OPERABILITY ISSUES ENCOUNTERED IN GENERIC AERO GAS TURBINE ENGINES

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Abstract

This paper discusses about typical fighter aircraft engine development, flight testing and a case study depicting the importance of engine gas dynamic stability during flight testing. A low risk engine development and test plan generally spans over a period of 7 years followed by flight testing. This paper brings out the time line chart of engine development and testing and also the significance of each test. Further a generalized flight test plan is discussed explaining the points to be looked for during flight testing. Then a case study where a series of flame out cases has been encountered in a Fighter Aircraft fitted with a straight flow twin-spool turbojet engine during reheat engagement due to lower gas dynamic stability problem has been discussed. Corrective actions undertaken followed with flight test at critical pinch points has been discussed. The experience gained through the above case studies will enhance the knowledge base and forms the guideline for any similar problems arising in the future.

Keywords: *Engine development; Flight test; Flameout; Operating envelope*

Abbreviation

FETT = First Engine To Test
PFR = Pre-Flight Rating
ISR = Initial Service Release
OCR = Operational Compatibility Readiness
SFC = Specific Fuel Consumption
AMT = Accelerated Mission Test
ASMET = Accelerated Simulated Mission Endurance Test
AOA = Angle of Attack
AOSS = Angle of Side Slip
AB = After Burner
N1 = Low Pressure spool RPM in %
N2 = High Pressure spool RPM in %
IAS = Indicated Air Speed
T4 = Jet Pipe Temperature
ACS = Altitude Controller Screw

Introduction

This paper discusses about typical fighter aircraft engine development, flight testing and a case study depicting the importance of engine gas dynamic stability during flight testing. The case study pertains to a series of flame out cases encountered in a Fighter Aircraft fitted with a straight flow twin-spool turbojet engine during reheat engagement. After thorough testing and experimentation on 3 different engines, solution is realized by reducing acceleration fuel flow rate to the main combustion chamber by adjusting Altitude Controller Screw (ACS). Further, the corrective actions undertaken and flight test plan at critical pinch points were also discussed.

Engine Development Plan

Engine development test plan is a complex, program-specific process, and plans must be tailored to meet individual cost, schedule, and performance requirements to

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ensure development of a high-integrity operational system. Fig.1 indicates a typical military engine development plan.

This notional test plan shown in Fig.1 spans seven years from contract authorization through OCR and includes five component rigs, 12 development engines, and approximately 10,000 ground-test hours. Out of 12 engines, one each is allotted for Aero mechanical, sea level development and operability testing, 4 are for endurance and AMT, 1 is for AB ASMET, 1 for controls and integration testing in altitude and 3 for environmental testing. The number of flight test engines are not included here which would be determined by the needs of the aircraft flight test team. Ground-test engines are typically not transferred to the flight test program due to specialized instrumentation needs and the unquantifiable wear accumulated during ground test.

Engine Flight Testing

Functional Checkout - Steady-State and Transient Operation

Functional checks should be performed to confirm that the engine operates properly, with no control system instability, flameout, over-speed, hang-up or any other unacceptable behavior. Transients should include slow, snap and Bode throttle movements at representative points throughout the flight envelope. Bode throttle movements should be timed for throttle reversal at the most critical condition, typically 70 to 75% corrected fan speed. These transients should be performed at key points throughout the opening envelope during stabilized 1G level flight and during aircraft maneuvers.

These tests should be completed prior to the more aggressive envelope expansion tests describe below:

Afterburner Light-Off and Throttle Transients

The flight test program should include sufficient test points to verify normal light-off capability at installed flight conditions. This testing typically consists of advancing the throttle to Minimum and Maximum Afterburning Power from Idle and Max and may be done concurrently with other engine and aircraft testing. Specific test conditions should be based on Aircraft mission requirements and are suggested to coincide with other planned flight tests.

Engine Operation During Aircraft Operations

Tests of engine operational characteristics and throttle response and aircraft handling should be performed to confirm normal engine function during various aircraft operations. These tests may be performed concurrently with other tests.

