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Comparative Study of Ram Air Turbines based on Wind Tunnel Study for Specific Air Borne Energy Extraction

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ABSTRACT

Ram Air Turbines (RAT) are used for emergency on-board power generation on aircraft and associated systems. Many studies on usage of RATs have shown promising results in terms of using RATs as a source of emergency on-board power generation. Many external podded systems on aircraft utilise RATs for self-sufficient adaptation. These pods generate their own power using RATs for their power requirements instead of depending on the mother aircraft power. Commercial cargo planes use RATs for generating emergency hydraulic power. A RAT was suggested to be used for emergency power, during failure of main alternator on a prototype aircraft. A specific requirement of the RAT was also to produce high drag for aerodynamic braking when deployed and concurrently generate electrical energy. Three models with different solidity were studied in wind tunnel at different wind speeds for suitability of this drag-energy combination. This paper presents the results of the study. Based on the results, a suitable RAT was selected for further analysis and ground trials.

Keywords: Ram air turbine; Tip speed ratio, Angular velocity; Co-efficient of performance; Solidity; Energy; Aerodynamic braking

1. INTRODUCTION

During integration of new systems, there was a shortage experienced in terms of electrical energy availability. The additional energy was required during failure of main alternator and during approach and landing phases of flight. Alternate solutions of providing this additional energy was being explored by designers. Innovative Ram Air Turbines (RAT) for airborne power generation have been studied by many scientists and are in use on many commercial aircraft[1,2,3]. In airborne weapon systems, thermal batteries are extensively used as source of energy. However, once operated these batteries cannot be reused. Ram air based fans are used as cooling devices in brake discs and environmental control (ECS) Systems in many aircraft[4,5]. Based on studies pertaining to availability of additional space, previously adopted methodologies and the requirement, a proposal of utilising RAT was explored. RATs have been in use for emergency electrical and hydraulic energy on various fighter and commercial aircraft[1,7,8]. Effective fuel saving methods using RATs have been studied for use in automobiles also[9,10,11]. RAT with high drag characteristics which can also augment as an aerodynamic braking device was required to be studied. Aerodynamic braking devices for high speed trains have already been studied by Mengling, *et al.* in 2013[10,11]. Three RATs with high drag characteristics were selected for the study. These RATs were subjected to Wind Tunnel testing at various speeds. This paper presents the methodology adopted for wind tunnel study and results obtained during the studies.

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2. METHODOLOGY

A mounting was fabricated for assembling the RAT perpendicular to the wind flow axis. Six-gauge strain gauge balance was used inside the mounting in order to measure the drag force and hence deduce the co-efficient of drag. A suitable RPM sensor was mounted in order to exactly derive the RPM.

A variable rheostat was used to the load the electrical output and a voltmeter was connected in parallel to measure the voltage generated (Fig. 1).

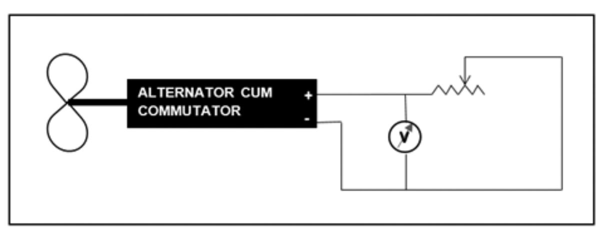

Figure 1. Wind tunnel set-up of the RAT-generator.

3. RAT MODELS CONSIDERED FOR THE STUDY

3.1 Model A

Model A was having three blades with a wetted surface area of 0.1521 square meters. The solidity ratio was 50%. The relevant details of the RAT are shown in Fig. 2.

