Shape Optimization and Modular Discretization for the Development of a Morphing Wingtip

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Mechanical and Industrial Engineering
University of Toronto

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Abstract

Better knowledge in the areas of aerodynamics and optimization has allowed designers to develop efficient wingtip structures in recent years. However, the requirements faced by wingtip devices can be considerably different amongst an aircraft's flight regimes. Traditional static wingtip devices are then a compromise between conflicting requirements, resulting in less than optimal performance within each regime. Alternatively, a morphing wingtip can reconfigure leading to improved performance over a range of dissimilar flight conditions. Developed within this thesis, is a modular morphing wingtip concept that centers on the use of variable geometry truss mechanisms to permit morphing. A conceptual design framework is established to aid in the development of the concept. The framework uses a metaheuristic optimization procedure to determine optimal continuous wingtip configurations. The configurations are then discretized for the modular concept. The functionality of the framework is demonstrated through a design study on a hypothetical wing/winglet within the thesis.
Acknowledgments

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<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_w$</td>
<td>winglet span</td>
</tr>
<tr>
<td>$c_r, c_t$</td>
<td>wing root chord and tip chord</td>
</tr>
<tr>
<td>$C_D$</td>
<td>coefficient of drag</td>
</tr>
<tr>
<td>$C_L$</td>
<td>coefficient of lift</td>
</tr>
<tr>
<td>$C_{L_{\text{max}}}$</td>
<td>maximum coefficient of lift</td>
</tr>
<tr>
<td>$C_L/C_D$</td>
<td>lift to drag ratio</td>
</tr>
<tr>
<td>$D$</td>
<td>drag</td>
</tr>
<tr>
<td>$E$</td>
<td>endurance</td>
</tr>
<tr>
<td>$i$</td>
<td>number of wingtip panel partitions</td>
</tr>
<tr>
<td>$I$</td>
<td>performance index</td>
</tr>
<tr>
<td>$K$</td>
<td>drag due to lift factor</td>
</tr>
<tr>
<td>$L$</td>
<td>lift</td>
</tr>
<tr>
<td>$m$</td>
<td>number of morphing modules</td>
</tr>
<tr>
<td>$n$</td>
<td>number of flight regimes</td>
</tr>
<tr>
<td>$q_b, q_o, q_r, q_{\Lambda}$</td>
<td>variable geometry truss mechanism actuator branches for module span, twist, cant and sweep, respectively</td>
</tr>
<tr>
<td>$R/C$</td>
<td>rate of climb</td>
</tr>
<tr>
<td>$\text{sfc}$</td>
<td>specific fuel consumption</td>
</tr>
<tr>
<td>$\text{s, s}_x$</td>
<td>parametric wing curve</td>
</tr>
<tr>
<td>$s_x, s_y, s_z, s_{\alpha}$</td>
<td>$x, y, z$, and twist components of the parametric wing curve</td>
</tr>
<tr>
<td>$S$</td>
<td>wing area</td>
</tr>
<tr>
<td>$t$</td>
<td>wing curve parameterization</td>
</tr>
<tr>
<td>$T/W$</td>
<td>thrust to weight ration</td>
</tr>
<tr>
<td>$V_\infty$</td>
<td>free stream velocity</td>
</tr>
<tr>
<td>$w_i$</td>
<td>induced velocity</td>
</tr>
<tr>
<td>$W$</td>
<td>aircraft weight</td>
</tr>
<tr>
<td>$x, y, z$</td>
<td>local module coordinate axes</td>
</tr>
<tr>
<td>$X, Y, Z$</td>
<td>global coordinate axes</td>
</tr>
</tbody>
</table>
$b_i, \alpha_i, \Gamma_i, \Lambda_i$ = panel partition span, twist, cant and sweep, respectively

$b_m, \alpha_m, \Gamma_m, \Lambda_m$ = module span, twist, cant and sweep, respectively

