AN APPROACH TO HIGH AoA TESTING OF THE TEJAS LCA

Wg Cdr VIKRAM SINGH
National Flight Test Centre, ADA

1. **Introduction.** Modern fighter aircraft are a complex combination of aerodynamic designs, flight control systems, and engines. These modern designs demand modern test methods to evaluate their Out-Of-Control Flight (OOCF) and High Angle-of-Attack (HAoA) characteristics. Testing has traditionally progressed from approach to stall maneuvers through full stall series to spins and stalls with aggravated inputs. This approach to testing has evolved significantly with the introduction of highly augmented flight control systems in increasingly maneuverable aircraft through decreased stability. Advances in control system technology and to a lesser extent, aerodynamic design, have led to a shift of emphasis from investigating post stall behavior and recovery to prevention of departure in modern combat ac. The fly-by-wire flight control laws resident in the Tejas LCA, in addition to providing the basic command and stability augmentation functions, will also include departure prevention through boundary limiting / carefree maneuvering features to enable the pilots to fully exploit the capabilities of the airframe. The departure resistance features in the control laws also maximizes the useful angle of attack range of the aircraft while maintaining adequate levels of stability. Provision of a boundary limiting function in the control laws in the initial phase of flight testing does not guarantee that the aircraft will not depart during large amplitude maneuvering since the aerodynamic data used for control laws design are based on wind tunnel data which can exhibit different characteristics in flight especially at higher angles of attack where the data is highly nonlinear.

2. Flight testing the boundary limiting functions incorporated in the control laws is therefore a high risk activity and hence great emphasis and care must be given to all aspects related to recovery from stall / spin in case of inadvertent entry, and this

includes various aspects related to the design of the safety critical spin chute system and a recovery with a flamed out engine.

3. **Historical Perspective**. The Indian aviation industry has never embarked on an undertaking of such complexity and size before. Consequently little experience is available in the design, certification and test community. Experience in the HAoA field comes from the early 50s investigations of the spin behaviour of the HT-2, where the first prototype was lost on its second flight due to failure to recover from spin, the stall investigation of the full scale wooden mockup of the HF-24 Marut fighter, extensive spinning trials of the HJT-16 Kiran basic trainer and the HPT-32 piston powered trainer. In the case of the latter two ac, several spinning problems dogged the ac in their initial years of service. However, extensive testing including 18 turn spins on the Kiran provided significant data and understanding to the design community. Inadvertent entry into an inverted spin during an aggressive recovery from an erect spin led to investigations into inverted spinning on the Kiran Mk II in 1978. HAoA investigation on a high performance ac first began on the maritime Jaguar during integration of the Sea Eagle anti shipping missile. The highly risky nature of such an undertaking was brought to the fore when the test ac and pilot were lost in a tragic accident during the test campaign.

4. Test Item Description.

5. Aerodynamic Characteristics. As shown at Fig-1, the Tejas flying configuration was selected for good balance between supersonic and subsonic performance and good handling characteristics throughout.

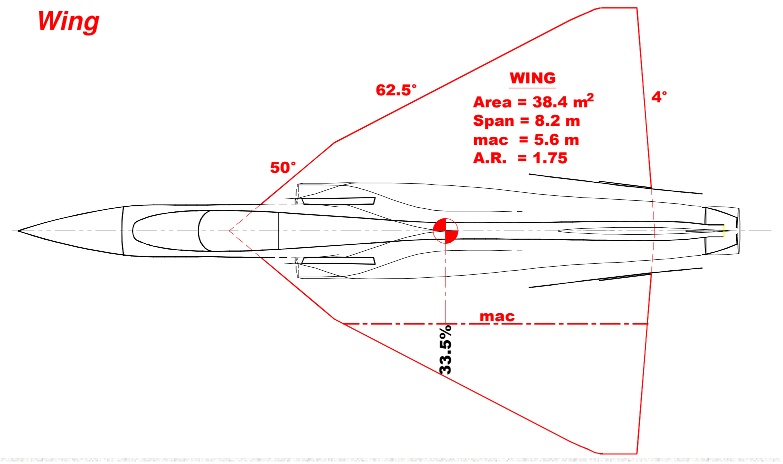


Fig-1: Tejas Plan View

It consists of a pure double delta configuration with leading edge angles of 50^0 and 62.5^0 and a trailing edge forward sweep angle of 4^0. The CG lies about 33.5% of MAC and the wing area is 38.5 m^2. The only augmentation devices are three-piece leading edge slats, which are automatically, scheduled with AoA and IMN to improve L/D, delay pitch up and increase usable AoA.

6. Stability and Control. The Tejas LCA has been designed to be aerodynamically unstable in the longitudinal axis to obtain improved maneuverability and agility over the entire flight envelope and hence, has to be stabilized artificially by the use of active control technology. The flight control system is a digital, quadruplex redundant full authority system exercising control through two sets of paired elevons and a single rudder. The stability and control cycle is updated every 12.5 milli secs through high fidelity, rate and acceleration sensors and high rate control actuators. Tejas instability is defined by ‘time to double amplitude’ and is one of the lowest amongst contemporary ac in the world. Graph at Fig-2 depicts this value across a Mach vs altitude scale. The region from 0.5M to 0.7M and from 3Km to 8 Km is the zone of the highest instability with time to double amplitude dropping to 200 milli secs. This implies that any disturbance in pitch would cause an increase in amplitude by 32 times in a sec.

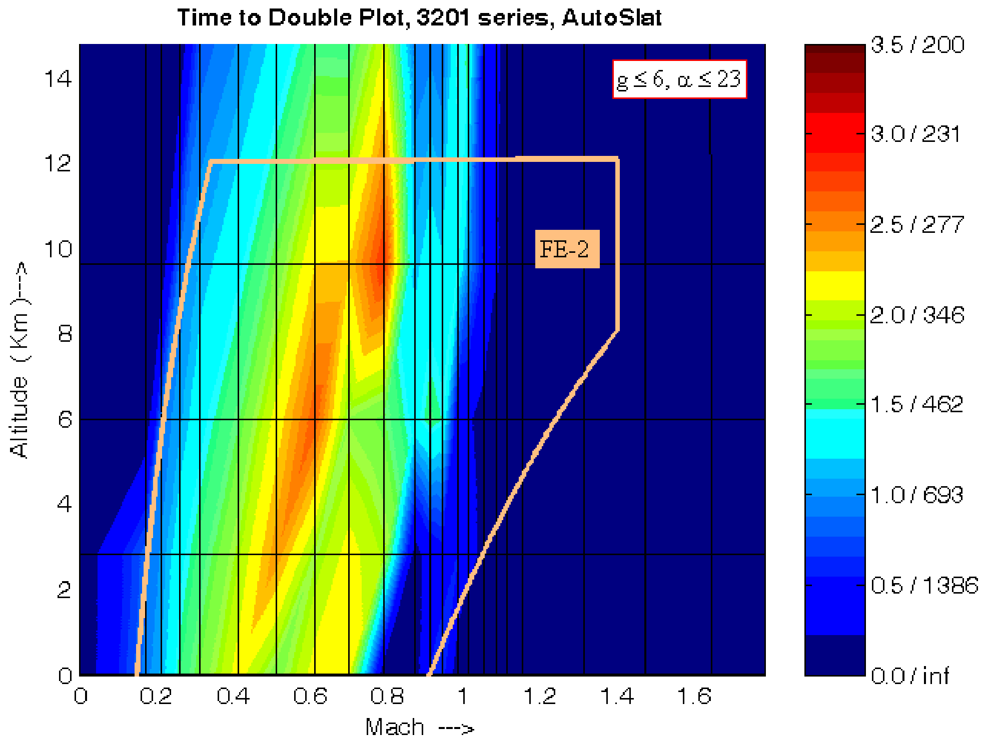


Fig-2: Time to Double Amplitude

7. **C_L Max And Usable Aoa Considerations.** Wind tunnel experiments have indicated that CL max continues to improve till approx 35^0 AoA as shown at fig-3.

