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Innovative Method for the Estimation of Closure Velocity between RAT Driven Drogue and IFR Probe: Air-to-Air refueling Flight Trials

A. Arunachaleswaran[#,@,*], A. Kabadwal[#], Rajeev Joshi[#], Siddarth Singh[#], M. Prabhu[#], A.P. Singh[#], S. Elangovan[@], and M. Sundararaj[@]

[#]*National Flight Test Centre, Aeronautical Development Agency, Bengaluru - 560 017, India*
[@]*Department of Aeronautical Engineering, Bharath Institute of Higher Education and Research, Selaiyur - 600 073, Chennai*
[*]*E-mail: aarunachaleswaran@yahoo.com*

ABSTRACT

Air-to-air refueling for a fighter platform is a force multiplier in terms of increasing its combat radius and payload carrying ability. Adapting for such a facility especially for an aircraft under design and development is a challenging task. It requires rigorous ground and flight testing to meet the certification standards. One of important flight test parameter that needs to be validated for structural impact load calculations and certification needs is the closure velocity. The air-to-air refueller was equipped with a Ram-air-turbine powered drogue and chute system. An innovative methodology of estimating the closure velocity between the drogue of the mother aircraft and the in-flight refueling probe of the receiving aircraft was evolved. The method was employed and validated during the air-to-air refueling trials of a prototype fighter platform. The intention of this paper is to explain the methodology employed and deliberate the results obtained with respect to the air-to-air refueling certification.

Keywords: Air to air refueling; In-flight refueling probe; Drogue basket; Closure velocity; Ram air turbine; Flight trials; Photogrammetric analysis; GPS tracking

1. INTRODUCTION

Air-to-air refueling has the potential to enhance the endurance of a fighter aircraft and increase its radius of action to a greater extent apart from providing flexibility of carrying more weapon payloads. In order to provision air to air refueling capability for a fighter aircraft (receiver), its entire fuel system needs to be modified. The process is complicated and needs certification, the following are the major activities:

(a) Identification of certified in-flight refueling (IFR) probe
(b) Assessment of suitable location of probe on the aircraft considering pilot's vision, effect on other systems like air data probes/ angle of attack vanes/ side slip vanes, safety requirements, real estate, clearances and ease of plumbing
(c) Design of suitable mast for mounting the probe
(d) Provision of necessary plumbing, valves (both safety and open/ close valves)
(e) Lightning protection, vapour pressure build-up and explosion protection
(f) Load and strength requirements, weak link load
(g) Ground and flight testing.

The compatibility of receiver aircraft to a specific tanker aircraft is important before undertaking the modifications on the receiver aircraft. The details of compatibility assessment include geometric compatibility, aerodynamic compatibility, Performance compatibility including implementation of suitable control law algorithm for optimum handling qualities, loads compatibility, fuel system compatibility, electro magnetic interference/electro magnetic compatibility and lights compatibility[1]. The loads compatibility involves assessment of the interface design loads between tanker and receiver aircraft over the entire operating envelope including static, dynamic and impact loads. The Aerial Refueling Systems Advisory Group provides the guidelines for undertaking flight testing of air-to-air refueling systems. The document also provides a maximum value of closure rate (10 knot) for impact load of 100 lbs[1,2]. Therefore, it is imperative to measure the closure velocity and study the impact load along with obtained closure rate. The designers at Aeronautical Development Agency, Bengaluru and Hindustan Aeronautics Limited, Bengaluru have studied and designed a flight test instrumentation scheme using strain gauging network for obtaining the various loads on the probe including the impact loads. However, obtaining the closure rate was a challenge, as the tanker and the receiver aircraft both were moving platforms in air. Literature survey was carried out to arrive at a suitable method for estimating the closure velocity between the drogue basket and the IFR probe attachment. The intention of this paper is to present an innovative method for the estimation of closure velocity of the fighter receiving aircraft with respect to the tanker aircraft using video graphic data from chase aircraft.

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2. PROCEDURE, SET-UP AND METHODOLOGY

The tanker aircraft consisted of a probe-drogue refueling pod (ARP-3) in which the probe was reeled-in and reeled-out using hydraulic power derived from the Ram-air-turbine (RAT) of the pod. The RAT drives a hydraulic pump with the help of splined shaft connected between them. The RAT driven pod reeling out the drogue from the tanker aircraft is as shown in Fig. 1.

