THE AERODYNAMIC DESIGN OF AN OPTIMISED PROPELLER FOR A HIGH ALTITUDE LONG ENDURANCE UAV

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Abstract

The aerodynamic design of a propeller optimised over a given flight profile is presented. The initial design is carried out utilizing a method based on minimum induced loss theory in order to obtain a relatively optimal solution. This is followed by a final optimisation of the blade geometry to maximize the mission effectiveness of an Unmanned Air Vehicle (UAV).

1 General Introduction

The design of a propeller for use on an airframe that climbs from sea level to 15 000m is an interesting exercise. A propeller designed for flight at high altitudes does not necessarily perform well at the lower altitudes and flight at an altitude of 15 000m can itself be difficult. Optimising of the propeller is required in order to maximise effectiveness over the flight profile.

This paper goes about describing the design and optimisation process of just such a propeller for use on a High Altitude Long Endurance (HALE) Unmanned Air Vehicle (UAV).

2 UAV Concept

The need for reconnaissance of the long coastline and borders of South Africa is of national interest. Fishing by other nations within our territorial waters and border crossings by illegal immigrants warrants the need for monitoring.

A HALE UAV platform that could patrol long distances at sufficient altitude not to conflict with commercial air traffic was considered. A total range of 2 500km was envisaged at a ground speed of approximately 60m/s.

The UAV considered in this paper does not exist. The parameters describing it are based on a previous study undertaken by the author some years ago [1].

The airframe concept is a high aspect ratio twin-boomed configuration surveillance platform intended for assisting in border or coastal patrols. It is envisioned to be powered by a Rotax 912 engine, turbocharged to maintain 80hp to an altitude of 15 000m. The pusher propeller is connected to the engine through a speed reduction system mounted at the rear of the fuselage. See Figure 1. for configuration.

The diameter of the propeller has been limited to 2.8m for ground and boom clearance reasons. For maximum efficiency, this diameter was chosen for this study.

In order not to compromise the propeller design to the detriment of overall system performance, it was assumed that the UAV is assisted in acceleration in the take-off phase to a climb speed of 5 knots above stall speed. Once sufficient velocity has been attained, the UAV continues with the mission under its own power. As will be seen later the speed attained during this initial phase has a relatively large effect on the final propeller design.

3 Assumptions

Changes in atmospheric conditions with altitude are assumed to correspond to the International Standard Atmosphere (ISA) even though the temperatures peculiar to South Africa are generally greater than those of ISA. This choice has been justified as it is expected that the take-offis would be carried out relatively early in the mornings or later in the evenings to avoid commercial air traffic and the relatively strong mid-day turbulence found in many areas of the country.

The minimum climb rate of the UAV was set to be a minimum of 2.5m/s throughout the climb phase to minimise the time passing through commercial air traffic altitudes.

The flight profile followed is a climb from sea level at maximum power to 15 000m followed by cruise flight at minimum drag speed at 15 000m for as far as possible followed by a descent back to sea level. Maximising mission effectiveness was defined simply as maximising distance covered.

At 15 000m the UAV is flying above the troposphere. The local air density is approximately one sixth of that at sea level and the speed of sound is approximately 20% lower than that at sea level.

A useful mass of fuel of 100 kg was assumed. Due to the efficiency of the airframe and its operational altitude, the size of the fuel reserves needs to be relatively small. They were ignored in this study.

The effects of wind have been ignored in this study.

4. Design Process

The propeller initial design is based on the minimum induced loss principle first expounded by H Glauert [2], [3] and S Goldstein [4], earlier this century. Their work was resurrected by E Larrabee in 1979 [5], [6] and published in an easily understandable form that has formed the basis from which various man-powered aircraft groups and others have developed their propellers.

There are three assumptions made in the method: small angle approximations are used, low disk loadings are assumed and the expressions for the induced velocities do not include viscous terms. The effect of these limitations on the outcome is minimal for lightly loaded propellers such as that being applied here.

The method is useful for the design of a propeller operating at a particular point characterised by disk loading, flight speed, air density, rotational speed and number of blades. It was felt that this method would be applicable to the design of a propeller for a HALE UAV that maintains flight at an optimal lift coefficient and hence flies within a relatively small speed range.

The method requires inputs of power, rotational speed, diameter, velocity and the radial distribution of lift coefficient and drag/lift ratio. The first three parameters are relatively easily chosen as functions of the engine and airframe geometry. The latter two require some experience and circumspection.

The initial propeller design is carried out using this method.

The analysis routine used to predict the off-design propeller behaviour is a radially graded momentum theory based on Glauertís and Larrabeeís work. This method showed small errors when analysing the propeller at its design conditions. These are partly due to the approximations inherent in the method and partly due to the actual aerofoil data being used in the analysis being more accurate than the simplified data used in the design algorithm.