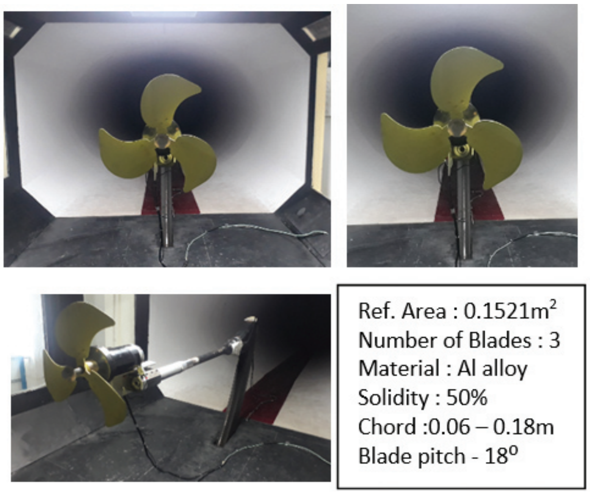

Figure 2. Details of RAT Model A.

3.2 Model B

Model B was a three bladed high drag RAT with wetted surface area of 0.1280 square meters. The solidity ratio was 70%. The relevant details of the RAT are shown in Fig. 3.

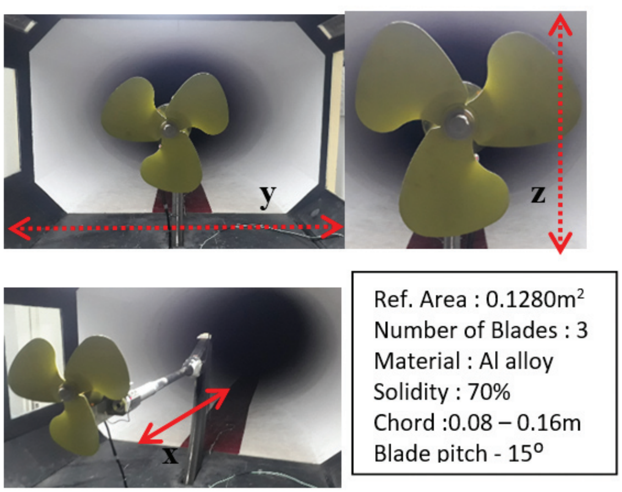

Figure 3. Details of RAT Model B.

3.3 Model C

Model C was a four bladed high drag RAT with wetted surface area of 0.1385 square meters. The solidity ratio was 85%. The relevant details of the RAT are shown in Fig. 4.

4. EXPERIMENTAL SET-UP

4.1 Wind Tunnel

The test section of the wind tunnel was 9 feet (y-axis - width) x 6 feet (z-axis - height) x 12 feet (x-axis - length). The dynamic pressure range, wind speed range and the mass flow range were adequate for conducting the wind tunnel studies of the RAT models.

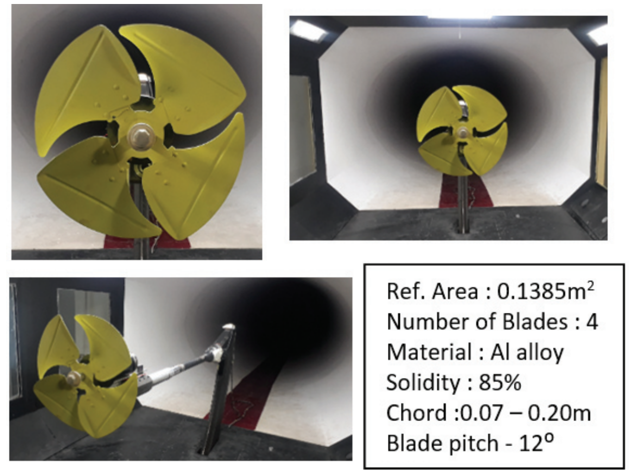

Figure 4. Details of RAT Model C.

4.2 Mounting of Model

A suitable mounting was fabricated such that models could be mounted along the central line of tunnel wind flow axis. The mounting shaft was fabricated in such a way that a six-component strain gauge balance could be accommodated inside the mounting. The strain gauge balance was calibrated to measure the horizontal x-axis force (drag) generated by the RAT models. The models were first coupled to the generator and then the model-generator assembly was mounted to the mounting boom inside the wind tunnel. The generator was equipped with a RPM sensor as mentioned above.

