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Utilisation of Ram Air Turbine on a Fighter Platform for Energy Extraction : Failure Mode Study

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ABSTRACT

Aircraft electrical system needs to be robust enough to cater for electrical power requirements of all the systems of the aircraft and all the safety/degraded mission critical systems in failure modes. Designing such a robust electrical system for a developmental aircraft program is a challenge. A developmental aircraft during its various phases would involve integration of additional systems and new weapons (in case of fighter aircraft). Integration of newer systems imposes fresh challenges in managing the electrical system architecture especially in failure modes. Weapon integration in a prototype fighter program is dynamic as newer contemporary weapons are developed at faster pace and ever evolving. Power crisis through existing on-board power generation systems in failure mode was felt during an indigenous aircraft development program. A novel idea of introducing a Ram Air Turbine and utilize the power generated during main alternator failure for critical systems was studied. The intention of this paper is to cover the details of the study carried out towards utlisation of such a Ram Air Turbine in landing phase for extraction of energy in case of main alternator failure.

Keywords: Ram air turbine; Air brake; Failure modes; On-board power generation; Wind tunnel studies; Co-efficient of drag

1. INTRODUCTION

Design and development of a prototype fighter platform is a complex and multi-pronged activity[1]. One of the critical aspects of any aircraft design and development is electrical load estimation and selection of suitable on-board power generation system to cater for estimated load[2,3]. During the process of design, development and further in service, there would be multiple changes and additional systems which would be integrated. The additional power requirements for these need to be catered by the power generating system. The guideline for spare electrical energy that needs to be catered for during prototype development of a fighter platform has been given in MIL-STD-704 and MIL-E-7016[3,4]. In one of the indigenous fighter platform development, during weapon integration phase a requirement was felt that power requirement for a critical air to air weapon 'Article A' in landing phase (in failure mode) could not be accommodated by on-board power generating system. The landing phase of the aircraft requires additional electrical loads especially for landing lights. Generally, prior to landing, airbrakes are used in the approach phase to steepen the approach and thereby reduce touchdown speed and ground roll distance. Fighter platforms typically use aerodynamic devices like air brakes in order to achieve a steeper approach and the same is also used for during combat phases of flight[5]. Additionally, meeting the power requirement to the critical weapon 'Article A' posed a serious challenge in failure mode and was required to be resolved. Ram Air Turbines (RATs) have been tried out on aircraft for providing hydraulic power and electrical power for emergency systems and various podded systems like in-flight refueling pod and electronic warfare pods. The intention of this paper is to dwell upon providing additional power through RAT (mounted on the existing airbrake compartment) during landing phase for 'Article A' and provisioning spare power capacity. The drag produced by the RAT could also be used for aerodynamic braking[5]. The mounting details of the RAT has been shown in the schematic sketch place at Fig. 1. For this study a commercially available generator was employed for proving the concept and in the detailed design phase a more efficient alternator of airworthy military standards shall be employed.

2. PROCEDURE AND METHODOLOGY

2.1 Study of Load Distribution of the Aircraft

The schematic electrical architecture of the aircraft is given in Fig. 2. The aircraft has been powered with an engine driven alternator with a capacity of 25 kVA (ALT1). A hydraulically driven second alternator with 5 kVA capacity has been provisioned to cater for additional AC loads. The direct current (DC) loads for the aircraft are provided through two sources. ALT1 has been connected with two transformer rectifier units (TRUs) which act as the primary source of DC power and the second source is through an engine driven 5 KW DC Generator. The redundancy levels have been worked

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Figure 1. Schematic sketch showing the proposed location of RAT (existing Air Brake compartment).