The analysis is an iterative method that predicts local angle of attack radially along the blade and hence the thrust produced and power absorbed by the blades. The solution requires few iterations to converge from even relatively inaccurate initial estimates of the local angle of attack.

Over the flight profile the pitch of the propellers has to be altered through large angles to match the engine power and flying conditions.

One of the limitations of this method is that at the relatively large negative pitch angle required of some propeller designs at low speeds, the pitch angle at the stations near the blade tips change sign. This causes discontinuities in the analysis code and usually causes erroneous predictions of power. This in turn reduces the chance of convergence.

It would be irresponsible to use gradient methods to optimise the blade parameters unless the initial starting point was chosen quite carefully.

As the intention of this exercise was to produce a propeller that would perform as efficiently as possible, it was expected that the range of pitch angles required of the propeller over the flight profile would have to be limited. Optimally one would want the range of pitch angles to be such that the local aerofoil sections do not operate out of their useful range of angles of attack.

In addition, as mentioned previously the accuracy of the analysis method is best when predicting performance not too far from the design point. The method chosen here to determine the starting point for the optimisation was to design a propeller that was optimum for a flight condition close to those which the UAV would experience but that would require a limited range of pitch angles.

Once such a propeller geometry had been found, the effect of small variations in its geometry would be evaluated to further optimise its shape. It should now be possible to use a gradient method to converge to an optimal solution using the graded momentum theory analysis.

5. UAV Performance

The UAV airframe performance was previously estimated at discrete altitudes over a similar flight profile [1]. The altitude-corrected drag profile for the UAV was used in all further work.

Based on a revised propeller efficiency and power requirements, an estimate was made of fuel consumption over the flight profile. The optimum climb velocities based on the aircraftís characteristics were then calculated and one iteration carried out to determine a more accurate fuel usage and hence optimise the flight velocities for each phase of the flight profile.

6. Engine Performance

The Rotax 912 ULS engine performance data and fuel consumption figures were entered into the analysis code.

A speed reduction ratio of 1:4 was assumed at the outset and was not changed throughout the process. This ratio was chosen to produce a maximum tip Mach number of 0.7 over the flight profile based on the original estimated flight data and the maximum propeller diameter of 2.8m. This was below the critical Mach number for the tip aerofoil section.

7. Propeller Performance Estimates

In order to obtain an idea of both the geometry and more importantly the characteristics of optimal propellers for each flight condition, propellers were designed for the conditions found at various points in the flight profile.

These propeller geometries were analysed to identify the types of aerofoil characteristics that were needed throughout the flight.

The variation in blade geometry and twist distribution can be seen in Figures 2. and 3.

The radial variation in Reynolds Number and Mach number are illustrated in Figures 4. and 5.

An initial estimate of drag/lift ratio for the sections of 0.02 was made for each radial station in order to produce a first order solution. The CL range chosen varied linearly from 0.7 at the root to 0.4 at the tip. The lift coefficients were chosen to be approximately 10 degrees away from their expected stall angles in order to allow for the pitch angle changes required at the low speed end of the design.

It was interesting to note that due to the large diameter and even with low advance ratios the tip velocities are sufficiently high that any concern around low Reynolds numbers for the potentially small chord sections especially near the tips is unfounded. At the root the Reynolds numbers approach zero due to the very small local chord and the relatively low speeds, however, the effect of aerofoil inefficiencies in these areas on the overall blade efficiency is very small.

The propeller was then analysed at increments in altitude of 2 000m up to 14 000m and then at an altitude of 15 000m for flight speeds corresponding to minimum power and maximum efficiency at the expected fuel load and at the final fuel load.

8. Aerofoil Data

The bounds of the aerofoil section requirements in terms of Reynolds and Mach numbers and expected lift coefficient ranges had been determined enabling an initial look at the characteristics required of the aerofoils. A series of aerofoils were then designed for these conditions at their particular radial position using both the well-known Eppler [7] and Xfoil [8] codes.

The basis for these aerofoils was a series of existing sections designed by Martin Hepperle [9]. The aerofoils were modified to produce the expected characteristics required by the propeller.

The aerofoil characteristics were analysed over various Reynolds numbers and angles of attack in order to determine their characteristics. However, one limitation of both the Eppler and Xfoil codes is their inability to predict post-stall behaviour. Due to the range of angles of attack that the propeller sections were expected to undergo, the post stall lift coefficient loss is an important parameter.

An assumed loss of 30% of the maximum lift was assumed. The drag curve was simply extrapolated through the stall angle.

