Challenges in Development and Flight Testing of Air-to-Air Refuelling on “Tejas” Light Combat Aircraft

Group Captain Malteesh Prabhu (Retd)
Group Director (Flight Test Engineering)
National Flight Test Centre, Aeronautical Development Agency, India

1.0 ABSTRACT

The Indian Light Combat Aircraft (LCA) is integrated with a Probe and Drogue refuelling system for Air-to-Air Refuelling. The probe was integrated late in the development phase of the aircraft, well after Initial Operational Capability was achieved. Being a small aircraft, there were challenges in design of the fuel system for Air-to-Air refuelling. The digital flight control and air data systems also needed modifications to ensure safe refuelling operations.

This paper traces the development of air-to-air refuelling system on the LCA. It briefly presents the challenges faced, system modifications, ground and flight tests carried out for successful certification of the system. A technique for quantification of drogue tracking performance using video processing was developed by the National Flight Test Centre (NFTC) and successfully used during these trials. Those results are presented. Differences in HQ ratings were noticed between the commonly used drogue tracking and AAR hook up tasks. Possible reasons for the same are also discussed.

2.0 ACRONYMS AND ABBREVIATIONS

AAR	Air to Air Refuelling
ADP	Air Data Probe
AOA	Angle of Attack
AOSS	Angle of Side Slip
APC	Aircraft Pilot Coupling
AUW	All Up Weight
CAS	Calibrated Air Speed
CFD	Computational Fluid Dynamics
CHR	Cooper Harper Rating
CLAW	Control Law
C of G	Centre of Gravity
Config	Configuration
ERV	Electric Refuelling Valve
FCS	Flight Control System
FOC	Final Operational Capability
FPA	Flight Path Angle
FTI	Flight Test Instrumentation
HL	High Level
HQ	Handling Qualities
HUD	Head Up Display
IOC	Initial Operational Capability

LCA	Light Combat Aircraft
LG	Landing Gear
NFTC	National Flight Test Centre
NRV	Non Return Valve
PEC	Pressure Error Correction
PIO	Pilot In-the-loop Oscillations
PStick	Pitch Stick
PSD	Power Spectral Density
RStick	Roll Stick
RTS	Real Time Simulator
SHA	Ssfety and Hazard Analysis
SOP	Standard of Preparation
SOV	Shut Off Valve
SRV	Surge Relief Valve
Thr	Throttle

3.0 INTRODUCTION

The LCA “Tejas” is an indigenously designed, single engine, tailless, delta wing aircraft with a longitudinally unstable aerodynamic configuration. It has a single seat fighter version and a twin seat trainer version. The trainer is fully capable of undertaking all operational missions as the fighter. Both versions can carry an external load of 4,000 kg including Beyond Visual Range and Close Combat missiles, iron bombs and smart weapons. Initial Operational Capability (IOC) of Tejas fighter was achieved in 2013 and Final Operational Capability (FOC) in 2019. A probe-and-drogue type of Air-to-Air Refuelling (AAR) system was part of FOC Standard of Preparation (SOP) and therefore was integrated quite late into the programme. This included a fixed probe installed on the front fuselage slightly on starboard side, with a clear line of sight between pilot’s station and probe tip. The probe is presently under integration on the twin seat version.

Integration of the AAR system was completed in 2018. Two phases of flight tests followed, in Sep 18 and Oct 21 respectively, to prove the system within the entire flight envelope, in various configurations, and against both IL-78 and Su-30 tanker pods. This paper focusses mainly on Phase-2 of the trials, which was extensive and all encompassing.

3.1 Fuel System Description

Tejas aircraft had two integral fuselage tanks and one tank in each wing (Fig 1). Tanks F1 and F2 were connected internally and were essentially one F1/F2 “collector” tank. Apart from these, the aircraft had five wet stations which could carry drop tanks, four under the wings and one under the fuselage. The F1 bottom tank contained the fuel booster pumps that fed the engine and also functioned as inverted flight compartment. F1 top tank contained float and transfer valves needed to sequence fuel transfer to F1/F2 from the other tanks. Fuel transfer from all tanks to the collector tank was effected using pressurised air from the Environmental Control System. F1/F2 was an unpressurised tank.

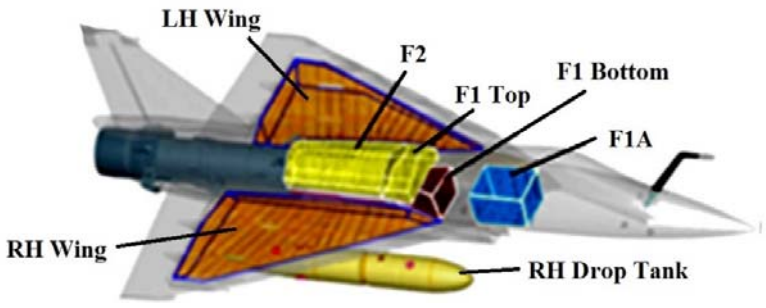


Fig-1 Location of Fuel Tanks

3.2 Flight Control System Description

The aircraft featured a quadruplex digital Flight Control System (FCS). It had two pairs of split elevons on the wing for pitch and roll control and a fin mounted rudder for directional control. The control laws in longitudinal axis used a blend of normal acceleration (n_z), pitch rate, angle of attack and airspeed feedbacks. Pitch stick deflection essentially demanded n_z at high speeds and Angle of Attack (AOA) at low speeds. In lateral axis, roll rate was demanded.

The aircraft had three Air Data Probes (ADP) for measurement of static pressure, total pressure and pressure-based AOA and AOSS. These probes were mounted on the nose tip and on either side of the cockpit. The aircraft also had two AOA vanes, located near the side ADP, and an AOSS vane located under the nose. In normal state, a weighted average of all three ADPs were used to derive altitude and airspeed/ Mach number. Similarly, an average of the two AOA vane outputs was used to derive AOA. Redundancy management logics allowed selection of the best sensor in case of failures.

4.0 CHALLENGES FACED

Challenges in design, development and flight testing of a modern fighter are many, even to the most experienced design houses. Some of the challenges faced by the Tejas program, related to development of AAR capability are highlighted below.

4.1 Lack of Previous Data or Experience

Tejas was a 4th gen fighter incorporating many new technologies. The previous in-house design was the HF24 “Marut”, which flew its maiden flight in 1962 and was in service with the Indian Air Force until 1983. There was a four-decade gap between design of Marut and Tejas. Thus, the expertise, technical know-how and database needed to design and develop a state of the art, software intensive, digital fly-by-wire aircraft with composite wings and all-glass cockpit. was virtually non-existent when the Tejas program was launched. This meant that all learning had to be done from scratch and by the hard way. The journey was long and arduous. While the Indian Armed Forces operated several aircraft with Air to Air refuelling capability, the country had no experience in designing such a system from the drawing board.

4.2 Design for Small Volume

As the name suggests, LCA was designed to be a small and light-weight aircraft. This brought its own set of challenges in locating, shaping and sizing of fuel tanks. The wing tanks were very thin and flat, while the collector tank was of a complex shape, fitting into the space left in the forward/ centre fuselage above the air intakes and in the aircraft spine region. The F1 top tank ended up being a long and shallow tank with a semi-circular upper cross section, and a very small depth (about 10 cm). Due to this, the float valves for various tanks (Wing / F1A tank, Wing and Fuselage drop tanks) had to be mounted with a vertical separation of just 1-2 cm from each other. Optimisation of these locations for fuel transfer took a lot of time.