Inlet Compatibility and AOA/AOSS Envelope Expansion

The objective is to demonstrate inlet/engine compatibility throughout the aircraft flight envelope. Evaluation of engine performance and operability, and compatibility with the Aircraft inlet during steady-state and transient throttle operation should be performed during aircraft manoeuvres.

The inlet evaluation should also include "buzz" margin testing consisting of chops from Max AB or Max to idle and at progressively increasing Mach numbers, with variations in angles of attack and sideslip. Testing may be performed at a series of altitudes, such as 10K, 20K, 30K and 40K ft.

Installed Vibration Measurements

Engine vibration levels should be monitored during flight test. Data should be recorded with onboard tapes or telemetry as the operating envelope is expanded and also during routine flight operations for verification. These taped events should be reviewed prior to the next day's flight for abnormal vibration.

Data is recommended for the initial Idle to MaxAB at take-off or low altitude. Flight Idle-MaxAB data is requested at typical cruise conditions and a series of altitudes such as 10K, 20K, 30K and 40K ft. In addition, Flight Idle-MaxAB data is requested during envelope expansion where such maneuvers are practical for the aircraft.

Engine Bay Environmental and Cooling

Testing to demonstrate adequate engine bay cooling is recommended. This may be conducted concurrently with other testing. The data should be acquired throughout the flight test program during ground operation and during all of the flights to show that the engine components are within temperature limits.

Aircraft/Engine Fuel System Integration and Operation

Fuel system pressures and temperatures should be monitored throughout the flight test program. To verify operation with no aircraft boost assist, at least one ascent with the aircraft boost system de-energized should be performed. Key parameters are inlet Fuel Pressure and Temperature and FADEC Cooling Fuel in and Out Temperatures.

Engine Anti-Icing System

Functional checks of the engine anti-icing system should be conducted to demonstrate proper function and confirm the effects on engine performance and operation. Key parameters include air pressure and the anti-ice on/off discrete signal.

Engine Oil System

Testing should monitor the proper operation of the engine lubrication system. Inverted flight, knife edge, 45 degree bank, max G turns, and zero G maneuvers may be particularly critical to the engine lubrication system. Key parameters include engine oil pressure, lube oil cooler inlet and temperatures and scavenge oil temperature.

Engine Installed Performance

Performance flight testing should be conducted with in-flight thrust and airflow data processing to close on overall aircraft system thrust and drag performance, including verification of engine installation effects of Inlet recovery, bleed and power extraction. In addition, it is recommended that an engine performance and functional trending process be developed and implemented during the flight test program to support management of both the flight test and subsequent operational activity.

Case Study

This case study brings out the flame out cases encountered in a Fighter Aircraft fitted with a straight flow twin-spool turbojet engine during reheat engagement. This also discusses the investigation attempts in sequence, root cause identification and most importantly, flight testing for substantiation of the corrective action complied.

From last batch of said engines, 7 cases of flame out during reheat engagement at low/medium altitude had been reported. Additional works on engine was carried out and subjected to a series of flight trials in 3 specially selected aero engines (Engine A, B and C) at critical pinch points. During flight trials, the engine C flamed out in air during reheat engagement and some innovative methods have been adapted to solve the problem. As a follow up, compressor assembly of the engines were evaluated for surge margin by water injection method. Stability assessment in terms of surge margin loss was carried out taking into account upward migration of operating line due to back pressure, as reheat fuel pressure reported to be high during test bed regulation. It was due to leakage of gas between the flaps and spacers of the jet nozzle.

During ground run as well as up to altitude of 8 km, afterburner behavior of Engine C was virtually identical as that of other two engines previously flight tested. At altitude of 10.4 km (Fig.2), after light up of afterburner, up to 1.5 sec, N1 hardly increases, followed with flame-out.