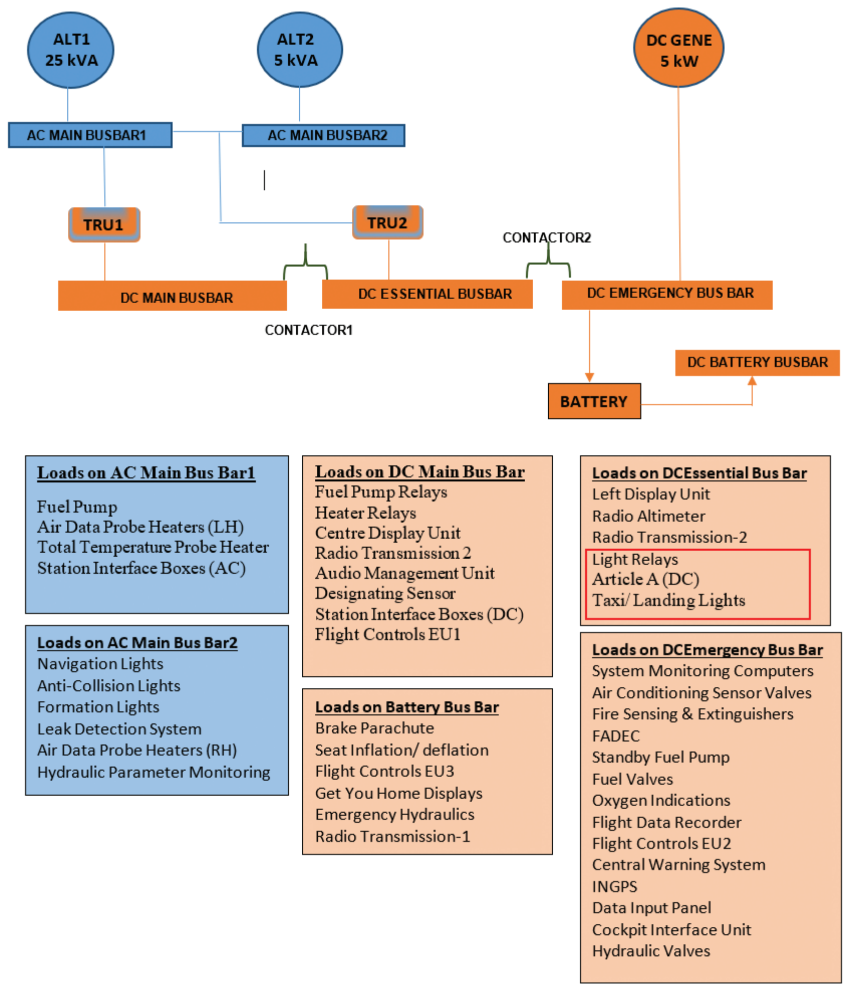

Figure 2. Schematic electrical architecture of the developmental aircraft.

out in such a way that the aircraft could be safely recovered even with ALT1 failure and DC Generator failure. In addition degraded mission accomplishment could be possible with the main alternator failure. In addition, a 24V Ni-Cd battery has been provided as a last resort in order to provide 20 min of endurance to safely recover the aircraft in case of both Alt1 and DC Generator failure. The details of the architecture have been summarized in Table 1.

2.2 OPTIMIZATION STUDY

During the initial design stages the spare capacity of the alternator and DC generator were as per the guidelines given in the MIL E 7016[3,4], however when more and more systems were required to be integrated a crisis was felt. Redistribution of electrical loads was undertaken by the designers to improve the spare capacity. However, the optimized electrical loads could not cater for 'Article A' in landing phase (in failure mode) as the landing lights were also required to be used. 'Article A' is a critical weapon that is required to be powered at all times for self-protection. Both Taxi/ landing lights and 'Article A' are being powered through DC Essential bus bar. In case of failure of ALT1, the architecture is such that these are required to be powered by DC Gene whose capacity is 5 KW. DC gene capacity or ALT 2 capacity of 5 kVA could not be upgraded since both of them were directly or indirectly driven by the aero engine. The loads on the aero-engine were already optimized and limited to the existing values by the aero-engine original equipment manufacturer. Therefore, an alternate means of provisioning power to 'Article A' and landing/ Taxi lights was required to be studied. In certain aircraft thermal batteries have been successfully employed for emergency power generation as studied by Kaufmann[6], *et al*. However, the thermal battery cannot be re-used and cannot support the drag requirements.