4.3 Strain Gauge Balance

Internal strain gauge balance with six components was used for measuring the forces and moments[6]. The forces measured along the axis of strain gauge balance was converted to the model axis using proved and available calibration model. The drag force measurement errors were within the acceptable limit for this study.

4.4 RPM Measurement

The RPM was measured using a non-contact type photo-electric sensor. A similar set-up was demonstrated for measuring RPM of a scaled wind turbine model in wind tunnel by Sivamani[12], *et al*.

4.5 Voltage Measurement

The voltage generated by the generator was measured using a voltmeter connected parallel to the load (rheostat). The voltage could be directly read using a calibrated & validated software of the wind tunnel system.

5. RESULTS AND DISCUSSIONS

Three models were subjected to the wind tunnel tests. Drag force measured & voltage generated were directly measured as explained above. The power generated (V^2/R) was computed using voltage (V) and load resistance (R) connected[6,13]. The results have been tabulated in Tables 1, 2 and 3 for Models A, B and C respectively. The power obtained for all the three models have been summarised in a graph shown in Fig. 5. The wind speed was varied between 20 m/s to 45 m/s.

Table 1. Wind Tunnel Results of Model A

Model A				
RUN No: 22139 **Reference Area**: 0.1521 m^2 **Load** : 25-30 Ohms **Reynold's Number** – 0.4 – 0.65 x 10^6 **Density of Air** = 1.123-1.126 kg/m^3				
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 2. Wind Tunnel Results of Model B

Model B				
RUN No: 22135 **Reference Area:** 0.1385 m^2 **Load :** 30 Ohms **Reynold's Number** – 0.4 – 0.65 x 10^6 **Density of Air** = 1.123-1.126 kg/m^3				
Wind speed (m/s)	**Drag force (N)**	**Voltage (V)**	**Power = V2/R (W)**	**RPM**
20	45.3	61.2	124.85	1350
25	68.2	86.4	248.83	2035
30	100.5	109.3	398.22	2564
35	143.7	122.8	502.66	3115
40	189.4	147.4	724.23	3685
45	234.5	161.4	868.33	4230

Table 3. Wind Tunnel Results of Model C

Model C				
RUN No: 22146 **Reference Area**: 0.1280 m^2 **Load** : 30 Ohms **Reynold's Number** – 0.4 – 0.65 x 10^6 **Density of Air** = 1.123-1.126 kg/m^3				
Wind speed (m/s)	**Drag force (N)**	**Voltage (V)**	**Power = V^2/R (W)**	**RPM**
20	40.1	58.3	113.30	1200
25	64.25	83.2	230.74	1750
30	88.3	102.5	350.21	2215
35	113.4	108.2	390.24	2535
40	144.7	132.5	585.21	3235
45	186.7	151.4	764.06	3765

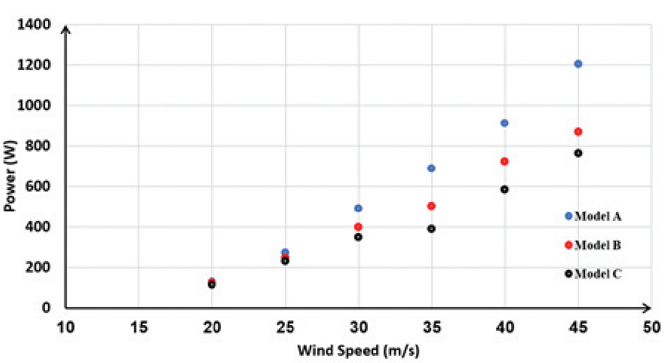

Figure 5. Power obtained versus wind speed for Models A, B and C.

In order to characterise the RAT, the drag co-efficient was derived from the drag forces measured[6,14-17]. The C_D for RAT was computed using the equation

$D = ½ \rho A V^2 C_D$ where,

ρ – density of air in kg/m^3

A – reference area of RAT in m^2

V - wind speed in m/s

The mean values of C_D were found to be 1.14, 1.16 and 1.17 for Models A, B and C respectively.

