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Experimental Characterization of Propulsion System for Mini Aerial Vehicle

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Abstract

In recent times, mini and micro aerial vehicles have shown significant potential as miniature unmanned aircraft for surveillance and reconnaissance purposes. Selection of correct combination of engine and propeller is very crucial step in the design of this class of vehicles. The objective of present study is to establish measurement system and obtain performance maps for available mini/micro vehicle class propellers and engines. Wind-Tunnel facility was developed and different experimental set-ups were designed for measuring thrust and power of different power plant systems. Results of experimental facilities were validated with those available in literature for particular power plant. Established measurement system complements for optimizing propeller design and selecting best engine or motor for given geometry of vehicle with given mission requirements.

Keywords: Mini Aerial Vehicle, Propulsion System Characterization, Wind-Tunnel Testing, MAV IC Engine, DC Electric Motor, Optimization of Propeller

Nomenclature

C_P = Coefficient of power
C_T = Coefficient of thrust
C_Q = Coefficient of torque
D = Diameter (m)
J = Advance Ratio
MAV= Mini Aerial Vehicle
N = RPM
n = RPS or Rotational frequency (1/s)
P = Power (W)
P_I = Input Power (W)
Ps = Shaft Power (W)
η = Efficiency
P_A=Power Available (W)
Q = Torque (N.m)
SFC= Specific fuel consumption (kg/W.s)
TSFC=Thrust specific fuel consumption (kg/N.s)
T = Thrust (N)
T_A = Thrust Available (N)
V_∞ = Upstream flow velocity (m/s)

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1. Introduction

Design and development of miniature unmanned aerial vehicles has recently received worldwide attention. They have wing span in the range of 0.3 to 2.5m (1 to 8 ft) and their weight lies between 1 and 10 kg with payload carrying capacity up to 1kg. With this payload capacity they can carry aerial camera, chemical/biological sensors etc for military applications, data collection, surveillance, hazard mitigation or traffic management. An electric powered, 1.7 kg class 'backpack boomerang MAV' developed for military applications is shown in fig 1 whereas an IC engine powered, 13 kg class vehicle 'Aerosonde' used for atmospheric data collection is shown in fig 2.

Fig 1: boomerang backpack UAV

Fig 2: Aerosonde MAV[9]

Whether micro, mini or macro usually for all classes of vehicles propulsion system constitutes around 60% of gross weight of vehicle (Fig 3). Sensitivity Analysis study of some of micro aerial vehicles show that an additional 0.01 N (1 gram) of drag would decrease the endurance by 180 seconds and an additional 1 gram of mass would decrease the endurance by 30 seconds[2**]. Hence sizing and weight of propulsion system plays critical role in performance of these vehicles. Propeller has been most useful as a source of thrust for conventional and contemporary small aircrafts and MAVs. Among currently available technologies small internal combustion engines and electric motors look promising as a source of power. For IC engines methanol based fuel is best energy source whereas for electric motors batteries and solar cells are good options (Fig 4).

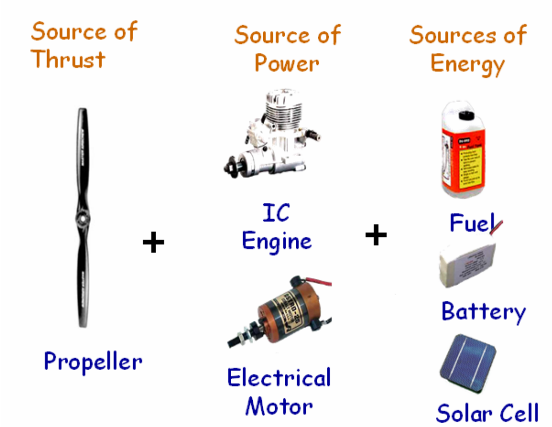
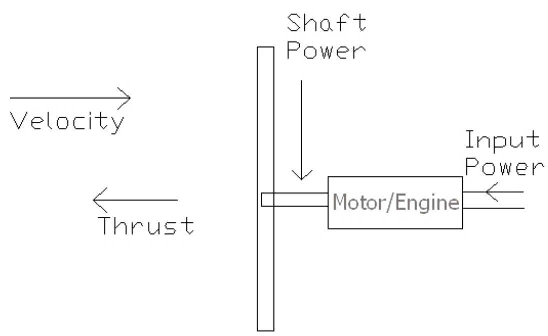


Fig 3: Ingredients of MAV Propulsion System

Fig 4: Weight Contribution in a Aircraft[2]