Table 1. Summary of electrical architecture

Bus Bar	Details
AC Main Bus bar1	AC Main Bus bar will normally be supplied by ALT1 and in case of ALT1 failure, the AC Main bus bar looses power.
AC Main Bus bar2	During normal power up condition AC Main Bus bar 2 will get supply from AC main bus bar1 i.e. from ALT1. In case of failure of ALT1 5kVA alternator (hydraulically driven) will supply power to AC Main Busbar2.
DC Main Bus bar	Under normal conditions, DC Main Bus bar will be supplied by AC Main Bus bar1 through both TRUs. In case ALT1 fails, DC Main Bus bar looses power. However, in case of TRU1 or TRU2 failure, the healthy TRU powers DC Main Bus bar. Redundancy available only for TRU failures.
DC Essential Bus bar	In normal mode, the DC Essential bus bar will be supplied by ALT1. When ALT1 fails, the DC Essential Bus bar will be fed by DC Gene through DC Emergency Bus bar.
DC Emergency Bus bar	In normal mode this bus bar is fed by ALT1 through TRUs. In case of failure of ALT1, DC Gene will provide supply to this bus bar. In case of ALT1 failure coupled with DC Gene failure, then this bus bar shall be supplied by Battery for certain fixed period within which the aircraft could be recovered safely to the nearest airfield.
Battery Bus bar	For total electrical failure.

2.3 Estimation of Additional Power using RAT

As an alternate measure of generating energy during failure of ALT1, Ram Air Turbine Generator was studied. A Ram Air Turbine (RAT) is a small turbine that is installed in an aircraft and used as an alternate or emergency hydraulic or electrical power source[7-9]. The RAT, when it is deployed can generate power based on the speed of the aircraft. RATs are used widely in various aircraft as an emergency source of power. A lot of studies have been carried out in the past in the field of generating green energy in aircraft and use of RAT for emergency power generation[10,11]. Altoma[12], *et al*. has studied RAT for generating electrical energy during emergency[12]. The British Aerospace Hawk trainer aircraft also deploys RAT for emergency hydraulic power generation[13]. The estimation of drag forces and computation methodology has been explained by Ortiz[14], *et al*. Deriving energy out of marine current turbine has been simulated and found feasible by Eddine[14], *et al*.

Energy for electric wheel drive taxiing concept has also been examined and reported by Teo[16], *et al*. Concept of using air drag in effective fuel saving has also been studied by Dhanasekhar[17], *et al*. and Krzysztof[18], *et al*. The generation of emergency hydraulic energy and critical technologies has been studied by Guo[19], *et al*. Ram Air Turbines are also used in some podded system to generate hydraulic or electric power. For example RAT is used in Refueling Pod (ARP-3) for generating hydraulic power for reeling in and out of hose[20]. RAT is also used in Electronic Warfare pods such as AN/ALQ 99 which makes it adaptable to any platform[21]. Taking cues from these studies an attempt was made to generate power using RAT in case of failure of the main alternator. The schematic sketch of the modified architecture is shown in Fig. 3.

3. EXPERIMENTAL ANALYSIS

A three bladed RAT was selected for Wind Tunnel studies in order to generate electrical energy and also to generate adequate drag during the descend phase. The selection of the RAT was carried out by carrying out Wind Tunnel studies of three models of similar solidity ratio. The RAT which gave the best combination of power and drag was chosen. The details of experimental set-up have been covered below:

3.1 Wind Tunnel Description

The Wind Tunnel was a typical closed circuit, closed jet sub-sonic Wind Tunnel (electric motor driven fan) with a test section of size 9 ft (lateral) x 6 ft (height) x 12 ft (longitudinal). The tunnel has the capability to test models for a speed range of 3 m/s to 72 m/s. The dynamic pressure range of the tunnel was from 40 kg/m^2 to 300 kg/m^2 and the mass flow range was between 140-390 kg/s.

3.2 Internal Strain Gauge Balance

A typical internal six-component strain gauge balance system consisting of strain gauge, transducer balance elements, string support structure, balancing and recording system was used to determine the forces and moments of the models tested on the wind tunnel. The longitudinal force computed using the balance was transformed to the wind axis in order to arrive at the drag forces. The maximum error in drag measurement using this set-up could be ±0.002.

3.3 Generator

The generator used was a permanent magnet generator with commutator with rated revolutions per minute (rpm) of 6000 clockwise, 200 V, 50 Hz and 7.5 Amps.

3.4 Ram Air Turbine

A three bladed turbine with a reference area of 0.1521 m^2 and a solidity ratio of 50% was used for the study. The chord of the turbine varied from 0.06 m (root) to 0.18 m (tip) and the blade pitch was 18°. A customized airfoil optimized using computational fluid dynamics (CFD) studies was used. The schematic set-up of the RAT in the wind tunnel is shown in Fig. 4.