The power obtained using Model A with 50% solidity was found to be higher than both Models B and C with 85% and 70% solidity ratio respectively. Angular Velocity (Ω) in radians per second was computed, using the formula[14,17-20],

$\Omega = (2\,\pi/60) * (\text{RPM})$

Then, the tip speeds were obtained using the formula[20-23],

$T_S = (2\pi/60) * R * \text{RPM}$

The tip speed ratio (λ) was then computed using Ω, radius of the RAT (R) and wind speed (V), using the formula[19-21],

$\lambda = R\,\Omega/V$

The results are tabulated in Table 4. The tip speeds were also found to decrease with increase in solidity ratio as expected and reported by Rajesh Kumar et al in their study[13]. It can be clearly seen that with increased solidity, the power extraction was found to decrease. At wind speed of 45 m/s, the power extracted reduced from 1.2 kW to 0.76 kW when the solidity was changed from 50% to 85%.

Table 4. Angular Velocity, Tip Speed and Tip Speed Ratio of RAT Models

Wind speed (m/s)	**Angular velocity 'Ω' (rad/s)**	**Tip speed (m/s)**	**Tip speed ratio (RΩ/V)**
Model A			
20	206.72	37.21	1.86
25	252.77	45.50	1.82
30	321.85	57.93	1.93
35	392.92	70.73	2.03
40	483.56	87.05	2.18
45	567.29	102.12	2.27
Model B			
20	141.30	21.20	1.06
25	213.01	31.95	1.28
30	268.37	40.25	1.34
35	326.04	48.91	1.40
40	385.70	57.86	1.45
45	442.74	66.41	1.48
Model C			
20	125.60	20.10	1.01
25	183.12	29.31	1.17
30	231.84	37.10	1.24
35	265.33	42.45	1.21
40	338.60	54.18	1.35
45	394.07	63.01	1.40

The Co-efficient of Performance or the Power co-efficient of the RAT (*Cp*) was computed using the formula[6,16,24,25],

$C_P = P_E / P_{MaxAv}$

where, P_E is the Power Extracted and P_{MaxAv} is the Maximum Power Available in the wind is given by[24,25],

$P_{MaxAv} = 0.5*\rho*A*V^3$

ρ is the density of air (which was computed to be in the range of 1.123 – 1.126 kg/m^3), A is the reference area of the RAT exposed to wind in m^2 and V is the wind speed in m/s. The efficiencies of power generation of RAT models tested, were found to range between 10-15%. The efficiencies of the tested RAT models were within a range of 10-20%[10,14,15]. The theoretical maximum power is restricted to Betz limit which corresponds to a maximum efficiency of 59.3%[16,24].

The curve showing the power extracted and the C_P at 45 m/s for the three models are shown in Fig. 6. As seen, at 45 m/s, the power obtained, and the C_P of Model A was the highest compared to Models B and C. The tip speeds of the RAT at various wind speeds are shown in Fig. 7.

The tip speeds of Model A were relatively higher compared to that of Models B and C with higher solidity. The tip speed ratio is considered to be a good estimate of the RAT efficiency as reported by Kumar, *et al.*[13,25,26]. Efficient RATs are already being utilised in externally carried electronic warfare pods and Air to Air refueling pods. These RATs make them self-sufficient in terms of meeting their own power requirements and not depending on the mother aircraft[27,28].

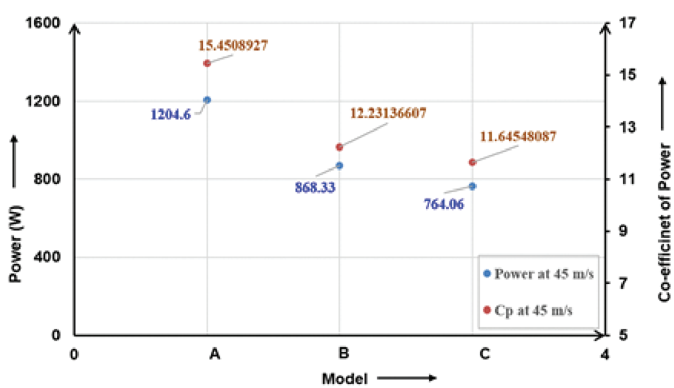

Figure 6. Power extracted and co-efficient of power of three Models at V = 45 m/s.

