Title: Design of Efficient Propeller for Flight in Thin-Density Atmosphere

In-depth literature review showed that at Reynolds number (Re) <60,000, propeller performance predictions begin to depart from wind tunnel test data. Several research point towards poor quality 2D airoil data as a major reason why these disagreements exist. While many commercial micro sized unmanned aerial vehicle propellers are available today, optimum performance are obtained by operating the propellers at Reynolds numbers >100,000 where better performance is likely. Below Reynolds number <60,000, propeller performance significantly drops off. A low Reynolds number propeller design method that accurately predicts propeller performance and reduces discrepancy between theoretical performance prediction and wind tunnel tests would establish the groundwork from which improvement in efficiencies can be pursed. This work is focussed on improving performance prediction for propellers operating at Reynolds numbers <25,000.

Over the last three decades and a half, there has been huge effort to develop high performance propellers suitable for flight in the rarefied Martian atmosphere. At low Reynolds number below 30k the aerodynamic flow physics makes accurate measurement of forces acting on an airfoil force difficult. Propeller are particularly attractive because they can be operated using electrical energy, avoiding the use propellants or fuels. Hence, propellers have been tipped as one of the most promising means of unmanned aerial vehicle propulsion in Mars. Achieving flights in the rarefied Martian atmosphere would require a propeller-driven air vehicle to operate at Reynolds number between 10^4 to 10^5. However, since propellers rotate and translate in the fluid medium in which they operate, the problem of flying in Mars atmosphere is compounded by low speeds of sound, which in turn restricts propeller tip speeds or length.

The first section of this thesis describes work undertaken in validating vortex theory in the design of a heavily loaded propeller with high solidity and chord-based Reynolds number of ≈60k (calculated at 75% radius) at design point. the entire blade design was made using SD7037 2D airfoil experiment data. The data was collected at Reynolds number of 60,000. At design advance ratio, more than 50% of the entire blade radius operated between 40,000 – 60,000 Reynolds numbers. This was a deliberate design to minimize variation in Reynolds number from hub to tip radius. Wind tunnel tests of the fabricated propeller was carried out in an Eiffel-type, open-no-return wind tunnel at Kyushu Institute of Technology.

The second section of the thesis focusses on investigating discrepancies between theoretically predicted propeller performance and wind tunnel test data at Re ≈ 25,000. The challenge of analysing propeller performance designed to operate within this low Re number flight region is in two folds: (1) Blade Element Momentum Theory (BEMT) code as applied in the design and analysis of propellers operating at Re >5 x 10^5 does not adequately apply to Re <6 x 10^4; (2) at Re < 60,000, obtaining reliable 2D airfoil experiment force data becomes increasingly challenging, largely because of the inherent difficulty in measuring aerodynamic forces acting on an airfoil. To overcome the latter problem, 2D airfoil data at this Reynolds number regime of interest (≈25,000) where experiment data is unavailable, Xflr-5, a numeric code was used to predict the 2D airfoil force data. Then using the airfoil data from numeric source, a propeller was designed to operate at 20k Reynolds number. The propeller design was carried out using a Minimum Induced Loss BEMT code Xrotor. Airfoil lift and drag estimates are approximated in Xrotor using a linear function for lift and a quadratic function for drag coefficient. The use of functions in estimating airfoil lift and drag data makes Xrotor a good design tool to under study relationship between airfoil force coefficients and propeller performance. Parameters in the lift and drag estimation functions in Xrotor can be individually manipulated and the overall effect on propeller performance can be isolated and theoretically studied. Using Xrotor, a propeller designated as SDL18M was designed, fabricated and tested at Kyushu institute of technology wind tunnel facility. The result show discrepancy between predicted propeller performance and wind tunnel test data. Through a careful manipulation of four (4) key parameters in the functions defining lift and drag in Xrotor, it was possible to match predicted propeller performance to wind tunnel test. Following a successful performance matching, a semi-empirical correction function that corrected the flow velocity relationships in the wake and plane of the propeller in classical BEMT formulation was developed. Figure 1 captures velocities at the wake and induced velocities due to propeller action at the propeller plane.

