantial deflections of the control surfaces (including differential deflections of the elevator) to counteract the developing yaw rates. The remaining longitudinal elevator authority does not suffice to recover the aircraft. As shown in Fig. 8, the earlier F-16 model does not exhibit these negative characteristics and self recovery is achieved.

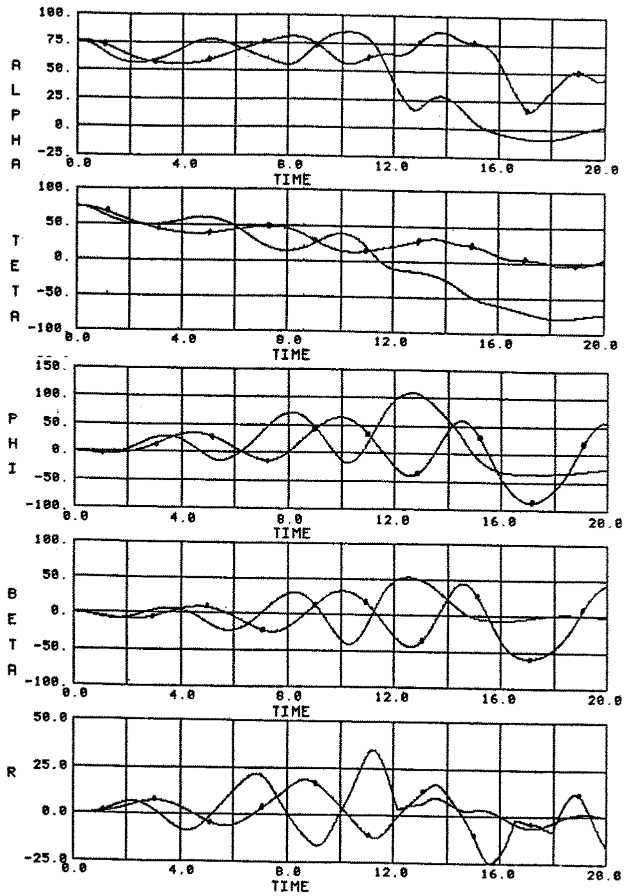


Figure 8: Configuration Effect
—— Early F-16 model
—●— Recent F-16 model

Timing Effect

When MPO cycling is required to achieve recovery from developed deep stall conditions, pilot inputs coordinated with aircraft pitch motion are mandatory. Figure 9 shows a comparison between coordinated and uncoordinated pilot inputs. A one second delay in pilot input can determine the failure of the recovery.

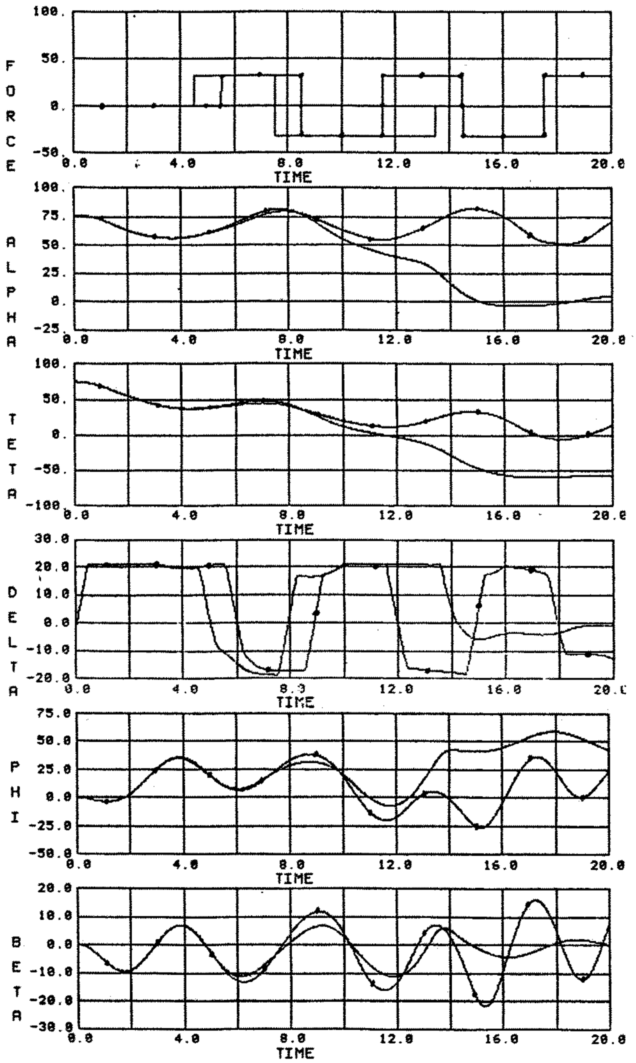


Figure 9: Timing Effect
—— In Phase Pilot Command
—●— Out of Phase Pilot Command

3. Recovery Stage

This phase requires positive recognition of impending recovery to engage nominal control laws as early as possible. By definition, the aircraft is at very low airspeeds at the moment of recovery and will return to deep stall conditions unless nominal control laws prevent this. Fig.10 shows the aircraft drop rapidly from an upright to an inverted deep stall condition during a flight test.