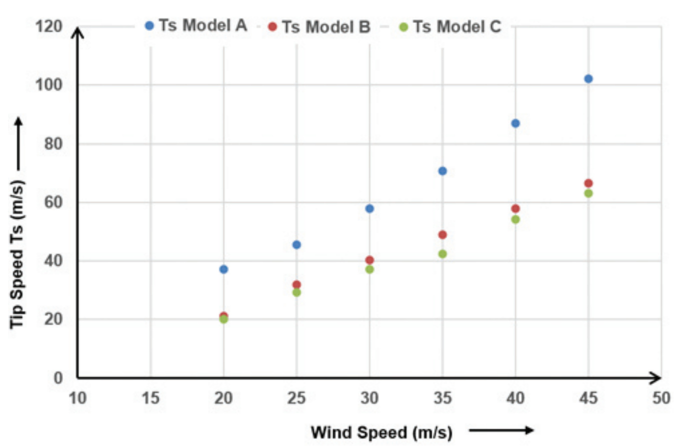

Figure 7. Tip speeds of RAT Models A, B and C at various wind speeds.

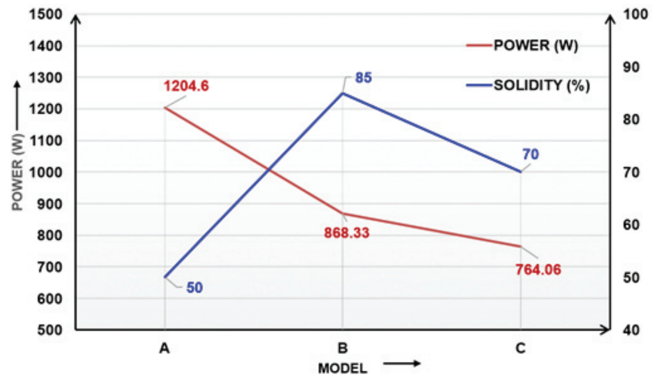

Figure 8. Solidity versus power extracted at V = 45 m/s.

The drag co-efficient of 1.14 of Model A was also comparable to the other models. For a drag based RAT, a C_P of 15% was acceptable and adequate. It can be clearly seen from the graph placed at Fig. 8, that with increase in solidity, the power extraction was reducing and the optimum solidity with the required drag characteristics was limited to 50%. Therefore, using the comparative study and analysis, Model A was selected for power generation in failure mode.

5. CONCLUSION

Additional requirement of power in failure mode during integration of new systems was experienced. In order to explore the feasibility to utilise RAT for the generation of power during failure mode, wind tunnel studies were carried out on three selected RAT models.

A specific requirement of producing adequate drag during the deployment of RAT was also provided. Based on the results of Wind Tunnel studies it was found that RAT was potential to be used for dual purposes of generating electrical energy and provide aerodynamic braking. Using this study, Model A was selected for further studies.

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He has contributed towards conceptualisation of the entire study, selection of turbines, wind tunnel studies and detailed data reduction & analysis of results. He as the first author has and drafted & structured the paper.

Mr Muralidhar Madhusudan 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 optimisation 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 conceptualised 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 characterisation of the air-brake and RAT.

Ms Ramya Arunachaleswaran has been working as a Software Test Architect in Siemens Gamesa Renewable Energy, Bangalore. She has more than 15 years of experience in the field of Software Testing and Quality Control of Wind Turbines. She is a certified Scrum Master and has successfully cleared the advanced ISTQB certification. She is specialised in the field of Wind Turbine and Farm testing and has undertaken outstation assignments in Denmark for the same.
She has provided her technical expertise on wind turbines, testing data and validation of results.

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 specialised in the field of CFD. He has published research papers in journals and conference proceedings.
He is 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.