The small volume of Tejas also meant that space was restricted for laying out pipelines. The aircraft was initially built for gravity refuelling. The service tank was unpressurised, to keep structural weight low, since fuel transfer was by differential pressure. If the collector tank was pressurised, all other tanks had to be pressurised to higher values, which would have a direct impact on structural weight. Since it was unpressurised, any pressure build-up in this tank during refuelling had to be relieved immediately. When pressure refuelling was integrated a few years after first flight, there were many issues related to over pressure and overflow. The existing vent lines were found inadequate and some of the vent lines and ports had to be replaced with larger sized ones to prevent pressure build up. The vent holes within wing tank spars were small and were below the High Level (HL) switch at some attitudes, causing blocking of vent lines before the tank was full. Resizing the venting system was a challenge because most of the free space was already taken. By the time an implementable design solution was in place, most of the prototype aircraft had already been produced. Finally, pressure refuelling capability could be built only on the twelfth and last prototype, more than 12 years after first flight.

4.3 Absence of Fuel Test Rig for AAR

Development aircraft need test rigs and simulators for testing systems on ground before getting airborne. The design agency had these rigs and simulators, but some of them were not capable of simulating all the conditions experienced in air.

In the case of AAR, a fuel test rig that replicated the aircraft fuel system without the AAR probe was available. The system could be rotated to the desired pitch and bank attitudes and normal pressure refuelling and transfer carried out in that attitude. But the dynamic conditions experienced in flight, like acceleration and fuel slosh effects, which significantly affected system performance, could not be reproduced. Although these were modelled and simulated on a computer, simulation was still far from perfect. During the trials, some problems surfaced that did not show up in simulation, but when the same was run after flight tests, it could be replicated. Clearly, we had missed a few test cases before getting airborne.

4.4 Lack of Realistic Simulation for HQ Assessment

A high-fidelity Real Time Simulator (RTS) was available for control law development, which simulated the Tejas FCS and all store configurations accurately. However, there were aspects where the simulator did not truly replicate the AAR environment, like tanker wake, downwash and jet efflux effects, drogue motions, hose reeling in/out after engagement, fuel transfer sequence with drop tanks and resulting C of G shift and contact of drogue with probe. Initially, a physical probe was located on the nose cone of the simulator, that resulted in the virtual drogue and physical probe being a distance apart at contact. The drogue was seen to fly away past the probe during contact. A virtual probe was then implemented, which was better, but was still not realistic.

Normally, most HQ tests, including failure cases and simulated atmospheric turbulence were conducted on RTS and only the critical cases were evaluated in flight.

but due to above limitations, this was not possible for AAR tasks and most of the HQ evaluations had to be conducted through flight tests only. As sufficient turbulence was not encountered during flight tests, ability to successfully engage probe with drogue under turbulent conditions likely to be encountered during operational employment could not also be assessed adequately. Another significant limitation was that HQ test manoeuvres could not be practiced adequately and fine-tuned before flight tests. Notwithstanding these limitations, RTS was used still to the best extent possible.

4.5 Risk Management

Probe-to-drogue AAR is widely recognized as one of the most demanding, high-gain pilot tasks. Risks during AAR include collision with tanker due to Aircraft Pilot Coupling (APC), damage to one or more air data sensors due to impact with drogue, failure of fuel system valves or high level switches resulting in no refuelling or excessive refuelling / overpressure leading to fuel overflow and fire risk, shearing of weak link of AAR probe due to overload caused by adverse hose reel response, excessive closure and limited deceleration capability or adverse flying qualities / PIO, damaged basket, hose whip or basket slap, and engine stall /shutdown due to fuel spray or drogue wake disturbances. An extensive Safety and Hazard Analysis (SHA) was performed and risk mitigation measures were incorporated either in design or in procedures. Risk mitigations included more pre-contact flight, confirmation of deceleration capability with targeted closure rates, no flight in moderate to severe turbulence, limiting maximum closure rates to 5 knots, etc.

A freak case of AAR mode getting disengaged automatically and not displayed to the test crew as an alert occurred during flight trials. This was because at that instant, a benign air data failure was posted which, by mistake, had been assigned a higher priority and was displayed instead. It had not been envisaged that AAR mode might get disengaged during refuelling phase. In this incident, an excessive error in CAS occurred during refuelling, which the FCS interpreted as “outside the refuelling envelope” and disengaged AAR mode. Therefore, a benign air data failure masked a critical failure and the pilot continued to remain in contact and refuel with AAR mode disconnected. In another instance, the AAR mode got disengaged during approach to contact and the alert was displayed in cockpit, but this was not noticed by the pilot. Coincidentally, there was no R/T communication with telemetry at that time, resulting in the contact being made with AAR mode OFF. The SHA did not capture these cases. Identifying all risks is a very important part of aircraft development. The vast body of knowledge available with SFTE and SETP must be utilised to build up the hazard database.

4.6 Optimising Flight Tests

The refuelling tankers with the IAF were heavily committed for operational tasks. Availability of tanker for extended duration on any given day and for several days in a test campaign was a difficult proposition. Optimisation of tests and test configurations was therefore a challenge. In Handling Qualities (HQ) testing, a minimum number of tests are recommended at each test condition and by at least three evaluation pilots before arriving at the HQ rating. Ten store configurations were identified for flight testing - one clean, five configurations with external drop tanks and the remaining were Max AUW, max asymmetry, forward and rear C of G configurations. Of these, some were intended for assessment of HQ and some were for evaluation of the fuel system, but tanker effort was not available for all tests. For example, even though it was not felt necessary to test 1200L and 800L drop tanks at the same station for HQ, it was necessary for the fuel system. Due to the limited tanker effort available, the need to restrict the number of engagements in one test flight from pilot fatigue considerations and the large number of configurations and flight conditions to be tested, each test condition could not be evaluated sufficiently. As a result, results across test conditions had to be combined together and presented in some cases. Extrapolation of results to other test conditions was inevitable. Although the initial intent was to use the highest gain pilot among the three for non-repeated tests, it was not always possible. This was a significant limitation during the test campaign.

4.7 Test Crew Training for HQ Testing

Each prototype is usually built to a different SOP to perform different tasks, hence having up-to-date knowledge of hardware and software SOP of each prototype and configurations cleared for flight testing is a challenge in itself. The National Flight Test Centre (NFTC) typically has a handful of test pilots and flight test engineers on its strength, most of them deputed from the Indian Air Force or Navy for 3 to 4 years. Since the same set of test crew fly all prototype aircraft, it becomes critical to ensure that correct procedures, including emergencies, and aircraft operating limitations are briefed and understood before each test flight. Periodic rotation of test crew adds additional burden to this process. Prototype flight publications need to keep pace with changing SOPs, which often does not happen. These are significant risk areas, particularly when multiple aircraft programs are handled by the same crew.

Insofar as AAR was concerned, the test crew needed adequate proficiency and currency in Handling Qualities test techniques and procedures. HQ evaluation, as opposed to Systems testing, requires test crew to have a different frame of mind which can only come with a lot of practice. This called for additional training on the RTS. Unfortunately, RTS was not co-located with NFTC and getting adequate training hours on the simulator was a challenge, particularly because the limited test crew available with NFTC were involved in Design, Development and Testing of multiple concurrent programs. A total of five pilots took part in the AAR flight tests – three in the first phase and three in the second. Two pilots who participated in Phase-1 evaluation were not available for the second phase and were replaced by two new pilots, who fortunately had previous AAR experience.

5.0 AERODYNAMIC STUDIES

Computational Fluid Dynamics (CFD) studies showed that the effect of AAR probe was negligible on total and static pressure measurements from the nose and the side ADPs in subsonic flight, but all pressure measurements from side ADPs were significantly affected by the shocks emanating from the probe in transonic and supersonic regimes.