The sequential corrective actions attempted are given below:

Jet Pipe Opening Delay Kept At ‘0’ Sec

As next step, ‘0’ sec delay of flap was chosen in engine control box in order to reduce the back pressure after reheat light up,(with comparatively larger jet nozzle diameter compared to 0.5 sec delay of flap) thereby increase in the pressure differential across the LP turbine, enabling increased growth of N1 rpm. Further during this process there will be decrease of N2 rpm as well as HP compressor exit pressure, moving the operating point down. This would enable temporarily increase of gas dynamic stability margin ensuring smooth acceleration transient as in low bypass turbofan engine.

With ‘0’ sec flap delay, ground run was attempted. After that flight test plan was discussed and pilot planned reheat engagement at altitude of 7, 9 and 10 km at IAS of 500 kmph. At H=9 km and IAS of 500 kmph again engine flamed out with bang sound.

Then, Engine C was adjusted for 0.5 sec flap delay and tested at altitude of 9 km and 500kmph IAS. It was seen that N1 and N2 rpm drop at the moment of reheat light up is around 2%. The rate of increase of T4 after AB light up, with flap delay of 0.5 and 0 sec are same.

Acceleration Fuel Flow Rate (ACS) Adjustment

Altitude Controller Screw (ACS) present in the main fuel pump was screwed in by turn, in order to reduce rate of acceleration fuel supply to the main combustion chamber after A/B light up. At 10 km, the primary fuel pressure rise rate got reduced by 0.3 $kg/cm^2/s$ (from 1.36 to 1.04$kg/cm^2/s$). Adjustment is effective at altitudes of more than ≈ 8km, when the fuel pressure in the primary main fuel manifold at maximum dry rating is less than 40 kgf/cm^2. After the ACS screw adjustment, AB engagement was attempted IAS of 500 km/h at altitude of 7, 9 and 10 km. In all tested conditions, AB was stable and no flame out was reported (Fig.3).

Inference

Given the fact that engine flameout was eliminated only after reducing acceleration fuel flow rate to the main combustion chamber (changes in the normal control ACS), it can be argued that the flame out in Engine C and most likely in other engines of that series, is connected with the low gas dynamic stability margin of compressor.

Substantiation Flight Test

The typical tactical fighter operating envelope shown in Fig.4 provides a framework for discussion of the various demands that can be placed on the system. Flight along line A requires that the aircraft operate at or near peak lift coefficients, due to the low dynamic pressure q available to produce lift. This results in relatively large aircraft angles of attack and inlet lip flow incidence angles that can produce high inlet pressure distortion. Generally, the engine must be able to tolerate this distortion, since the supersonic inlet lip is usually less blunt than on typical subsonic inlets to allow reasonable supersonic drag. The lip shape is a compromise between drag and distortion during maneuvering. This situation can affect compression system blade design and may influence the ultimate selection of the compression system operating line to allocate sufficient margin for surge-free operation. The intersection of lines B and C, or peak Mach number, is generally the inlet design point. Here, inlet recovery and drag, as well as other determinants of engine thrust, are given much emphasis and tailored in conjunction with the aircraft drag polar to ensure that the vehicle can meet or exceed its design speed. Lines C and D define the locus of maximum dynamic pressure conditions and, therefore, are significant to the design of both the inlet and engine structure and the engine cycle, since they represent pressure and/or temperature extremes. The aircraft combat arena is denoted by the box E, which in practice may be fairly extensive. In this region, severe angles of attack and yaw can confront the inlet (typical fighter maneuver requirements is shown in Fig.5). These aircraft attitudes must not be exceeded in order to avoid engine instability or surge.

As previously mentioned, the fuselage and wing can produce local inlet flow angles that differ significantly from the aircraft flight path angles of attack and yaw. For this reason, supersonic inlet verification tests are usually conducted with at least a partial fore-body and wing simulation to produce inlet flow fields typical of the actual aircraft operation [1].

Considering the above discussed points, flight test schedule has been evolved (Table-1) which effectively explores key operating envelope points. The recovered engines were flight tested as per the schedule shown in Table-1. Engines have successfully passed the flight test thereby substantiating the efficacy of corrective actions incorporated.

