Flight Testing of Control Laws and Air Data System: Technology development towards Product realization

Rohith M[@], Ambalal V. Patel[$] and Vijay V. Patel[$]

@ Member, National CLAW Team, FM&CL, ARDC, HAL, Bangalore-India (rohith.m@hal-india.com)
$ Member, National CLAW Team, IFCS Directorate, ADA, Bangalore-India (avpatel@jetmail.ada.gov.in, and vvp2069@jetmail.ada.gov.in)

Abstract

When discussing about flight testing of relaxed stability aircrafts with an active stabilisation using control laws (CLAW), the effectiveness of the control laws and its execution to perfection is limited to the *accuracy of the inputs what it receives from the feedback sensors* (like accelerations, angular rates, flow angles and airdata measurements) and *accuracy of the mathematical model of the aircraft* with which the control laws are designed. Though, the mathematical model for aircraft is generated using data from wind tunnel tests carried out on scaled model and further assisted using computational fluid dynamic (CFD) tools, the “truth model” lies in the full scale aircraft and that is proven only through flight testing. This paper presents the few case studies where flight testing helped in calibration of airdata sensors as well as identification of aircraft characteristics. Experiences gained and lessons learnt during the flight tests carried out in association with National Flight Test Centre (NFTC) for Tejas aircraft are shared in this article.

Keywords: Flight Test, Control Laws, Air Data System, Calibration

1. Introduction

The Fly-By-Wire (FBW) Flight Control System (FCS) involves design and development of the hardware and software. The Flight Control Laws (FCL or CLAW) and ADS algorithms as part of the application layer in the software does involve extensive clearance activities [1]. The clearance activities primarily involve to prove that how correct and safe is the design which has arrived by using the proprietary procedures and the data obtained from Computational Fluid Dynamics (CFD) and / or wind tunnel or from both as part of the aerodynamics studies and analysis. Usually, CFD provides an estimates of the aerodynamic effects / results obtained by using the basics of fluid dynamics implemented in the software tools. These estimates of the plant (aircraft) dynamics are verified and tailored by using the on-ground experimental data obtained through wind tunnel. This process provides confidence in using the on-ground generated data for design and development of the on-board system. Thus, it paves the way with proper planning for experimental flight tests.

However, based on the initial expertise and common simplistic situations, the assumptions of good hold on CFD are continued to be used for computing the estimates for the subsequent development in the aircraft programmes without verification / validation with the wind tunnel experiments. In such a situations validation of the features / design by flight testing becomes more critical. Therefore, sometimes, the features in the on-board systems are required to be incorporated to gather the data by venturing into the either complete or partially unknown territory of the flight envelope.

Whether, every situation could be imagined prior to and dealt with during the flight testing depends on the micro-level planning of the system development which of course includes the flight test for validation. The brainstorming on top-down development would bring out the need for considering the various situations and generating the relevant data or evidences. It has been experienced with the LCA / Tejas programme that, occasionally the flight testing only revealed the additional effects experienced on the systems which were subsequently accounted for improvement. A few of such situations experienced during the development of the Control Laws and ADS have been shared in this article.

System development involves dealing with the two broad aspects, ‘system design’ and ‘implementation’. In the present context, implementation is being referred to the implementation of the software for the Control Laws and ADS. The system is said to be perfect only when both, design and implementation are made alright. However, there could be scenarios wherein one of them or both of them could have some issues. The prior paragraphs already dealt about design by using the CFD / Wind tunnel data and clearance using the proprietary procedures. Thus, the flight testing also has to deal with planning for any flaw in the implementation, although well proven at on-ground test rigs / Iron Bird [2-5]. The software implementation error has caused a loss of life as well [6]. Refer to [7-8] for more details on the FCS and testing.

The paper is organised as given below: Section 2 provides flight testing related aspects for Fly-By-Wire Flight Control Laws (CLAW) assessment, Section 3 presents on Airdata Calibration and testing of the features, Section 4 presents on Telemetry support (Normal, Flight envelope expansion), Section 5 presents on the Flight Data analysis, Section 6 presents on the efforts towards the flight testing and clearance for production standard aircrafts, and Section 7 concludes the paper.

2. Control Laws (CLAW) Assessment

2.1 **Take-off:** Though not a phase of active closed loop flying, due to interactions with the landing gear dynamics can cause disconcerting effects during rotation. As part of mitigating the issue, a trend analysis of aircraft response parameters (Nz, q, surface deflections & surface rates) were kept under post flight data scrutiny to confirm that they are within the threshold/acceptable limits. For ride comfort point the parameters monitored were Nz and q. From the control perspective, the impact was found to be higher with surface position saturation & surface rates. Mitigation was mainly carried out by adding more damping in the landing gear system. However, applicable reduction of the order of 30% in system feed back gains were implemented in control laws based on "on-ground" status. This was to ensure that surface rate/position saturation does not occur even with additional excitation due to undulations on runway during take-off roll. Figure-1 gives a representative trend plots during take-off.