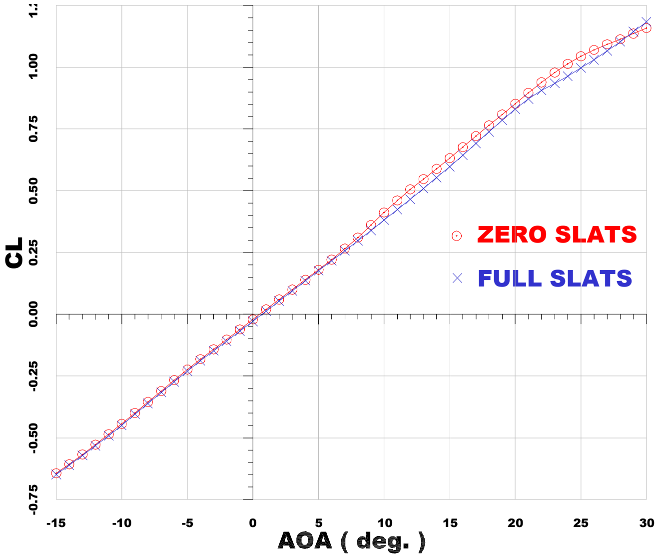


Fig-3 Lift Coefficient

However, directional characteristics indicated the proverbial ‘cliff’ with a sudden drop in Cnβ, CRM (Coefficient of Rolling Moment) and CYM (Coefficient of Yawing Moment) at approx 25^0 AoA as shown at fig-4 and 5. These phenomena require the High AoA trials to be limited to 24^0 (as shown in dotted line) until directional stability is bolstered and augmented by rudder control up to an expected 26^o. Currently the Tejas is flying to AoA limits of 20^o and 22^o never exceed. Fortunately as shown in fig-6, the LCA has significant rudder authority (CYM-Del R) even up to 30^0 AoA that will allow artificial stabilization in yaw at high AoA

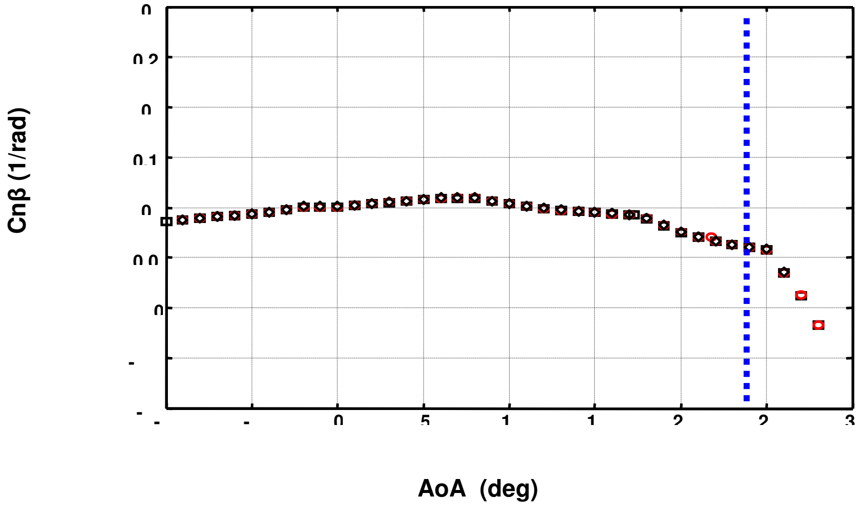


Fig-4: Directional stability at Mach 0.21, Slat30 deg, Fuel 1900

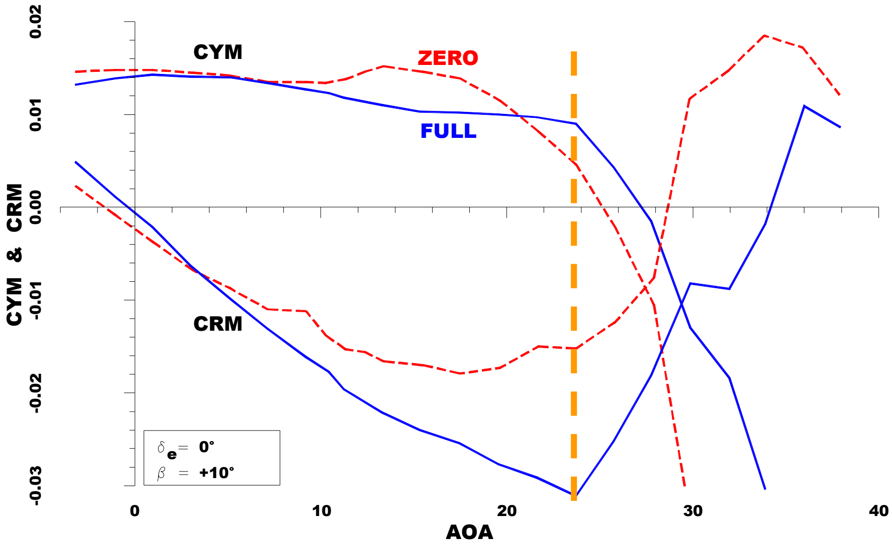


Fig-5: CYM and CRM Vs AoA

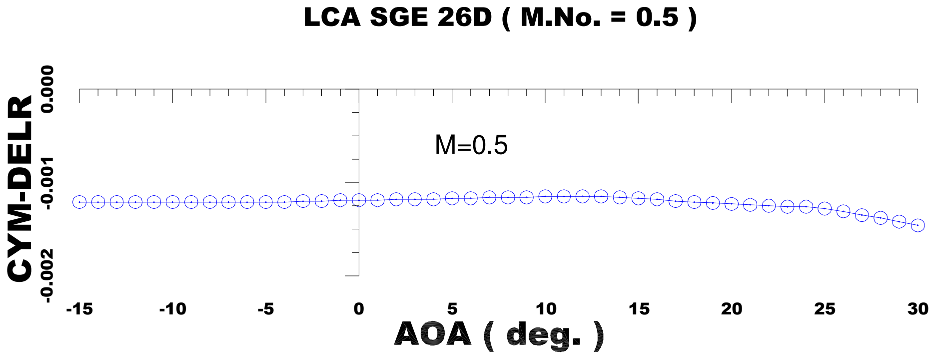


Fig-6: Rudder Authority Vs AoA

8. **Design Intent**. The Tejas design mandates the notion of a Carefree Handling (CFH) concept as an accepted fundamental principle called for in the ASR. To this end, a requirement to support CFH throughout the envelope includes a need for the pilot to operate the ac safely at the lowest possible airspeed. The design must also cater for a reasonable level of system failures, tolerances and atmospheric disturbances.

