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FEASIBILITY STUDY FOR AN ACTIVE AEROELASTIC CONTROL SYSTEM FOR THE F-16 AIRCRAFT

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I. ABSTRACT

This paper describes a Feasibility study to develope an Active Aeroelastic Oscillation Control System (AOCS) for the F-16 A/C as a means of suppressing flutter and Limit Cycle Oscillation (LCO). The study, conducted as a joint adventure between G.D and the Israeli Air Force (IAF), covered the entire span of subjects necessary for implementing such a system in the A/C. This paper presents the user's point of view in handeling flutter and LCO as an Obstacle in improving flight Quality and expanding operational flight envelope. This paper also presents a few ways to deal with the need of engage/disengage the AOCS according with the loading/downloading flown. also presented a rough estimation of required Flight tests to progress the project.

II. INTRODUCTION

The extensive development of new stores to be carried by fighter A/C like the F-16, forces the Israeli Air Force (IAF) to explore ways to expand the operational flight envelope and the available store configurations beyond those supplied by the A/C developer. One of the difficulties in developing A/C to store compatibility is flutter - an aeroelastic dynamic instability.

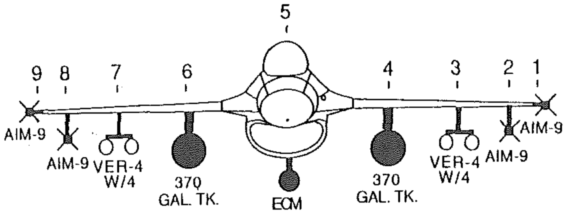
A type of flutter known as LCO (Limit Cycle Oscillation) was encountered during flight tests for two new store configurations presented in fig. 1 . This LCO is expressed as oscillations with limited magnitude that increase with speed and/or load factor. Two specific mechanisms of LCO were identified to be the most restricting (see fig.2). Although LCO occured only for a relatively small number of downloadings, it limited the flight envelope of the configuration and degraded the flight quality.

Considerable efforts have been expended by manufacturers and operators to use the A/C Flight Control System (FCS) to improve aeroservoelastic caracteristics. Analytical and wind tunnel reports that had been published identified the FCS as a good candidate to supply an efficient cure.

Although LCO was basicaly identified as a non- linear behavior, linear flutter analysis succeded to indicate the existance of aeroelastic instability. Good prediction was achieved in identifying the frequency and shape of diverting motion, while the LCO speed was less accurate. In view of that, linear analitical tools were considered to be a reasonable and well known selelection.

PRIORITY I STORE CONFIGURATIONS

STORE CONFIGURATION Ia



STORE CONFIGURATION Ib

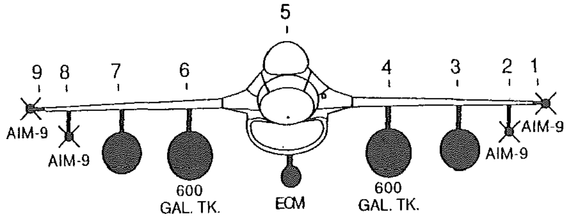


Fig.1

IAF objective was to develop one common control law to supress LCO of the two mechanisms in several different downloadings, using existing sensors and major control surfaces. The prefarable solution was to engage an actibe control law in the flight control system continuously for all downloadings. Nevertheless, in order to avoid exesive risk, a non-adaptive control system was chosen as a design point.

STORE CONFIGURATION Ib

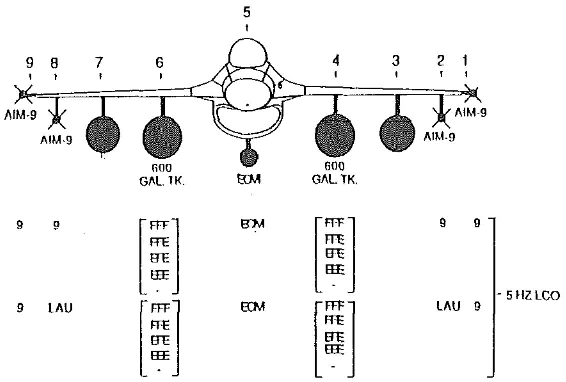


Fig.2 (part 1)