2.2 **Landing:** Considered to be the similar to take-off in terms of CLAW mode, however, more involved Pilot activity in this phase. It becomes more exciting in the presence of cross wind. Extensive testing was carried out to the available crosswind levels in the country at various locations and was extended by about 20% through modelling & simulation.

2.3 **Limiter Assault Manoeuvres:** Large amplitude inputs with full stick travels have been carried out to ensure the care free capability in terms of limiter efficacy. These manoeuvres are considered as "dirty manoeuvres" (on a lighter note) by Piloting community, however excites the cross axis dynamics and were quite helpful in quantifying the maximum possible variations in actuator rates and limiter effectiveness.

2.4 **Envelope expansion:** Programmed inputs are used to excite in the longitudinal/lateral/directional axis. This allows the flexibility of using tailored inputs to excite specific frequencies and is essential from the system identification perspective. Digital flight controls allow the freedom of injecting these synthetic inputs to the trimmed aircraft, whether with zero rates or steady rates. A novel procedure to compute near real-time margin estimation [9-10] to confirm the safety for further envelope expansion is explained in Section 4.2. A recommendation by SETP [11] which was successfully implemented is explained in Section 4.3.

2.5 **Handling Quality Assessment:** Tracking symbol of a target aircraft on head up display (HUD) was tested. Suggested pattern in MIL-STD [12], which varies the orientation of the target symbol in pitch as well as in roll was used (similar one was used in real time simulator-RTS also for HQ evaluation). Provision was given to offset the starting point in pitch to cater for the power requirements for different speeds. It also helped in the optimisation of power requirements to cater for ascends and descends during the tracking exercise due to the variation in the attitudes of the target. Figure-2 gives a typical tracking task carried out during flight.

2.6 **Experimental Features:** In the age of digital fly-by-wire (FBW), it is easier to implement certain test features that can be made selectable in flight for validation. This was extensively used in Tejas program for CLAW testing from the initial stages itself. Even feedback parameter alpha had a selectable feature during first block of scheduled gain flight testing.

3. Airdata Calibration and Testing of the Features

Air Data System (ADS) forms an integral component of the Digital Fly-By-Wire (DFBW) Flight Control System (FCS) [13]. It measures, processes, and then computes the following parameters which are used for feedback and gain scheduling to the Control Laws, and also for navigation:

1) Flow angles: Angle of Attack (AOA) and Angle of Side Slip (AOSS)
2) Pressure: Total Pressure (Pt), Static Pressure (Ps). Compute derived parameters like Pressure Altitude, Calibrated Air Speed (CAS), Mach No.

The ADS, especially algorithms involve [14-15]:

1) Position corrections to the local measurements to have free signals,
2) Redundancy management of the measurements from multiple sensors for failure detection, isolation of failed signals / sensors and selection of healthy / valid signals, and
3) Additional signal processing and reconfiguration for Wake encounter protection [16], dealing with effects of external devices mounted on the aircraft and during Air-to-Air Refuelling (AAR) operation, etc.

The following subsection highlights how flight testing revealed some unknown phenomenon and a few things verified by well planning:

3.1 **Measurement exceeding Transducer range:** It is quite a known fact that position errors in air data measurements are high in transonic speeds. At times it can be as high that the local measurement may go beyond the transducer range.

Algorithms were developed to cater for flying with dual range transducers (narrow and wide range) for continuing developmental flight testing (high AOA PID flight tests for envelope expansion) and supporting for flying the squadron aircrafts. All generations of algorithms have been developed by incorporating unique features and went through iterations. However, these algorithms were exclusively for supporting continuation of flight testing for overall development.

The background for this development is as given below: During the flight tests with prior generation algorithms, static pressure and few selected flow angle pressures were found to be saturating to their limits. Saturation of the sensor for flight control system results in working with open loop system, which is not expected. Tracing back led to identify that the maximum pressure computed from the estimates found to be much lesser than the local pressure measured by the sensors at high dynamic pressure region. It could be due to the fact that the initial coarse estimations obtained with the then available resources and tools at that point of time could be reasonable. Based on those estimates, the available transducers having the nearest higher range (to the estimates) might have been picked up. It may be noted that too much wide range of the transducer results in loss of resolution in the measurement.