9. **Overall Test Philosophy.** Modern fighter aircraft are designed to be flown near their maximum performance limits to capitalize on advantages over other aircraft. This can result in departures from controlled flight. A pilot rarely enters out-of-control flight intentionally. When it does occur, it's usually in a dynamic and disorienting manner. Due to the normally forgiving handling qualities of the Tejas and its contemporary aircraft, OOCF incidents are quite surprising to the pilot and challenging, violent and unexpected motions can be encountered. This testing must therefore be extremely thorough so that hidden traps are not passed on to the user where costs are

likely to be high. However, a full investigation of HAoA characteristics of a high performance ac including spinning is a very high risk, high cost and time consuming proposition. Considering the large number of external stores configurations and the need to clear a two seater version, the test campaign could well take a few years of work up, flight test, analysis, re design and certification. Given the Tejas' flat, fast and oscillatory nature of predicted spin modes, the sharp cliffs in critical stability derivatives and the internationally evolving philosophy of testing departure prevention rather than post departure behaviour, it was decided that the ac would not be intentionally spun. Departure prevention, rather than spin recovery, will form the basis of test philosophy with full preparation for an OOCF event and its recovery. In this regard it may be recalled that in the recent CFH test campaign of the BAe Typhoon II ac not a single departure was encountered and the spin chute was never used, although the ac was subjected to every combination of OOCF causing events. Further, although several spin recovery techniques have been identified in the vertical tunnel experiments, no recourse to a "piloted" recovery will be made and the spin chute will be used immediately on departure to protect hydraulics and provide fastest possible recovery.

10. **The Challenge Of Vehicle Characterization**. An air vehicle is characterized in numerical parameters by a set of 'aero data'. The initial flight control laws are designed based on this wind tunnel aerodynamic data generated using scaled models, and hence, have to be validated in actual flight using parameter identification techniques. Further, in order to cater to the large variations in aerodynamic characteristics of the airframe across the flight envelope, the control law gains and coefficients are scheduled based on air data parameters obtained from external sensors. These air data sensors (vanes / pressure probes) mounted on the nose and fuselage measure only the local values of flow angles, total and static pressures, and hence need to be corrected suitably at each instant to get the true free stream values which are required by the flight control laws. The correction factors are initially estimated from CFD studies and wind tunnel measurements and therefore can have significant errors especially at transonic Mach Nos. Thus in any new combat aircraft programme a significant part of the flight test programme consists of experiments which are directed towards aero data validation and air data calibration. Based on the flight test results and the closeness of match with the corresponding wind tunnel data the envelope is systematically expanded in stages to ultimately cover the boundaries including the nonlinear high angle of attack regimes. Since HAoA regimes are defined based on these very elements of AoA and CAS, it becomes necessary to calibrate the air data sensors and validate the aero data at HAoA to help assess the accuracy of predictions and actual air data. This is the necessary first step before commencement of full investigations. Advances in nonlinear analysis tools and simulations allow the designer to characterize the behaviour of the aircraft at high angles of attack and determine the lift boundaries, which forms a basis for clearance prior to high angle of attack flights.

11. **Predicted Aircraft Behaviour And Spin Modes.** The high angle of attack database for LCA has been generated in static, rotary balance and forced oscillation

wind tunnels at TsAGI, Moscow. Trials were carried out on a 1:15 scale model in the T-105 Vertical Tunnel. Various model configurations were tested to capture effects of external stores, airbrake, slats, landing gear and variations in mass, CG and inertia. In addition, control surface deflections and spin parachute deployment were tested. The objectives of the tests were to identify spin modes of LCA and their characteristics, establish best recovery controls and sizing of the spin parachute. The main spin mode observed was flat spin with high angular rate and oscillations in pitch and yaw. Different combinations of rudder, aileron and elevator were tested and the best control deflection for recovery along with its magnitude, direction and sequence was established for different aerodynamic configurations. Photomontage at Fig-7 below depicts the 1:15 model and tests underway.

Fig-7: 1:15 Scale Model and Spin Tests Underway

Detailed and extensive analysis of the high angle of attack database indicates that LCA has very few stable spin modes. Further, the airframe exhibits fast flat spin modes with the trajectories in general being oscillatory and unstable making it extremely difficult to predict the aircraft behaviour beyond stall. The general qualitative observations were as below.

(a) Angle of Attack (most spins in the range of 70-80 deg)	57 – 85 deg
(b) Angular Rate (most spins around 2 rad/sec)	0.7 – 2.8 rad/s
(c) Turn Duration (most spins around 3 sec)	2.3 - 8.3 sec
(d) Rate of Descent	76 - 83 m/s

12. **Predicted Spin Recovery Techniques.** After several runs with various combinations of offset CG, asymmetric mass deployment, positions of airbrakes, undercarriage, controls and slats the following conclusions emerged.

(a) Recovery With Control Surfaces

(i) Deflect full OUT-SPIN rudder simultaneously with IN-SPIN ailerons followed by down elevator after 2 sec delay. Recovers within 2 turns.

(ii) Some other configurations (stores, zero slats etc.) showed more difficult recovery.

(iii) Some configurations required 18.5 deg In-Spin Aileron (e.g. Zero Slat, A/B etc.)

(iv) Some configurations required 25 deg In-Spin Aileron (e.g. Ext. Store configs.)

(v) Recovery from Inverted Spins easier (Neutral Aileron sufficient)

(b) Recovery With Spin Parachute Restore rudder and aileron to NETURAL. After a delay of about 2 secs, deploy parachute and restore elevator to neutral. Recovery within 2 turns.

13. A typical stick position chart at fig-8 depicts the control positions found most suitable for recovery from an erect right spin. The depiction assumes full out spin rudder being applied.

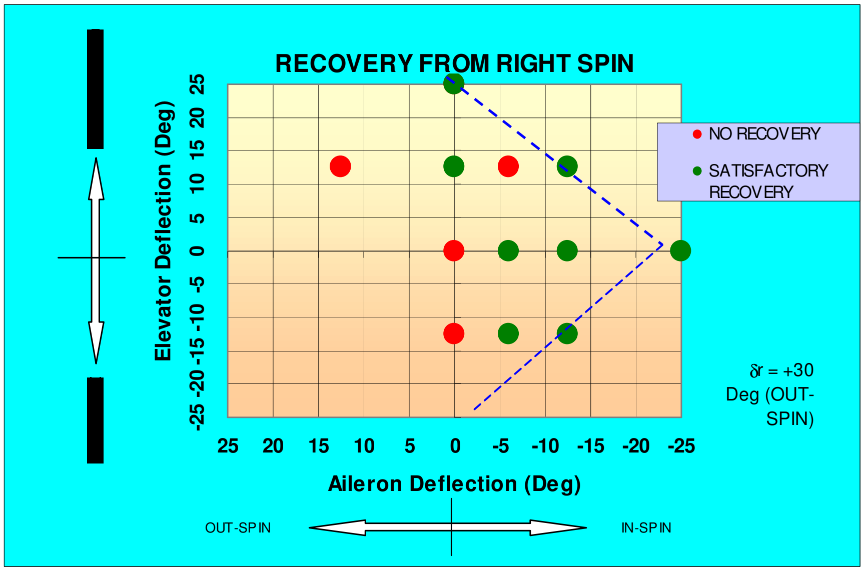


Fig-8: Control Positions Required to Recover From Right Spin

Clearly the spin recovery technique is an involved procedure requiring good orientation (knowledge of spin direction) and timing of controls. This is not a satisfactory situation considering the very high rates of rotation and build up of longitudinal acceleration at the pilot's location. During several similar programmes abroad it was decided that the max negative longitudinal (nx) acceleration permissible at the pilot's location is –4g. Beyond this value the pilot would not be able to assume the correct posture to eject. As estimated from the vertical tunnel tests, the spin axis would pass through a point between the pilot and the ac cg. This point would move backwards and finally pass through the cg. Thus the 'eye balls out' acceleration felt by the pilot would continue to increase. Considering all the above, no attempt to recover the ac through use of controls would be made and spin chute would be deployed immediately the CAS drops under chute operating limits.

