# Aerodynamic Characteristics of a Generic Micro-Aerial Vehicle to Investigate Propeller Interactions

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# Declaration

I, Jasmine Warner, hereby declare that this thesis submission titled *Aerodynamic Characteristics of a Generic Micro-Aerial Vehicle to Investigate Propeller Interactions* is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the University or other institute of higher learning, except where due acknowledgement has been made in the text. Specifically, the work I contributed consists of:

1. Conducting the literature review
2. Producing a 3D model of the generic micro aerial vechicle
3. Wind tunnel testing of the generic micro aerial vechicle model
4. Analysing data of wind tunnel results; and
5. Writing this thesis report.

Assistance was received from my supervisor in the areas of:

1. Distinguishing relevant literature in respect to this thesis
2. Indicating critical software required; and
3. Ameliorating this thesis through constant feedback.

| | |
|---|---|
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# Acknowledgements

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Abstract

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# Chapter 1

# Introduction

Unmanned aerial vechicles (UAV) are used throughout various industries to conduct missions which are either dangerous, difficult or tedious for humans to perform. The development of technologies and demand for smaller aerial vechicles has lead to the development of Micro aerial vehicles (MAV) [2]. MAV's will become evermore important for both commerical [3] and millitary [4] [5] use as advancements are made in navigation systems, cooperative control of multiple MAV's, advanced vision systems, embedded computational systems and navigational systems.

Despite the small size of MAV's there are three main categories these aircraft fit into. These are fixed wings [6] [7], rotary wings, flapping wings [8] or a combination of these. Due to the small size and Reynolds numbers at which these aircraft operate at (typically around Re=$10^5$ [9]), insects and other small animals are often studied to understand the flight dynamics which occur for small flying bodies [10]. The additional complexity to the design of MAV's occurs due to several factors:

- Low Reynolds number flight
- Small physical dimensions
- Structural strength
- Reduced stall speed
- Low inertia

Fig. 1.1 MAV speed reynolds number region with respect to flying bodies

With the increased complexity of MAV designs, there has also been increased interest in the reasearch and design of optimized MAV models [11]. Traditional methods of aircraft design have generally focused on larger aircraft which operate at Reynolds numbers of $10^6$ or more [12] [13]. There currently does not exist a fully validated, optimised and reliable optimization technique for MAV aircraft. In order to optimize MAV designs, software designed to numerically optimise models are generally based on aerodynamic properties, weights, stability and maneurability [14] [15] [16]. The low Reynolds number flight dynamics and non-linear flight dynamics are of particular importance for MAV development [17] [18].The low Reynolds number that MAVs fly at and the influence of an operating propeller on the rest of the MAV is currently unvalidated with physical wind tunnel testing. The main goal of this thesis therefore aims to fill in this gap.

Many groups of research have created software to optimize MAV's by using optimization algorthims such as generic algorthims, non-dominating sorting generic algorithms, particle swarm optimization and sequential quadratic optimisation programs. While some have accounted for low Reynolds numbers [19] [15] [20], no optimization techniques accounting for propeller interaction effects currently exist. Many investigations into propeller effects show the propeller has significant effects on wing aerodynamics, both in regards to performance and also stability [21] [22] [23] [24] [25] [26] [27]. None have validated these results with physical wind tunnel testing.

## 1.1 Background

### 1.1.1 Proliferation of MAV's in the Aerospace Landscape

UAV's have existed for centuries and have been predominately used for survellience and millitary purposes [28]. The recent shift to the miniturization of components, systems and aerial vehicles has already influenced the military sector with several developments underway to reduce visibility of reconansance aircraft and reduce the likelihood of aircraft being detected during missions [28] [29] [30] [31]. What started as a small initial interest in smaller and smarter drones has resulted in exponential growth in the sector [2] [32] . This coupled together with the growth in camera sensors and computer development, has led to the exponential growth in the capabilities of MAV seen today [33] [34]. Where an inital drone supported only low camera resolution with meagre flight times, today incoporates several systems such as gyrostabilisation, GPS capability with waypoint guidance, beyond the line of vision control, speeds of 70 km/h with a 30 minute flight time and a 20 megapixel camera (DJI Phantom 4) [35].

### 1.1.2 Limitations of Current Developed MAV

While MAV technology is more accessible and viable to mass market than it has ever been before [34], there is no fully developed and validated way to optimize a MAV for a specified mission [19] [20]. Procedures today involve developing a CAD model of the MAV or using software to do so based on aerodynamics. This model is either then run through aerodynamic optimization software and/or tested in a wind tunnel to detemine the main characteristics of the MAV [36]. The largest drawback of which is the lack of propeller effects accounted for which are known to have a large effect on aerodynamics and stability [26] [37]. MAV model tests have been conducted with a fixed position propeller [21] [38]. Models are however typically tested without a free-flowing propeller, although these have been included in several aerodynamic software programs and specific tests [17]. A lack of validation from wind tunnel testing however, means that a full understanding of the effects a propeller has on MAV's has not been achieved. Due to the small size of MAV and the large relative size of the propeller rotor disc compared to both the wing and body size the propeller will significantly affect the stability, noise, overall endurance, performance and power consumption of a given MAV [39] [22] [23] [24] [25] [26] [27].