However, this incident made to evolve the improved procedures for estimation of the sensor and transducer ranges. With the revised estimates, earlier narrow range transducers were replaced with wider range transducers. However, it took a while to evolve the procedure and procure the new transducers. Therefore, in order to continue developmental flight testing with multiple aircrafts, algorithms were developed to cater for dual range transducer usage with reconfigurations for envelope limits and indications to the pilot.

The algorithms dealt with:

- Indicating the pilot regarding protected region of the envelope due to transducer range, and
- Dealing with inadvertent exceedance during flight by protecting the system from declaring simultaneous failures, and freezing the feedback to the control laws in that regime

3.2 Effects of presence of a fixed refuelling probe (referred to AARP or IFFRFP):

It is positioned ahead of air data sensors made shock wave interaction with the side air data probes in the transonic and supersonic flight regime. This section highlights, how systematic flight test planning helped to understand the unknown effects on the sensors and mitigate them in the subsequent updates.

The effects of the AARP found on the ADS measurements can be broadly classified as given below:

1) ***Measurement Truncation:*** *Measured speed found to be significantly less than corrected speed:* It means aircraft actually fly at supersonic, however sensor measurement truncates to transonic regime. Thus, measured data not available for local to free stream corrections at Supersonic regime.
2) ***Multi-valued function:*** Indicates that at the same measurements more than one values of corrections applicable. These values were very large, and selection is non-deterministic,
3) **High Sensitivity:** A *Large Magnitude variation and a Sharp change (very sensitive)* to measurements.

Therefore, the on-board ADS measurements require additional corrections in the presence of AARP over and above the normal position error corrections (PEC). The nature of large corrections also affects the sensor redundancy management aspects including the failure thresholds thereof. Therefore, ADS algorithms as part of the on-board software have to cater for both the configurations, i.e., without and with AARP mounted on the aircraft and provide the accurate measurement without compromising the redundancy.

Although, it was planned from the beginning to have AAR capability on the TEJAS aircraft, however, AARP location got finalized after IOC and only then the CFD data showing the large effects on the ADS sensors due to AARP presence was made available. Till then the entire ADS for configuration without AARP was developed and finalized for operation over the entire envelope through various phases and iterations including the calibration and wake protection features.

The development of the algorithms to cater for AARP presence was carried out in three phases. Prior to commencing the development and implementation, it was decided to verify the effects of AARP on the ADS sensors by flying the aircraft with AARP mounted, but without updating the on-board ADC software for AARP reconfiguration features (flying with the prior software / algorithms). Therefore, there was a need to find out how much part of the envelope can be cleared with the existing algorithms for flying with AARP mounted on the aircraft. A systematic approach was evolved to estimate and identify the flyable envelope (very limited subsonic envelope). The process was accepted by the certification and thus it enabled to carry out the flight tests. The trends in the flight test data confirmed the expected large effects of AARP on the ADS sensors.

The second phase of the algorithm / software development provided clearance for entire subsonic regime. It enabled to carry out Air-To-Air (AAR) Refueling operation successfully. The third phase of development enabled to fly the aircraft over the entire envelope (Transonic and supersonic Mach regime) with AARP presence without compromising the redundancy. It has been flight tested successfully.

3.2.1 Effects during AAR Operation and Resolutions

During the AAR operation, the following two distinct phenomena observed:

1) **Effects due to the Movement of the Drogue:** Either prior to engagement or after disengagement, the movement of the AAR drogue affects the ADS sensor measurements, especially total pressure and thus the speed in a spiked manner. It resulted in generating warnings of nuisance category, which were highly distractive to the pilot during this high intensive task, and
2) **Effects after Drogue engagement with AARP:** There was a reduction in the static pressure measurement from the right side probe. The magnitude of the reduction was found to be a function of speed. At some point of time it resulted in declaring the sensor failure too.

Prior to the AAR flight tests, the CFD estimates showing the effects of drogue movements prior to the engagement and effects after engagement were not available as it was not thought of. Therefore, these issues have been resolved appropriately in the third phase of algorithms along with resolving the issues of enabling to fly at transonic and supersonic with AARP [15, 17-19]. Systematic planning and execution of flight tests were made to verify the efficacy of the entire design. A safety procedure as part of the flight testing was worked out jointly by system designers' and NFTC not only for flight test points, but also by collating various caution, warnings indication for all concerned, i.e., pilot, telemetry alerts etc [20] for quick actions and exit.

3.3 Calibration

Data of the extensive flight testing carried out for evaluation of all systems as well as that of dedicated calibration flight tests has been used for ADS calibration. Due to the paucity of the time for presentation at the designated platform (SFTE Symposium), the contents of the article has been limited, and hence details of the calibration aspects, especially dealing through flight testing are not covered herein. However, following points for ADS calibration would like to mentioned herein:

After dealing with such an extensive calibration exercises [21-24], the question remains there whether such an extensive flight testing is required for ADS calibration? The answer lies in the accuracy of the estimates obtained from the CFD or Wind tunnel experiments or both. CFD and wind tunnel tests have got their merits and limitations as well.