$b, \alpha, \Gamma, \Lambda$ = wing span, twist, cant and sweep, respectively

$\theta_c$ = climb angle

$\kappa$ = curvature as defined by Frenet-Serret

$\lambda$ = wing taper ratio

$\rho_\infty$ = free stream density

$\tau$ = torsion

$\chi$ = total curvature

$\bar{\chi}$ = average total curvature

Acronyms

AMP Aircraft Morphing Program

AoA Angle of Attack

BW Pitch Bandwidth

DOF Degree of Freedom

FE Finite Element

GA Genetic Algorithm

HM Harmony Memory

HMCR Harmony Memory Consideration Rate

HS Harmony Search

MAS Morphing Aircraft Structures

MDO Multidisciplinary Design Optimization

PAR Pitch Adjustment Rate

SAR Specific Air Range

VGT M Variable Geometry Truss Mechanism
Chapter 1

Introduction and Literature Review

The design and development of aircraft is a perpetually evolving process, even though the fundamentals of aircraft design have remained relatively the same over the years. Engineers are continually looking for new ways to improve aircraft performance and efficiency. Within the aeronautics industry it is common knowledge that the design of conventional aircraft is a compromising process. Generally, aircraft are designed to meet the requirements essential to a narrow range of mission profiles. Within a mission profile, the different and often conflicting requirements of various flight regimes (e.g., climb, cruise, descent) also complicate the design process. As a result, traditional aircraft designs offer less than optimal effectiveness when operating outside of their intended mission. In our natural environment, however, we observe several species of birds and insects that can adapt throughout flight to accomplish a variety of tasks with near optimal performance. To emulate these observations researchers are looking toward the development of morphing aircraft. Morphing can be defined as applying a set of technologies, which permit a significant level of geometric changes to the aircraft, to either adapt to mission segments or enhance performance. While devices such as flaps and slats are traditionally used to augment wing geometry, the shape changes acquired through these devices are not generally classified as morphing changes. Researchers now anticipate using adaptive structures and more advanced actuators, which exercise smart materials, to develop morphing systems that permit a much larger range of geometric change.

A particular area of interest, and one that is highly applicable to morphing, is the subject of wingtips. The use of various wingtip devices (e.g. tip fences, winglets, raked wingtips, spiroids
etc.) has continued to expand since the developments initially made by Richard Whitcomb of NASA Langley [1]. The primary function of these devices has been to reduce lift induced drag, which may comprise large portions of drag in the climb and cruise segments of flight. To further reap the benefits of these devices it would be favourable to have a wingtip device that can reconfigure to adapt to the varying requirements imposed by different flight conditions. A wingtip of this type would allow the accomplishment of several dissimilar flight conditions with improved efficiency over traditional devices.

1.1 History of Aircraft Morphing

Aircraft morphing is by no means new to the aeronautics field, as shown in Fig. 1.1. Historically, morphing has focused on methods to alter wing chord, dihedral, span, sweep, and twist. For example, the Wright Flyer in 1903, denoting the beginning of powered flight, used a twisting wing for roll control [3] whereas the much more recent B-1 Lancer employs a variable sweep wing for improved drag performance over a larger range of flight speeds [4]. Other morphing aircraft have used similar tactics to enhance particular performance characteristics. Fig. 1.2 demonstrates the most prevalent wing morphing changes while Table 1.1 summarizes some of the characteristics associated with each of these changes.