### 1.1.3 The General Micro Aerial Vechicle

Today the interest, research and development of MAV's is continually increasing, however in order to focus on particular aspects or compare various designs, a "baseline" geometry is required. An example of this is the GENMAV [1]. While there are various models which have been tested to determine the main aerodyanmic properties [1], none have completed a physical wind tunnel test while accounting for the effects of

add 2 more examples at least

a powered propeller. Inital GENMAV aerodynamic data was determined by using the vortex-panel method [1] and did not involve wind tunnel testing. The effects of propeller induced flow has also been studied for both fixed and free-spinning propellers but currently no data is avaliable for wind tunnel tests of a powered MAV.

### 1.1.4 Optimization Techniques and Validation

Many non-standard aircraft designs are evaluated using software in order to analyse aerodynamic characteristics and then optimized through a variety of typical software engineering methods such as the particle swarm method [40]. These procedures are typically used as non-standard aircraft designs are more tedious to design and even more complex to setup and test than compared with standard aircraft designs.

## 1.2 Problem Statement

MAV's are set to increase the ability to conduct a variety of missions which predominately have military or survellience objectives [28] [29] [30] [31]. In the past troopers would venture on dangerous missions in order to "hopefully" gather useful information while risking their lives [2]. Survellience was conducted initally from hot air balloons, again risking human lives. Later aircraft (mainly helicopters) would be used, costing companies large sums of money in order to survey from a birds eye view [28]. Today drones and UAV's often conduct this work (within certain limits due to range and flight time) [2] [28]. The next major technology jump sees the optimization and miniturization of these aircraft to produce MAV's.

MAV's fit a niche and growing market. These aircraft are mainly used for military purposes due to the MAV's main deffering attributes; its smaller size, lower radar visibility and lower noise output. With MAV design becoming one of the fastest growing areas of development in the aerospace industry, there comes an increasing need to have accurate experimental data in order to validate, simulate and model the numerous MAV configurations being investigated.

## 1.3 Objectives

The objectives of this thesis are as follows:

1. To carry out a review of current published literature and determine areas with insufficient or no research avaliable for further development and research.
2. To design and produce a 3D model of a generic micro aerial vechicle with interchangable empennage.
3. To conduct wind tunnel testing of the generic micro aerial vechicle model with and without propeller effects.
4. To analyse data of wind tunnel results and detail the affect that propeller effects have on general micro aerical vehicles.

## 1.4 Outline

An outline of the proposed final submission is listed below, however is subject to change.

- Chapter 2: Background and literaure review of relevant topics and reasearch for this thesis
- Chapter 3: Proposed setup of analysis
- Chapter 4: Implementation
- Chapter 5: Results
- Chapter 6: Discussion
- Chapter 7: Conclusion

# Chapter 2

# Background

This section outlines the core theory and topics which are relevant for the optimization of MAV's and the effect of propeller interactions on the main wings of small MAV. MAV design is more complex than general aircraft design due to factors such as the non-linear lift distribution, low aspect ratio wings, low Reynolds number flows, structural integrity due to the small size and

## 2.1 Aerodynamic Parameters

The characteristics of an aircraft is given by a combination of the aerodynamic parameters that describe it. For MAV's this is more complex as these aircraft do not allow for the same assumptions to be made in calculations. New methods for determining the aerodyanmic parameters are currently being developed and proposed [41] [42] in order to address these differences. Aerodynamic forces are cruical to the overall design of any aircraft [43]. In order to determine these forces for MAV's a variety of techniques have been used such are the simple vortex lattice method [1] [**?** ]. However this method lacks the ability to predict the separetion of flow as lift is assumed to increase linearly with respect to the angle of attack [17]. This is not the case at low Reynolds numbers [44].

[45]. [37]

## 2.2 Low Reynolds Number Effects

Low Reynolds number compressible aerodynamics affect many different varities of aircraft. Aircraft used to survey martian terrian and MAV's are particularly influenced due to the change in atmosphere and small geometry respectively[46]. This especially critical for propeller based systems as the root and tip of the mach numbers can vary significantly[46]. Typically aircraft fly at high Reynolds numbers ($>10^6$), MAV's however generally fly between ($10^4 and 10^5$) [47].

## 2.3 Propeller Wing Interaction

## 2.4 MAV Optimization

Many optimization techniques exist which aim to optimize the aerodynamic design of MAV's. Algorithms such as genetic algorithms, artificial neural networks [48],

### 2.4.1 Wing Planform

### 2.4.2 Tail Planform

## 2.5 Non-Linear Lift Distribution

Early on in the study of aerodynamics, theories which were developed from the study of conventional aircraft were applied to the bodies of small flying objects and animals such as birds. Traditional aerodynamic theories provide good results and insights when steady flows move across a staionary body. They could not however explain what allows small insects and birds to fly leading to the paradox of "a bee cannot fly" [**?** ] [**?** ]. The issue lies in the fact that the flight of biological creatures is mainly characterized by non-linear and steady flows [**?** ]. This non-linear lift distribution is largely caused by the low Reynolds number that these small bodies fly at and also the low aspect ratio that MAV aircraft typically have.