4. RESULTS AND DISCUSSIONS

The co-efficient of drag (C_D) was derived from the drag forces measured in the wind tunnel tests of the chosen RAT.

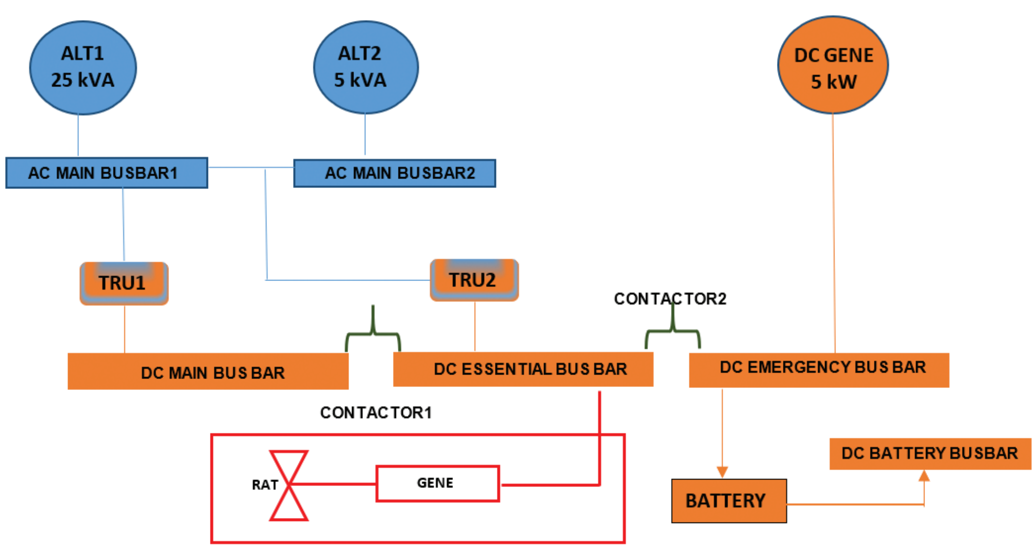

Figure 3. The modified electrical architecture with alternator driven by RAT.

The set-up of RAT along with generator mounting is shown in schematic sketch at Fig. 4 and photographs at Figs. 5 and 6. The hydraulic power used for deployment of Air brakes could be utilized for deployment of the RAT-generator. The structural integration and attachment of RAT is beyond the scope of this paper and not included here. The results of the Wind Tunnel studies of RAT are given in Table 2. The C_D values for the existing Air brake on the developmental aircraft was estimated using the guidelines given in ESDU 70015[22] and shown in Table. 3.

The C_D for RAT as a whole was evaluated from $D = \frac{1}{2}\rho A V^2 C_D$ [17]. The average value of C_D was found to be 1.14. The maximum power available from wind could be computed using the relation $P_{MAX} = \frac{1}{2}\rho A V^3$ [6]. The maximum efficiency with which the power could be extracted from the wind is limited to Betz limit which corresponds to 59.3%[23,24]. Generally, drag based RATs work within an efficiency range of 10-20%[6,7,10,25]. The efficiency of power generation of RAT model used has been found to range between 10-15%. The remaining energy was being used to generate drag and heat. As seen from Tables 1 and 4, the power generated using the RAT was adequate for providing power required for 'Article A'/landing lights during failure mode. The general approach speed of aircraft in clean configuration of the aircraft was of the order of 60-70 m/s. By extrapolating the experimental data and catering

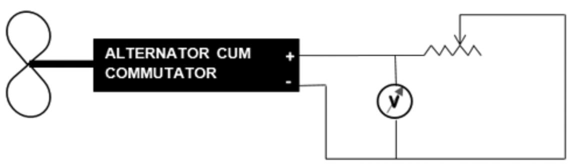

Figure 4. Schematic sketch of the wind tunnel set-up of the RAT-Generator.