<table>
<thead>
<tr>
<th>Year</th>
<th>Aircraft</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1903</td>
<td>Wright Flyer</td>
<td>(variable twist)</td>
</tr>
<tr>
<td>1931</td>
<td>Makhonine MAK-10</td>
<td>(variable span)</td>
</tr>
<tr>
<td>1935</td>
<td>Makhonine MAK-101</td>
<td>(variable span)</td>
</tr>
<tr>
<td>1940</td>
<td>Bakshaev RK-800</td>
<td>(variable chord)</td>
</tr>
<tr>
<td>1947</td>
<td>Makhonine MAK-123</td>
<td>(variable span)</td>
</tr>
<tr>
<td>1951</td>
<td>Bell X-5</td>
<td>(variable sweep)</td>
</tr>
<tr>
<td>1964</td>
<td>North American XB-70 Valkyrie</td>
<td>(variable dihedral of outboard wing)</td>
</tr>
<tr>
<td>1964</td>
<td>General Dynamics F-111 Aardvark</td>
<td>(variable sweep)</td>
</tr>
<tr>
<td>1969</td>
<td>Tupolev TU-22M</td>
<td>(variable sweep)</td>
</tr>
<tr>
<td>1969</td>
<td>British Aircraft Corporation Concorde</td>
<td>(variable engine air intake, variable pitch nose)</td>
</tr>
<tr>
<td>1970</td>
<td>Rockwell B-1 Lancer</td>
<td>(variable sweep)</td>
</tr>
<tr>
<td>1974</td>
<td>Grumman F-14 Tomcat</td>
<td>(variable sweep)</td>
</tr>
</tbody>
</table>
Table 1.1 Summary of morphing characteristics [5]

<table>
<thead>
<tr>
<th>Morphing change</th>
<th>Positive Factor</th>
<th>Offsetting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord</td>
<td>Increase results in higher lift</td>
<td>Increase results in higher drag</td>
</tr>
<tr>
<td>Dihedral</td>
<td>Increase results in higher lateral stability. Decrease results in higher maneuverability.</td>
<td>Increase results in lower maneuverability, Decrease results in lower stability.</td>
</tr>
<tr>
<td>Span</td>
<td>Increase results in improved performance parameters (e.g. range). Decrease results higher maneuverability.</td>
<td>Increase results in higher wing root bending moment.</td>
</tr>
<tr>
<td>Sweep</td>
<td>Increase results in better dash performance</td>
<td>Increase results in lower lift coefficients.</td>
</tr>
<tr>
<td>Twist</td>
<td>Increase results in higher lift and can be used to tailor aerodynamic loading.</td>
<td>Increase results in higher drag.</td>
</tr>
</tbody>
</table>

Figure 1.2 Wing morphing shown in traditional aircraft coordinate system
Fig. 1.1 also demonstrates the magnitude and complexity to which morphing methods have been employed throughout history. Morphing has traditionally been restricted to military class of aircraft and has been achieved through somewhat simplistic morphing concepts. Undoubtedly a high level of research and development has gone into past concepts. However, the morphing methods themselves have been largely restricted to 1-degree of freedom (DOF). For instance, the Makhonine MAK-101 aircraft permitted variable span, which is an in plane single DOF motion. Several, current morphing methods are looking to expand morphing capabilities by avoiding 1-DOF morphing as discussed in the next section.

1.2 Current Morphing Research

Morphing is a subject that has once again gained popularity within the aeronautical industry, reflecting recent developments in adaptive structures and smart materials. A surplus of morphing concepts is now being studied, which primarily focus on the development of morphing wings. Despite the diversity in concepts, the aim of these methods is to positively affect the aerodynamics, stability, and performance characteristics of aircraft beyond the capabilities of static designs.

Morphing methods can be classified into two general categories; those that permit local (2D) level morphing and those that allow global (3D) level morphing. The aim of local morphing is to predominately affect local aerodynamic characteristics of the airfoil. This is achieved by permitting changes in the wings cross section, such as altering the geometry of the airfoil as seen in [6]. Alternatively, the purpose of global morphing is to modify the overall wing load distribution and aerodynamic characteristics. This is accomplished by changing geometric properties along the span of the wing. Current examples of global morphing include concepts with variable dihedral [7], variable span [8], variable sweep [9], and variable twist wings [10]. As mentioned previously researchers are also investigating concepts which combine multiple morphing modes. Methods such as these can be seen in the works of [5, 11] where adaptive structures are used to allow individual and/or simultaneous dihedral, span, sweep, and twist morphing.