Study of flow field around IL78 and Su-30 and Tejas at various positions behind the tanker was performed in order to see the effect of tanker wake. The tanker aircraft with refuelling pod, hose and drogue were modelled. IL-78 engines were assumed to be in shutdown state, but Su-30 engine jet was modelled. Drogue was considered to be of the same size on IL-78 and Su-30.

The purpose of the analysis was three-fold: (1) to identify hazard regions behind the tanker which Tejas should keep away from (2) to determine the forces and moments experienced by Tejas at different locations, and (3) to assess effect of flow field on Tejas engine and air data sensors.

The wing pods of IL-78 were considered to be more critical during simulation as fuselage pod was further below the wing wake, and hence safer. Studies showed that the wing tip vortex wake of both tankers was well clear of Tejas during approach to contact but the Tejas experienced downwash of tanker which led to reduction in coefficients of lift, drag and pitching moment. However, the elevon and rudder deflections required to trim the aircraft were small and there was no controllability problem at any position.

Hazard boxes were defined for both aircraft by determining the position of vortex core at specific locations behind tanker and the “radius of influence” of the vortex in that plane. The region of influence was estimated by determining the distance where the induced velocity reduced to 10% of the peak value in vortex core. It was seen that LCA Tejas lay outside the edges of the hazard box (Fig 2) in both lateral and vertical directions during simulated approach to contact and the effect of wake on aircraft stability was minimal.

The effect of drogue on LCA intake, side air data probes and overall flow field were analysed. Studies showed that air data parameters measured by the ADPs were significantly affected by the presence of drogue. After contact was made, the nose ADP was relatively free of disturbances, while the side ADPs and AOA vanes continued to be affected by the drogue. The port and starboard vanes were found to measure different local AOA in the presence AAR probe. The local AOA measured by starboard vane differed significantly from the port vane when drogue was attached, which was expected. The difference was much lesser at pre-contact position.

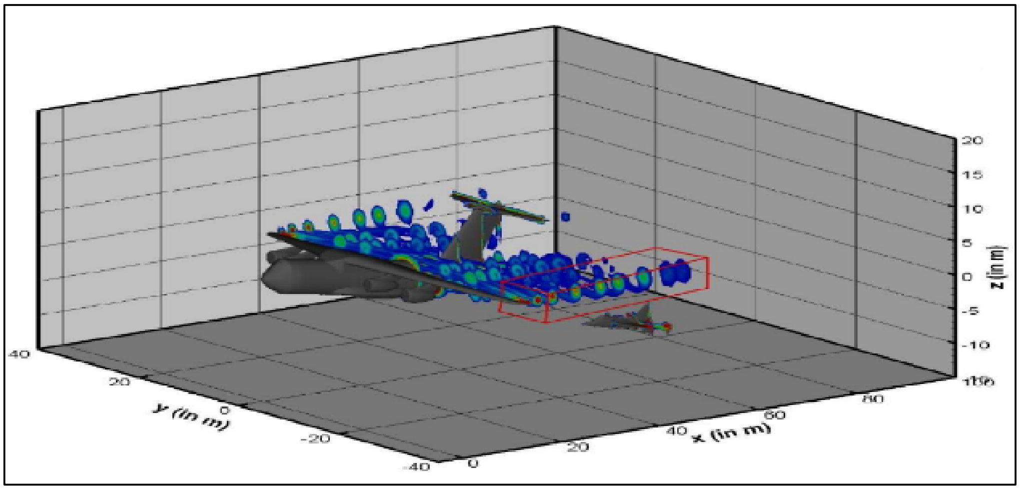


Fig 3. Wake Vortex Pattern and Hazard Box behind IL-78 Tanker

6.0 SYSTEM MODIFICATIONS

6.1 Modifications to Air Data System

Based on CFD studies, air data selection logics and control laws had to be modified during AAR. Changes included incorporation of different Position Error Corrections (PEC) to side ADPs with AARP installed and not installed. No additional corrections were required for nose probe with probe present. PEC was further fine-tuned based on flight tests. Failure detection and sensor redundancy management algorithms during Air-to-Air Refuelling phase were modified to reduce the weightage given to or discard the affected sensors. Total pressure from side ADPs were usable after corrections in transonic and supersonic flight conditions, but corrections to static pressures were not possible. Failure detection thresholds required on static pressures were also found to be very large. This made it difficult to design a good failure detection and selection algorithm and it was decided to ignore the side probe static pressures in transonic and supersonic flight with AARP installed. Instead, two additional static pressure sources available in nose probe were used as redundant sources, which had not been used before.

Wake encounter protection features were also activated during AAR. Whenever rate limits were hit by AOA and AOSS vanes (as expected during any wake encounter), alternative AOA and AOSS signals were computed using INS data & aircraft angular rates.

6.2 Modifications to Flight Control System

The AAR mode was engaged manually using a cockpit switch before approaching the tanker. The switch had three positions – OFF, DRY and WET. FCS configuration was identical for DRY and WET positions; the difference being only in the fuel system. In WET position, the tanks were depressurised and fuel valves were operated for refuelling purposes. DRY position was only meant for practicing contacts without refuelling.

When AAR mode was engaged, existing AOA from vanes was disconnected and AOA derived from n_z was used for feedback due to errors in vane AOA. Further, pitch stick authority was reduced, AOA boundary limiting features were disabled and some changes were made to improve flight path tracking. Control law Gains were frozen at their last good value and advanced FCS automatic recovery features like Critical Altitude Recovery, Automatic Low Speed Recovery and Disorientation Recovery functions were disabled to prevent any unintended aircraft response.

6.3 Modifications to Aircraft Structure and Fuel System

The aircraft structure was reinforced in the nose region to withstand static and dynamic loads during drogue engagement. Electro-static discharge protection required bonding between the probe and aircraft structure and this was incorporated. Good conductivity at bonding locations had to be ensured, since LCA was largely made up of composite structures. As part of Flight Test Instrumentation (FTI), strain guages were installed at base of the probe to record compression, tension and bending moments applied to the probe.

To enable Air to Air Refuelling, the fuel system had to be modified. Tank pressurisation was automatically selected OFF using an electric depressurization valve during refuelling. During pressure refuelling tests, excessive pressure build up was noticed in the system due to poor venting; which necessitated resizing of vent lines. However, during the first phase of flight tests, even this was found inadequate. Other modifications included installation of High Level (HL) switches in all tanks, including drop tanks, whose location was optimized based on pitch attitude. Redundant fuel gauging probes were installed in drop tanks after the first phase of trials to cater for HL switch failures and prevent excessive pressure build up and structural damage. Software logics for ensuring correct refuelling sequence through Electric Refuelling Valves (ERV) were also incorporated.

In order to prevent propagation of flame caused by fuel vapour in the probe ignited by electro static discharge during contact, normal flying or in a lightning strike, a Shut Off

Valve (SOV) was introduced downstream of the probe. This valve was opened only during refuelling and was closed in all other flight phases.

7.0 GROUND AND FLIGHT TESTS

7.1 HQ Evaluation on Real Time Simulator

Evaluation of the FCS and aircraft HQ was initially conducted on the RTS. Within limitations of the RTS covered earlier, simulated contacts were performed in frozen and standby gains in various configurations, failure states, CG positions and turbulence. Overall, the HQ were assessed as good. The pilot compensation required for engagement was higher at high and low CAS as compared to mid CAS. Based on RTS tests, the flight test configurations were decided and the sequence of flight tests arrived at for each configuration – start from mid altitude, proceed to high altitude and finally low altitude. At each altitude, proceed from mid CAS to low CAS and then high CAS. However, in view of optimisation requirements caused by lack of tanker effort, this sequence could not always be followed.