The flight testing for calibration can be divided into two parts: (i) for gathering the data, and (ii) validation after updated calibration data. If the accuracy of the estimates is good, then it demands only flight testing for validation. Anyhow, either a few or more, flight tests are required initially to ensure the correctness of the ADS measurements (validation of the estimates). Only then, the ADS measurements can be used for feedback. Thus the part of the data gathering flight test efforts cannot be eliminated at all. However, flight tests for data gathering are the most challenging, as the aircraft ventures into the envelopes where accurate data is not available. Therefore, it requires extensive planning for conducting the flight especially exercising the test points or manoeuvres, and emergency procedures for safe recovery.

4. Telemetry support (Normal, Flight envelope expansion)

4.1 **Screens for Normal Flights:** All parameters relevant and that provides situational awareness should be part of the screen used for flight monitoring.

- 4.1.1) Catering for the failures, it can be arranged in such a way that during flight test itself the initial hints can be brought out in whether it is in hardware/ software/ algorithm.
- 4.1.2) It is a good practice to have limit markers with colour codes for critical parameters which are being monitored [25]. To give an example, during the approach phase aircraft need to maintain certain AoA depending on the configuration. Time history of AoA turns amber/red depending on how higher it is from the nominal value.
- 4.1.3) Based on the changes in the testing software, necessary amendments are to be made to the monitoring screens and should be current

4.2 **Screens/Procedures for Flight Envelope Expansion:** As explained above, programmed inputs are used to excite in the longitudinal/lateral/directional axis and is essential from the system identification perspective. During initial days of flight testing (when flights were carried out in fixed gains), these synthetic inputs were used to excite the aircraft and the telemetered data recorded at monitoring station was used to compute near real-time margin estimation [9,10] to confirm the safety of further envelope expansion. Synthetic input 3-2-1-1 in pitch axis was used for the estimation of margins. A two step method consisting of first determining the aircraft parameter frequency responses using FFT signal analysis followed by estimation of analytical transfer functions of the aircraft from the FFT derived frequency response.

It is a good practice to have an expected response boundary during the conduct of the flight test, so as to get a first cut feel for the match in response with mathematical model. As we progress towards system identification tests at higher AoA and higher Mach numbers, the manoeuvres could be steeper and disorienting. It is recommended to have a close watch through telemetry on the altitude loss during dive pull out, especially at higher speeds.

4.3 **An implementation recommended by Society of Experimental Test Pilots (SETP)**: It was useful in successfully achieving this objective during the flight test. By definition Time Safety Margin (TSM) is *the time aircraft may continue on its worst case vector until the planned recovery manoeuvre will no longer be sufficient to prevent impact with the ground* as explained in the SETP paper [11]. Figure-3 explains the concept of TSM. An extension of TSM was implemented by displaying the altitude at which pilot should initiate the level out, while carrying out dive pull-outs, wind-up turns during high AoA parameter identification etc. Offline simulations were carried out to find the altitude loss incurred once the level out is initiated. To absorb the uncertainty, only 85% of the maximum achievable Nz was considered. Figure-4 shows the effect of Nz available and speed during pull-out on the TSM. Figure-5 presents a time history of estimated safe altitude to pull-out so as the aircraft does not breach the safety altitude set, and variation in aircraft attitudes during the flight profile. This section highlights on how systematic flight test planning helped to gather the data, understand the unknowns and take suitable measures in the flight control laws.

4.4 **Telemetry arrangement:** It is recommended to have seating positions of related systems nearby (eg: CLAW & FCS)

5. Flight Data analysis

Data analysis and presentation of it can be done in many ways. However, during the development it matters a lot from the following perspectives, especially for IFCS:

5.1 **Basic Analysis**: It should include the tabulation of minimum and maximum flight parameters and it should be confirmed that there was no parameter exceedance during the test flight. Identify any flaw in the system and to impose any restrictions during next flight or phase, pilot error and corrective measure required for gathering the data, issue with the aircraft and clearance thereof for next sortie.

5.2 **Automation in the analysis procedure for quick clearance:** Automation of the generation of data debrief presentation in a .PPT format for enabling quick turn around servicing (TRS) was introduced. Further this was helpful in implementing into the unified video and data recorder (UVDR) analysis tool which generates a GO/NOGO status and is used by the maintenance crew for clearing aircraft for subsequent sorties in the squadron.