Research in the area of morphing is quite diverse and is being tackled using an assortment of techniques that have had varying levels of success. For instance, the work performed by B. D. Roth and W. A. Crossley [12] investigates the use different optimization techniques for the conceptual design of morphing aircraft. In the work the aircraft is represented through basic sizing variables, such as aspect ratio, and corresponding morphing variables. Results showed a
morphing aircraft design is beneficial in terms of minimizing the aircraft takeoff gross weight as compared to a fixed aircraft design. However, the success of the different optimization techniques that were examined varied. Roth and Crossley found that the response surface approach was not able to successfully search the design space as a result of multiple discontinuities. Alternatively, the design space could be handled using a genetic algorithm (GA). Researchers have also turned toward experimental techniques to investigate wing morphing. As an example, H. Yuanyuan and G. Shijun [13] constructed a wing model that integrates a seamless morphing control surface. Using the model a series of vibration tests were conducted to validate and improve a representative finite element (FE) model.

Larger coordinated research efforts have also been put forth by organizations such as NASA and DARPA who have initiated the Aircraft Morphing Program (AMP) [14] and Morphing Aircraft Structures (MAS) program [15], respectively. The goal of the AMP is to couple research across a wide range of disciplines to integrate smart technologies into aircraft applications. This is being accomplished by considering seven disciplines of research including acoustics, controls, flow physics, integration, materials, structures, and systems and multidisciplinary optimization [14]. The aim of the research is to investigate these technologies to make a major impact on air and space travel as well as the way in which aircraft and spacecraft are manufactured [14]. Conversely, DARPA’s MAS program has the goal of obtaining significant wing planform geometry changes during flight using advanced actuators. Through the program a wind tunnel demonstrator was developed and tested. The tests validated the concept as well as the morphing wing operability under realistic aerodynamic loads. The information is to greatly aid in the development of future morphing aircraft.

1.3 Overview of Wingtips

Before discussing morphing as it pertains to wingtips, it is beneficial to consider wingtips in general and why traditional wingtips are valuable additions to aircraft wings. The next two sections are dedicated to outlining the benefits of these devices as well as their historical development.

1.3.1 Induced Drag and the Vortex Wake

Important to understanding the benefits of various wingtip devices is the notion of induced drag and the vortex wake. In considering the total drag produced by an aircraft one can distinguish two primary contributors; (1) skin friction drag and (2) pressure drag. Skin friction drag is a result of viscous effects in the boundary layers surrounding the aircrafts surfaces. Pressure drag, on
the other hand, is a result of much more complicated flow mechanisms such as viscous effects, shocks, and the global effects of lift [16]. As a partial contributor to pressure drag, induced drag can be defined as the portion that results from the global effects of lift. The intent of traditional wingtip designs is to mitigate this portion of drag. While the sources of pressure drag are known, it is difficult to distinguish the magnitude of drag that comes from each of the flow mechanisms. This is a result of the mechanisms overlapping and interacting in such a way that their effects do not add in a simple linear manner [16]. The magnitude of induced drag, however, can be estimated using vortex lattice theory which is based on an idealized flowfield model using the distribution of vortex panels over a lifting body. Further detail regarding this approach is provided in subsequent sections of the thesis.

Within a flowfield, induced drag manifests itself as a result of the aircraft redirecting the oncoming airflow, thus, producing kinetic energy that must be dissipated downstream. The kinetic energy produced is a result of large-scale air motion (Fig. 1.3) caused by lifting forces. The air motion is primarily perpendicular to the direction of flight and is characterized by downward flow between the wingtips and upward flow outward of the wingtips. There is also a directional change in the horizontal components of velocity at the wingtips, which can be understood as the tendency of air to flow from a high pressure region (i.e. under the wing) to a low pressure region (i.e. above the wing). As a result of such a flowfield the lift vector of the wing is tilted backward slightly, the backward component of lift being felt as induced drag.