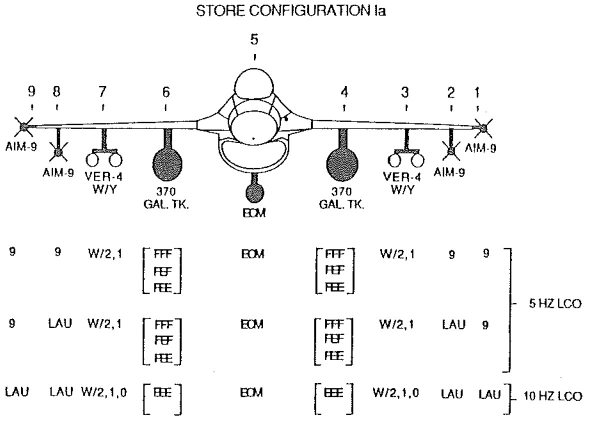


Fig.2 (part 2)

III. LIMIT CYCLE OSCILLATION (LCO) PHENOMENA

LCO is defined as a limited amplitude oscillation of the airframe which is self - sustaining and results from a structural/aerodynamics interaction. The response is at a distinct frequency (narrow band oscillations) and feels like buffet in amplitude. The magnitude of oscillation increases with velocity and sometimes with load factor. Several theories were suggested as an explanation of LCO. The most acceptable theory relates LCO to lowly Damped vibration modes that tend to respond if they have the proper characteristics to couple with non - linear aerodynamic forces.

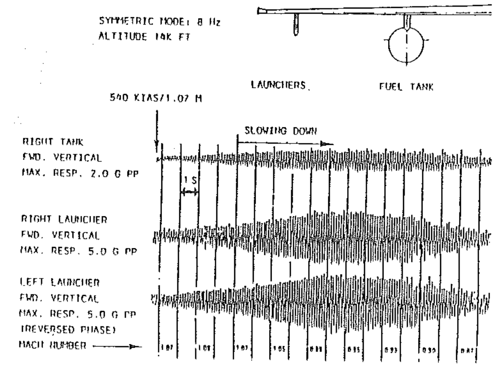
F-16 LCO is of two types:

1) subsonic (M<0.9) typical to heavy air to ground stores, fuel tanks, and tip missiles, and with sensetivity to speed and Angle of Attack (AOA).

2) transonic (0.9<M<1.2) tipycal to light air to air stores and wing tip launchers, and with sensetivity to mach and AOA.

Although the non-linear characteristic of LCO, linear flutter analysis succede, to indicate the existance of aeroelastic instability. The success is mainly in predicting the critical loading and oscillation freq. Poor velocity prediction is the critical difficulty.

The LCO induces strong lateral vibration in the cockpit (for A/S mechanisms), low flying Qualities, pilot discomfort, and difficulties in using the head up display and to aim the weapon. structural hazards were also encountered like the separation of a/c panels. Fig 2A demonstrate a tipycal LCO measurments.



RECORDINGS OF ACCELEROMETERS DURING FLIGHT FLUTTER TESTING OF FIGHTER-TYPE AIRCRAFT I

Fig.2A

IV. TECHNICAL APPROACH

Store configuration to be analyzed were symmetric with respect to the airplane centerline. If LCO were encountered with a non-symmetric store configuration the oscillatory motion would be non-symmetric (i.e neither symmetric nor antisymmetric). Non - symmetric external store configuration were considered to be a variation with similarity to each of the two symmetrice configurations, that will be checked at a later stage.

The antisymmetric oscillations (5HZ & 10 Hz) encountered during flight tests focused the effort in antisymmetric analysis. All flutter and control law development analyses were antisymmetric.

A finite element representation of the structure was employed. This model has been used for computing natural modes of vibration of the F-16. Good correlation between computed natural modes and ground vibration tests (GVT) measured modes was demonstrated. Only one side of the plane of symmetry was represented, employing antisymmetic boundary conditions. An idealization of the structure is shown in figure 3 by the solid lines, including the Location of the Flight Control System (FCS) sensors.