** Numbers written as superscript represents number of reference given at the end of paper

2. Theory and Background



Schematic Diagram of MAV Propulsion System

For aviation vehicles, best propulsion system is the one with maximum overall efficiency for given requirements and minimum weight. Overall efficiency of propulsion system is defined as product of efficiency of propeller and efficiency of power source (say motor)

$$\text{Overall efficiency} = \eta_p \times \eta_m \tag{1}$$

Where η_p is propeller efficiency given by[4]

$$\eta_P = \frac{P_A}{P_s} = \frac{T_A \times V_\infty}{P_s} = J \times \frac{C_T}{C_P} \tag{2}$$

Where P_s is power at the shaft of engine, J is advance ratio, C_T is thrust coefficient and C_P is power coefficient. J is given by[1]

$$J = \frac{V_\infty}{nD} \tag{3}$$

$$C_T = \frac{T}{\rho n^2 D^4} \tag{4}$$

$$C_P = \frac{P}{\rho n^3 D^5} \tag{5}$$

For electric motor, efficiency is measured as ratio of shaft power to the input power whereas for IC engine's performance is measured in terms of SFC and TSFC[4],

$$\eta_m = \frac{P_S}{P_I} \tag{6}$$

$$SFC = \frac{Fuel\_mass\_flow\_rate}{Power} \tag{7}$$

$$TSFC = \frac{Fuel\_mass\_flow\_rate}{Thrust} \tag{8}$$

3. Design and Development of Experimental Facilities

3.1 MAV Wind Tunnel Facility

Wind-tunnel of test section size 1m x 1m x 1.25m has been developed at CASDE, IIT Bombay specifically designed for propulsive and aerodynamic testing of MAV (Fig 5). It is a closed Jet open circuit tunnel. Air inside the tunnel is circulated using two 10HP, 960 RPM motors controlled using a 440V and 30A auto-transformer. This tunnel is suited for experimental testing of MAV as it provides flow velocities in the range of 0-25 m/s which is the operating range of MAV usually. Test-section has been designed in such a way that a 0.6m x 0.6m (2ft x 2ft) MAV model or prototype can be mounted inside tunnel for aerodynamic load measurements (Fig 6). For propulsion system testing Power Measurement set-up (Fig 7) and Thrust Measurement set-up (Fig 8) are mounted inside tunnel using various fixtures. This enables in-situ testing of different propeller-engine or propeller-motor combination.

Fig 5: MAV Wind-Tunnel Facility, IIT Bombay

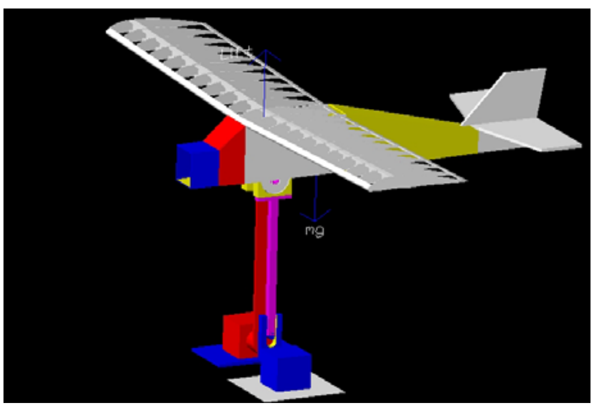


Fig 6: CAD-Drawing of MAV model mounted inside wind-tunnel on Load Balance

3.2 Power Measurement Set-Up

Power Measurement Set-up (Fig 7) uses a torque sensor at the centre with the propeller and motor mounted on either side of sensor. For principle, one can visualize a central shaft from motor at extreme right to propeller at extreme left passing through sensor. This central shaft is mounted on four bearings, two on either side of the sensor. On one end motor works as prime mover whereas on other end, torque required to run propeller is measured by the sensor. Product of this torque with rotational velocity gives the shaft power (P_s). Power losses in bearings are measured by running the motor on this set-up under no load condition (without propeller) and characteristics of power loss as a function of RPM is obtained. Lower block shown in fig is a channel, selected to minimize the blockage behind the propeller. Inside this channel a small optical RPM sensor is mounted. RPM sensor consists of an infra red light transmitter and a receiver. Light emitted by transmitter is reflected from white patch painted behind the propeller. Receiver generates a count each time it receives reflected light which gives RPM.