14. **Peculiarities Of A Fly-By-Wire Configuration And Impact Of Full Authority Flight Control System.** As opposed to conventionally controlled ac, in the case of a full authority closed loop control ac such as the LCA, departure will cause the controls to oppose the ac motion. Since little response will be seen to these inputs, the controls will hard over at up to max actuator rate. Thus oscillatory post departure/spin characteristics will cause full deflection, max rate, and oscillatory deflections of control surfaces, which will result in large hydraulic system demands. If the engine flames out, the emergency hydraulic pump will not be able to cope with this demand and will stall or cavitate. Therefore the emergency hydraulic system must be capable of supporting these control system actuator demands. Further, the control system will apply out spin roll controls, which in the case of the Tejas, post stall AoA, will be pro spin. Therefore to be able to achieve quick and full recovery it is desirable to provide the pilot with full and direct control surface authority. LCA being a highly augmented aircraft, under normal flying conditions, the control laws significantly reduce the pilot's command authority over the control surfaces. Therefore, in the post stall flight regime the control laws should be inhibited from reducing the pilot authority over the control laws and this is achieved by incorporating an additional pilot selectable spin recovery mode in the control laws which disconnects the feedbacks from the inertial sensors and scales the pilot stick input to give full authority over the control surfaces. However, as the Tejas is unstable and unflyable without the CLAW, the ac will have to be stabilised by a spin parachute before the pilot takes over manually.

15. **Spin Recovery Parachute Requirements.** The spin chute when deployed in flight automatically generates recovery moments in yaw and pitch which drive the aircraft towards low angles of attack and sideslip and also stabilize the ac in pitch. These moments are sufficient to recover the aircraft from post stall and spin regimes provided the drag area and sizing of the parachute canopy is sufficiently large. Importantly, it stabilizes the ac even when the FCS stabilization is disconnected. The sizing of the riser and rigging length are critical to proper deployment. Spin chute development is in it self an involved activity currently undertaken by only two vendors in the world. Besides the spin parachute drag area and combined length of riser and rigging lines, the specified speed range for operation, altitude range and maximum rate of descent, and aircraft mass were also identified. The system consists of a main and a pilot parachute packed in their individual deployment bags and placed end to end in a cylindrical container mounted on 'spin gantry' as shown in Fig-9.

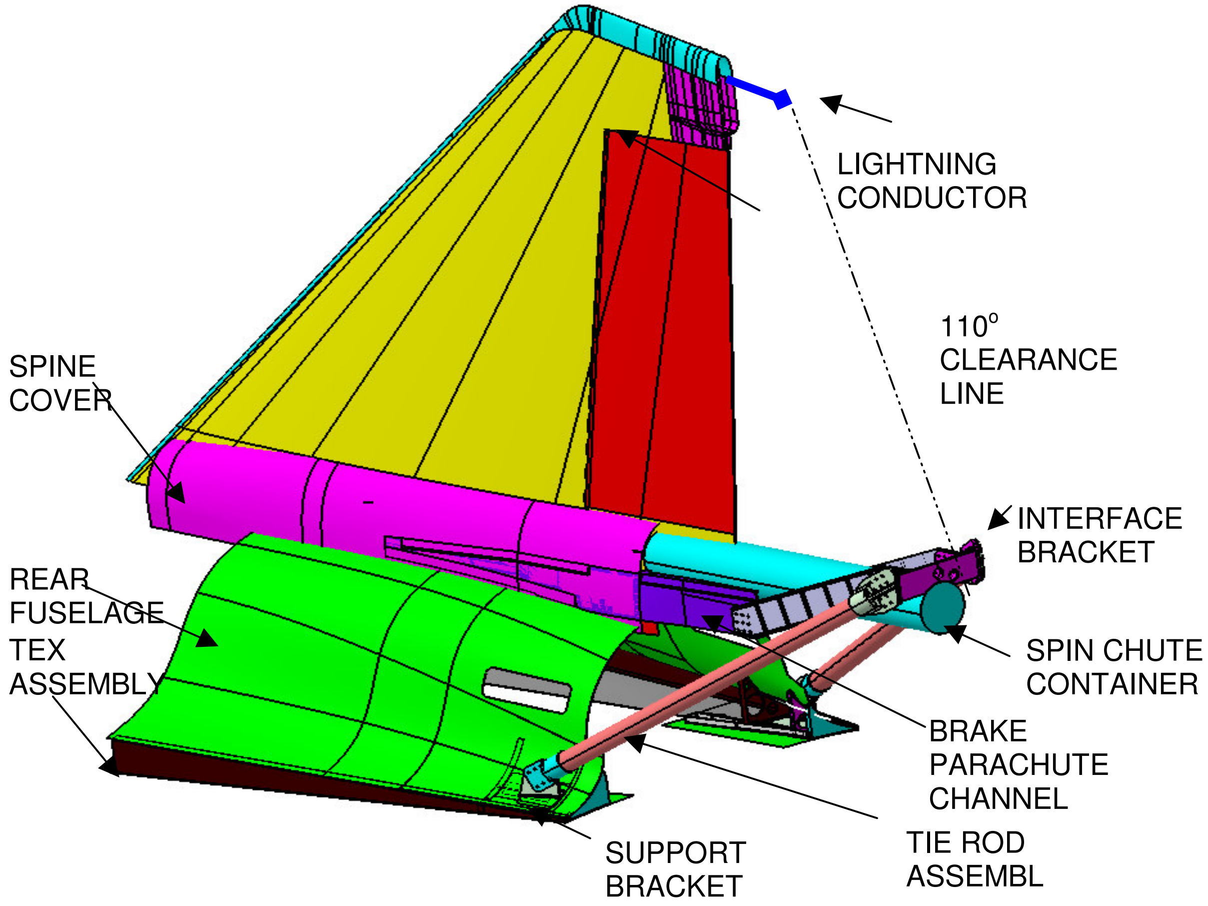


Fig-9: Spin Gantry Modification on Rear Fuselage

16. The entire chute assembly is packed in the tail chute compartment of the ac. A suitable ac with internal structure stiffness to support such an assembly would have to be identified. On command from the pilot, a lid plate separates through firing of a drogue gun, which also ejects a slug that deploys the pilot parachute. The pilot parachute in turn extracts a conical ribbon main parachute away from the aircraft wake. After the main parachute is deployed, the pilot parachute separates through a weak tie. On recovery, the pilot selects a pyro-activated release mechanism to jettison the main parachute. In case of failure of the release mechanism, the pilot has to dive the ac so that a shear notch in the link will snap as the aircraft speeds exceed 30% of the maximum parachute design speed, thereby providing a backup procedure for jettisoning the parachute. In case of an engine flame out during the spin, the pilot would have to dive to this speed without the benefit of engine thrust entailing steeper dive angles and increased loss of height before recovery. This is a critical design consideration for the

design of the weak link which must also cater for transients from the drogue release, strop extending and chute opening which in turn should be designed with sufficient delays to prevent them from adding up. Further, to prevent entanglement of the riser with the fin, the chute attachment point should be at a location aft enough of the fin to allow for a riser angle of at least 110^0.