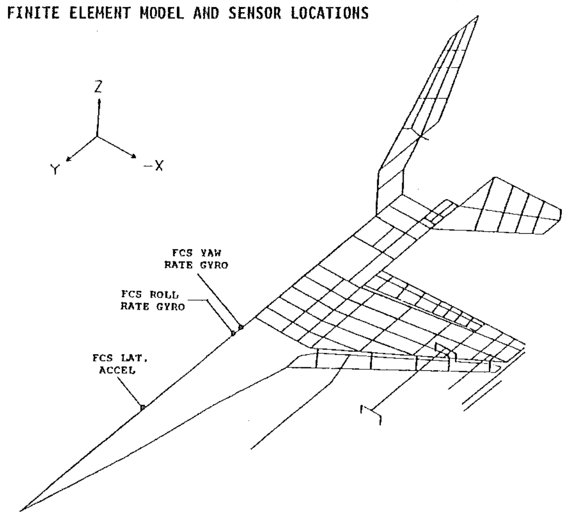


Fig.3

The unsteady aerodynamic pressure was computed by the Doublet Lattice Method (DLM). The aerodynamic model is shown in figure 4, Consisting of lifting surface panels, slender body segments, and Interface panels. The tip missiles were modeled, while all other external stores were not modeled aerodynamically. The calculated Aerodynamic terms for rigid body degrees of freedom were tuned, for use in frequency response calculation, using wind tunnel rigid stability derivatives modified for static aeroelastic effects. This type of tuning produced the needed correction in the low frequency region of the Frequency Responce Function (FRF) with no change in computed flutter speed. All analyses were conducted for 0.9 Mach number and sea level altitude, Covering the required operational flight envelope.

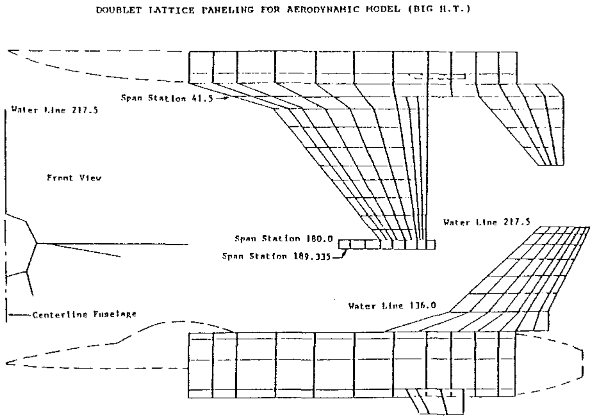


Fig.4

Flutter analyses were conducted by the convential V-G method without engaging the FCS. An example of a flutter analysis result (damping & frequency vs. velocity) is presented in figure 5.

The structural model andd the aerodynamic model were combined to represent the unaugmented airplane. The stability of the unaugmented A/C was determined by a v-g flutter analysis. The FRF is generated by closing all the FCS loops except the channel to be analyzed as presented in figure 6 for the roll channel. The block diagram for the FCS yaw & roll loops as used in these analyses are shown of fig 7.

The stability of the A/C with the FCS loops closed at the flight condition analyzed was determined by the Landhal method. A plot of the determinant of the system's matrix is shown in fig 8(If an unstability is present,a clockwise reversal in a small frequency range centered of the frequency of the instability will occur).

The FRF relating generalized coordinate response to one degree of flaperon excitation was computed. Each generalized coordinate FRF was multiplied by the deflection per unit generalized coordinate at a sensor location. These products were summed and then converted to angular velocity or acceleration.

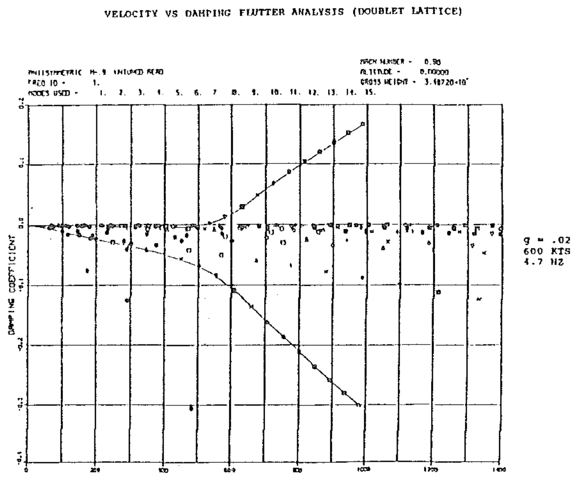


Fig.5 (part 1)