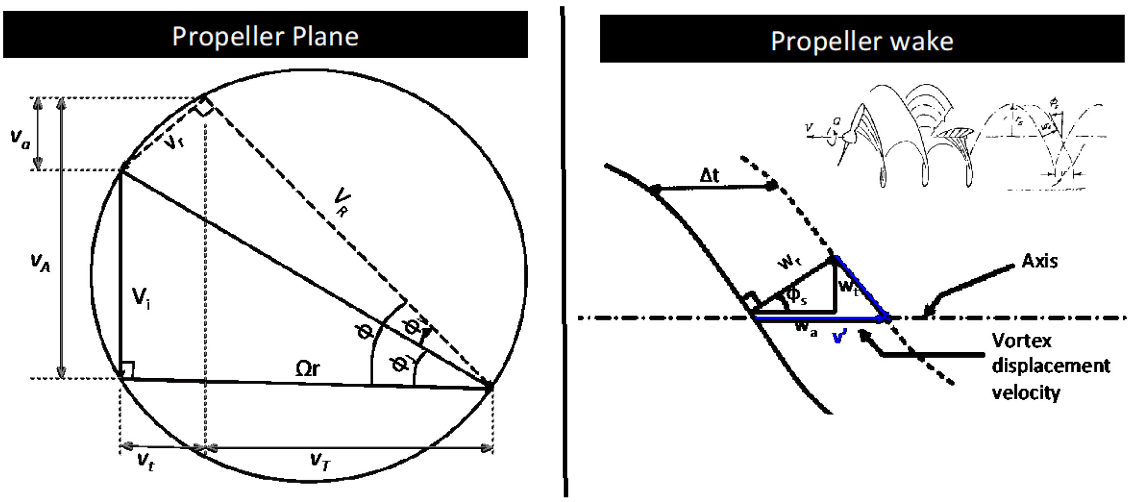

Figure 1: Propeller wake velocities and induced velocities at propeller plane

The third of the dissertation deals with the application of the semi-empirical correction function developed in the previous section on propeller design. A BEMT code was written in Matlab in which semi-empirical correction function was integrated. 2D airfoil force data is supplied to the BEMT code in a M by N matrix chart which can be populated with data from either experiment sources or numerical code. However, because the Reynolds number regime of interest in this work are in the orders not available from experiment, airfoil force data was obtained from Xflr-5 by setting Ncrit value of 1. Utilizing the developed BEMT code, two (2) propellers designated as SDL20Y and SDL20Y-2 were designed, fabricated and tested in wind tunnel experiments. SDL20Y-2 is a 2-bladed unmodified propeller design output from classical BEMT code written for the purpose of this work, while the design of SDL20Y was modified by applying the semi-empirical correction developed in the course of this research. Beside the semi-empirical correction applied in the design of SDL20Y, all other design parameters were kept exactly the same with SDL20Y-2.

Conclusively, wind tunnel tests from both propellers showed that when compared with SDL20Y-2, SDL20Y has excellent agreement between predicted performance and wind tunnel test data. Hence, the semi-empirical correction functions proposed in this work were shown to be effective in accounting for uncertainties from 2D airfoil data from Xflr-5 by modifying the propeller wake and induced velocities relationship in the BEMT code around Reynolds number of interest, which is 25,000. The table below capture the propeller models and a brief description of each of the three propellers.

Table 1: Three model propellers used for study: SDL20M, SDL20Y-2, and SDL20Y.

Designation	**Model**	**Description**
SDL20M		The blade shape is a direct output from Xrotor. Semi-empirical correction function was developed by manipulation of lift and drag function parameters in Xrotor.
SDL20Y-2		The blade shape is a direct output from BEMT code – no corrections on the induced velocities were made.
SDL20Y		The blade shape output from Xrotor was corrected by applying corrections on the induced velocities. The correction functions are shown in equations 1 and 2 below.