7.2 Ground Refuelling Tests

A test set up was fabricated to refuel through the AAR probe from a ground refuelling vehicle (Fig 3). Tests focussed on verifying refuellable capacity of tanks, measurement of fuel pressures under different conditions and various failure cases. The aircraft was positioned at attitudes up to 8 deg pitch and 3 deg bank by raising the nose & one main wheel. Refuelling pressure of 50-60 psi and a flow rate of 350 to 720 lpm were maintained, which simulated AAR conditions.

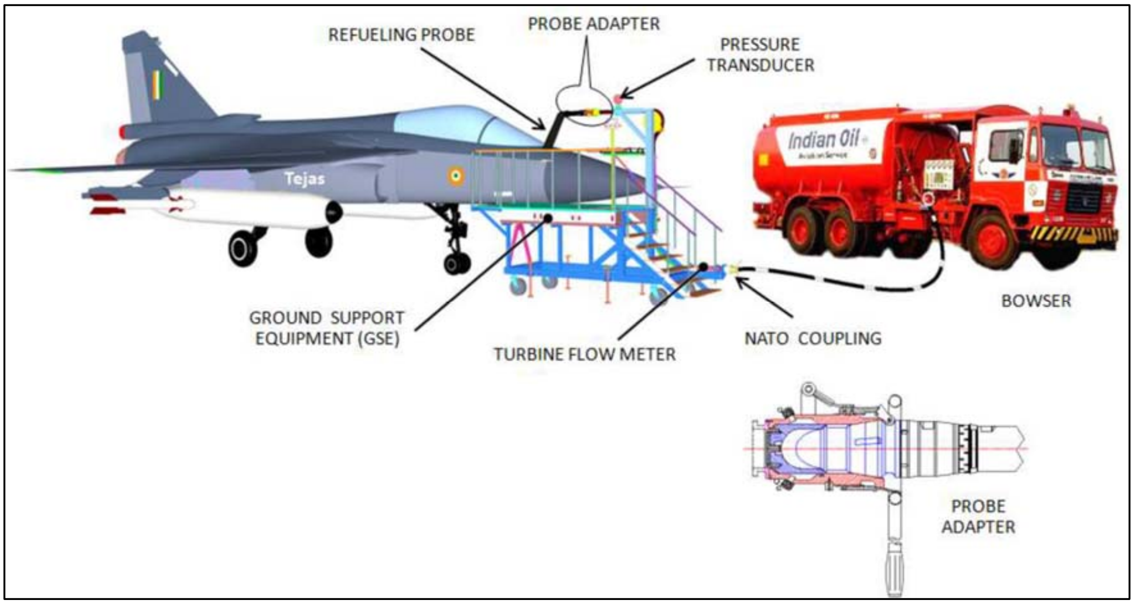


Fig 3. Ground Test Setup

After successful completion of the above tests, refuelling from an IL78 tanker was carried out on ground at max pressure and flow rates. Tejas was positioned at 5 deg pitch attitude. During a refuelling test with pressurisation ON (as a failure case of tank pressurisation not going OFF), excessive pressure rise was seen in drop tanks. In a few cases, during top up, surge pressures recorded were in excess of structural limits.

Addressing these issues required modification to the venting system and relocation of some sensors. However, since the test aircraft had already ferried to the trial venue, the first phase of tests was completed with adequate precaution, ensuring that drop tanks were not topped up and refuelling pressures were built up slowly to the peak value.

7.3 Flight Test Objectives

The primary flight test objectives were:

- Verify Position Error Correction (PEC) with AAR probe throughout the cleared flight envelope
- Verify absence of air data failures with AAR probe
- Evaluate Handling Qualities during AAR
- Verify probe loads during engagement
- Assess fuel system performance and cockpit indications during “wet” contacts
- Develop procedures for fleet operations

7.4 Envelope Expansion with AAR Probe

After integration of AARP, flight envelope expansion was performed through air data calibration and aero data validation tests. During initial flight tests, in spite of CFD predictions and corrections based on it, air data failures occurred in supersonic flight due to exceedance of mis-track threshold limits among the ADPs. These limits had to be increased based on extrapolated flight test results. Even these failure thresholds were found inadequate as seen during flight tests with Su-30 drogue during the second phase of flight tests, where normalised static pressure corrections were found to be dependent on Mach number, which was not seen with Il-78 drogue. This resulted in air data failures during high-speed engagements with Su-30 tanker.

7.5 Wake Survey behind Tanker

Refuelling flight tests started with conduct of a wake survey behind the tanker to validate the hazard box predicted using CFD studies and also to identify any issues regarding air data, aircraft response and controllability. This involved positioning the Tejas at specific locations in 3D space during approach to refuelling. At each location, the pilot was required to move the aircraft up/down and laterally left/ right by a few metres and assess effect on ac response, controllability and effect on air data parameters. This was done against both IL78 and Su-30, initially without the drogue deployed and then with it deployed. These tests largely validated CFD predictions.

7.6 Drogue Tracking HQ Tests

Assessment of HQ was conducted using drogue tracking tests and AAR hookup tasks. Drogue tracking task required the pilot to track the centre of the drogue with a fixed reticle on HUD. A tracking symbol was planned, but could not be implemented in the mission computer due to other constraints. As a result, tracking was performed with reference to a point on the nearest “pitch” bar (Flight Path Angle (FPA) indicator). The pilot had to track the drogue at a fixed distance from probe tip, for a period of at least 20 s and assign HQR. Performance objectives were as follows: -

- Desired Performance: Longitudinal position keeping within ±2 feet and tracking accuracy within half radius of drogue.

- Adequate Performance: Longitudinal position keeping within ±4 feet and tracking accuracy within radius of drogue

An algorithm to quantify the tracking error and drogue position by processing HUD video was developed in house (Ref 1). This was used to validate tracking performance against HQ requirements. Tracking accuracy was evaluated in terms of deviation between a fixed point on HUD and centre of drogue at every instant. Deviation and diameter of the drogue were both computed at each instant. Finally, the deviation was overplotted against drogue diameter for the duration of the test point.

Typical plots of control deflections (stick and throttle), aircraft attitudes and Power Spectral Densities (PSD) of control movements during the test are shown in Fig 4. PSD was used as a measure of pilot compensation. Based on correlation with pilot comments, PSD of more than 15 dB/Hz and frequency band of 2Hz or more were considered as “considerable” or higher compensation.