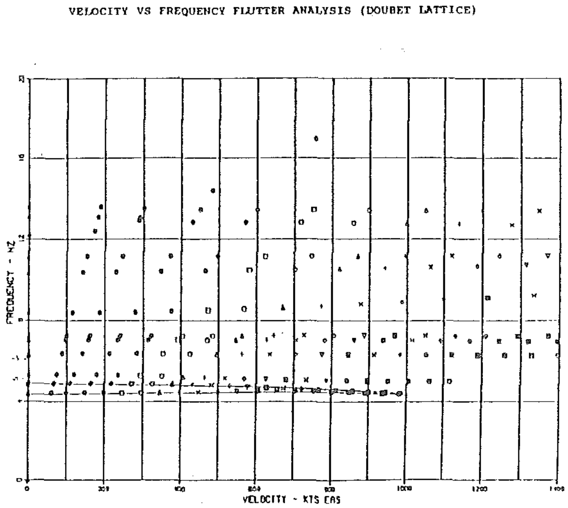
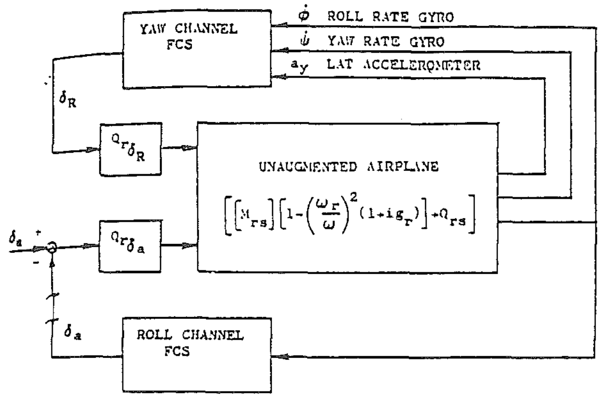


Fig.5 (part 2)

The FRF also includes the FRF for actuator and high pass filter of the form S/(S+20) since both of these functions must be included in the control law development. The actuator transfer function (has to be included since it is the means of actuating the flaperon, the high pass filter is included to reduce the effect of the AOCS on the FCS in the low frequency spead. An example of the FRF in the form of a polar plot (Nyquist plot) is presented in Fig 9.

Conceptually, the design objective for the additional components of the control law is to locate the maximum magnitude of the response near the flutter frequency, near the positive real axis (refering the nyquest plot) while suppressing the magnitude of all the other loops such that they lie inside the unit circle, or do not produce a clockwise encirclement of the ninus one point. When the response loop associated with the flutter speed is on the right hand side it will grow in magnitude as the flutter speed is approached and above the flutter speed the phase angle at the peak response will shift 180 degrees and form a counterclockwise loop encircling the minus - one point (for negative feedback).

FIGURE 6
ROLL CHANNEL



M_{rs} = Generalized Mass
ω_r = Mode Frequency
ω = Forcing Frequency
g_r = Mode Structural Damping
Q_{rs} = Generalized Aerodynamic Force
$Q_{r\delta_R}$ = Rudder Forcing Function
(Per Degree Rudder Rotation)
$Q_{r\delta_a}$ = Aileron/Horizontal Tail Forcing Function
(Per Degree Aileron)*
δ_R = Rudder Rotation Angle
δ_a = Aileron Rotation Angle*

* 1.0° Aileron and Horizontal Tail are slaved together

F-16 FLIGHT CONTROL SYSTEM
ANALOG ROLL CONTROL CHANNEL

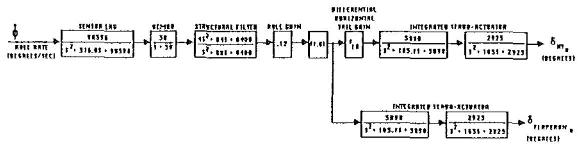


Fig.7 (part 1)