Initial assumptions of drag/lift ratios are required for input into the design code. These values have a small but noticeable effect on the final blade planform.

The various aerofoils were analysed over the expected range of Reynolds and Mach numbers using Xfoil. These parameters were used in an iterative fashion within the design code.

9. Optimised Propeller Performance

In optimising a propeller design there are a large number of parameters that can be varied, diameter, pitch, pitch distribution, chord distribution, rotational speed, etc. It would be difficult and time-consuming to let a optimisation routine loose on the design without choosing a relatively optimal initial point.

It was thus important to determine the bounds within which designs could exist which could perform throughout the flight profile without exceeding the aerodynamic limits of its aerofoils at any radial station (apart from possibly the inboard 10% of radius where the effect is relatively small).

Through designing a number of propeller geometries which demonstrated these characteristics, the bounds of the useable design space were determined.

From such analyses it became apparent that once such an initial design has been chosen, the improvements gained through optimisation of the blade planform would be relatively small.

These propellers were defined not by their geometries but by their design inputs. Thus a propeller designed for full power at 10 000m at 50m/s would be analysed over the flight profile to determine its performance and the range of pitch angles that it would be required to move through. In this particular case the analysis would not be able to converge at the low speed end due to the tips of the blades acting at a negative angle of attack as the pitch reduces to match the available power from the engine at low speeds.

Quite often, due to the erratic nature of the prediction method, when some of the blades exceed pitch angles of 13 degrees or less than -10 degrees it often happened that a propeller not that different from those which worked well may not converge to a solution. While it may be unreasonable to discount those propellers on the basis of there possibly being a not sufficiently robust convergence method, it however also became obvious that the propellers whose pitch angle change within the flight profile was too large generally produced lower performance.

The final solution space was - not surprisingly - bound by propellers designed for a mid range of parameters ñ a power of approximately 30kW at 10 000m for an airspeed of approximately 30m/s.

When the performances of these propellers were compared against each other, the climb performance differences resulted in times to climb to altitude that varied by of the order of 10% of the climb time. That is approximately four minutes out of the approximately forty minutes required to reach altitude.

However, the variation in cruise time and hence cruise distance between the various propellers was a much smaller percentage and the potential variation was sometimes lost within the increment of 10 minutes used in time stepping the cruise performance prediction algorithm. While reducing the time increment with which the flight duration routine is solved would be a way to improve the accuracy of the solution, it was felt that the other inherent inaccuracies of the method would then play a larger role in the results.

As the differences in performance of the UAV with the various propellers were relatively small but continuous over the solution space, a series of gradient methods was used to select the optimal propeller. The chord and twist distributions were globally varied (all increased or decreased by the same factor radially) to result in the optimal propeller geometry shown in Figures 6. , 7.and 8. Further modifications to the geometry resulted in lower performances.

The range of pitch angles attained by the propeller over the flight profile is illustrated in Figures 9. plotted against altitude, and 10. plotted against velocity. Note that the angles remain within the predicted optimal performance range of -10 to 13 degrees.

The final propeller design matched to the airframe produces the following results: time to climb to altitude is 41.5 minutes and a range of 2 550km is achievable albeit with the first 90kms being the climb portion of the flight profile.

Thus, the design requirements for 2 500 km cruise at 15 000m is only just not attained. However, in the context of the requirements being somewhat arbitrarily chosen, the overall result appears to be acceptable.

10. Conclusions and Recommendations

The optimisation methodology used to produce the propeller design is somewhat unusual in that a propeller optimised for a particular flight condition is used as the baseline geometry and is only slightly modified in overall chord and twist to obtain the optimal performance. However, this method modifies fewer variables to produce an optimal propeller. How close it is to producing the optimum propeller remains unknown.