17. A detailed test of spin chute integration itself will entail several taxy and flight tests. It may not be out of context to mention that the Eurofighter Typhoon II had eight failures of the spin chute before a fix was found. PVI issues and reliability of deployment and jettison controls are critical to safe operation both prior to the HAoA test point and during activation. Considering that this may be the only method of recovery available, the entire spin chute system must be at least duplex redundant.

18. **Engine Behaviour and Relight Considerations.** Although the GE 404 engine is cleared surge free in its entire operating envelope, it is important to assess surge margins and identify a power setting to prevent surge at HAoA. The effects of over temping the engine and the effect of high rotational rates and corresponding gyroscopic moments on the engine need also to be studied before embarking on the campaign. Even if the engine does not flame out, the test director may have to decide between shutting down the engine to protect the engine or keep it on to protect the hydraulics. A clear criterion to help to decide this will have to be laid down. All planning for recovery from spin must assume that the engine will flame out. Thus height required for one failed relight plus a successful relight must be catered for. Lastly relight must be attempted after chute jettison only.

19. **Requirements for Aircraft General Systems.** All the ac systems will have to be checked for their capability to sustain high angular rates and n_z up to +8g.

(a) Hydraulic System. The hydraulic system is critical to recovery from spin as it powers the controls and ironically will be the first system that will be lost in case of engine flameout. The Emergency pump can supply flow for three min but not at the rate desired for full control activity. Thus it is necessary to provide a backup hydraulic power source, preferably for both main and emergency systems, of approx 60 lpm. The critical period for consideration whilst sizing the back up Emergency power Unit (EPU) pump will be from recovery to relight, when the chute would have been released and the ac flown in frozen gains until relight and recovery of on board hydraulics. While an APU could be used, it would probably not be able operate at the test altitudes. Currently the international standard is to use a hydrazine driven pump. However handling of this fluid has its own safety requirements and the EPU would have to be replenished at the taxy holding point prior to take off and a EPU contents indication should be available at telemetry. The triggering of this pump is also of importance as too early (switching it on before the test point) would deplete EPU fuel unnecessarily, and switching it on too late could lead to damage of the ac hydraulic system and delayed recovery. Linking the EPU to engine RPM or reducing actuator rates with RPM could be one of the options.

(b) Fuel System. The effect of high rotational rates and longitudinal accelerations on fuel sloshing, sticking of float sensors, blocking of vents etc must be checked for assessing effect on relight fuel supply. Effect of fuel slosh on cg and its effect on spin modes and recovery need to be studied.

(c) Electrical System. All critical displays such as the HUD etc should be powered from the DC emergency bus. Also none of the DFCC channels should lose power due to flame out to ensure quick recovery. This will require an additional battery.

20. **Air data System Requirements.** Currently the LCA Air data system is not fail-Op, fail-safe and needs to be upgraded, as air data is critical to vehicle stabilization and test conduct. Further a beta vane will have to be fitted and calibrated to a high level of accuracy with a flight test boom. It is likely that speed sensing will be oscillatory during spin due to probe misbehaviour and an envelope of peaks may have to be used for decision. Lastly, air data may be lost during spin and would need to be reset after recovery before the spin mode is deselected. Considering all the above, it would be safe to cater for a +/- 2^0 tolerance in regions where AoA calibration is not accurate. In this regard it should be noted that the high AoA database might never be assessed for match with real values, as the ac may never depart.

21. **Cockpit Controls and Display Requirements.** Special cockpit indications will be required to assist the pilot in assessing the following

(a) To identify the departure (AoA)
(b) Identify whether he is spinning (yaw and roll rates)
(c) What kind of spin (-ve or +ve AoA)
(d) When to deploy spin chute (speed)
(e) What kind of recovery controls to apply (yaw, roll, speed, AoA and Nx)

22. Location of spin recovery and chute switches need to be planned carefully for access during spin due to the large and disorientating motions involved. Essentially the spin mode switch should be located in the centre of the instrument panel so that the pilot can slide his hand along the thigh and operate it under high rate rotational motions. Similarly, the chute deployment switch should be on the left coaming so that the pilot can easily reach it. Light displays and aural cues will also assist the pilot in monitoring ejection height and Nx, which is critical to safe ejection. It is expected that beyond -4g longitudinal acceleration at pilot location, the pilot will not be able to assume a safe posture to eject. Thus if the Nx approaches this value the pilot would have to perforce eject. The modifications planned in the Tejas cockpit for HAOA trials are depicted below at Fig-10.