F-16 FLIGHT CONTROL SYSTEM
ANALOG YAW CONTROL CHANNEL

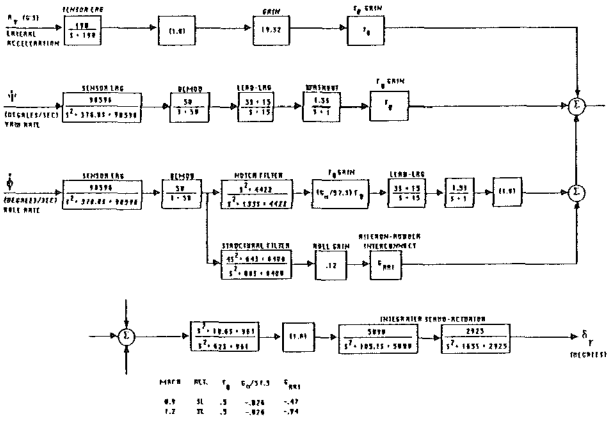


Fig.7 (part 2)

DETERMINANT OF THE A MATRIX
STORE CONF. 1a-3, .794M, SL, FLAPERON OPEN, TUNED AERO
DOF - 15

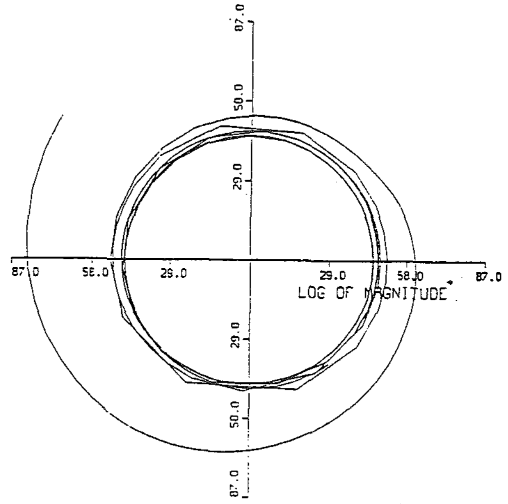


Fig.8 (part 1)

DETERMINANT OF THE A MATRIX
STORE CONF. 1a-3, .794M, SL, FLAPERON OPEN, TUNED AERO
DOF - 15

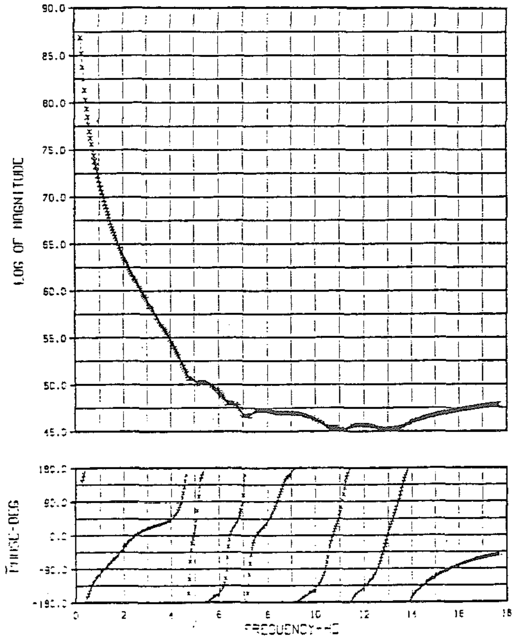
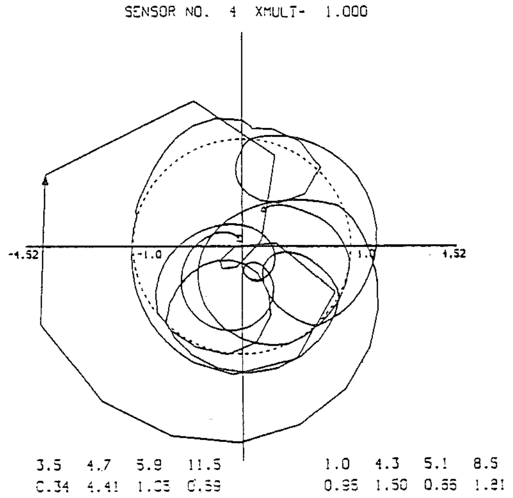