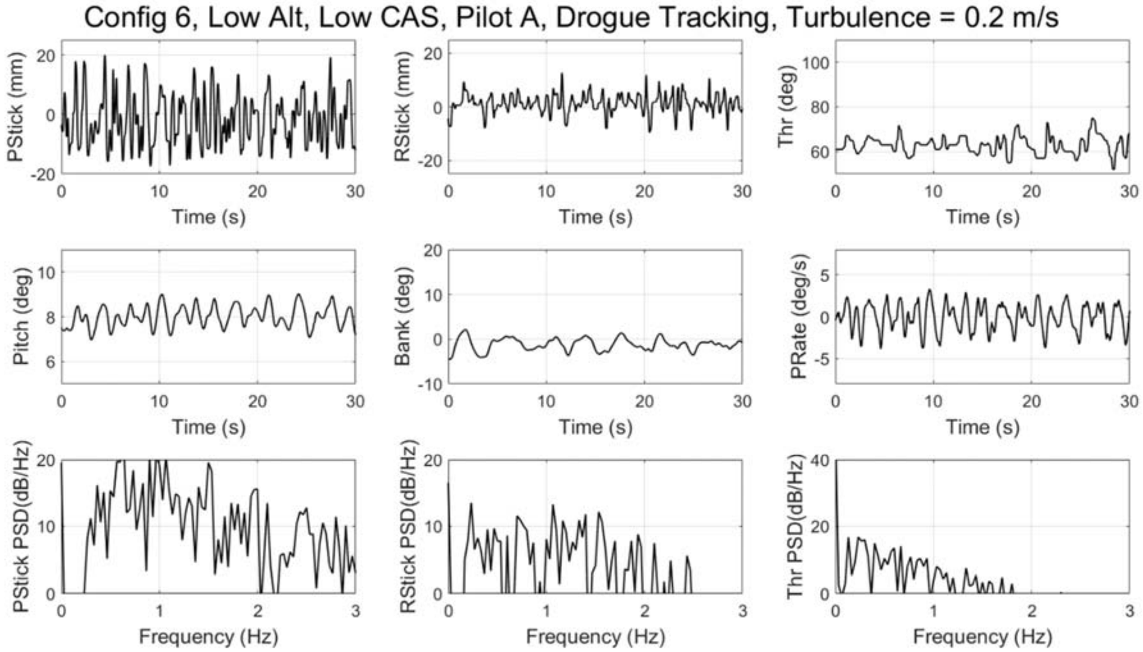
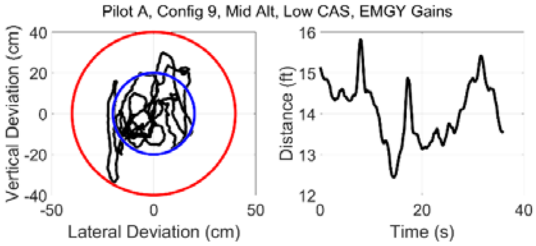
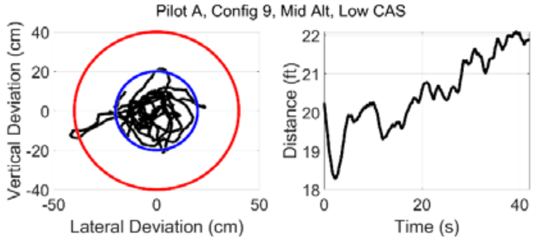
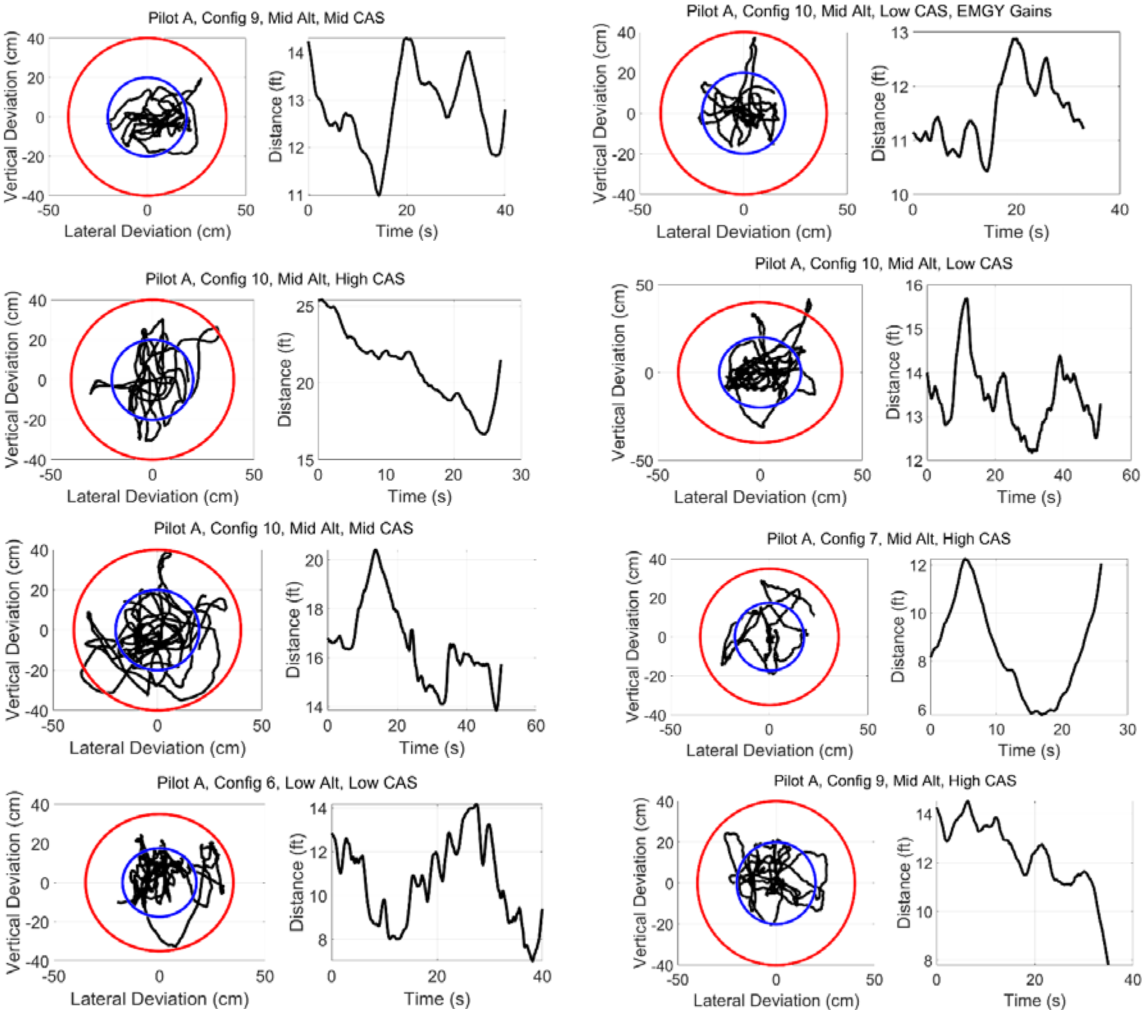


Fig 4. Typical Control Movements during Drogue Tracking

Typical tracking performance plots are shown in Fig 5. The outer circle depicts drogue diameter (for adequate performance) and inner circle depicts half the diameter (for desired performance).






Pilot A, Config 9, Mid Alt, Mid CAS

Pilot A, Config 10, Mid Alt, Low CAS, EMGY Gains

Pilot A, Config 10, Mid Alt, High CAS

Pilot A, Config 10, Mid Alt, Low CAS

Pilot A, Config 10, Mid Alt, Mid CAS

Pilot A, Config 7, Mid Alt, High CAS

Pilot A, Config 6, Low Alt, Low CAS

Pilot A, Config 9, Mid Alt, High CAS

Fig 5. Drogue Tracking Performance

Although no clear trends in terms of configuration or pilot were observed, a significant variation in use of controls during the tests was seen. In some tests, nearly 80% forward pitch stick was used while in other cases significantly lower inputs were used. Similarly, nearly 50% roll stick on either side was used for some tests and much lower for some others.

In general, the drogue could be tracked within its diameter, but not within half-diameter, i.e., desired performance objective was not met in many cases. HQ was assessed as Level 2 in all tests. Surprisingly this was at variance with HQ during AAR hook up tasks, where Level-1 HQ was consistently reported, as covered in the next section.