Conclusions

The paper has discussed a typical fighter aircraft engine development test plan and flight test requirements. Further a case study was discussed where the engine was suffering from gas dynamic stability, followed by the corrective actions undertaken and flight test at critical pinch points. The experience gained through the above case studies will enhance the knowledge base and forms the guideline for any similar problems arising in the future.

Reference

1. Gordon C. Oates., "Aircraft Propulsion Systems Technology and Design", American Institute of Aeronautics and Astronautics Inc., 1989.

Table-1 : Flight Test Schedule for Evaluating Gas Dynamic Stability

Sortie No.	Test Point	Throttle Slam/AB Engagement Parameters			
		Height km	IAS km/h	Throttle/Slam	Criteria
1	1	6	500	Idle-Max	Engine Stability check Accl Time Accl < 10"
	2	6	500	Max-Max AB	AB Light up and Stability
	3	7	500	Idle-Max	Engine Stability check Accl Time Accl < 10"
	4	7	550	Max-Max AB	AB Light up and Stability
	5	7	500	Max-Max AB	AB Light up and Stability
	6	8	500	Idle-Max	Engine Stability check Accl Time Accl < 10"
	7	8	550	Max-Max AB	AB Light up and Stability
	8	8	500	Max-Max AB	AB Light up and Stability
	9	9	500	Idle-Max	Engine Stability check Accl Time Accl < 10"
2	1	7	500	Max-Max AB	AB Light up and Stability
	2	9	550	Max-Max AB	AB Light up and Stability
	3	9	500	-"-	
	4	10	500	Idle Max	Engine Stability check Accl Time Accl < 10"
	5	10	550	Max-Max AB	AB Light up and Stability
	6	10	500	-"-	AB Light up and Stability
	7	11	Accl 1.5	Max AB	Match .9 M to 1.5 M
3	1	9	500	Max-Max AB	AB Light up and Stability
	2	11	500-550	Max	Check N1/N2 Fluctuations
	3	11	500	Idle-Max	Engine Stability check Accl Time Accl < 10"
	4	11	500	Max-Max AB	AB Light up and Stability
	5	12	600	Max	Check N1/N2 Fluctuations
	6	12	600/IM	Max-Max AB	AB Light up and Stability
	7	12	Accl 1.85	Max AB	Match Accl to 1.85 M
4	1	5	600	90% - Max AB	St and Level
	2	5	550	-"-	-"-
	3	5	600	-"-	Turns AOA 18
	4	5	550	-"-	Turns AOA 18
	5	7	600	-"-	St and Level
	6	7	550	-"-	-"-
	7	7	600	-"-	Turns AOA 18
	8	7	550	-"-	Turns AOA 18
5	1	4	950	Max-Max AB	AB Light up and Stability
	2	4.2	550	2nd Reheat	Descent till engagement (3.7 - 4 Km) and climb till dis-engagement