Fig.8 (part 2)

STORE CONFIG 1a-3, TUNED AERO, NYQUIST PLOT
FLAPERON OPEN, FCS YAW, ROLL CLOSED
0.794 MACH SEA LEVEL



ROLL RATE GYRO COORD 1372/HIPASS, ACTUATOR

Fig.9

The control law design objectives above the flutter speed are to maintain the counterclockwise loop in a position such that it encircles the minus-one point while preventing any of the clockwise loops from encircling the minus-one point.

V. CONTROL LAW DEVELOPMENT

The critical downloading were identified using a V-G flutter analyses. since The flutter characteristics are changed when the FCS channels are engaged, it was desirable to determine the new flutter speed. The speed and frequency at which the system becomes unstable have been determined by examining the determinant of the system's matrix plots computed for a sequence of speeds and determining the speed at which a phase reversed is first detected and the frequency at which the phase reversed occured.

A complementary and more accurate method used to determine augmented A/C flutter speed was an aeroservoelastic analysis. The FCS yaw channel was engaged and the open loop FRF for the feedback in FCS roll channel was computed. The same procedure was repeated reversing the yaw and roll loops. The two flutter mechanisms (5 HZ & 10 HZ ; antisymmetric) found during flight tests caused instability in different configurations.

FRF's for the FCS lateral accelerometer, roll rate gyro and yaw rate gyro computed at conditions below and above the flutter speed proved the roll rate gyro as the best of the three FCS candidates. several control laws were developed using the FCS roll rate gyro as the sensor. several iterations were applied until satisfied behavior was achieved for several configurations.

one of the design options is shown in fig 10. the iteration procedure's objectives was to stabilize unstable configuration with a single control law and with minimum distabilized effect on stable configuration. configuration instability changed with bombs and missile loadings and external tanks fuel quantity.

A single control law was found to have a potential to supress all 5 Hz flutter mechanisms up to the desired flight envelope. a different control law was required for the 10 hz mechanisms. the effect of the supression control system was found to be unfavorable in many configuration that carried previous favorable aeroelastic behavior.

NYQUIST PLOT OF OPEN-LOOP FRF FOR CONTROL LAW 12-3
CONFIGURATION Ia-3, TUNED AERO, FCS YAW AND ROLL LOOPS CLOSED

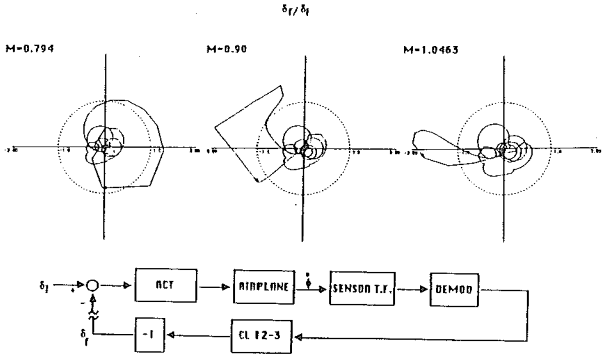


Fig.10 (part 1)

BODE PLOT OF OPEN-LOOP FRF FOR CONTROL LAW 12-3
CONFIGURATION Ia-3, TUNED AERO, FCS YAW AND ROLL LOOPS CLOSED

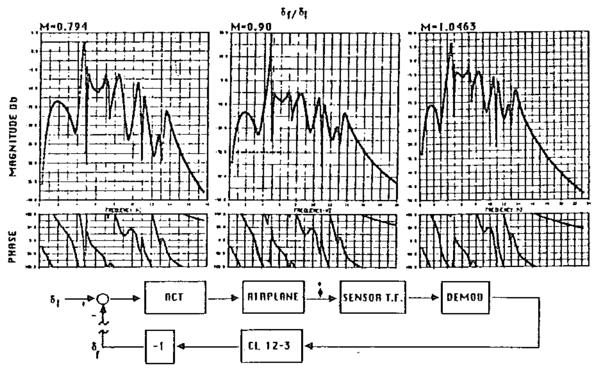


Fig.10 (part 2)

this effect lead to the conclusion that the control laws would have to be disengaged for many of the store configurations that are not expected to encounter LCO.