5.3 Observations during flight test and their categories

5.3.1) General Observation:

1. Flight Characteristic
2. Improvement possible

5.3.2) Deferred snag:

1. Certainly needs to do improvement. However, flight test can continue and other pilots can also observe
2. Mandatory improvement. Further flight testing not required for data gathering purpose. Flight restriction

5.3.3) **Flight envelope restriction:** Flight restriction and No further scope for any improvement (eg: Airframe modification)

6. Production Flights

Production flights (acceptance sorties) also require support in terms of certain updates for the sensors. (Eg: AoA /AoSS vane bias update). Evolving a flight test plan for the features present in the CLAW. Certain level of hand holding is required till the production house takes over on their own. Till that period support needs to provided for production flight testing and its data analysis requirements.

7. Conclusions

Design and development of the Control Laws and Air Data System for the fly-by-wire Flight Control system for the TEJAS aircraft includes several milestones: algorithm design, redundancy management, software development, on-ground testing, aircraft level integration, flight testing, and calibration. Significant efforts have been devoted to achieve the highest level of accuracy, redundancy, and reliability in the ADS measurements as well maturing of the Control Laws. Flight Testing has played a significant role in getting the feedback for improvement of these systems. Lessons learnt from this development have paved the ways not only for developing the enhanced system for future aircrafts, but also evolving the several improved procedures and technologies for all associated aspects. A quest for good understanding of the aircraft systems by the designers and flight test community plays a significant role in providing the matured systems and in turn the aircraft.

Acknowledgments

The authors are grateful to Director General (ADA) & Director (ADA), GM(ARDC), and TD(IFCS) for the support and encouragement provided as well for permitting this work to be published. Thanks to the members from the National CLAW Team (NCT), all stake holders of the Integrated Flight Control System (IFCS) of Tejas from ADA, NAL, ADE, HAL, NFTC, and RCMA for all their support, co-operation, and participation in healthy deliberations for the associated activities required for design and development. All their efforts and contributions are highly acknowledged here.

References

[1] Shyam Chetty, Girish Deodhare, B.B. Misra: "Design, Development and Flight Testing of Control Laws for the Indian Light Combat Aircraft", AIAA Guidance, Navigation and Control Conference, Monterey, CA, August 2002

[2] Ambalal V. Patel, Vijay V. Patel, Girish S. Deodhare, and Shyam Chetty, "*Clearance of Flight-Control-System Software with Hardware-in-Loop Test Platform*", *AIAA Journal of Aircraft, Vol. 51, No. 3, May-June 2014,* DOI 10.2514/1.C032404.

[3] Ambalal V. Patel, "*Functional Level Data Acquisition Requirement Specification Formulation for Embedded Systems: Challenges, Experiences and Guidelines*", International Journal of Engineering Research and Application, ISSN: 2248-9622, Vol. 7, Issue 10, (Part -5) October 2017, pp.75-84, DOI: 10.9790/9622-0710057584

[4] Y.V. Jeppu, K Karunakar and P.S. Subramanyam, "Testing Safety Critical Ada Code Using Non Real Time Testing", Reliable Software Technologies ADA-Europe 2003, edited by Jean-Pierre Rosen and A Strohmeier, Lecture Notes in Computer Science, 2655, pp 382-393.

[5] D. Sitarama Raju, Girish Dixit, P.S. Subramanyam, and B. Subba Reddy, "LCA integrated flight control system evaluation on iron bird," Workshop on Control Systems for Defence Applications (CONSYS-2002), pp. 61-65, February 2002, held at RCI, Hyderabad, India.

[6] Nancy G Leveson, "The Role of Software in Spacecraft Accidents", AIAA Journal of Spacecrafts and Rockets, Vol 41, No 4, pp 564-575, July 2004.

[7] Roger W Pratt, Flight Control Systems, Progress in Astronautics and Aeronautics, Vol. 184, AIAA and IEE, 2000

[8] T. Smith, "Ground and flight testing of digital fight control systems – chapter 6" of "Flight Control Systems" edited by Roger W. Pratt, Volume 184, Progress in astronautics and aeronautics, AIAA, 2000

[9] Vijay V. Patel, Girish S. Deodhare, and Shyam Chetty, "*Near Real Time Stability Margin Estimation From Piloted 3-2-1-1 Inputs*", , *AIAA Aircraft Technology Integration and Operations (ATIO2002) Technical Forum,* Los Angeles, CA, October 2002.

[10] Vijay V. Patel, Girish Deodhare and Shyam Chetty, "*Accelerated Flight Envelope Expansion Using Near Real Time Stability Margin Estimation*", Journal of Aerospace Sciences and Technologies, vol. 58, No. 4, pp. 274-286, November 2006.