7.6 Pilot Gain

The control inputs and their PSD for all drogue tracking test points are plotted in Fig 6 for the three pilots – the first plot for A, second for B and third for C. Going by the PSD of control inputs and their frequency, Pilot A was clearly “high gain” and Pilot C was “low gain”. Pilot B was in between.

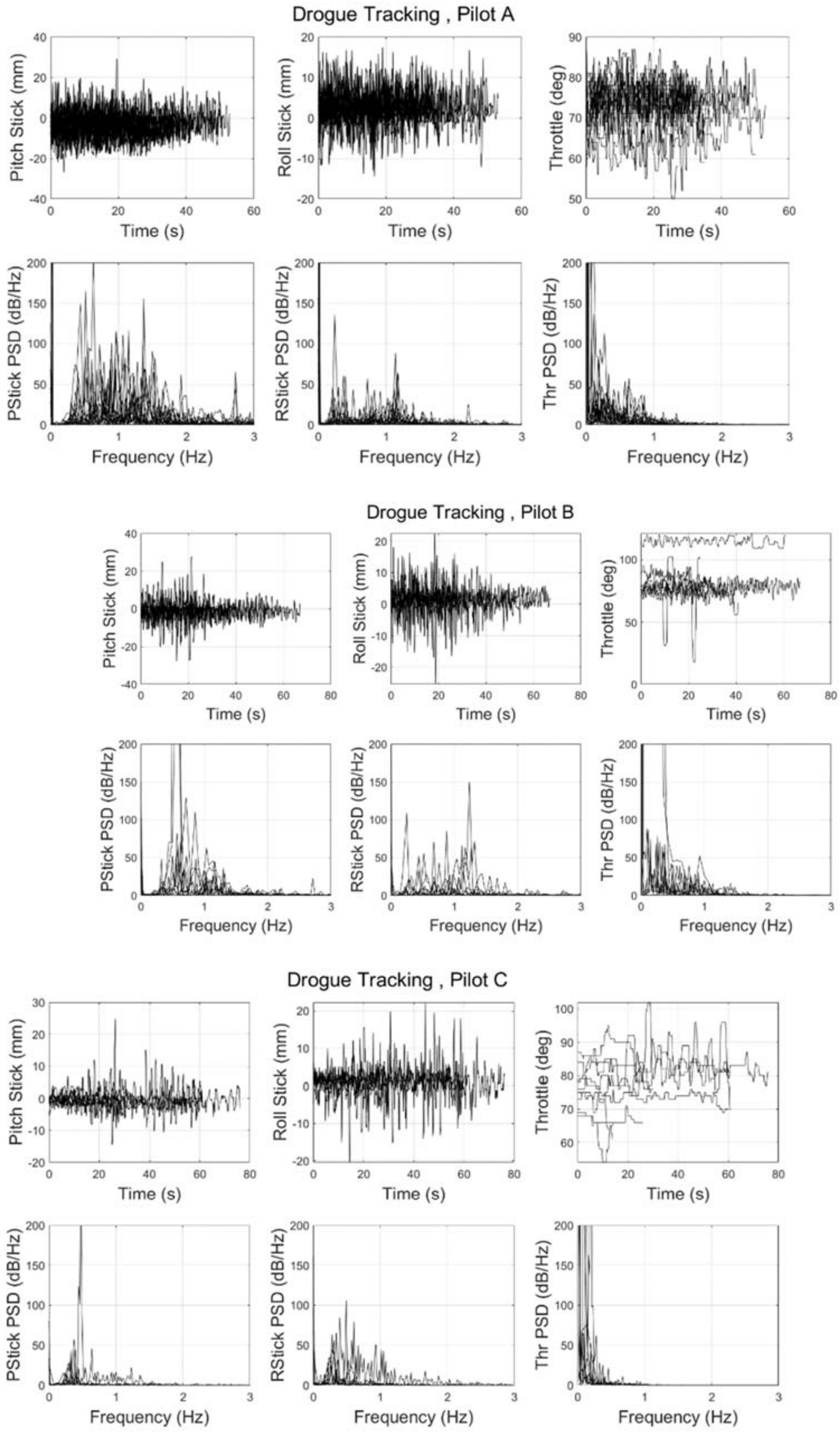


Fig 6. Estimation of Pilot Gain

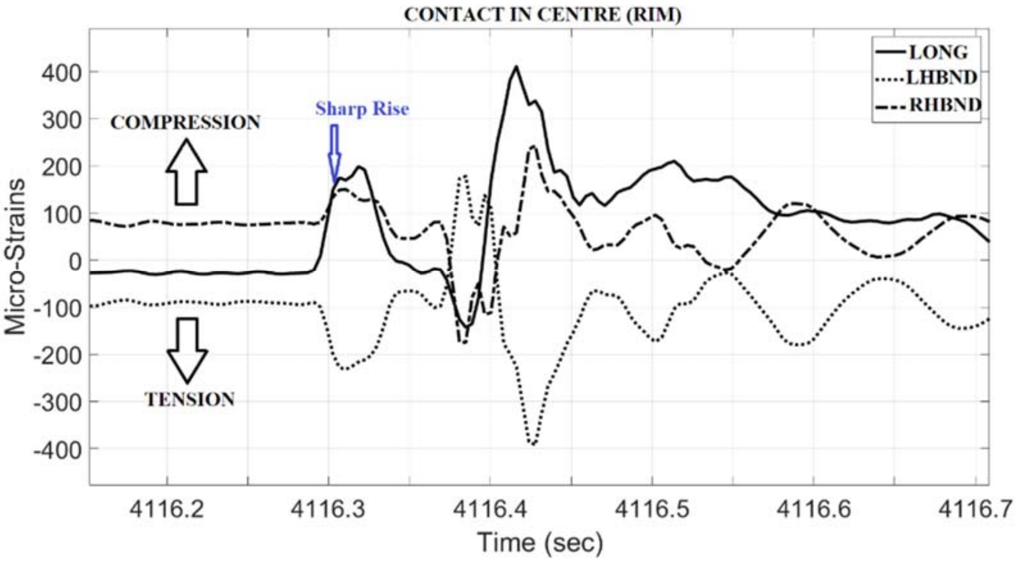
7.7 AAR Hook up Tasks

The AAR hook up task consisted of probe and drogue engagement at 1 to 3 kt closure rate. Performance objectives for assigning HQR were as follows:

- Desired performance: Hook-up with acceptable workload and without touching the drogue webbing in at least 50% of attempts; No PIO
- Adequate performance: Hook-up with acceptable workload in at least 50% of attempts

Six to 12 hook-up attempts were recommended at each test condition by Ref 2, but only 8 to 12 tests, including 4 to 7 hook ups, could be executed in a typical flight, spanning different flight conditions. This was due to the limited availability of the tanker and pilot fatigue considerations. Although this did not meet the requirement, adequate data was gathered to assess the aircraft's HQ with a reasonable degree of confidence.

Overall, 85% of hook up attempts were successful. Aborts due to excessive drogue motion were not counted. When seen pilot-wise, Pilot A had 88% success, Pilot B had 87% and Pilot C had 81% success in engaging the basket. Location of probe contact with basket was assessed visually from HUD and fin camera videos. When in doubt, data from strain gauges mounted on the probe was referred, which was found to be accurate and reliable. The strain signature when the probe contacted the metal rim at the centre was distinctly different from the signature when probe contacted the webbing (Fig 6). In the former, the longitudinal (compressive) strain rose sharply on contact whereas in the latter, bending strains dominated for a fraction of a second before longitudinal strain showed a rise (when the probe hit the rim before sliding into the socket). The time difference depended on closure rate. The contact clock code could also be estimated from strain data based on relative magnitude and sign of the strains.