11. References

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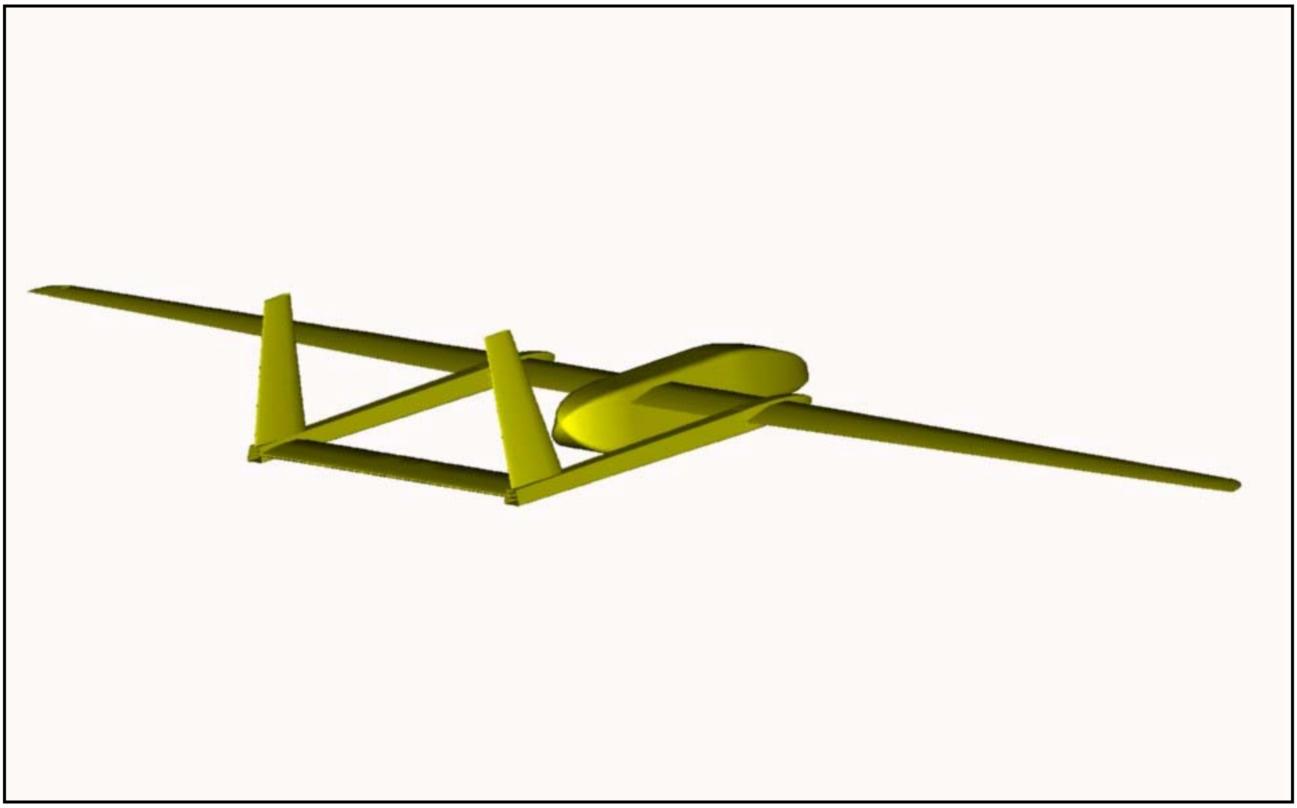