Fig 7: Power Measurement Set-Up

3.3 Thrust Measurement Set-Up

Thrust measurement set-up uses a load cell of capacity suitable for MAV class propellers (here 6 kg load cell was used). DC electric motor clamped between two C-clamps fixed on perspects bench is mounted on one end of load Cell. Other end of load cell is clamped to rigid support. This load cell works as cantilever beam. Thrust produced by propeller acts normal to the vertical axis of load cell and equal amount of force is registered at one end of load cell as shear force. RPM is measured using optical sensor as explained in previous section. As this set-up is mounted inside the tunnel for measuring thrust produced by the propeller at different flow velocities, drag produced by set-up is significant. Hence drag coefficient of set-up is obtained experimentally and correction for drag of set-up is incorporated.

Comprehensive list of instruments used for measurement purpose with details is given in Table 1.

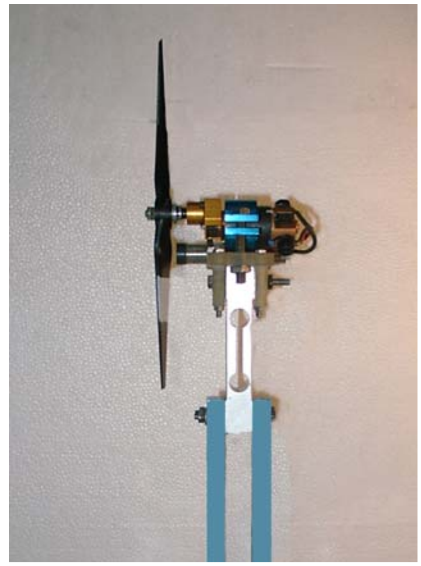


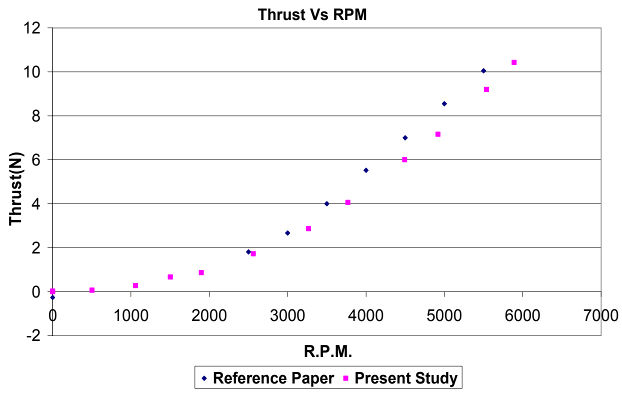
Fig 8: Thrust Measurement Set-Up

Table 1: List of sensors used and their Parameters

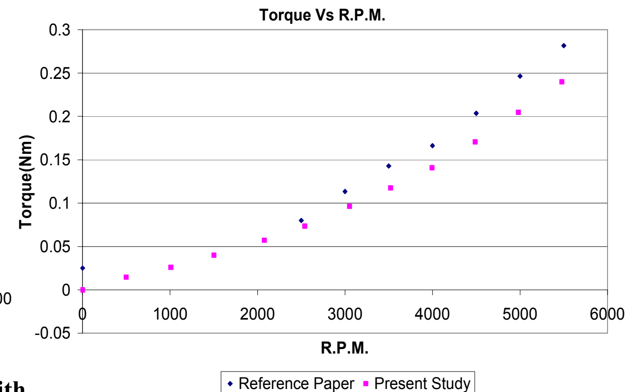
Sr. no.	Parameter	Sensor	Image
1.	Thrust produced by propeller	Load Cell	
2.	Torque at the shaft of motor	Torque Sensor	
3.	Flow Velocity inside tunnel	Pitot-tube and Micro-manometer	
4.	Voltage and Current consumption of motor	DC Regulated Power Supply	
5.	RPM of propeller	Optical Sensor	
6.	Room temperature and Pressure	Digital Barometer	

4. Validation of Experimental Set-Ups

A 12X8 APC propeller [12 inch is diameter and 8 inch is pitch (0.3X0.2 m)] for which thrust and torque (or power) characteristics are available in literature is used for validation of experimental set-ups. Graphs 1 and 2 compare measured thrust and torque with that available in literature. Present study shows 10% less in measured thrust values (at 5000 RPM) which can be attributed to drag of different set-up in slipstream for which correction has not been incorporated. In case of Torque measurement, reference paper data has not been corrected for zero RPM Torque hence showing consistently higher values for all RPMs. This exercise confirmed that results given by set-ups are reliable and experiments can be performed on propellers and motors for which data is desired.