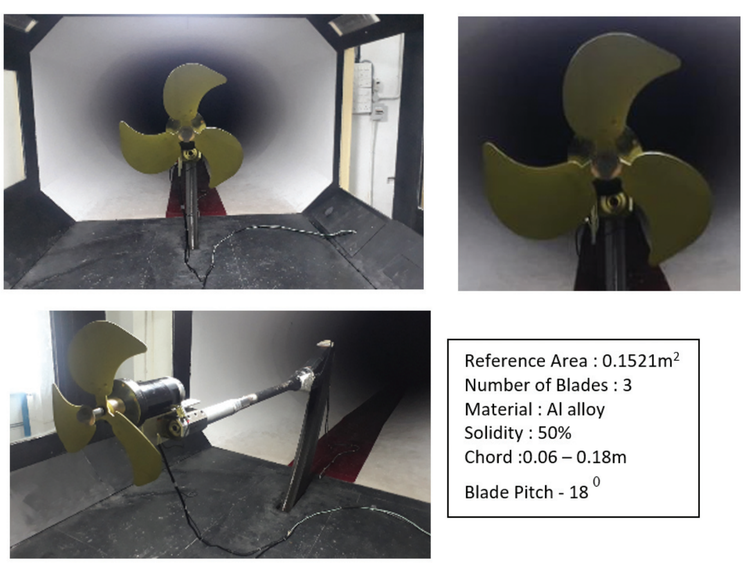

Figure 5. Photographs of RAT in wind tunnel.

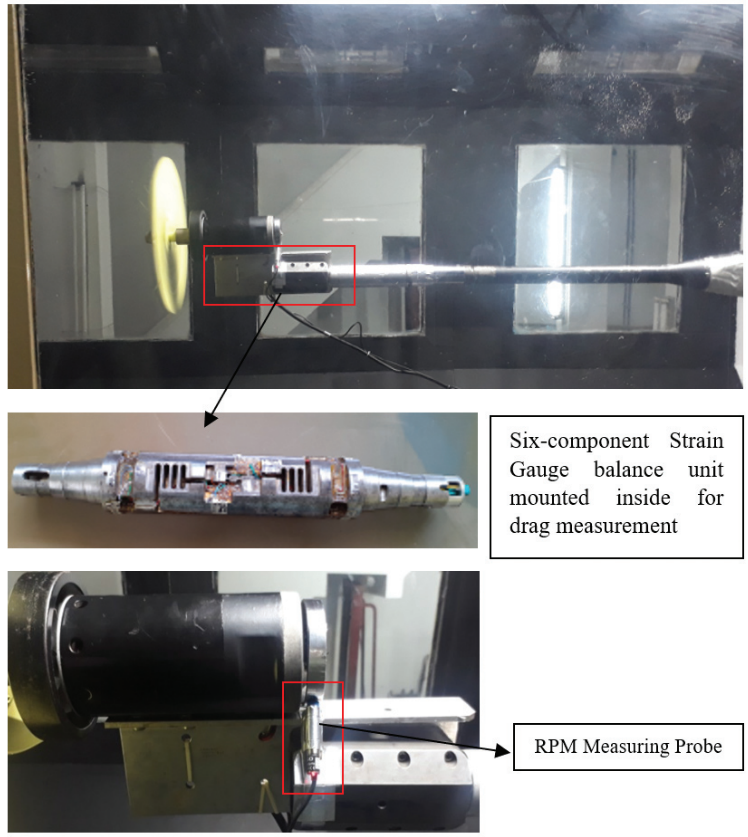

Figure 6. Photographs showing the mounting details of Strain Gauge system and RPM measurement probe.

Table 2. Wind tunnel data of RAT

RUN No: 22139 ReferenceArea: 0.1521 m²
Load : 30 Ohms
Reynold's Number – 0.4 – 0.65 × 10^6
Density of Air = 1.123-1.126 kg/ m³

Wind speed (m/s)	Drag force (N)	Voltage (V)	Power = V^2/R (W)	RPM
20	42.2	65.7	129.4	1975
25	66.2	92.1	273.0	2415
30	95.4	117.3	492.1	3075
35	130.2	139.7	688.3	3754
40	170.1	159.8	911.9	4620
45	216.3	175.6	1204.6	5420

Table 3. Drag data of air brake

Area : 0.63 m²

Wind speed (m/s)	C_D	Drag Force (per Airbrake) (N)
20	1. 18	100.7
25	1.18	158.2
30	1.18	228.4
35	1.18	310.4
40	1.18	405.3
45	1.18	513.2

for additional heat loads, the power generation possible using the RAT could be conservatively estimated at 2000 W. The choice of generator and turbine blades could be further studied and optimized. The error in drag computations measured using strain gauge balance has been estimated to be within ±0.002N. The error in pressure computations could lead to an error of ±0.25 m/s in wind speed measurements. The, the maximum error in voltage measurement has been estimated to be 5%. These errors were considered to be negligible and were not likely to affect the inference of the study. The electrical power requirement for landing/taxy lights and 'Article A' is given in Table 4.