A byproduct of the flowfield displayed in Fig. 1.3 is the vortex wake (Fig. 1.4). This is a consequence of the flowfield being shed from the trailing edge of the wing as the aircraft moves forward. The wake is made up of two distinct vortex cores that form downstream of the wing. The cores are what is commonly referred to as the ‘wingtip vortices’ although the wingtips are not the sole source of the vortices. In actuality, the vortex cores are a result of the vorticity emanating from the entire trailing edge of the wing. This flow pattern can persist over long distances downstream and can be a source of significant stability and efficiency issues for the aircraft as well as potentially hazardous to surrounding air vehicles. For instance, during high lift low speed conditions or high subsonic cruising speeds the drag induced from the flowfield shown Fig. 1.3 can account for up to 50% of the total drag [17]. To mitigate this problem, and in essence decrease induced drag, engineers aim to change to global flowfield surrounding the wing, so as to reduce its total kinetic energy. Theory and experimentation has shown us that this can be achieved through a variety of wingtip devices.
1.3.2 Introduction and History of Wingtips

Wingtips have a long history which dates back to the 1800s. The origin of these devices may be accredited to the work performed by an engineer named Frederick W. Lanchester [18]. Lanchester’s work focused on how a wings shape can influence its aerodynamic efficiency. Through theoretical and experimental studies, Lanchester was able to develop a qualitative understanding of the flow patterns surrounding lifting wings which included the vortex wake. He found that placing a vertical surface at the wingtip, or ‘endplate’ (Fig. 1.5), could reduce wing drag under high lift conditions. This was accomplished by disrupting the lift induced inflow above the wingtip and outflow below the tip. Unfortunately, the drag reduction benefits were not realized during cruise settings [18]. Although the endplate was able to reduce induced drag, the benefits of the device were offset by an increase in viscous and interference drag. These
penalties were a result of the enlarged wetted area of the device and the interacting corner flows which occur between the wing and endplate. Further initial developments came about through the work of Dr. Sighard Hoerner in 1952 [18]. Hoerner developed cut out wingtips that are commonly referred to as ‘Hoerner Tips’. The device was effective in redirecting the core of the vortex wake away from the upper surface of the wing. As a result, some small advantages in wing lift to drag ratio were noticed [18].

Significant advancements in wingtip technology did not come about until the work performed by Richard T. Whitcomb in 1974 [1]. Whitcomb took a somewhat different perspective on wingtip development, which was to perceive the wingtip as just another lifting system similar to the wing. As such, the wingtip should have an efficient aerodynamic cross section to reduce viscous drag and should be sized consistent with the efficient load carrying capacity of the cross section. He also exercised good aerodynamic design practice in order to realize some net benefit from his wingtip concept. Whitcomb dubbed his design the ‘winglet’ to emphasize the attention and care that is required of these devices, which is similar to that required of the wing [18]. Through a series of wind tunnel tests at lifting conditions the winglets showed a reduction in induced drag of 20% and an increase in wing lift to drag ratio of approximately 9% [18], effectively doubling what can be realized through a simple span extension.

Many major aircraft producers were interested in the technology following Whitcomb’s work. One of the first aircraft to utilize winglet technology was the Learjet Model 28 in 1979. It was found that the winglets improved directional stability and added 6.5% to the flight range [18].
Competitors such as Gulfstream added winglets to many of their aircraft models shortly after. In 1985 Boeing was one of the first to add winglets to large commercial transport, adding them to the 747-400. The range of the airliner was increased by over 3% using winglets [18].

As Whitcomb and many others have discovered, wingtips have a series of offsetting factors that contribute to their net benefit. Positive factors include a reduction of induced drag in climb and cruise conditions. While the offsetting factors include increased profile drag, due to an increased wetted area and junction flows, and increased weight, due to the device itself and additional structural support required in the wing. Nevertheless, winglets can be carefully engineered to positively affect the efficiency of aircraft through performance benefits such as [16]:

- Reduced fuel burn
- Increased range
- Reduced takeoff field length
- Increased cruise speed and altitude
- Reduced takeoff noise
- Increased stability
- Improved runway throughput by mitigating wake turbulence allowing closer spacing of aircraft