Graph 1: Comparison of Thrust Characteristics with that given in paper[3]

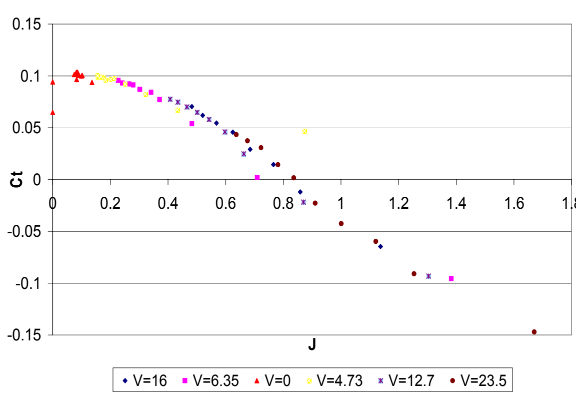


Graph 2: Comparison of Torque Characteristics with that given in paper[3]

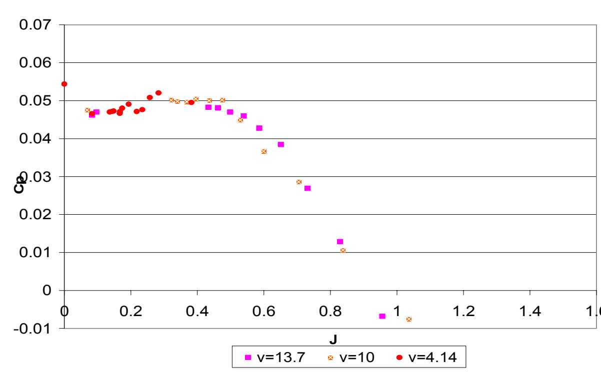
5. Applications

5.1 Characterization of Propeller

2.5 kg class vehicle 'Kadet' which is under testing and development stage at CASDE, IIT Bombay uses an 11 inch (0.28 m) diameter propeller. Hence characteristics for series of 11 inch diameter propeller were required to be determined. Four 11 inch series Master Airscrew propellers[6] (11X7, 11X8, 11X9 and 11X10) were tested out of which results for 11X8 have been given in Graphs 3 and 4 and maximum efficiency is coming to be 70%. Velocity of tunnel is kept constant and RPM of propeller is varied from zero to maximum to cover certain range of J. Similarly, it is repeated at different velocities to give values of parameters (Thrust and Power) for whole range of J from zero to wind-milling condition. At each J, C_T is obtained by measuring thrust whereas C_P is obtained by measuring torque.



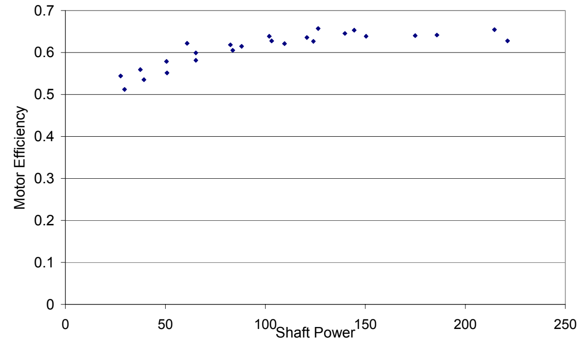
Graph 3: C_T Vs J for 11X8 Propeller



Graph 4: C_P Vs J for 11X8 Propeller

5.2 Characterization of Electric DC Motor

Selection of motors for MAVs is done on the basis two parameters, motor efficiency (equation (6)) and its shaft power to weight ratio. Higher the value of these parameters better is the motor, given it satisfies absolute sea level power requirement for the vehicle. Astroflight Cobalt geared motor[7] (model no. 615G) was tested with 11X7 propeller. Motor efficiency Vs Shaft Power characteristic is been given in Graph 5. Over a wide range of power motor efficiency is constant at 65 %. The value of shaft power to weight ratio for this motor is determined as 0.9 kW/kg.



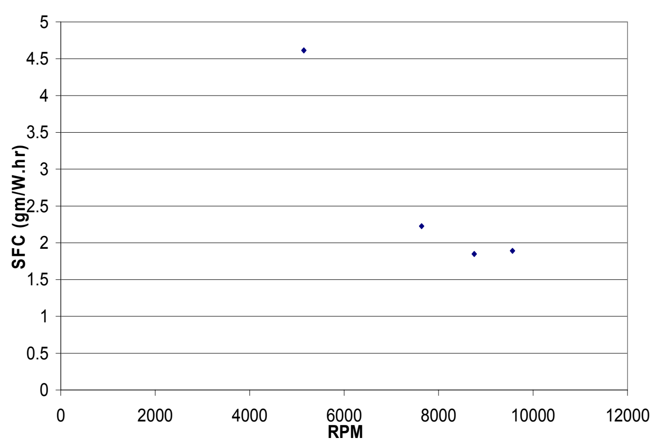
Graph 5: Motor Efficiency Vs Shaft Power for Astroflight 615G motor