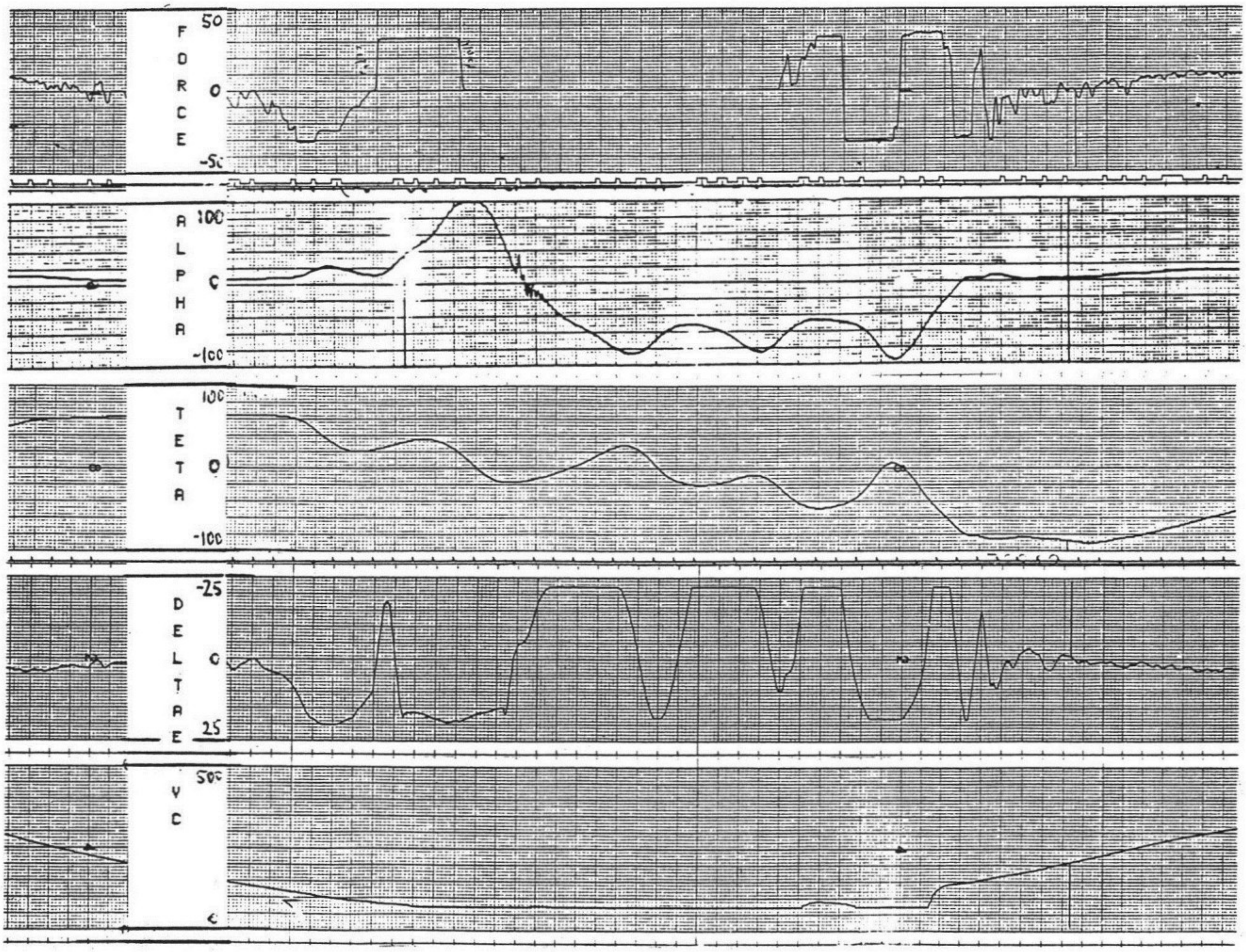


Figure 10: Flight Test - Upright to inverted Deep Stall

V. Control Law Modification

Operational experience with the newer F-16 models and unique Air Force store carriage requirements have provided the trigger to modify existing FCS control laws to improve unacceptable departure/deep stall characteristics.