Figure 1 HALE UAV Concept

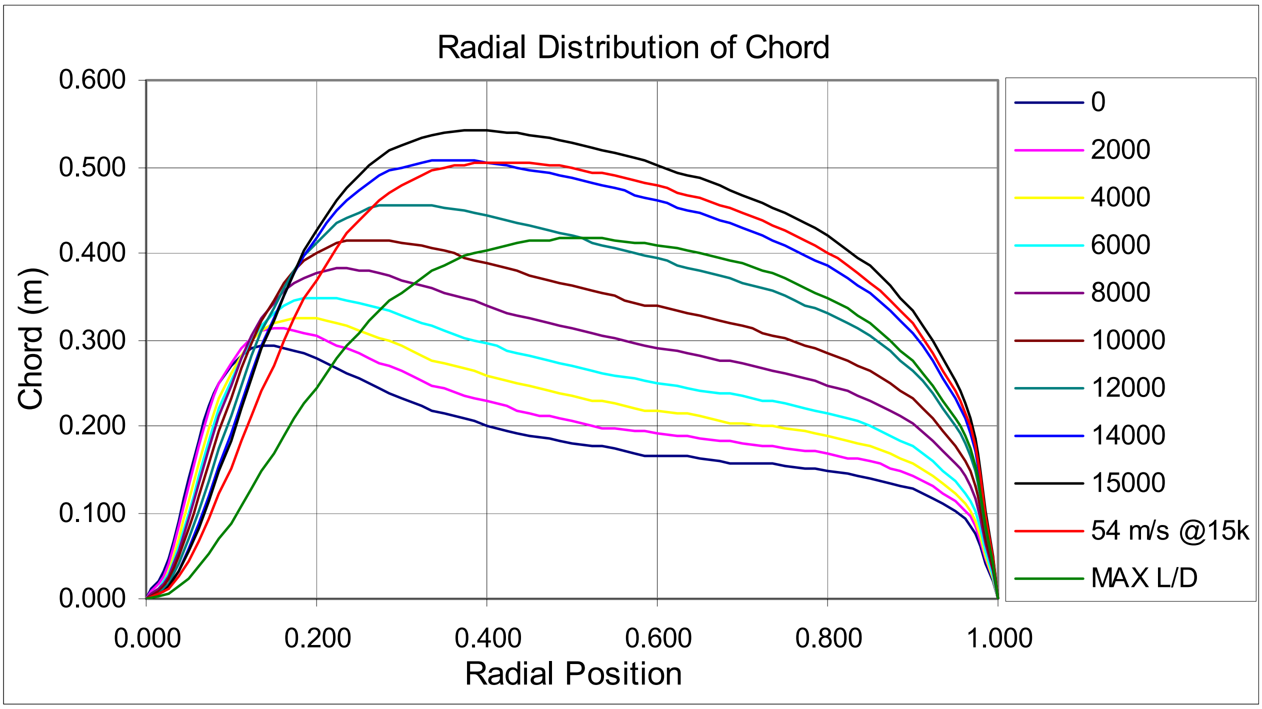

Figure 2. Radial Distribution of Chords for Various Optimal Propellers

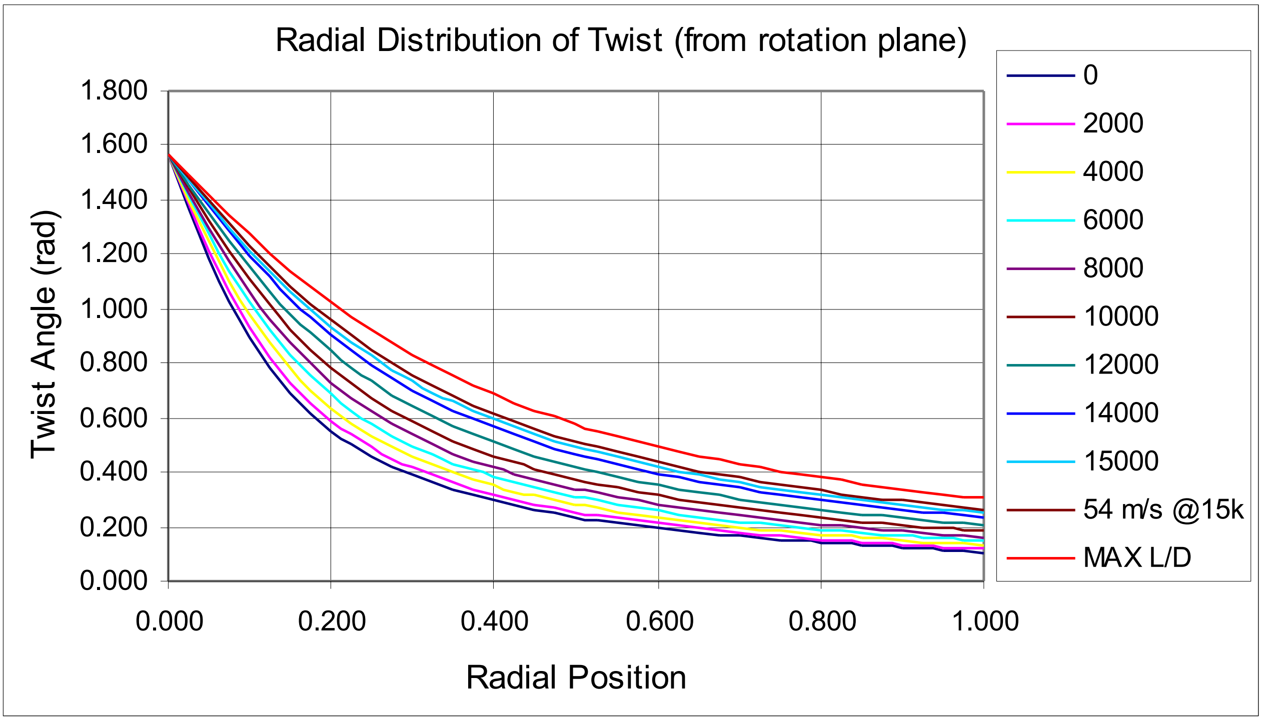

Figure 3 Radial Distribution of Twist for Various Optimal Propellers