[11] William R. Gray, III (AF) Chief Test Pilot, USAF Test Pilot School &James E. Brown, III (F) Lead Test Pilot, F-22 Combined Test Force, SETP, "Time Safety Margin : A Generalized Method For Dive Safety Planning", Society of Experimental Test Pilots Symposium Proceedings, 2010.

[12] Flying Qualities of Piloted Aircraft, MIL-HDBK-1797 dated 19th December, 1997

[13] R. P. G. Collinson, "Introduction to Avionics," Chapman & Hall, First Edition 1996.

[14] Functional Requirements of Fail Op / Fail Safe Air Data System for Air Data Computers, NCT/LCA/CLAW/005, Issue 2, Revision Nil, dated 9th January 2015.

[15] Functional Requirements of Fail Op / Fail Safe Air Data System for Air Data Computers, NCT/LCA/CLAW/005, Issue 6, Revision C, dated 9th June 2021

[16] Anup Goyal, Ambalal V. Patel, Amitabh Saraf, and A. A. Pashilkar, "Analysis of Effect of Wake Vortices on Air Data Sensors", p-141, Proceedings of SAROD 2011 conference held at Bangalore during November 2011.

[17] Changes to be incorporated in the ADS FRD to account for the effects of In Flight Fixed Refueling Probe and inputs received based on the LCA flight testing, NCT/TM/2886 dated 5th February 2016

[18] Analysis of the Flow angularity and Cp data at AOA Vane and SADP location for LCA Mk1 (AF) with In Flight Fixed Refueling Probe provided by CFD team for AOSS = [-5, 0, 5] deg, NCT/TM/2975 dated 31st March 2017

[19] Correction coefficients for computations of corrected static pressures from Nose Probe using flow angle pressure measurements (Pa1, Pa2, Pb1, Pb2) obtained from LCA flight data, NCT/TM/3083 dated 5th January 2018.

[20] Changes in CWP Indications and Warning Captions, ADA/LCA/IV&V/706/2012 dated 5th December 2012

[21] Edward A. Haering, Jr., "*Airdata Measurement and Calibration*", NASA TM-104316, December 1995

[22] Saraf A, Kumaresan G, "*Flight Calibration of Flow Angularity Sensors on TEJAS Using Advanced Parameter Estimation Techniques"*, IISc Centenary International Conf & Exh. on Aero Engg (ICEAE), May 18-22, 2009.

[23] Saraf, A., Viswanathan S., "Flight testing and calibration of TEJAS airdata system", *International Flight Test Seminar*, Aircraft and Systems Testing Establishment, Bangalore, 14-15 Feb 2008

[24] Amitabh Saraf, G Kumaresan, "*Flight Calibration of Flow Angularity Sensors on TEJAS Using Advanced Parameter Estimation Techniques"*, International Journal of Aerospace Innovations, Vol 2, No 1&2,pp 57-67, April 2010.

[25] William Kuhlemeier, Lockheed Martin, "A Better Way to Monitor Flight Tests in the Control Room: Limits-Based Displays", 57th Annual Symposium-SETP, 2013