The IAF has gained considerable experience in this area from combined IAF/Israel Aircraft Industries (IAI) research conducted in the framework of the LAVI FCS development and its considerable involvement with the F-16 development and improvement programs conducted by General Dynamics (GD).

Following are changes to the control laws that were/are evaluated and developed using digital computer simulations, handling quality simulators, and flight tests.

We have chosen to discuss in this paper the recent F-16 anti-spin control law modification developed by GD and the LAVI auto pitch rocker design developed by IAI.

F-16 Anti Spin Modification

The F-16 anti-spin control laws command the rudder, flaperons, and antisymmetric elevator deflection as a function of measured and filtered aircraft yaw rate (see Fig. 4).

The engineering challenge was the determination of the optimum set of gains and filter time constants to obtain the most benevolent post departure/deep stall behaviour.

To accomplish this, a major effort was made by the manufacturer to correlate the 6DOF simulation models and data bases in the higher AOA/post stall regime with accumulated flight test data.

The results of this effort indicated a considerable sensitivity of the deep stall characteristics in particular to the value of the filter time constant (T1 in Fig.4) and also to the control surface command gains (G1, G2, G3 in Fig. 4).

Figure 11 and 12 show a comparison of deep stall characteristics between the current F-16 nominal yaw rate limiter and its modified version.

With the new limiter, the aircraft oscillates at considerably lower lateral amplitudes than with the corresponding nominal version (Fig. 11).

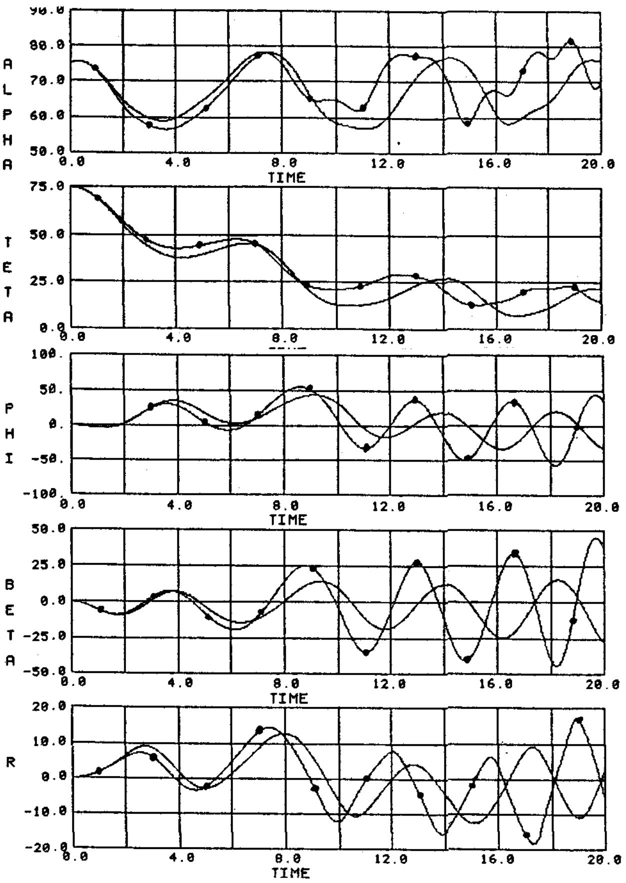


Figure 11: Deep Stall Characteristics
—•— Nominal Yaw Rate Limiter
—— Modified Yaw Rate Limiter

The damped oscillations improve the efficiency of the MPO commands and permit the aircraft to recover within one pitch rocking cycle while recovery could not be achieved from the higher amplitude oscillations. Larger lateral oscillating amplitudes of the nominal version prevent recovery (Fig. 12).

LAVI - Auto Pitch Rocker

As previously discussed, the coordination of the pilot input while in the MPO mode can be critical in determining whether recovery will be achieved or not.