Whitcomb's general idea of applying good aerodynamic design practice has also contributed to the development of other wingtip concepts such as tip feathers, raked wingtips, and blended winglets to name a few (Fig. 1.5). Many of these designs can be seen in operation and a choice between one or the other depends on the application. In the past the additional cost of these devices often outweighed their performance benefits. Now, however, considerable increases in fuel costs have driven aircraft manufacturers to further consider the addition of wingtip devices. For example, the Boeing company has retrofitted many of their aircraft with blended winglets. Although the winglets are estimated to cost $600,000 for an 8-foot set they are attributed with fuel savings that range in the hundreds of thousands of dollars per year for a single aircraft [18].

1.4 Morphing Wingtip Research

Researchers and engineers are looking toward the development of morphing wingtips to further expand the profits associated with varying wingtip devices. And although a substantial amount of research has been conducted towards the development of morphing wings, as mentioned
previously, much less has been done in the area of morphing wingtips. Nevertheless, a number of researchers have taken it upon themselves to strictly investigate morphing as it pertains to wingtips.

A notable morphing wingtip concept is the ‘MORPHLET’. The group behind ‘MORPHLET’ developed the term from a combination of the words MORPHing and wingLET. As a group, the ‘MORPHLET’ team has investigated areas including materials, structures, and multidisciplinary design optimization (MDO) (see refs [19-22]). The MORPHLET design is a four partition wingtip that is to be retrofitted on an existing narrow body aircraft. The design also augments the aileron panel of the aircraft wing. Initial optimization studies, using a GA, were performed in [19] and showed that active geometric scheduling of the wingtip during flight could significantly improve specific air range (SAR). The group has significantly advanced their optimization methodology since completing the work as presented in [19]. Currently, a MDO suite has been developed that incorporates several areas of design including aerodynamics, structures, and performance, see [21, 22]. The group re-examined the SAR optimization for a long and short range mission profile of the narrow body airliner in [22]. Results showed distinct geometric wingtip schedules to be used to improve aircraft performance. For the long range mission, a 6.0% SAR gain was shown across all cruise phases, in addition to achieving a 4.5% lift to drag ratio improvement in climb [22]. Considerable improvements were also shown for the short range mission profile. As a whole, the MORPHLET design has demonstrated substation improvement over the datum aircraft and blended winglets that have been investigated.

Other notable morphing wingtip research is that conducted by refs [23, 7, 24]. A. Gatto et al. [23] performed an experimental investigation into the use of bistable winglets to enhance wing lift characteristics. The winglet was manufactured using bistable composites that allow the winglet to snap between two stable states. During low speed operation the winglet is designed to resemble a simple span extension of the wing with adequate camber to enhance lift capabilities at takeoff. Under higher dynamic pressures, the winglet snaps to a configuration that more closely resembles that of a traditional blended winglet shape. Through a series of wind tunnel experiments the group was able to demonstrate the viability of the concept. However, the snap through process produced significant dynamic loads throughout the entire wing structure, suggesting further development of the concept.

Taking a somewhat different approach, P. Bourdin et al. [7] have investigated variable cant angle winglets for the control of morphing aircraft. In doing so, a wind tunnel model was developed to examine the flight dynamics associated with different cant arrangements.
Experimental and numerical studies showed the concept to be viable in terms of simple maneuvers. Unlike conventional control surfaces, the adaptive winglets enable the adjustment of moments about multiple axes, forming a highly coupled flight control system [7]. Additionally, a numerical study showed that a single pair of adaptive winglets cannot substitute for all the conventional control surfaces if one wants a full control envelope [7]. An alternative that is being considered by the group is to add a second pair of adaptive winglets on top of the existing ones to provide a full control envelope.

Finally, the work performed in [24] examined a novel morphing wingtip design using a MDO procedure. The procedure couples results obtained through commercially available FE and flow solving tools (i.e. ANSYS and CFX [25]) to optimize the wingtip geometry. The wingtip was permitted to change in toe angle, cant angle, and length. Using the MDO procedure, the wingtip was configured to optimize the lift to drag ratio in three flight regimes. Results of the study demonstrated that the morphing wingtip could outperform a static device in terms of the lift to drag ratio.