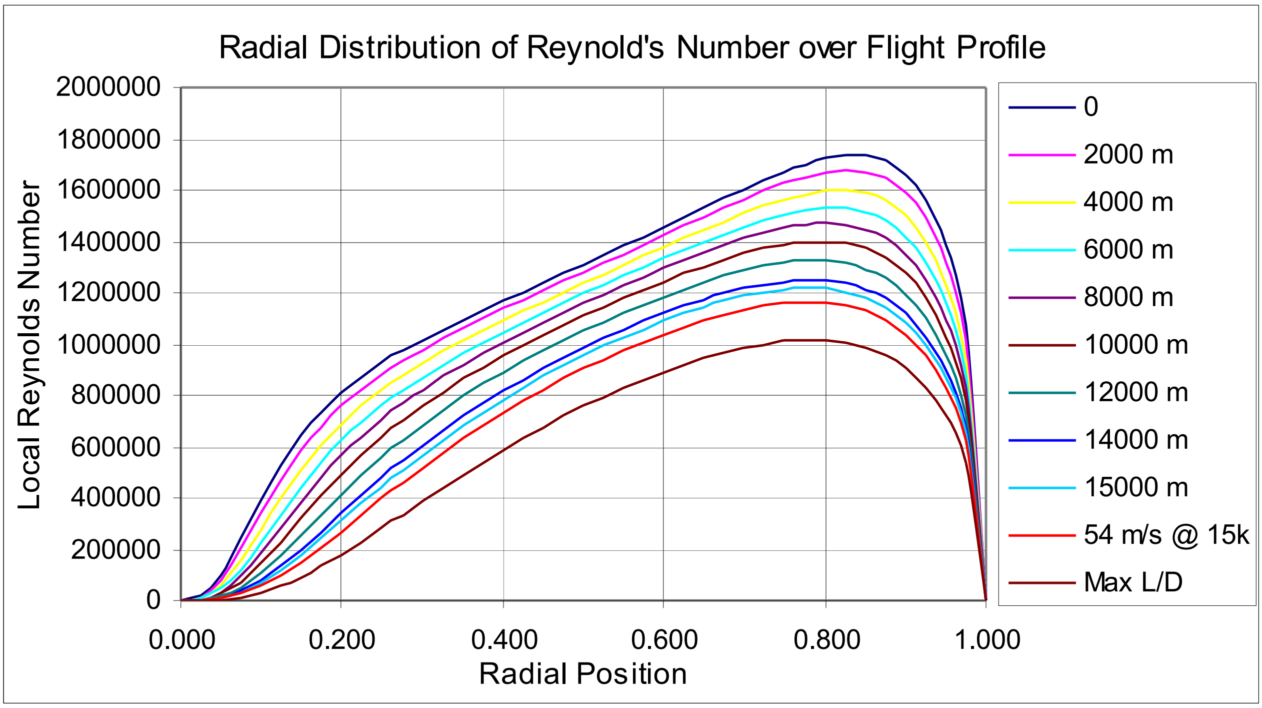

Figure 4 Radial Distribution of Reynolds Number for Various Optimal Propellers

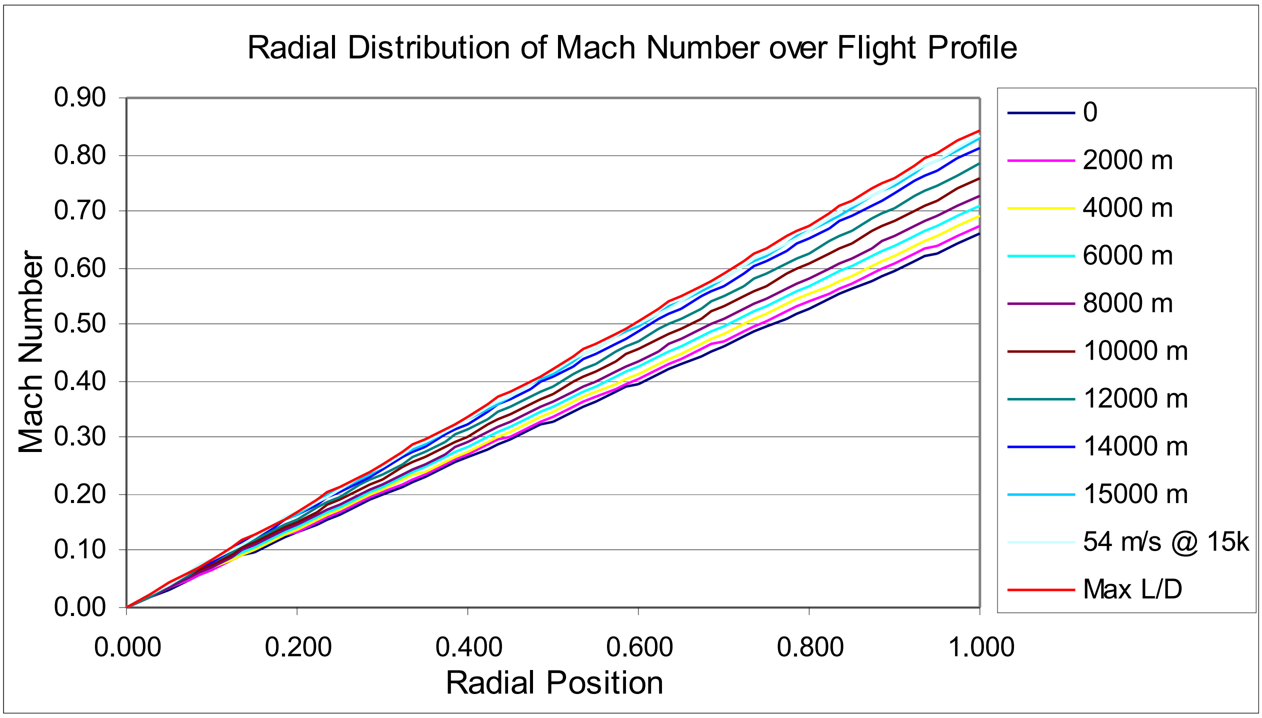

Figure 5. Radial Distribution of Mach Number for Various Optimal Propellers