The C_D values for the RAT model and the Air brake were quite comparable 1.14 and 1.18, respectively. The effective area (0.1521 m^2) of the RAT was however lesser compared to the existing Air Brake (0.45 m^2). However, the real estate available for the air brake can support nearly three such RATs and an equivalent drag as that offered by existing air brakes could then be generated using these additional RATs instead of one air brake. The major advantage derived would be additional energy that would be derived using the RAT and the weight of two air brakes would be similar to that of four such RATs. This derived energy would suffice the requirements of Landing/Taxy lights and 'Article A'. Thus, the experimental study indicated that the use of RAT based Air braking would be beneficial in generating aerodynamic braking as well as generating energy.

Table 4. Power requirement for 'Article A' and Landing/Taxi lights

Equipment	No. of units	Total power requirement (W)
'Article A'	2	500
Landing Lights	2	500

5. CONCLUSION

Requirement of additional power may crop up in any phase of fighter aircraft design and development program. The additional requirement may crop up in any phase of fighter aircraft design and development program. One such requirement was felt during integration of additional electronic warfare systems and new weapons on a developmental aircraft. The conflict between power availability for landing/taxy lights and 'Article A' was required to be resolved. A study was carried out to analyze the feasibility to generate additional electrical energy through RAT and as well as provide adequate drag to cater for aerodynamic braking. From the study it could be concluded that the RAT based power generating system has the capability to generate power up to 2 KW at wind speeds of 65-70 m/s which could be used for additional weapon and landing lights which requires 1 KW.

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CONTRIBUTORS

Gp Capt A. Arunachaleswaran is an alumnus of IIT, Kharagpur, graduate of the Air Force Test Pilots School. 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 is specialized in magnesium based metal matrix composites. He has published technical papers on Mg-based composites, ram air turbine system and air-to-air refueling of fighter aircraft in renowned journals.
In the current study, he has conceptualized the idea of using of Ram Air Turbine for generation of energy during electrical emergency. He also carried out the wind tunnel studies, played the key role in the correct selection of RAT and structured the technical paper.

Ms Shyni Thomas is a Scientist/Engineer F and presently the Group Director (Electrical Systems) at Aeronautical Development Agency. She has been involved in the design and development of electrical power generating system of LCA and its variants. She has pioneered the development of an electrical rig and responsible for testing and certification of electrical system solving all the challenges faced in ground trials. She was also responsible for evolving a flight test plan for electrical system and participated in the first flight of the LCA aircraft.
In the current study, she played the key role in the re-design of electrical architecture in order to introduce the RAT during alternator failure. She also contributed in setting-up the electrical output system for the wind tunnel experiments.

Mr Muralidhar Madhusudan has completed his BE (Aeronautical Engineering) from Madras Institute of Technology, Chennai, in 2007 and MTech (Aerospace) from Indian Institute of Technology, Kanpur, in 2009. Presently working as a mid-level scientist in Aeronautical Development Agency. His main research area is aircraft design and shape optimization with expertise in aerodynamics and flight performance. He has around 20 publications in various conferences and journals and has received the *DRDO Young Scientist Award* in 2015.
In the current study, he conceptualized the location of the RAT and studied the one on one replacement of Air Brakes with RAT. He was also involved in the study of drag characterization of the air-brake and RAT.

Dr Srinivasan Elangovan has completed his PhD in Aerospace Engineering from IIT, Kanpur. Currently, he is Dean (Aeronautics) at the Bharath Institute of Higher Education and Research. He has published research papers in journals and conference proceedings.
In the current study, he provided the literature support and theoretical guidance for the wind tunnel experiments. He also supported with independent verification and validation of results.

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 currently the HoD (Aeronautical Engineering) at Bharath Institute of Higher Education and Research (BIHER), Selaiyur, Chennai. He is specialized in the field of CFD. He has published research papers in journals and conference proceedings.
He acted as the supervisor and an independent guide for the entire work. He guided the team in carrying out the CFD studies for arriving at the correct shape of airfoil (for the RAT). He was also involved in the aerodynamic error estimation and validation of results.