1.5 Motivation and Thesis Overview

Modern day aircraft are designed and optimized only for a narrow range of flight conditions. As a consequence, operation outside of these conditions results in less than optimal flight characteristics. In the natural world, however, animals and insects have demonstrated the advantages of morphing to achieve near optimal flight performance and stability characteristics for a variety of flight conditions. Researchers have recently focused on imitating these features through the development of morphing airborne structures to positively affect the aerodynamics, performance, and stability of aircraft beyond the capabilities of static designs. Incessant advances in adaptive structures and smart materials are also encouraging the progression of highly unique morphing concepts. An area of particular interest is the establishment of morphing wingtips for civil aircraft, as the majority of existing morphing technologies have focused on military applications. In comparison to developing an entire morphing wing, the wingtip provides a small scale opportunity to introduce morphing technologies into civil aviation, both to exercise the technology and gain acceptance in this field. The wingtip can be used as a start point so that engineers have the opportunity to thoroughly develop their design and analysis methodologies prior to implementing them on large scale.

Consequently, this thesis focuses on the development of a particular modular morphing wingtip concept. The goal of the concept is to permit aircraft to operate in highly dissimilar flight
conditions with higher levels of efficiency, as compared to that achieved through traditional wingtips. Within the thesis a focus has been placed on outlining the design decisions which have led to the current concept being pursued. In developing the concept two major design challenges arise, which are:

A. Formulating the optimized geometric wingtip schedules required to meet specific performance requirements.

B. Determining the appropriate module spacing and density for the wingtip schedules.

The main objectives of this work are to validate the wingtip design and establish a fundamental conceptual design framework that can address challenges (A) and (B) above. The framework presented is a sequential process that first determines optimal continuous wingtip shapes. This is accomplished through use of a metaheuristic optimization procedure carried out on the wingtip. The framework then uses a discretization process to determine the optimal number and spacing of morphing modules to include as part of the wingtip. The model has been developed in the MATLAB platform and provides the option of including further framework developments for future research.

The thesis is organized as follows. First, in Chapter 2, design decisions leading to the current morphing wingtip approach are discussed. The goal of the chapter is to summarize the particular strengths of the concept, as well as to outline the designs challenges which are later addressed through the conceptual framework. In Chapter 3, the design framework is outlined in reference to the morphing approach. Detailed information on each section of the framework is also provided within the chapter. The framework is then used to validate the concept in Chapter 4. Within the chapter, an arbitrary wing planform is investigated with respect to three flight regimes to determine optimal wingtip configurations and associated module layouts. Finally, in Chapter 5, conclusions are drawn and recommendations for future work are discussed. A supplementary study, which entails low speed wind tunnel testing of the concept, is also presented in the Appendix. The study is used to validate the concept and to establish a database of aerodynamic load data. Restrictions and limitations associated with the study are discussed in the Appendix.
Chapter 2

Development of Morphing Concept

The development process required of aircraft systems and structures is becoming increasingly complex as these disciplines continue to evolve. The increasing level of sophistication in these areas is also making advancement more time consuming. As a result, today it is of critical importance to establish and capture the need and general requirements of any new design. The purpose of this chapter of the thesis is to outline the need and requirements of the morphing concept so as to provide the reader with an overall understanding of the development process. Additionally, in developing the concept, this chapter brings to light the design challenges which are met through the conceptual design framework in the proceeding chapter. The requirements of the wingtip are established through a top-down approach since the overall requirements of the morphing system are easily defined. There is then a back and forth shift between developing the concept requirements and developing the concept itself. This is done to account for the many ways in which a morphing wingtip can be established. A summarized description of the design decisions is provided in the following sections.