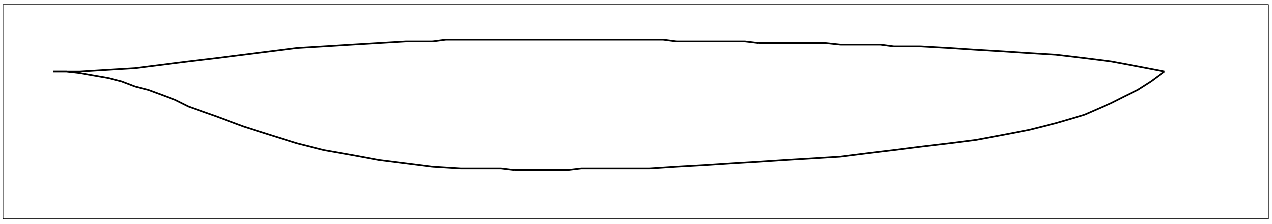

Figure 6. Front View of Final Blade Geometry (root at left)

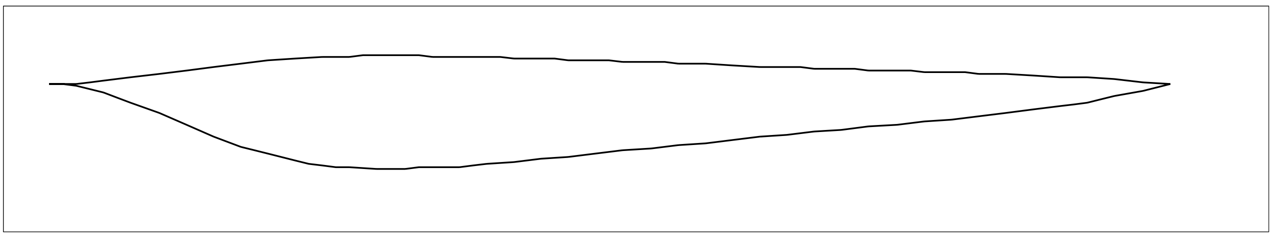

Figure 7. Side View of Final Blade Geometry (root at left)