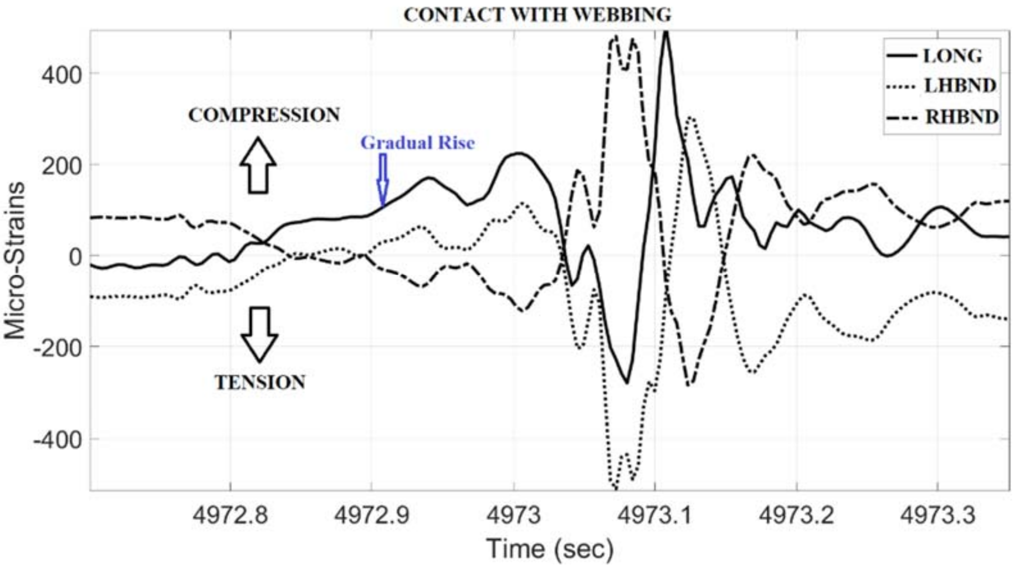
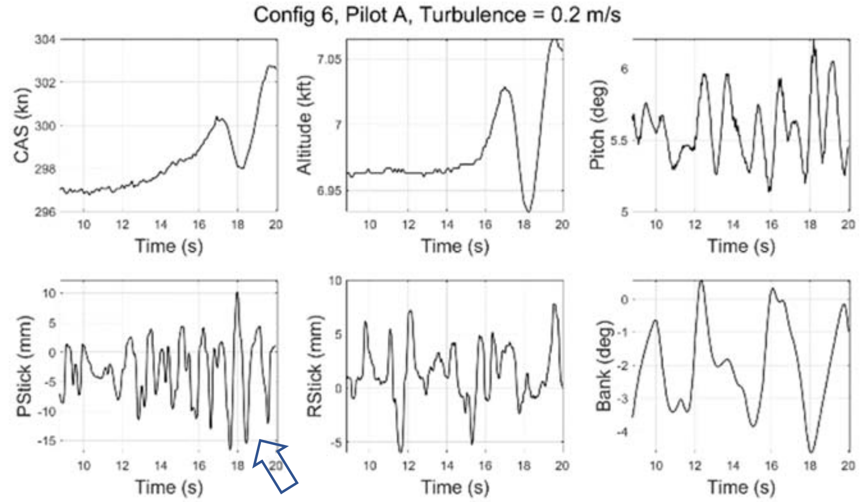


Fig 6. Typical Strain Signature during Contact

For the three pilots, 79%, 67% and 50% of the engagements, respectively, were in centre of the basket. This was a significant variation. It was seen that most of the off-centre contacts occurred on the lower half of the drogue and was analysed to be due to a small and often imperceptible movement of the drogue upwards as it approached and passed over Tejas' nose. Wear out pattern on the probe tip confirmed this. Drogue movement was insignificant at fast closure rates, but at very slow rate, it was noticeable. The average closure rate at contact was 2.5 ft/s for Pilots A & C and 4.5 ft/s for Pilot B. Although both Pilots A and C approached at low closure speed, it is surmised that, being "high gain", Pilot A did not hesitate to apply control inputs necessary to make contact at centre, even with slight drogue motion, whereas the "lower gain" Pilot C was happy to engage the webbing or abort the attempt without having to give large control inputs. Therefore, both contact and centre contact percentages of Pilot A were significantly higher than that of Pilot C. Control inputs of Pilots A and C corroborated this.

Moderate-to-large control inputs were required for achieving contact in a few cases – mainly by Pilots A and B. In a few cases, multiple cycles of pitch and/ or roll stick inputs were seen in data near the point of contact (Fig 6). While there were no adverse pilot comments, use of such control inputs to achieve contact was felt undesirable and is presently under detailed study by the FCS Control Laws design team.



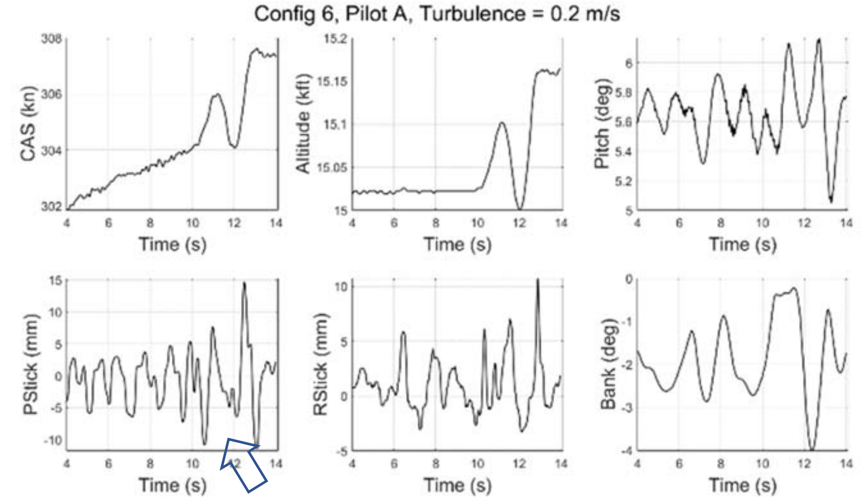
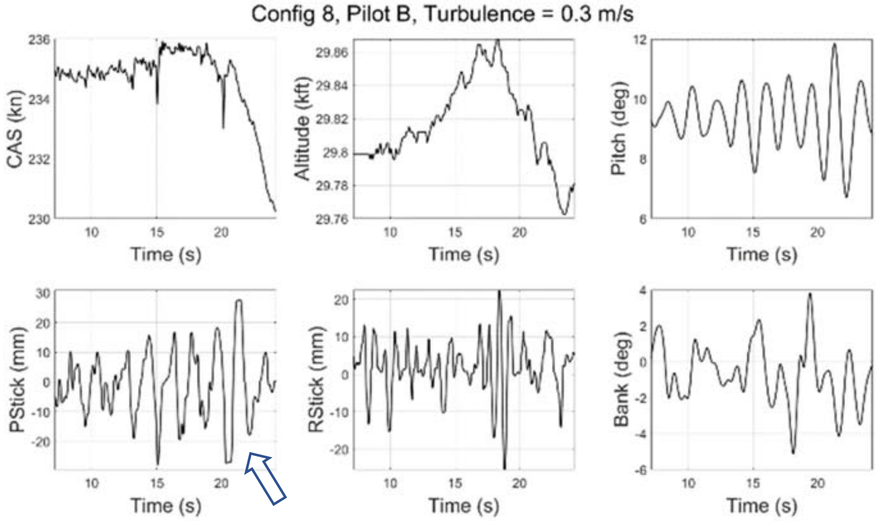