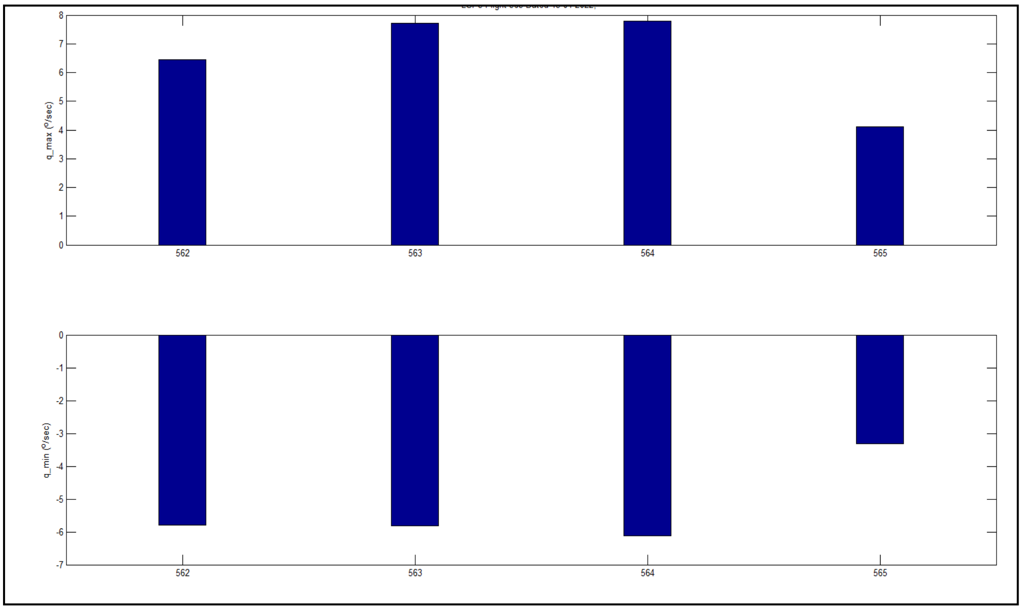

Figure 1: Trend plot of maximum pitch rate during take-off roll

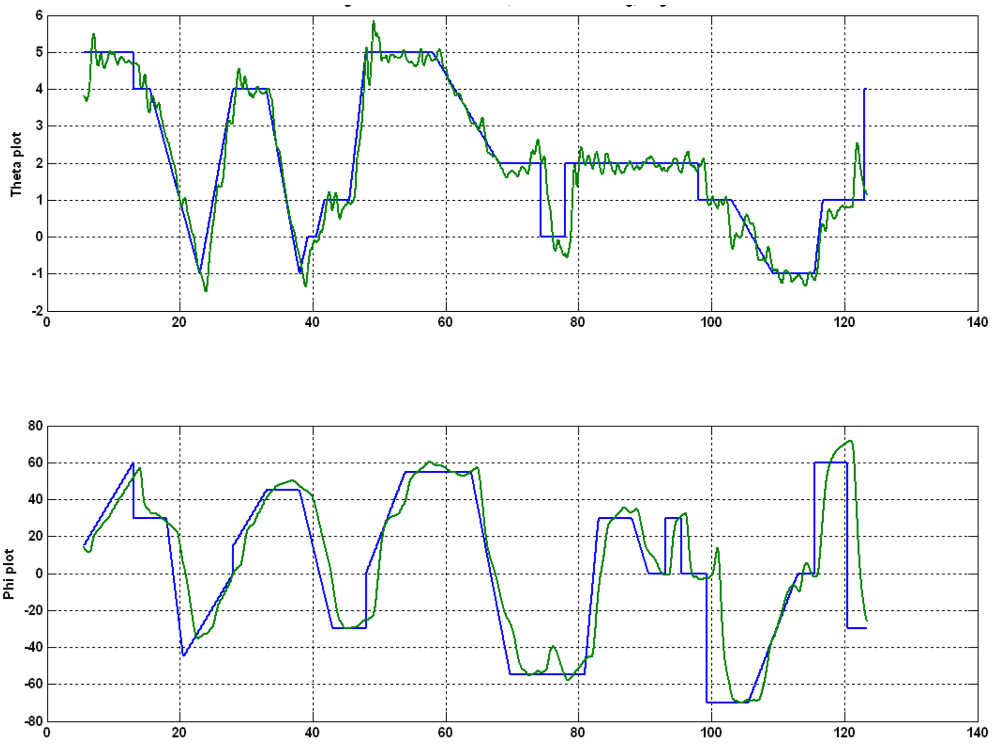

Figure 2: Pitch (Theta) and Roll (Phi) angles during tracking task

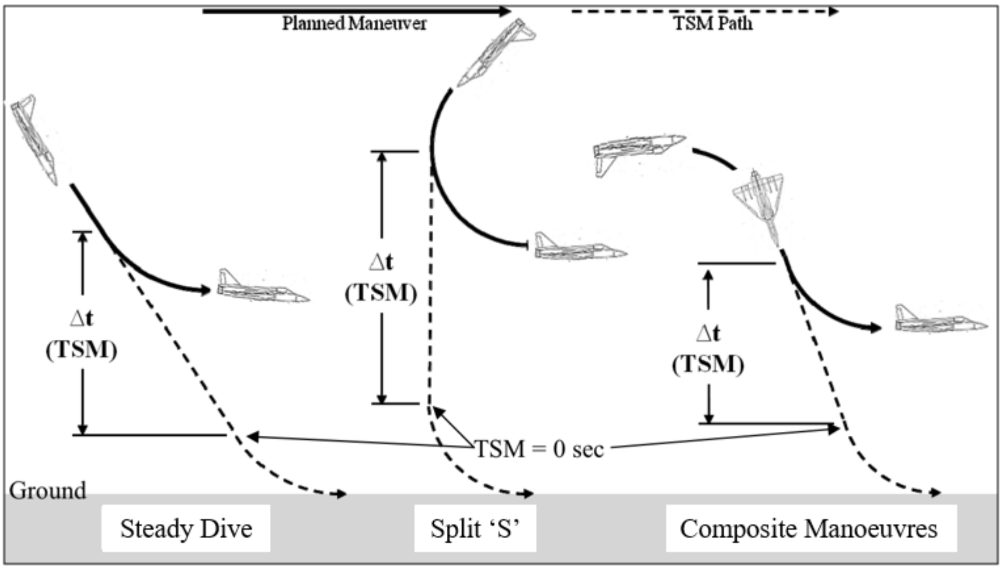

Figure 3: Examples for TSM and worst case vector in the planned manoeuvres [3]