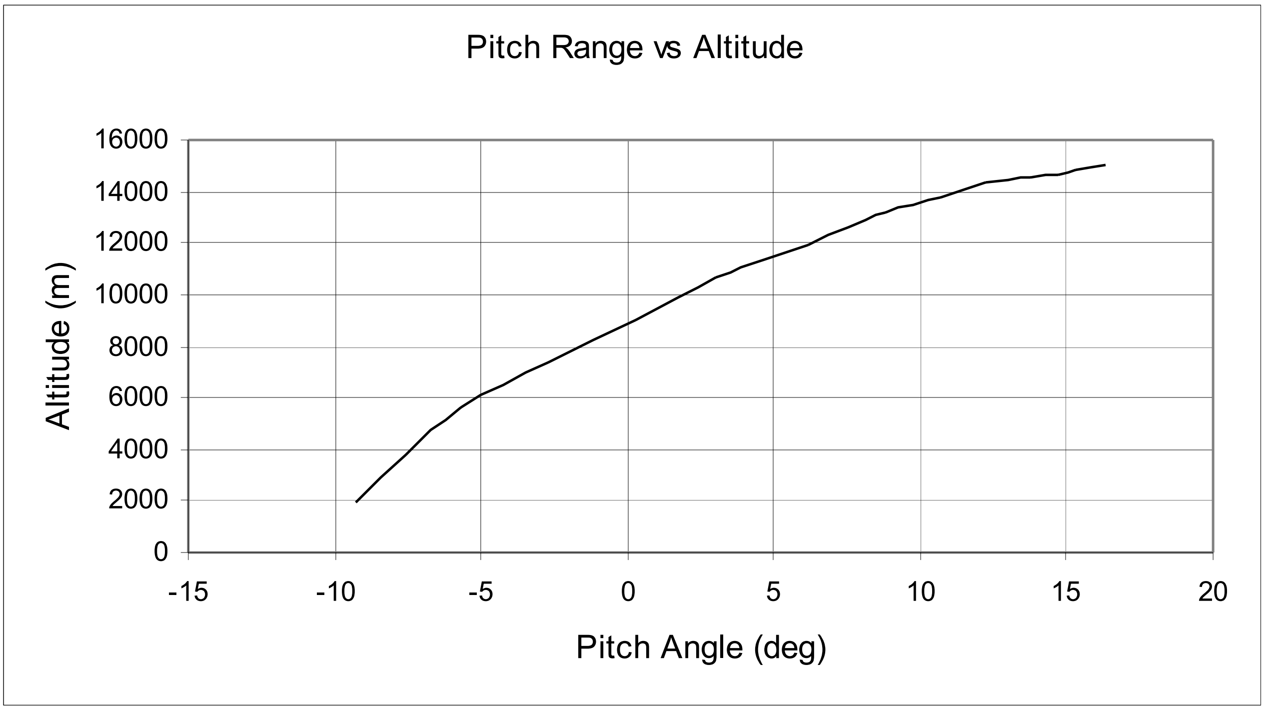

Figure 8. Pitch Angle Variation with Altitude for Final Propeller

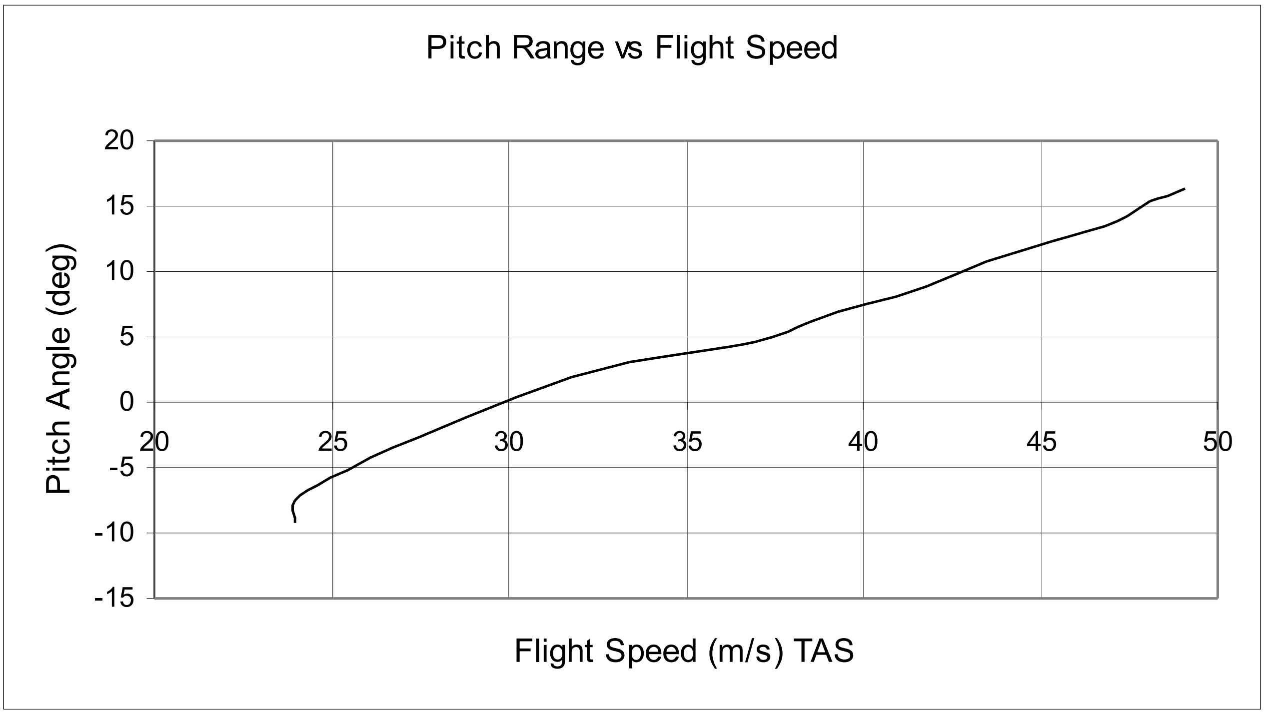

Figure 9. Pitch Angle Variation with Airspeed for Final Propeller