A Chase aircraft (twin cockpit) was planned to be flown two to three wing spans from the receiver and tanker aircraft set-up shown above. The rear crew was equipped with a video camera which was capable of recording continuous video at 30 frames per second (fps). The snapshot of the set-up obtained from the video of the chase aircraft video is as shown in Fig. 2. With proper planning and continuous feedback from rear crew the chase aircraft was flown parallel to the set-up. During the flight trials, care was taken to plan the flight tests in minimum air turbulence conditions so as to reduce the random behaviour/oscillations of the closure data between drogue and probe.

Similar work for the estimation of velocity and tracking were studied and demonstrated by researchers in the past. Implementation of a particle tracking velocimetry system in order to track the tracer particles in turbulent flow was studied and published by Maas[3]. Krimmel[4], *et al.* have successfully estimated ice velocity at the terminus of Columbia glacier using sequential photography technique. Estimation of position, attitude and velocity of a projectile was demonstrated by Zhao[5], *et al.* The precise estimation using video applications has also been highlighted by Miletic[6], *et al.* Vehicle speed detection algorithm developed by Rahim[7], *et al.* successfully demonstrated the use of frame differencing technique for the formulation of velocity of moving vehicles. Use of image analysis techniques using cameras to estimate the discharge from a glacial fed river was demonstrated by Young[8], *et al.* Taking cues from these studies and guidance given ARSAG document, the closure velocity was planned to be estimated from the chase aircraft video data. Two 200 mm x 200 mm marking stickers were stuck on the receiver aircraft at prominent pre-determined locations (both on starboard side and port side). The line joining centre of these stickers measured 82 cm and was parallel to the aircraft fuselage reference line (x axis of ac body frame reference).

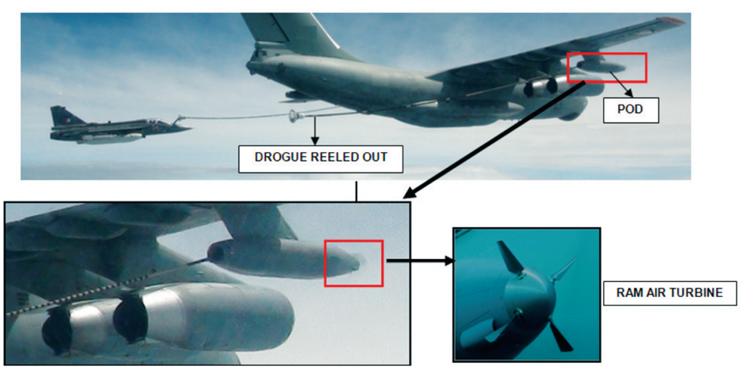


Figure 1. Ram air turbine pod reeling out the drogue basket from the tanker.

Figure 2. Snapshot of the set-up obtained from the chase aircraft video.

The videos were captured by the chase aircraft with the receiver aircraft in Astern position (the stabilised formation position behind the AAR equipment which is approximately 15 m - 20 m directly aft of the drogue with zero rate of closure to actual contact) and were analysed using open source tracker software -video analysis and modelling tool[9]. The distance between the stickers was used as reference and using the calibration tape tool available in the Tracker software, the distance between the probe and the basket contact point was obtained. The corresponding frame number, when distance between receiver aircraft probe and the contact point of the drogue basket was approximately 3 m, was noted. The final frame when the contact was first established was also noted. Using frame difference technique the closure velocity was estimated.

The global positioning system (GPS) device (Garmin 296) was carried in the tanker aircraft and the receiver aircraft was equipped with inertial navigation coupled with global positioning system (INGPS) system. The tracks of both the aircraft could thus be referenced to a GPS time. The time stamping of actual contact was identified with the help of FTI installed on prototype fighter aircraft and visual cues as seen from refueling director's cabin. The FTI was installed since it was a prototype aircraft used for flight testing which would not be available in a normal service production aircraft. Using GPS tracks of these two aircraft, the closure velocities were calculated and results were used to validate the video analysis. However, due to masking issues of GPS device installed on tanker aircraft, the GPS track data of tanker aircraft could be retrieved successfully only for seven contacts. The data obtained for these seven contacts were sufficient to compare and validate closure velocities. In addition, the qualitative comments and observations of experienced Flight Test Director (1000 h of AAR experience) were utilised for supplementing the obtained results. The GPS track method of validation was also discussed by Svanem during the velocity measurement of calving front using terrestrial photogrammetry and validation with GPS track[10,11].