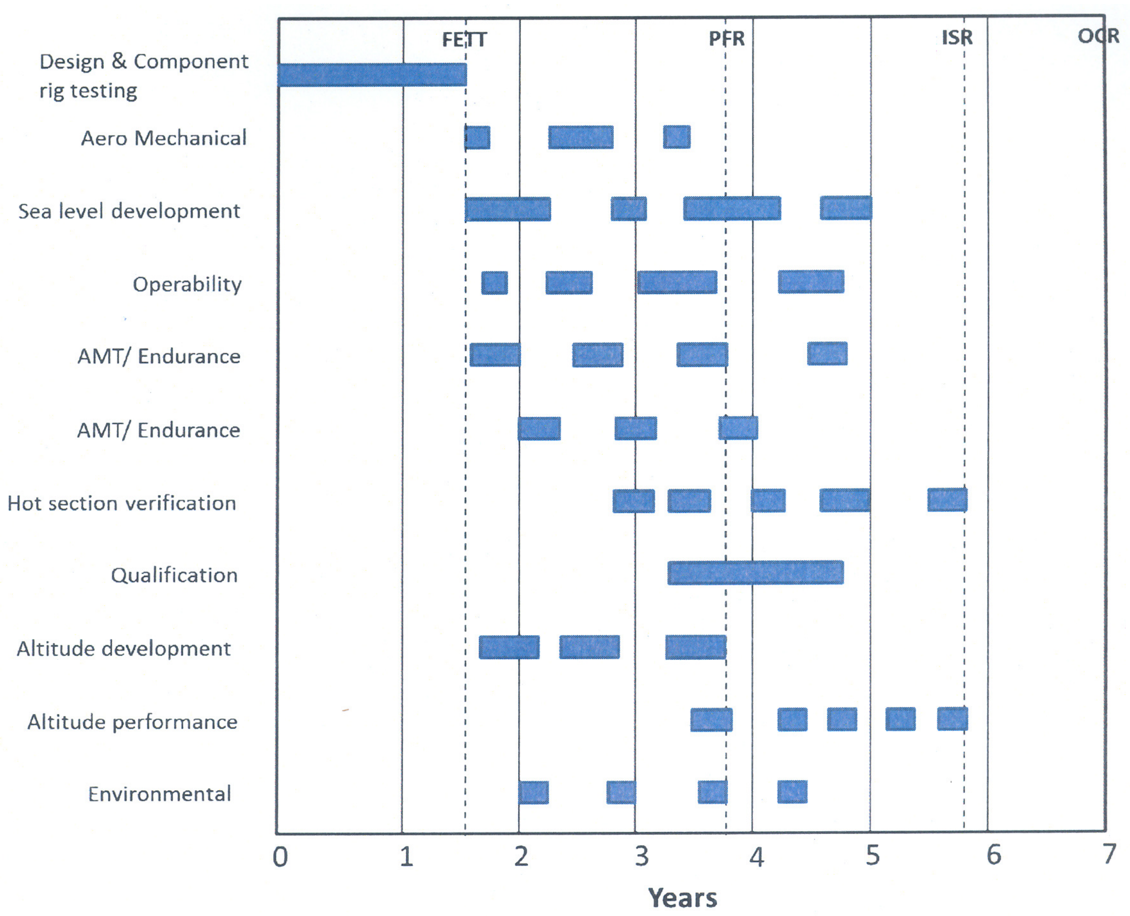

Fig.1 Typical Military Engine Development Test Plan

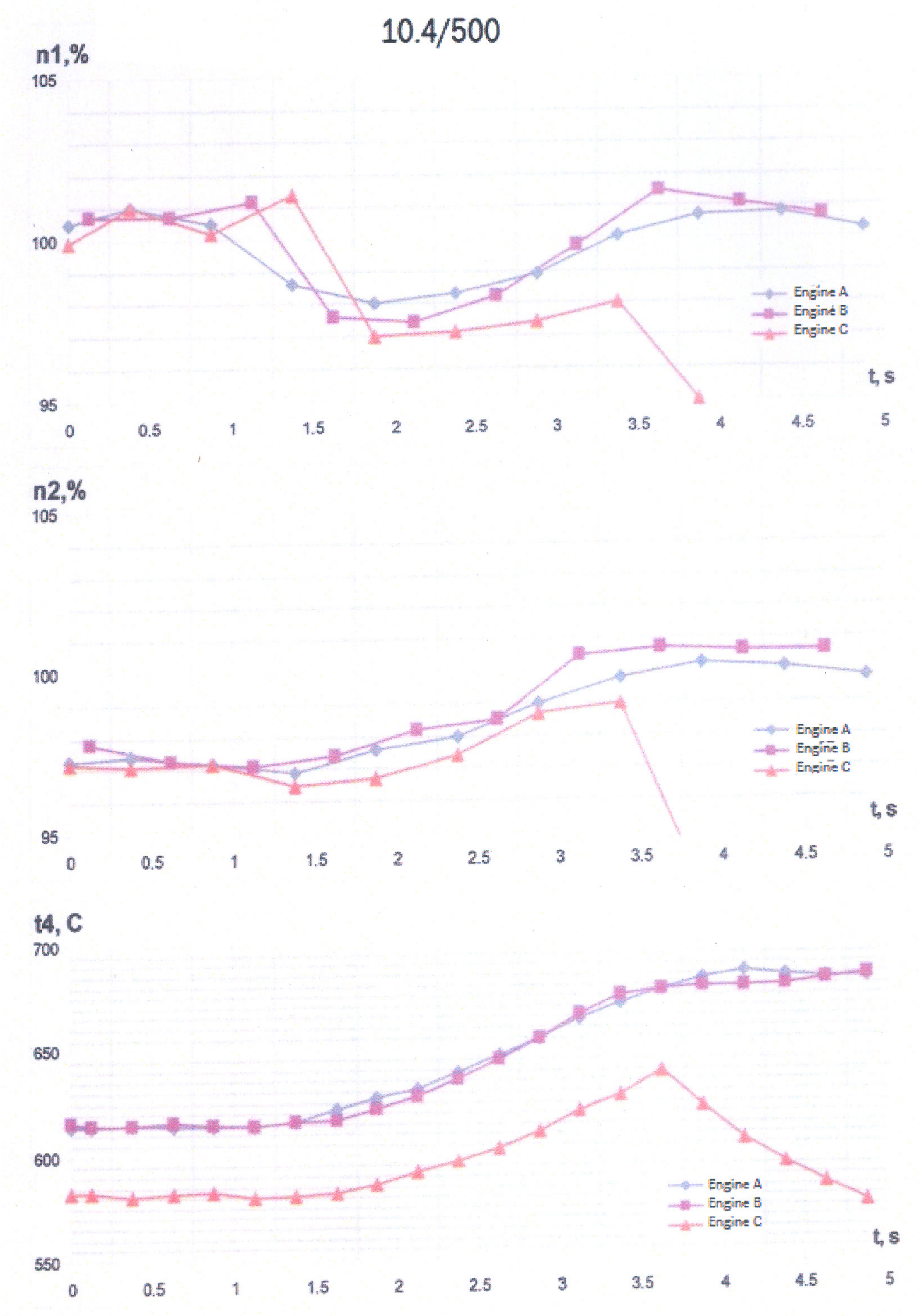

Fig.2 Change in the Engine Parameters when Switching on the Afterburner at H=10, 4 Km and IAS = 500 Km/h