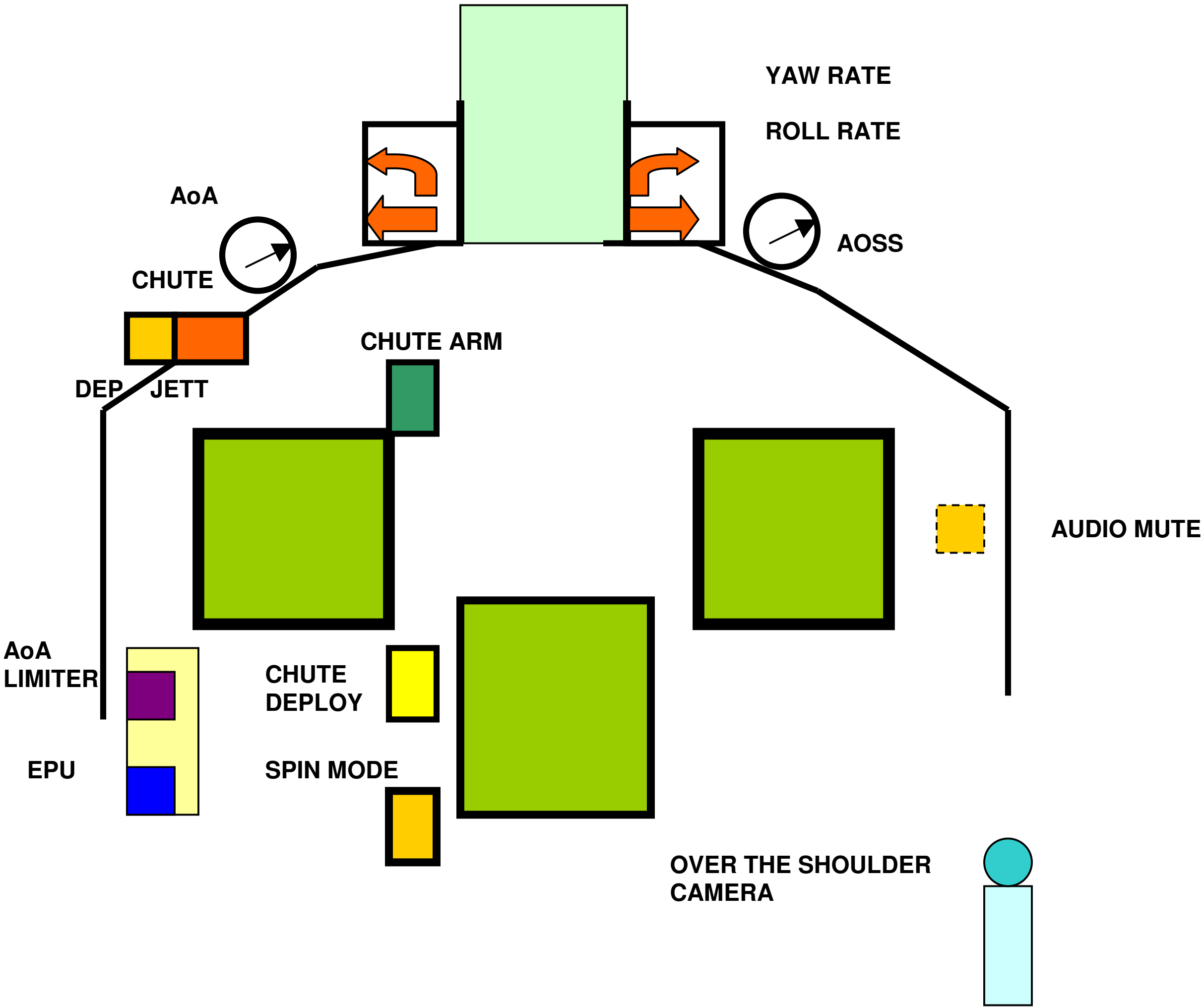


Fig-10: Cockpit Displays and Controls for HAoA testing

23. As engine failure and AC power supply failure is mandatorily to be catered for, a special set of pneumatic indicators for standard IAS, Altitude, M No, AoA, AoSS need to be provided. The importance of pilot cues for correct recovery action cannot be over emphasised. However, pilot assist in the shape of a display that indicates the control position required to recover from spin may not be easy to assimilate. Good telemetry-pilot coordination will provide faster, considered directions for spin recovery. However, aural cues will be able to announce departure, low altitude or excessive longitudinal acceleration to assist the pilot to decide on ejection.

24. **Telemetry System Requirements.** The use of real time telemetry and highly trained and coordinated telemetry crew are crucial to test success. As this will be the first time any of the participating crew will be exposed to such activity it is

important to train them thoroughly in what to expect. For this a traditional spin table will be used where in all the typical parameters can be generated using pot meters so as to provide numerical data on the telemetry screens as if for a real spin. Fig-11 depicts a proposed plan for such a table.

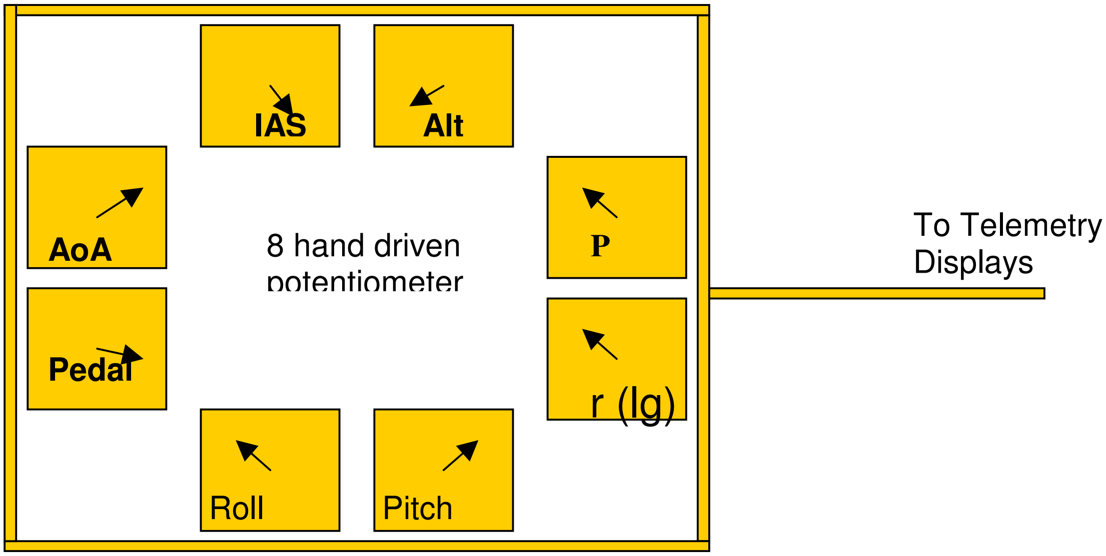


Fig-11:Typical Spin Table

24. To further increase realism in training and build team effort the RTS will be hooked up with the telemetry monitoring station via fibre optic cable so that while the pilot practices OOCF and recoveries, his ‘flight’ can be monitored in the telemetry as if it were a real flight. The pilot will also have radio contact with the monitoring crew so as allow telemetry to practice his test conduct and spin recoveries with the actual R/T calls. This near real simulation will provide great confidence to the team and work up the crew so that they are prepared for almost any OOCF eventuality. Considering the criticality of telemetry, the ac will have two transmitters and two antennae. To aid the test director to identify the spin mode and actions required to recover, a decision assist system will automatically signal telemetry calls required to be given. For instance a screen as shown at Fig-12 below will indicate the stick top and pedal position and required positions with AoA. Other boxes will light up when pre determined safety altitudes are descended through. Even the command “Jettison chute Eject” will come up on his screen. To provide an external real time view of the ac during spin a camera will be fitted in the RWR location on the fin top.

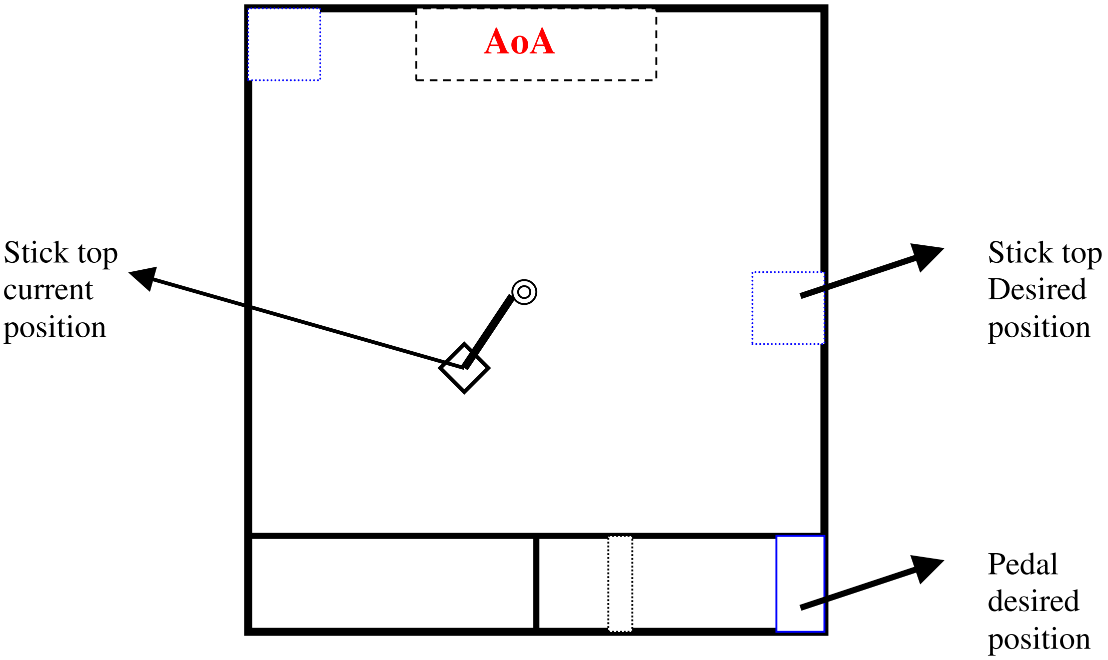


Fig12- : Telemetry Display of pilot control position vs desired for recovery

25. **Flight Control System Requirements.** As a first step it would be necessary to submit all the FCS elements to the high rates expected. Importantly the Rate Sensor Assembly (RSA) would have to be checked after it is submitted to accelerations beyond its max range. Will it behave correctly on spin recovery? Or will it derange. Further, will the A/D converters wrap around or change signs? And will the integrators wind up? These issues are vital for safe recovery into controlled flight after the ac is brought out of the spin recovery mode. To disconnect the feedbacks in the augmentation path and allow the pilot direct control over the surfaces, a Spin Recovery Mode will have to be provided in the DFCC. This mode will need to be activated by the pilot. Once engaged, this mode should disconnect all air data from the DFCC to the displays and display only nose boom data on the GUH displays. This is necessary as departure may cause the air data sensors to cross the mistrack thresholds and trip. With large variations in AoA during spin, the slats will keep operating, thus continuously changing the stability margins and ac response. Further, slats being simplex in hydraulics, it may be safer to set them in the safer extended position before each test point.