The predicted effectiveness of the control laws was limited to the 5 HZ and 10 HZ mechanisms in configurations with similarity to the design goal configurations. The design was found to have limited robustness and did not presume to supply an answer to all future antisymmetric 5 hz and 10 hz mechanisms.

VI. SYNTESIS

1. AOCS effects on handling qualities

The effects of the candidate control laws developed for the aeroelastic oscillation control system on the aircraft handling qualities were investigated. The effect of the AOCS control laws on the dutch roll mode characteristics and the roll axis stability margings were evaluated using linearized statically flexibilized aerodynamic data and a three degree of freedom representation of the lateral-directional FCS. It was found that the candidate AOCS control laws had negligible effects on the Dutch roll mode characteristics. Two high pass filters (washouts) in the AOCS control laws effectively decouples the low frequency Dutch roll mode from the frequency structural modes. The gain margins of the roll axis with the control loop open at the flaperon actuator for the candidate AOCS control laws and the basic F-16 are shown in Fig 11.

The gain margins are plotted versus roll moment of interia for five a/c loadings. The gain margins of the 10 HZ supression loop is above the minimum requirement of 6 db for all the loadings. The gain margin of the 5 HZ supression loop falls below the 6 db requirement, and would need to be disengaged for loadings with low roll moments of inertia. Maximum command roll maneuvers were made to envaluate the effect of the AOCS control law candidates on the roll performance. The roll performance was obtained using a nonlinear, six degree of freedom computer simulation of the a/c using nonlinear ,statistically flexibilized aerodynamics and the longitudinal and lateral-directional FCS. The strutural modes were not simulated.

Very little effect on the roll rate angle responses were found. The difference between the roll responses of the basic F-16 with the AOCS is negligible.

2. AOCS effects on maneuvers loads

The AOCS has very little effect upon overall airframe loads despite a noticeabl increase in roll acceleration and aileron deflection. A limited analysis consisted of examination of abrupt symmetric pull-ups and elevated load factor rolls within analysis grid limited to high loads points was performed.

As expected , the AOCS had no effect upon the maneuver response of the abrupt pullups. However , the elevated load factor roll response showed some slight differences. The differences when maximum load occurs were very slight (max increase of 3% at max. load time hack in wing root loads when AOCS is engaged, a negligible increase in store hardpoint loads, and a max. increase of 1% in horizontal tail).

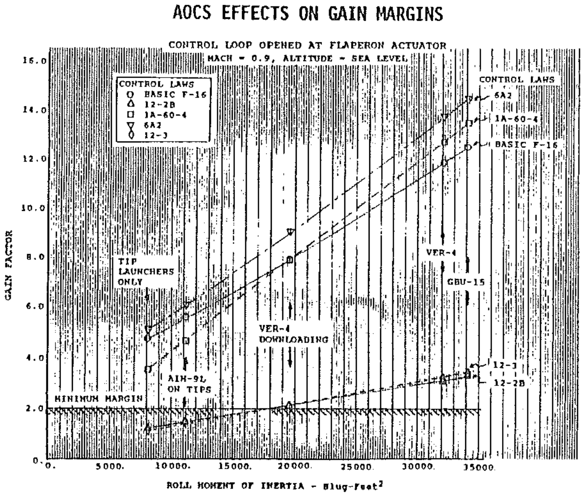


Fig.11

3. Switching implementation

One of the major considerations in the implementation of the AOCS was the method of activating and deactivating the system. The study to develope the AOCS control laws has shown the control laws cannot be active for some of the a/c loadings which are not subject to the LCO. At these conditions, activation of the AOCS control laws can drive the structural mode to a lightly damped, or insome cases, an unstable condition at a frequency near the LCO frequencies.