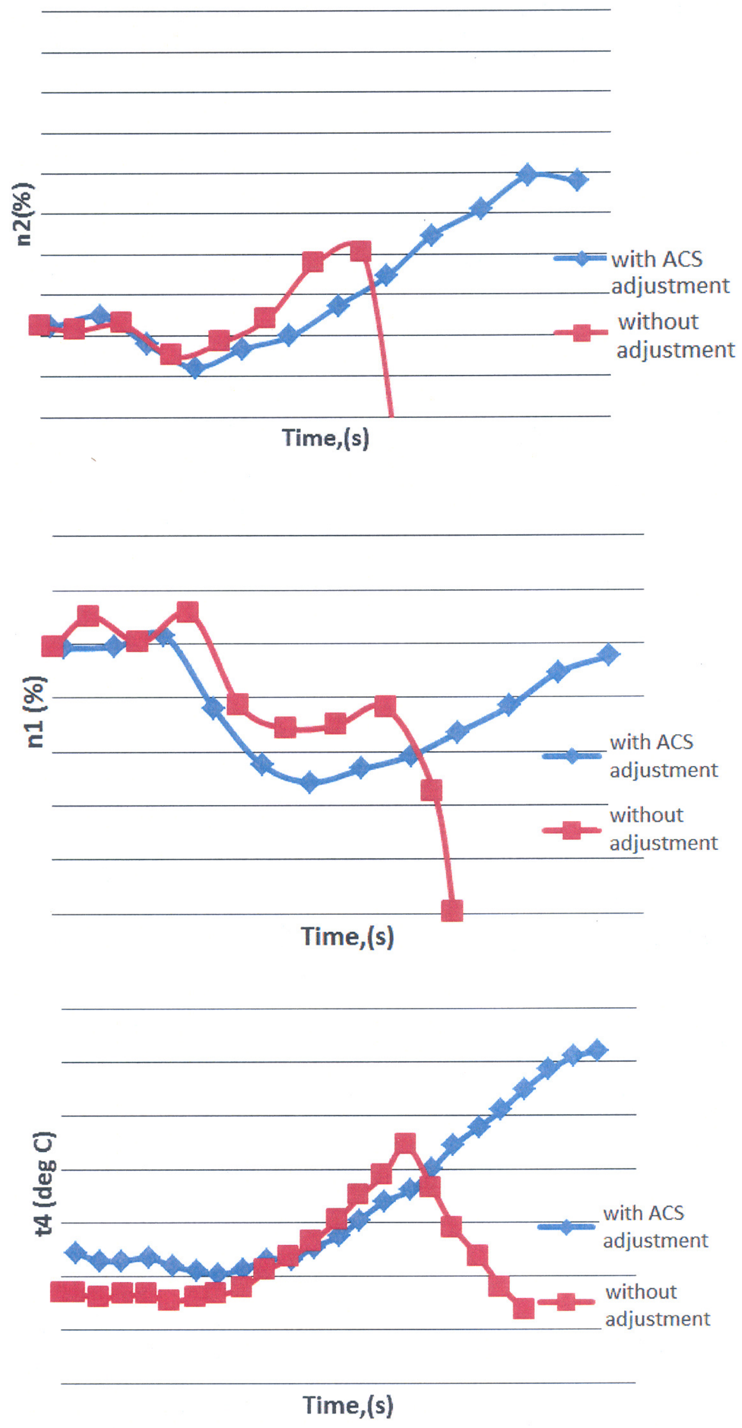

Fig.3 Engine C - Engine Behaviour During AB at Baseline and After Adjustment of ACS (10 Km/500 Kmph)

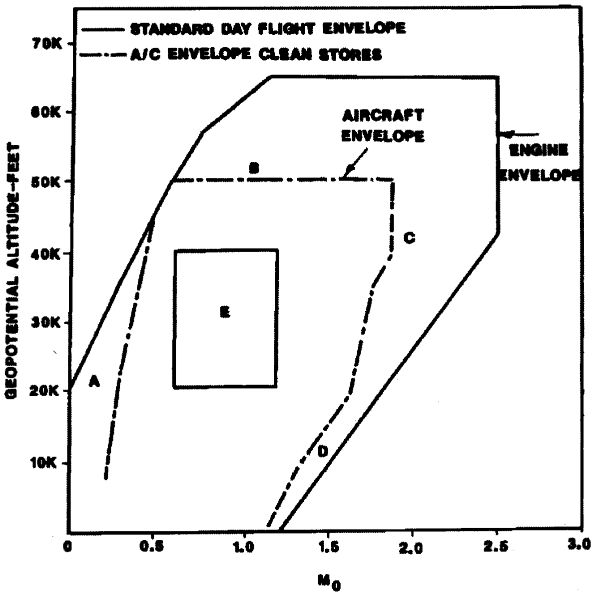

Fig.4 Typical Fighter Aircraft Operating Envelope

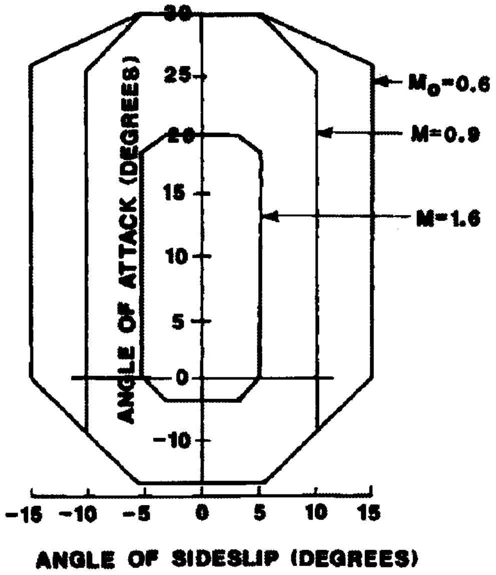

Fig.5 Typical Fighter Aircraft Maneuver Requirement