3. RESULTS AND ANALYSIS

The flight trials were carried out with two test pilots with difference experience levels piloting the receiver aircraft. The chase aircraft was flown by another experience test pilot and experienced flight test engineer as the rear flight test crew. The snap shots showing the set-up and markings obtained from the chase aircraft is as shown in Fig. 3.

The video data which was obtained in all sorties were analysed using tracker software[9]. The distance between the probe and drogue, ‘Distance B’ marked as shown in Fig. 3 was obtained using ‘Distance A’ as reference. Using the frame difference method, time for closure was obtained. The closure velocity (CV) was obtained by dividing the distance travelled and the time taken. The screenshot of one of the data analysis using the tracker software is as shown in Fig. 4. Figure 4(a) shows the initial frame when the distance between the drogue and probe was 2.083 m and Fig. 4(b) shows the final frame when the contact was first established (closure velocity obtained was 2.46 knots). The data obtained is compiled as shown in Table 1. The graphical representation is as shown in Fig. 5. The obtained data was validated for seven contacts with the data obtained using the GPS tracks of both the receiver aircraft and tanker aircraft. In order to synthesise and validate the closure rate data, it was required to time stamp video recording with GPS reference time and the change in strain data obtained from FTI. The maximum error obtained from these two methods was found to be less than 3.2 per cent. This maximum measured error of 3.2 per cent was not likely to affect the impact load measurement and its validation. The obtained results clearly indicated that the closure velocities (between the drogue of the tanker aircraft and the probe of the receiver aircraft) could be estimated using the chase aircraft video for air-to-air refueling (AAR) flight trials.

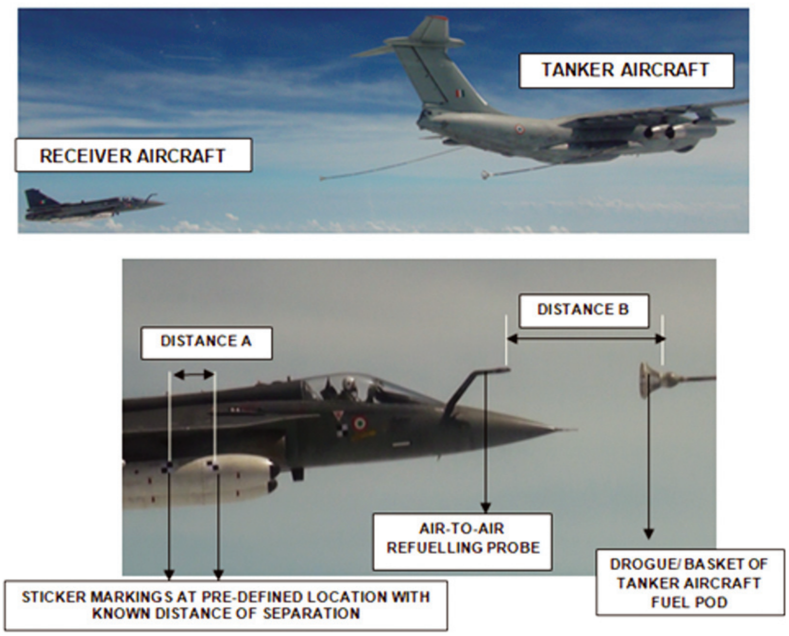
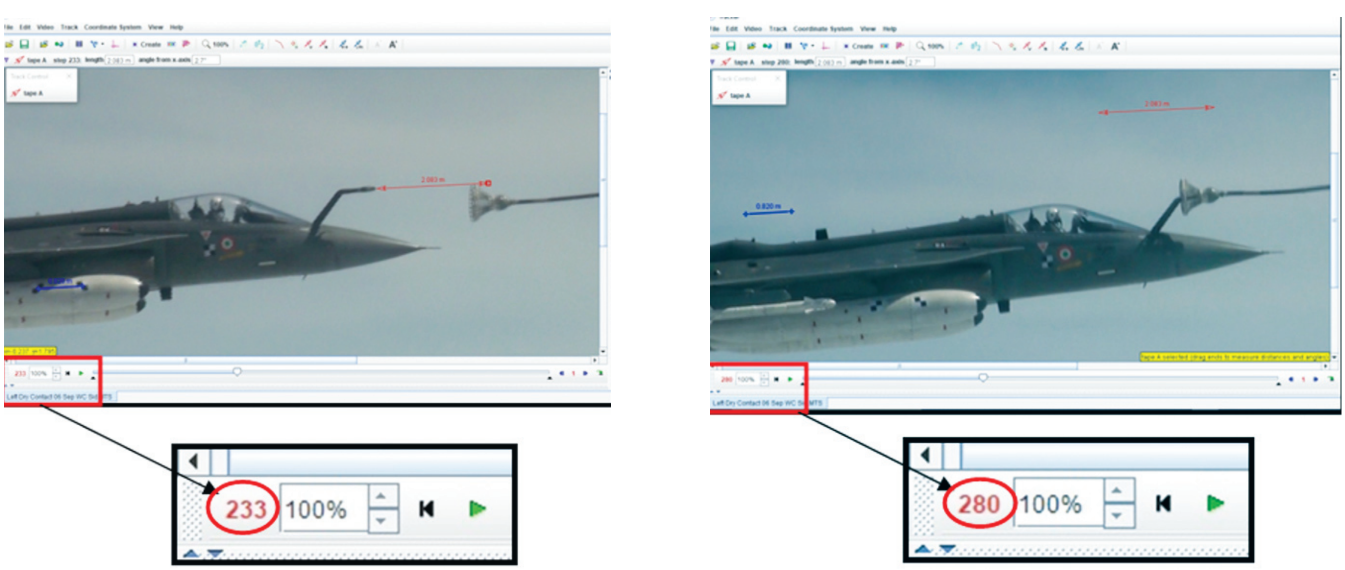