26. On recovery when the spin recovery mode is disengaged, the FCS may be in a failed state and air data will need to be re initialized. Thus disengaging of the spin mode must reset the FCS and air data. In cases where recovery occurs without the pilot resorting to the spin mode, the FCS may have entered a reversionary mode. A reset should be able to clear such failures also.

27. **Flight Test Techniques.** High AoA testing requires a comprehensive and logical build up program and studying of past results, simulator investigations and practice, experience in other ac and mental rehearsal will vitally arm the pilot to expect the unexpected. Given the overall aim, the objectives of flight test will be the following

(a) Lay down regions of max risk.
(b) Verify limiters at low risk conditions (risk free AOA/AoSS combinations).
(c) Test departure boundaries against predicted figures.
(d) Define boundaries in terms of AoA/AoSS/p/q/r and other dot derivatives.
(e) Provide sufficient protection even for low altitude high dynamic pressure departures.
(f) Test these boundaries for limiting with the following methodology:-
    (i) Commence with straight slow downs.
    (ii) Follow up with accelerated slow downs up to max AoA/g rolling entries.
    (iii) Repeat for two cg and altitude combinations (Mach effect on $C_{n\beta}$).
    (iv) Carry out boundary limiting tests for most unstable and asymmetric store configurations and lay down new limiting conditions.

28. High incidence testing is always high risk testing and pilot disorientation is a significant risk while the risk of engine flameout is also high. Therefore thorough trials preparation will require full preparedness for occurrence of the following

(a) Ac ***will*** depart
(b) Ac ***will*** spin
(c) Engine ***will*** flame out
(d) Pilot ***will*** be disoriented
(e) Spin Chute ***will*** be required to recover
(f) Spin Chute ***will*** fail to jettison
(g) Spin chute ***will*** have to be flown off to break weak link without engine power
(h) Two attempts ***will*** be required to relight the engine.

29. As a base line a dedicated pilot/standby pilot and two sets of telemetry crew teams should be earmarked for the trials. The pilots must be current in spinning on other types such as the Kiran and MiG-21. The USAF Test Pilot School provides OOCF exposure to its pilot on the F-16. This facility must be explored to acquaint test pilots to OOCF events on a highly augmented ac. Further, the disorientation facility at IAM will also be used to acclimatise pilots to potential disorientating phenomena. The responsibilities of each person must be defined and displays for each task must be provided. Training for all spinning characteristics, not just the ones observed in the spin tunnel, and all possible system malfunctions must be carried out meticulously. Establish minimum training requirements and currency requirements for each team member. This will ensure a good training standard during expected extended periods of ac groundings and unserviceability.

30. Considering the spin and recovery characteristics predicted by the wind tunnel and the Spin chute studies, it is expected that the total height lost would be an approx 8.3 km from entry to recovery. This calculation is depicted in fig-13 below.

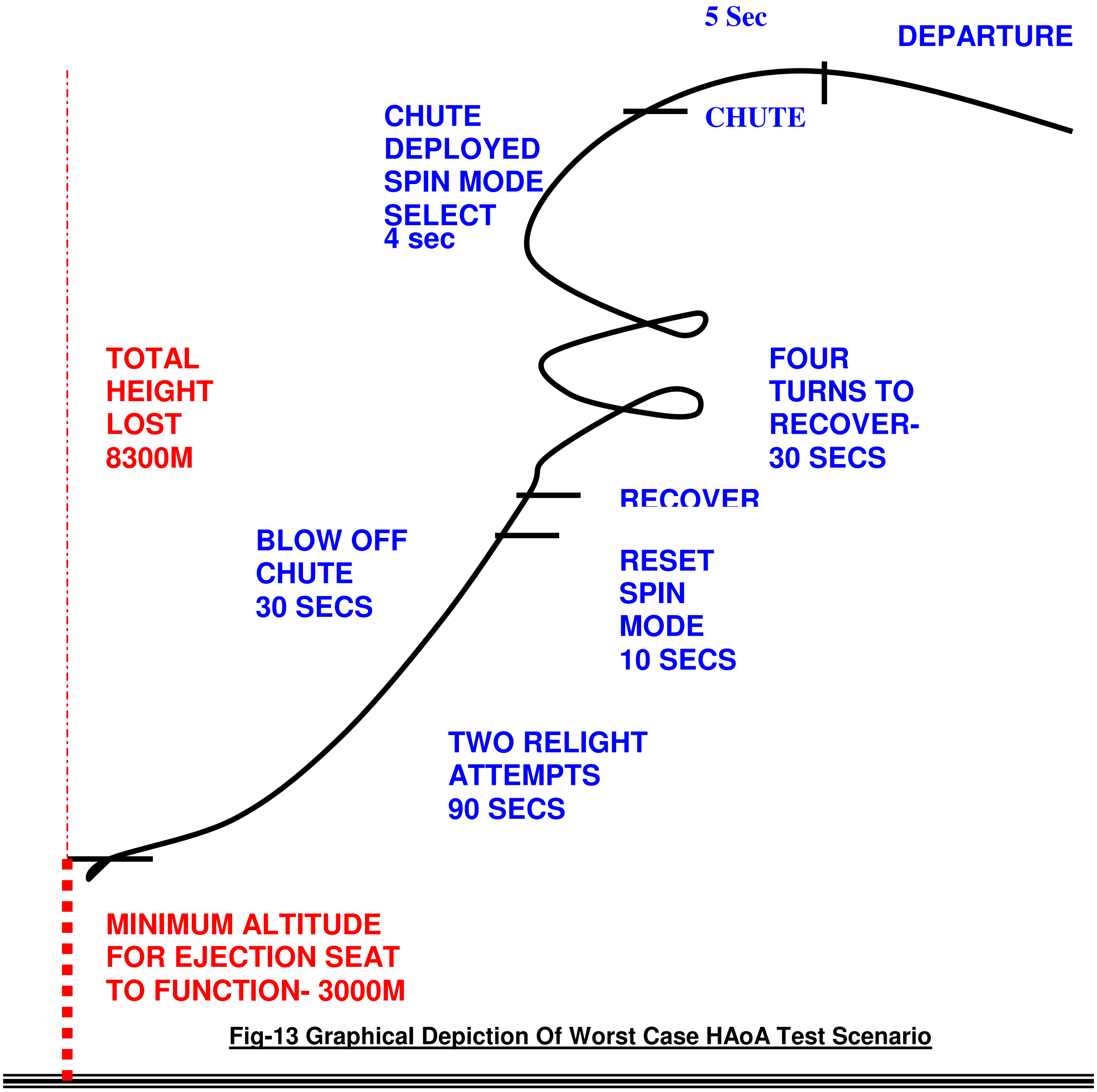


Fig-13 Graphical Depiction Of Worst Case HAoA Test Scenario

The calculations cater for four turns to recover and not the expected two and two full 45 sec relight cycles. Considering the minimum height of 3000m for the ejection seat to function satisfactorily at those rates of descent (in spin up to 80 m/sec), and Bangalore elevation of 880m, the trials would have to commence not lower than an approx 12,000m. A recommended procedure for test conduct is placed below:-