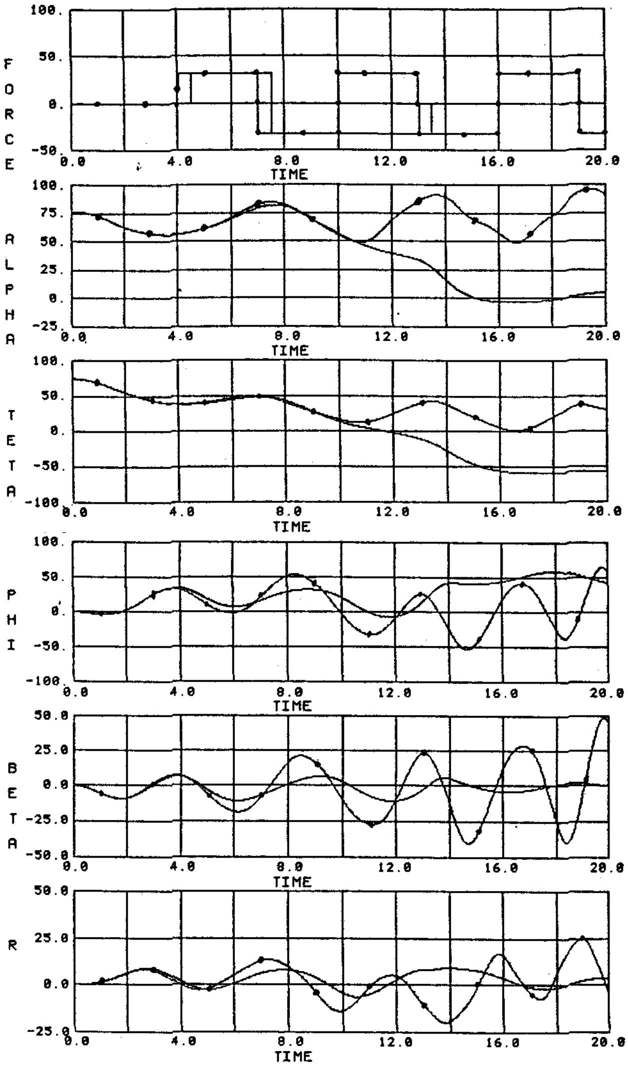


Figure 12: Deep Stall - MPO Recovery
—— Nominal Yaw Rate Limiter
—•— Modified Yaw Rate Limiter

As a result, engineers developed the automatic pitch rocker concept which represents the "perfect pilot input" and assures safe and quick recovery.

Figure 13 shows the basic logic of the auto pitch rocker concept as implemented in the LAVI FCS.

The control laws are based on maximum commands to canards and elevons with their sign changing depending on the direction of the pitch motion (max nose down for negative pitch rate, max nose up for positive pitch rate). The purpose of the pitch rate limiter is to avoid excessive pitch rates witch could result in the aircraft dropping through, from an upright deep stall to an inverted one and vice versa.

Figure 14 compares an automatic pitch rocker recovery to a standard pilot controlled recovery flown in a handling quality simulator. Note that the auto pitch rocker recovery was achieved within two pitch rocking cycles whereas 5 cycles were required by the pilot to effect recovery manually. The shortening of the recovery process is particulary significant in view of the high rate of descent of the aircraft in a deep stall. While the auto pitch rocker recovers the aircraft after a 3 K ft drop in altitude, manual recovery requires 10 K ft (!).

The exact engagement logic for the auto pitch rocker has not been finalized: Engineers push for an immediate automatic engagement upon departure recognition while pilots prefer manual engagement of the auto pitch rocker via a cockpit switch.