Figure 3. The snap shots showing the set-up and markings obtained from the chase aircraft.

The spread of closure rate data for two different pilots was clearly indicative of two different AAR engagement techniques. Pilot A was closing in faster compared to Pilot B. Such drastic difference in closure pattern could be attributed to the pilot’s experience on AAR and the previously flown aircraft types (background). This analysis also assisted in refining engagement techniques for this type of high gain tracking task. Besides, this methodology can also be deployed as a useful debriefing tool for the pilots being trained on AAR tasks.

4. CONCLUSIONS

Estimation of closure velocity between tanker aircraft and receiver aircraft for the assessment of impact loads is critical during the air-to-air refueling trials. An innovative method of computing the closure velocity from the analysis of videographic



(a) (b)

Figure 4. The screenshot of one of the data analysis using the tracker software– (a) Initial frame when the distance between drogue and probe was 2.083m. (b) Final frame when the contact was first established (closure velocity obtained was 2.46 knots).

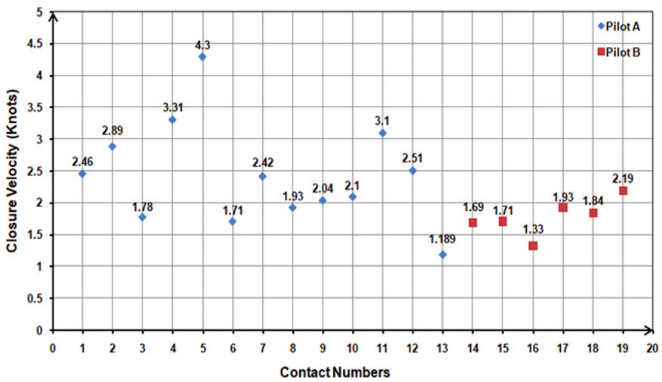


Figure 5. Graphical representation of closure velocities obtained using videographic Data.