Fig 6A. Stick Inputs before Contact



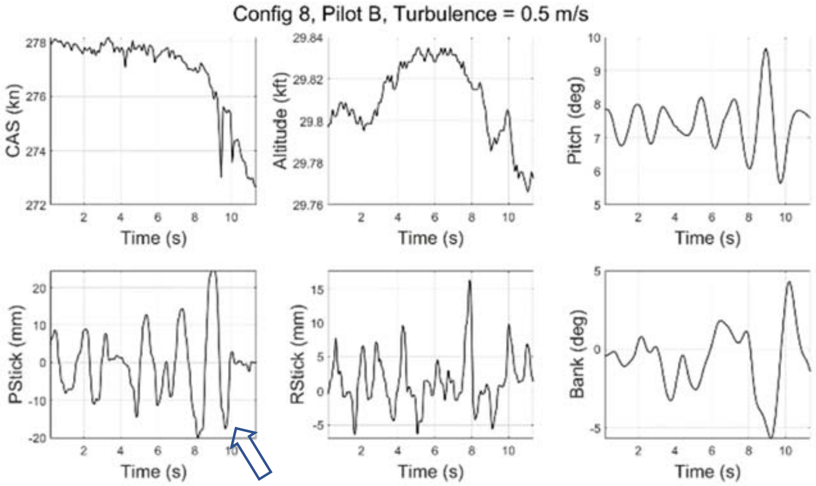


Fig 6B. Stick Inputs during Drogue Tracking

Hook ups clearly met the criteria for Level 1 HQ and the same was confirmed by pilot comments. In general, engagements with IL78 pod were relatively easier (72% contacts in centre) than engagements with the Su-30 pod (55% contacts in centre). HQ during position keeping after contact was also assessed as Level-1. There was no apparent difference when the C of G was varied either longitudinally or laterally. Engagement and disengagement in turns did not pose any problem. However, in the max AUW configuration, a slight sluggishness (“stick heaviness” as reported by the pilots) was noticed, but it did not seem to affect contact performance. Contact with LG extended, in emergency gains and AAR OFF (the last being an opportunity test, since AAR mode went off before contact) were all uneventful, which was a pleasant surprise.

As mentioned earlier, HQ during drogue tracking was Level-2 at the same flight conditions and configurations. The likely reasons for difference in HQ between the two tasks were as follows: -

- Use of FPA reference instead of an attitude reference was probably the most significant reason. Although control laws improved FPA tracking in AAR mode, higher frequency inputs during tracking as compared to contact resulted in a larger phase lag between pitch stick input and flight path angle, which affected task performance.
- The best distance for tracking, as documented in literature, was 6 to 10 ft and the same was attempted. However, as flight tests progressed and the difference between hook up and tracking became clear, an attempt was made to ascertain if drogue motion during tracking was a reason. Pilot comments and chase video analysis indicated that the drogue was probably affected by proximity of Tejas aircraft (bow wave effect) when it was closer than about 10 ft from probe tip, which caused it to move slowly, thereby affecting tracking performance adversely. Based on this observation, subsequent tracking tests were carried out at more than 12 ft, which showed better tracking performance but the tests were limited and inconclusive.
- The drogue tracking task was derived from Ref 2 and was used without modifications. The diameter of IL-78 drogue was smaller (690 mm) than the STANAG specification of 860 mm. Diameter of Su-30 drogue (800 mm) was larger than that of IL78, but still smaller than STANAG drogue. Tracking a larger drogue

within its diameter would be easier, but the effect of this difference was not considered to be significant.

7.8 Effect of Atmospheric Turbulence

Atmospheric turbulence was estimated using on board INS and air data. Computations were performed as given in Ref 3. Turbulence up to 0.5 m/s was considered as nil, 0.5 to 1.5 m/s was mild, 1.5 to 3.5 m/s was considered moderate and > 3.5 m/s was severe, based on a previous study where these values were correlated with meteorological data and pilot comments. It was seen that turbulence was absent or mild during most of the tests and the drogue was also relatively steady.

7.9 Fuel System Tests

Refuelling was carried out at different flight conditions within the AAR envelope. More tests were carried out at low speeds and high AUW to assess fuel system at high pitch attitudes, which was the worst case due to low air volume in tanks. Over pressure beyond the Surge Relief Valve (SRV) setting was observed twice under these conditions. During refuelling, fuel inflow into F1/F2 could occur along multiple paths – mainly through an electric refuelling valve (ERV), a path through the wing drop tank transfer circuit and another through the ventral drop tank transfer circuit. At high pitch attitudes, both the DT float valves remained in open (transfer) position allowing fuel to come in through all three paths at high pressure. At these attitudes, the F2 tank was full and the air volume above the fuel surface was marginal in F1 top tank. Before the tank high level switch could operate and close the ERV, excessive fuel had flowed in, raising the pressure beyond SRV limits. It was not possible to lower the float valves due to tank space constraints. To continue flight trials, ventral DT path was manually blanked which reduced the incoming fuel flow. Although this phenomenon was applicable only at extreme pitch angles in the low-speed region of the refuelling envelope, modifications have been carried out in the fuel system to allow refuelling only along ERV path, should such a flight condition be ever experienced by operating units.

In some flights, pressure built up to very high values (up to 320 psig) due to expansion of fuel vapours in the AAR probe after SOV was closed. On one occasion, the SOV could not be opened due to the locked-up pressure. A pressure relief valve was later introduced in the system to prevent such pressure build-up. Replacement of SOV with a Non-Return Valve (NRV) is also under consideration.

8.0 CONCLUSIONS

Handling Qualities of LCA for AAR task were assessed in all flown configurations, using well known HQ manoeuvres. Although flying effort was not adequate for an exhaustive evaluation, it did allow assessment of AAR HQ with high confidence. Results indicated that HQ was Level 1 for AAR hook up task and Level 2 for drogue tracking tasks; probable reasons for this difference are covered in the report. There was no significant difference in HQ among the different store configurations tested, including some failure cases.

Extensive use of flight test data and video was made to quantify HQ task performance, closure rates and point of contact between probe and drogue. With this, pilot comments and HQR were corroborated using data and thus the HQ ratings were validated. This was a high point of the trials.

Most of the flight test objectives were met, except that HQ could not be assessed under realistic turbulent conditions that could be encountered during operational use. This needs to be assessed during future flight trials or on simulator. The RTS needs to be upgraded for realistic assessment of AAR HQ.

The observations of multiple periodic moderate amplitude stick inputs during engagement and use of near full stick inputs are under analysis by FCS CLAW design team and is planned to be addressed in the next FCS software build.

9.0 ACKNOWLEDGEMENTS

The author gratefully acknowledges the efforts of Mr Prateek Kumar Sinha, Scientist 'D' of NFTC, who created the image processing algorithm and the script necessary for analysis of HUD video to quantify drogue tracking performance. Thanks also to the LCA Control Law and Fuel System design teams for providing information and material required for preparation of this paper.

10.0 REFERENCES

1. *Prabhu, M; Sinha, Prateek Kumar; Ghosh, Sayantan;* Assessment of Handling Qualities of Light Combat Aircraft (LCA-Tejas) in Air to Air Attack Mode by Analysis of Head-Up Display (HUD) Video of the Chase Aircraft, International Foundation for Telemetering, 2018-11.
2. MIL-1797B, Flying Qualities of Piloted Aircraft
3. *Johan Gingberg,* Wind Envelope Expansion Testing of the JAS 39 Gripen Single and Dual Seat a/c, SFTE, 2008.