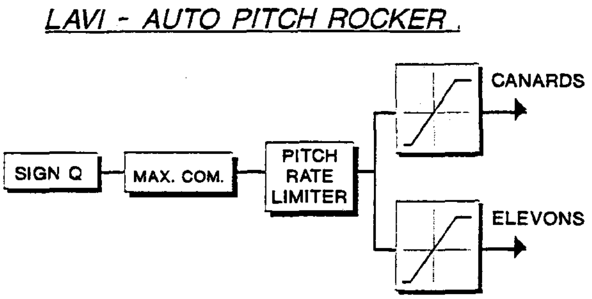
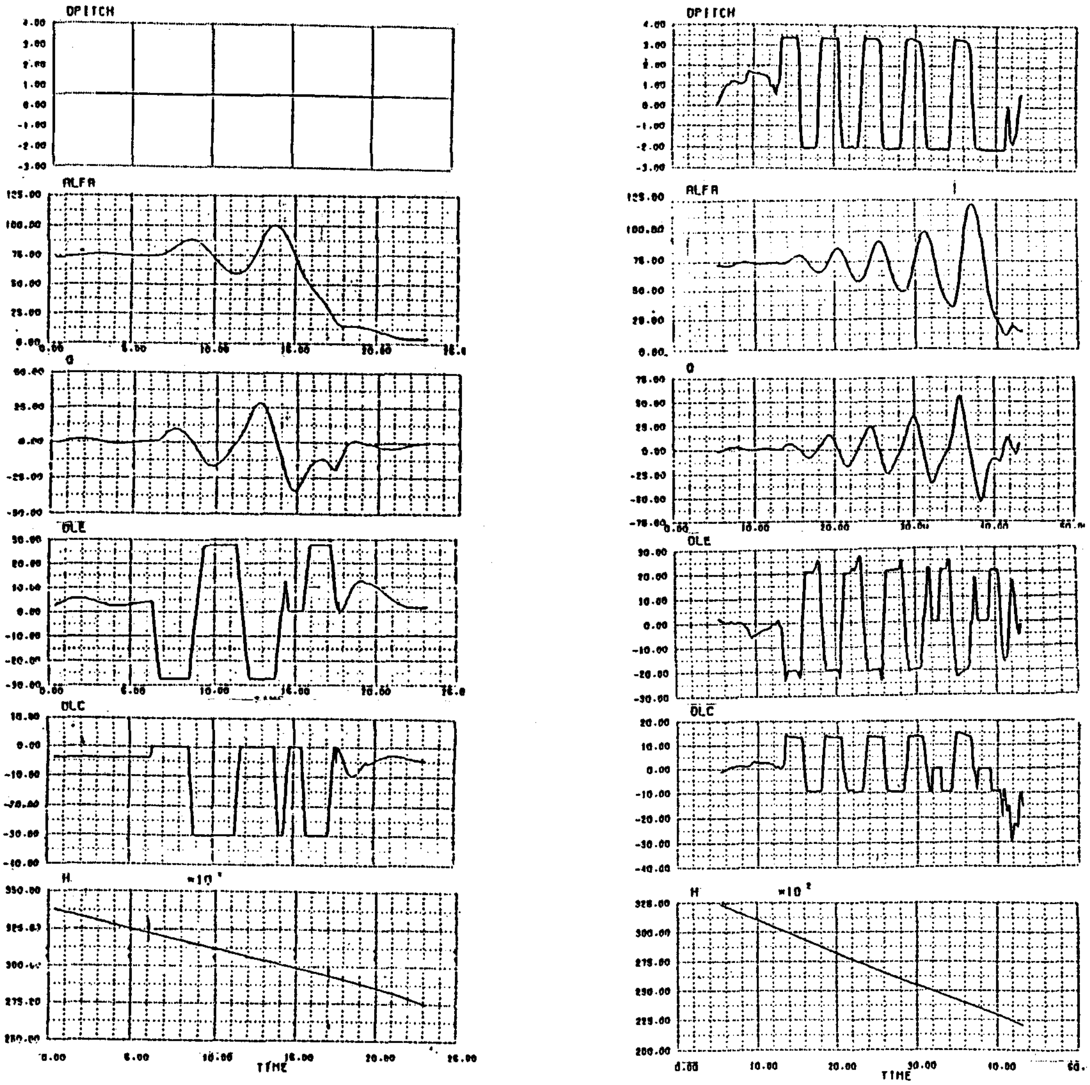


Figure 13: LAVI - Auto Pitch Rocking Logic

The auto pitch rocker was also developed for the newer F-16 models but to date has not been implemented.



Auto Pitch Rocking

Pilot MPO Input

Figure 14: Deep Stall Recovery - Handling Qualities Simulator Data

Conclusions

The continually changing operational requirements in conjunction with the ongoing aircraft modification programs have made it mandatory to deal with unacceptable departure/deep stall characteristics through redesign of the relevant control laws.

The modification of control laws requires a major engineering effort combining 6DOF digital simulations and flights. The considerable agreement between simulation and actual aircraft behavior that has been achieved even in the post stall/departure regime has made it possible to use the 6DOF simulation as a major development tool in the design of flight control system modifications.

The paper presented here indicates the complex nature of the deep stall phenomenon and the treatment of the post departure regime by advanced fly by wire flight control systems.

The introduction of automated recovery systems will greatly enhance the safety of flight and increase the operational flexibility of future fighter aircraft.

VI References

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Glossary

AOA-	Angle of Attack
Alpha-	Angle of Attack
Beta-	Angle of Sideslip
C.G.-	Center of Gravity
Cm-	Pitch Moment Coefficient
Cl-	Lift Coefficient
DELTAR-	Rudder Position
DELTAE-	Elevator Position
DELTAA-	Flaperon Position
DLE-	Elevons Position
DLC-	Canard Position
Dpitch-	Longitudinal Stick Position
FCS-	Flight Control System
FORCE-	Longitudinal Stick Force
g-	Normal acceleration
H-	Altitude
K ft -	1,000 ft
kt.-	knots
MPO-	Manual Pitch Override
P-	Roll Rate
PHI-	Bank Angle
Q-	Pitch Rate
R-	Yaw Rate
Time-	Simulation Time
THETA-	Pitch Attitude
6DOF-	Six Degrees of Freedom