(a) Climb to test altitude, check serviceability of all onboard systems. Hydraulics should be de aerated before each HAoA flight.
(b) Confirm full up telemetry and radio communication status.
(c) Check EPU contents
(d) Check Spin Chute Status. Chase to confirm Chute security
(e) Extend slats, confirm Airbrakes in
(f) Set engine power
(g) Mute all warnings to allow uninterrupted communication with telemetry
(h) Arm Spin Chute for deployment
(i) Switch on EPU
(j) Execute HAOA test point manoeuvre.
(k) In case ac departs
  (i)Adopt recovery controls position
  (ii) Check speed below chute limit, deploy chute
  (iii) Chute deployed, select Spin mode
  (iv) Monitor acceleration at cockpit and height
  (v) On recovery call from telemetry and/or cockpit indications, de-select spin mode. Jettison Chute

31. **Conclusion.** The approach to testing HaoA characteristics has evolved significantly with the introduction of highly augmented flight control systems in increasingly manoeuvrable aircraft. Advances in control system technology and to a lesser extent, aerodynamic design, have led to a shift of emphasis from investigating post stall behaviour and recovery to prevention of departure in modern combat ac. This testing must therefore be extremely thorough so that hidden traps are not passed on to the user where costs are likely to be high. However, a full investigation of HAoA characteristics of a high performance ac including spinning is a very high risk, high cost and time consuming proposition. Given the Tejas flat, fast and oscillatory nature of predicted spin modes, it was decided that the ac would not be intentionally spun. Departure prevention, rather than spin recovery, will form the basis of test philosophy with full preparation for an OOCF event and its recovery. Further, although several spin recovery techniques have been identified in the vertical tunnel experiments, no recourse to a “piloted” recovery will be made and the spin chute will be used immediately on departure to protect hydraulics and provide fastest possible recovery. Several challenges are expected during the HaoA test campaign, these are: -

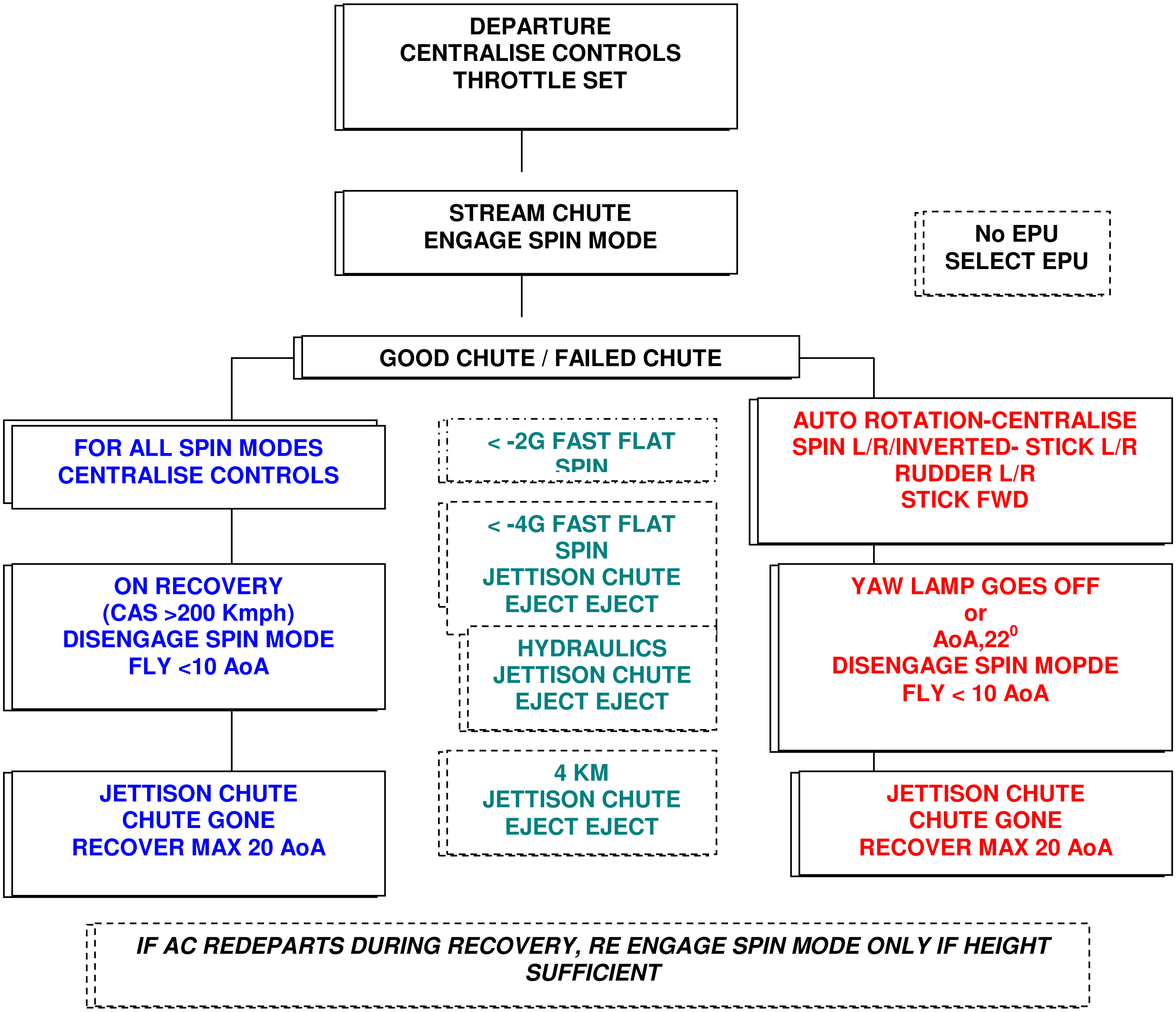
(a) Aero data validation and air data calibration in the non-linear HAoA regions.
(b) Addition of backup hydraulic and electrical power source.
(c) Design, testing and fitment of a spin parachute.
(d) Hardening of ac systems and FCS components to high accelerations and rotational rates.
(d) Designing the spin recovery mode.

(e) Modification of onboard FTI and telemetry stations for HAoA trials
(f) Modification of RTS and link up with telemetry for rehearsing test points.
(g) Simulation of all dynamic components from spin chute to ac behaviour during flame out with chute attached.

And lastly but probably the biggest challenge,

(f) To convince management to stay the whole course and resist programme pressures to reduce AoA limits and trim the carefree manoeuvring envelope.

31. A flow chart that will be used by the telemetry crew with likely contingencies and call outs is placed at fig-14 below.



<u>**Fig-14: Flow Diagram Of Events And Contingencies During HAoA test Point**</u>