5.3 Characterization of IC Engine

Set-up used for IC engine characterization (Fig 9) is extended version of thrust measurement set-up explained in section 3.3. Here objective is measuring TSFC and SFC at different engine RPMs. SFC or TSFC depends on the propeller, engine and fuel. Here Master Airscrew 11X7 propeller was tested along with OS MAX 0.46LA engine[8]. Fuel chosen consists of 75% Methanol, 20% Castor Oil and 5% Nitromethane. Along with main thrust measuring load cell, set-up consists of a stand fixed at distance of 1.5 ft from propeller. Fuel Tank is mounted on a load cell (This load cell functions as a weighing balance) clamped to base plate of back stand. Throttle of engine is controlled using servo rigidly clamped to base plate. Servo controls the throttle through a control rod. External pipe is provided for taking exhaust gases and oil out of lab.

Fig 9: IC-Engine Set-Up

During experiment engine is kept at fixed throttle setting to give constant RPM. Weight of fuel consumed is recorded in every minute for 10 minutes. As RPM is maintained constant, propeller produces constant thrust which is measured from main load cell. Hence Value of TSFC can be obtained using equation (7). Procedure is repeated for different RPMs. As every time, operating value of J is known, using C_P Vs J characteristics shaft power can be determined hence SFC can be obtained using equation (8). Graph 6 shows SFC (gm/W.hr) at different RPMs (under static flow conditions) for above mentioned combination of propeller, engine and fuel. In future this exercise will be repeated for different fuel, engine and propeller combinations.



Graph 6: SFC Vs RPM

6. Conclusions and Future Work

1) Literature survey and Preliminary analysis reveals that performance of propulsion system plays critical role in overall sizing and performance of micro and mini class aerial vehicles. Hence availability of experimental facilities for accurate power plant characterization is basic requirement for development of MAVs.
2) Different experimental facilities were designed and developed for experimental characterization of MAV power-plant. Validation of results obtained using these facilities with those available in literature reinforced the reliability of these facilities.
3) Developed infrastructure was successfully used to determine the required characteristics of propeller, engine and motor which are being considered for design of 2.5 kg ‘Kadet’ MAV here at CASDE, IIT Bombay.
4) Propeller characterization tests results show that propellers available in market are customized and have efficiency in the range of 50% to 70% for a particular operating range of J. Literature survey and Blade Element theory based analytical tool reveals that propeller design can be improved to give efficiency of the order of 80% for any given operating range of J[5,2].
5) Next exercise will be optimization of propeller design for given requirements. Optimized propeller will be developed using analytical tool (Blade element theory) coupled with an optimizer. Prototype based on optimized design will be tested experimentally and results will be compared with analytical results.
6) Similarly, by testing set of motors, motor of higher efficiency and higher shaft power to weight ratio for given seal level power condition can be selected.
7) On the same logic, best IC engine can be selected.
8) Based on historical data and experience, DC motor is best suitable for low endurance flight and low weight MAVs whereas IC engine is best suitable for high endurance flight and heavy MAVs. So mission requirements primarily govern the choice among these two.

References

1.Anderson, J.D. (2000),”Introduction to Flight”, Mc Graw Hill publishing company, Fourth Edition, page no. 595-602.
2. Joel M Grasmeyer and Matthew T Keennon (2001), “ Development of the Black Widow Micro Aerial Vehicle”, AIAA-2001-0127.
3. Jason Gaza, Kortny Hall, Ed Marks (2001), “Propeller Characteristics”, Dept. of Aerospace and Mechanical Engg. , University of Notre Dame, AME 342-05
4. Raymer D.P.(1999), “Aircraft Design: A Conceptual Approach”, third edition, AIAA education series, page no. 15-29,379-400
5. Martin Hepprele Home page (2004) “Aerodynamic Characteristics of Propellers”, Hepprele Airfoils. <http://beadec1.ea.bs.dlr.de/Airfoils/propuls3.htm>
6. Master Airscrew Propellers website (2004) <http://www.masterairscrew.com/techbull.asp>
7. Astroflight Cobalt Motros website (2004) <http://www.astroflight.com>
8. OS Max engines website (2004) <http://www.osmasxengines.com>
9. Aerosonde Official website (2004) <http://www.aerosonde.com>