Table 1. Closure velocities obtained using videographic data and GPS tracks along with Error

Contact	Pilot	CV (KTS) video	CV (KTS) GPS	Error (%)
1	A	2.46	2.50	+1.60
2	A	2.89	2.82	-2.48
3	A	1.78	1.73	-2.89
4	A	3.31	3.30	-0.303
5	A	4.3	-	-
6	A	1.71	-	-
7	A	2.42	2.5	+3.2
8	A	1.93	1.90	-1.58
9	A	2.04	-	-
10	A	2.1	-	-
11	A	3.1	-	-
12	A	2.51	-	-
13	B	1.189	-	-
14	B	1.69	1.65	-2.42
15	B	1.71	-	-
16	B	1.33	-	-
17	B	1.93	-	-
18	B	1.84	-	-
19	B	2.19	-	-

data was studied and demonstrated in the flight trials. The estimation of the closure velocity was also validated using the GPS track data and showed close match. This technique could also be used effectively by regular flying squadrons for training purposes as a debrief tool for the receiver aircraft pilot training.

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CONTRIBUTORS

Gr Capt A. Arunachaleswaran is an alumnus of IIT, Kharagpur. He has specialised in Mg-based metal matrix composites. He is a graduate of the Air Force Test Pilots School and is specialised in Weapons Testing. He is presently pursuing his PhD in Aeronautical engineering and has been working as a Flight Test Engineer at National Flight Test Centre for prototype flight testing of Tejas Light Combat Aircraft.
He was involved in innovating the idea of estimating the closure velocity and was also the rear cockpit test crew on the chase aircraft for the Air to Air refueling trials of the prototype fighter aircraft.

Gr Capt Anoop Kabadwal (Retd.) has completed his MTech in Material Science from Japan, in 2008. He is a graduate of Air Force Test Pilot's School, Bengaluru and has experience in flight testing. He is presently in Aeronautical Development Agency for prototype flight test duties of LCA.
He was the lead Flight Test Engineer and the Test Director of the Air to Air refueling trials.

Gr Capt M. Prabhu (Retd.) has completed his ME in Mechanical (Air Armament), MS (Software Systems) and MBA in Project Management. He is a graduate of the Air Force Test Pilot's School, Bungaluru. He has been in the field of flight testing. He is presently the Group Director, FTE at NFTC, ADA.
He has contributed towards flight test planning of the Air to Air refueling trials.

Gr Capt Rajeev Joshi is an alumnus of National Defence Academy (NDA). He has operational flying experience on MiG 23, MiG 21 and Mirage 2000 aircraft. He is a graduate of the Air Force Test Pilot's School, Bengaluru. He has been in the field of Flight Testing for the last 15 year. He is presently serving as a Test Pilot at NFTC for prototype flight testing of LCA.
He has contributed towards flight test planning and piloting the prototype fighter aircraft.

AVM Amar Preet Singh is an alumnus of National Defence Academy, Defence Services Staff College and National Defence College. He is a graduate of the Air Force Test Pilots School and has been a flying instructor in the school. He was the Project Director (Flight Testing) at NFTC managing flight testing of LCA. He is a proud recipient of Presidential award *'Athi Vishit Seva Medal'* for his distinguished service to the IAF.
He has contributed towards flight test planning and piloting of the chase aircraft.

Wg Cdr Siddarth Singh has completed his post-graduation in Computer Science engineering. He is a Fighter Strike Leader. He is a graduate of Air Force Test Pilots School and is presently deputed to NFTC for flight testing of LCA.
He has contributed towards flight test planning and piloting the prototype fighter aircraft.

Dr Srinivasan Elangovan has completed his PhD in Aerospace Engineering from IIT, Kanpur. He has served as Research fellow at IIT, Madras. He was Principal Investigator for many defence related projects funded by DRDO. He also held the position of Director of the Centre for Aerospace Research. Currently, he is Dean (Aeronautics) at the Bharath Institute of Higher Education and Research, Selaiyur, Chennai. He has to his credit many research papers published in reputed journals and conference proceedings.
He has contributed towards the academic research and literature support for the work.

Dr M. Sundararaj has completed his PhD from MIT, Anna University, Chennai. He is proficient in the field of fluid flow theory and CFD. He is the Principal Investigator for Research projects sponsored by AR & DB (Aeronautical Research Development Board), MoD. He is currently the HoD (Aeronautical Engineering) at Bharath Institute of Higher Education and Research, Selaiyur, Chennai.
He has contributed towards the academic research and literature support for the work.