The investigated LCO occured at two frequencies . One frequency was near the 5 HZ and the other was near the 10 HZ. Different AOCS control laws were found to be required to suppress the two different frequency modes. Therefore, two decisions are required: The first is whether the AOCS should be activated or deactivated, and the second is which control law should be activated. Several methods to activate and deactivate the AOCS were investigated. The simplest method was based on the pilot to manually engage or disengage the appropriate control law configuration. The rapid shifts between critical and non critical configurations during store release or missle firing limited the use of this method to the preliminary evaluation stage of the AOCS capability.

A more appropriate methed to deal with rapid multiple shifts was based on the Store Management System (SMS) to control the AOCS as a function of the store loading and the flight condition. The SMS was to identify a downloading with a LCO problem according to pre - programed configurations list.

The most sophisticated method to activate and deactivate the AOCS, considered in the study was to develop a LCO detector which would automatically determine when the AOCS should be activated (or deactivated without inputs from the SMS). One candidate method for detecting the LCO is to count the number of times that the roll rate response has a positive crossing of a threshold level. The frequengy is determined by the number of crossing detected in a set period of time. If the measured frequency is within a specified bandwidth around the nominal LCO frequency, the state of the AOCS engage/disengage switch is changed. A need for adjustment of the minimum value of the threshold to prevent erroneous crossings while flying through turbulence was identified.

There are several major concerns in the development of the LCO detection method. The first is that the AOCS control laws can create a lightly damped or unstable oscillation at approximately the same fequency as the limit cycle oscillations if it is engaged for some store loadings which are not subject to the LCO. The second concern is the length of time required to perform the computations necessary to verify that the oscillations are present. The oscillations must not diverge to unacceptable amplitudes within the time required for the LCO detection. A third concern is the effect of turbulence of noise which may cause an erroneous output from the LCO detector. This could turn the AOCS on or off due to turbulence rather than LCO. Band pass filtering upstream of the detection counter will be evaluted as a potential fix to this problem. The answers to these concerns will be obtained during the flight test demonstration. Since the control laws will be engaged/disengaged incorrectly for short periods of time when using the LCO detector, it must be shown in flight tests that the engagement/disengagements are attempted in flight.

4. system safety

A safety assessment of the AOCS produced three main safety concerns:

a. Consequences of system failing when needed.
b. Consequences of system activation when not desired.
c. Redundancy of SMS, FCC and fuel quantity measuring system if consequences of system failure are catastrophic.

Failure rates of several functions that could lead to the loss of the AOCS function indicate:

a. quad redundant flight control electronics for AOCS approximate 1.E-12 failures per flight hour.
b. fuel quantity measurment system approximates 1.E-04 failures per flight hour.
c. stores management system approximates 3.3E-03 failures per flight hour.
d. fire control computer approximates 3.3E-03 failures per flight hour.

If the consequences of losing the AOCS are catastrophic, the above failure rates are excessively high with the exception of the quad redundant flight control electronics. These high failure rates are the reason for concern of the redundancy of the SMS and FCC in the AOCS.

Safety Analysis also has a concern with the SMS controlling the AOCS during normal operation when the external store configuration changes during flight. When the "pickle" button is depressed or when the SMS is in a release configuration, i.e., during a sequenced store release, the computer is concerned only with that function and does not keep status. It has been stated that this could last as long as 20 to 30 seconds. This would be unacceptable if a store release would require a change in AOCS gains for aircraft safety.

Safety Analysis concluded that the flight test can be conducted with minimum safety risk by utilizing proper test procedures, e.g., moving deeper into the envelope in stage and determining the oscillation amplitude before proceeding further.

The complete safety risk can not be determined since the magnitudes of oscillations encountered when the system fails when needed and coming on when not required are not known.

VII. CONCLUSIONS

The feasibility study concluded that the FCS can be modified to supress LCO, using the existing FCS sensors and the existing control surfaces and actuators. The decision to use a non-adaptive approach was based on the estimation that the adaptive technology in aviation is not mature enough. The outcome of this decision is a non-robustic solution, approperiate to a limited number of configurations, and a necessity to engage and disengage the supression loop in conjugate to configuration changes.

The recommendation of this feasibility study was to conduct extensive flight test to evaluate demonstrate and tune the design of the AOCS.

The activity on this subject was suspended due to budjet shortage. Future activity will be persue if and when the appropriate funds will be found.