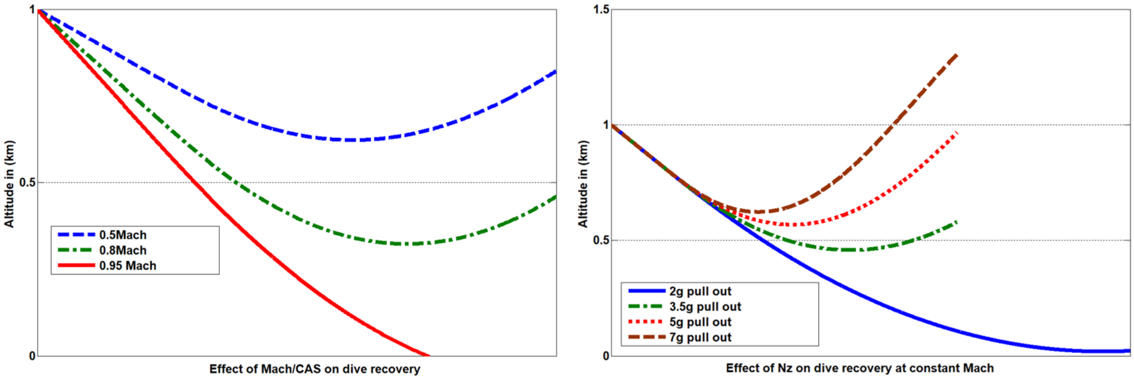

Figure 4: Effect of Nz available, speed during pull-out on the time safety margin

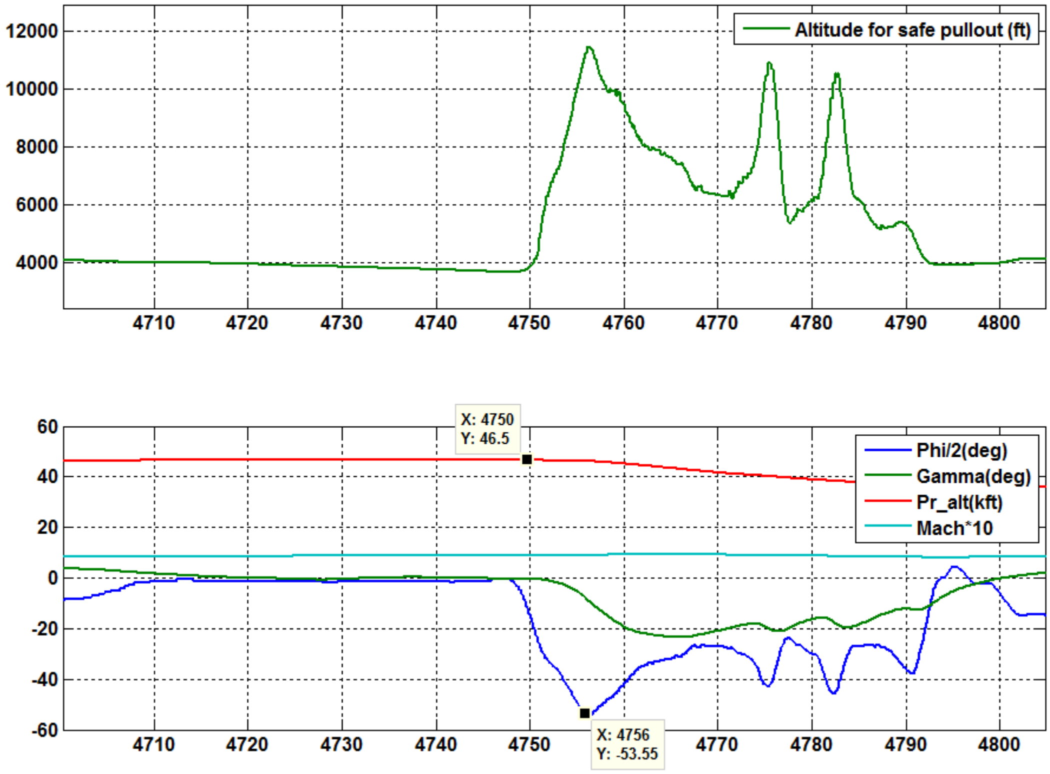

Figure-5: Flight profile along with the altitude for safe pull-out for one representative sortie.