Wingtip vortices are particularly important and even in general aircraft lead to regulations such as spacing rules between aircraft and aerodynamic noise [? ].

## 2.6 Stability

# Chapter 3

# Progress

The current progress completed is focused on a review of areas of research which are relevant to the main topic of this thesis. An analysis of current MAV optimisation techniques was conducted, and the development of a reasonble MAV baseline model is currently underway. The design and 3D of a MAV model which can be tested in different configurations is also currently in progres .

## 3.1 Problem Analysis

In order to understand the context of currently completed work it is essential to understand the main goal of this investigation. The main investigation of this thesis is to analyse the effects of propeller-wing interactions and determine how these affect small MAV aircraft.

## 3.2 Currently Completed Work

In order to analyse the propeller wing effects of a MAV in experimental testing, initial investigations of current baseline models were conducted to determine what shapes of aircraft are currently modelled. Aircraft generation code provided by Professor Dries Verstraete has been modified in order to produce a MAV design which has suitable characteristics for use in experimental testing.

A current example of this is again the GenMAV model [1] which does not allow for the addition of a propeller to test for the propeller interaction effects as seen in Figure3.1. An alternative design is suggested based on the NanoTalon as shown in Figure 3.2. The shape of this design however is optimized for manufacturability while still being testable within a wind tunnel, and in doing so, this aircraft loses a typical streamlined fuselage shape.

Fig. 3.1 GenMAV Model [1]

Fig. 3.2 NanoTalon Model [? ]

The main fuselage of the model which is still being developed takes into account the importance of interchangability in order to add and remove a propeler. It also considers that most aircraft will generally have a streamlined body shape as shown in Figure 3.3

Fig. 3.3 Current Model

Due to the complexity of the wing shape and airfoil, the main wing was modelled in VSP software and based on a model of the nanotalon as shown in Figure 3.4.

Fig. 3.4 Open VSP model of wing design based on nanotalon [? ]

This wing design was chosen due to its generic wing shape and simple design. The main geometry of the current model is given in Figure 3.5.

Fig. 3.5 Current Model

The general geometry uses a NACA4412 airfoil with a wing span of 860 mm and a max chord length of 183 mm. The main fuselage shape was modelled in order to represent a generic streamlined aircraft body shape. The main geometry features were based on the Nanotalon, although modified in order to better allow for a propeller to be attached and tested while operating. The tail piece is cut before the end in the model shown in Figure 3.5 due to the thickness being too small to use as a wind tunnel experimental model.

Experimental 3D models have been printed to determine the feasibility of the widths of certain sections as shown in Figure ??, in order for the model to carry the main propeller and battery. Consideration of the assembly of the main structure must also be considered and hence these inital prints provide validation into whether the current thicknesses are reasonable or will need to be adjusted. An example of the attachable head piece is shown in Figure ?? which was testing the feasibility of an interchangable model.

Fig. 3.6 3D Printed Model Testing

## 3.3 Experimental Setup

The main experiemental setup so far has largely been conductued through various software. Python was used in order to edit the aircraft generation code provided by Professor Dries Verstraete provided, in order to develop a MAV which is appropiate as a baseline model for further analysis. This model also has to be manufacturable and hence VSP and FreeCad have also been used in order to produce a reasonable airfoil wing design and to model the overall aircraft for printing. Software such as Cura and PrusaSlicer have also been used in order to 3D print models of current developments.

## 3.4 Constraints and assumptions

Major constraints in the development of the model are given below:

- Model must fit within the 4x3 low speed wind tunnel at The University of Sydney.
- Additional space must also be accounted for in the wind tunnel in order to mitigate the wall effect which occurs when testing within a wind tunnel.
- The width of the model sizings must be appropiate to both manufacture in a 3D printer and to assemble.

- The final designed model must be able to remain as one piece for testing within the wind tunnel with an operating propeller in both a tractor and pusher configuration.
- Space must be allocated for major components to fit inside including the battery and propeller housing.

## 3.5 Future Investigation

Future investigation on will look into developing the current baseline model further in order to test the same model in an unpropelled, tractor and pusher configuration. An interchangable empennage and fuselage will be used to change the model from a tractor to pusher configuration and allows for testing of the same basline in both configurations. Further investigation will involve an experimental investigation of the propeller-wing interaction by analysing the model in a low-speed wind tunnel. Wind tunnel tests are expected to occur from $5ms^{-1}$ to $25ms^{-1}$. This is for a range of incident angles which vary from -15° to 15 °. The force readings of this data will be gathered using either a nano17 or a nano25 force meter. A further data analysis will also be conducted using python inorder to determine the stability, aerodynamic co-efficients and influence of the propeller effects on the developed baseline model.

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