2.1 Morphing Wingtips

To establish the morphing concept it is first critical to outline the problem which is to be alleviated. This can then be translated into the need for such a device. In doing so, the general requirements of the morphing system can then be ascertained. The established need and requirements will then guide the design process in a way that will make a more effective concept.
As mentioned earlier, traditional static wingtip devices are a compromise between several positive and offsetting factors. Although these factors have been discussed in the introductory chapter they have been summarized in the Table 2.1 to stress their importance. Generally, these factors are addressed through a wingtip arrangement that offers the greatest performance benefits in terms of the sought objectives. Further, these factors become increasingly complicated when considering the many flight regimes and mission profiles that an aircraft can have. Varying flight conditions also have different aerodynamic and structural requirements. For instance, between the climb and cruise regimes there are different trade-offs between increased profile drag and the reduction in induced drag. The wingtip must also comply with geometric constraints imposed by airport terminals and maintenance facilities. Thus, the development of a static device is a highly compromising process in which the final design is a settlement between different and often conflicting requirements. Static devices, as a result, offer less than optimal effectiveness in each flight condition. A morphing device, on the other hand, can adapt to an optimal configuration for each flight regime, leading to a multi-phase improvement in aircraft efficiency. A morphing device could also address issues such as stability/manoeuvrability through alteration of the centre of gravity and moment of inertia. This can be translated into the need for a wingtip device that permits multidirectional geometry changes according to the design intent. As an example of operability, the wingtip could be geometrically scheduled throughout flight to meet a number of flight requirements with near optimal performance. To enable this functionality so called morphing technologies are essential.

The top level requirement of the wingtip can be stated as the desire to improve aircraft multiphase operation. Further requirements of the wingtip are established through

<table>
<thead>
<tr>
<th><strong>Table 2.1  Summary of wingtip trade-offs [16]</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Performance Benefits</strong></td>
</tr>
<tr>
<td>Positive Factors</td>
</tr>
<tr>
<td>• Reduction in induced drag</td>
</tr>
<tr>
<td>• Reduction in shock drag as a result of tailored spanwise load</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Overall Benefits</strong></td>
</tr>
<tr>
<td>Positive Factors</td>
</tr>
<tr>
<td>• Reduction in fuel burn</td>
</tr>
<tr>
<td>• Increased flight envelope including specific air range, cruise altitude, and cruise speed</td>
</tr>
</tbody>
</table>
consideration of the ways in which a morphing device may be conceptualized and developed. At the conceptual level, this task can be addressed by considering the three approaches below, which have also been outlined in [5]. Although these methods are directed towards morphing wing development in [5], they are equally applicable to the development of a morphing wingtip.

1. Active morphing is achieved through the structure with no consideration to skin morphing (i.e. assuming that the skin will also morph or that adequate space is provided for multi-body movement as in [8]).

2. Active morphing is achieved through the skin while a passive structure maintains the integrity of the wingtip under loading.

3. Active morphing is achieved through the structure while a passive skin maintains a smooth aerodynamic surface of the wingtip.

While some research has been conducted on morphing skins, either active or passive, the majority of research has focused on (1). The current work also stems from this perspective. Further requirements of the morphing system can be captured through contemplation of the level of morphing changes, the design methodology, the most appropriate morphing modes, and the morphing mechanism.

2.2 Local vs. Global Morphing

Important to the development of any morphing system is the differentiation between levels of morphing. When considering a morphing system one may choose to pursue local (2D) level morphing, global (3D) level morphing, or a combination of both. The aim of each of these methods as well as a number of examples has been provided in Chapter 1. To reiterate, local morphing involves cross sectional shape changes whereas global morphing involves shape changes in the spanwise direction (Fig. 2.1). The significance of each of these methods lies in the design objectives sought as well as in their capacity for performance improvement. As noted in [26], the modeling tools needed for each of these methods are also correspondingly different. It is clear that each level of morphing focuses on different design objectives. While low scale morphing (i.e., local morphing) has shown to be beneficial [6], global morphing is much more promising in terms of overall achievable performance gains for a variety of flight conditions [27]. This is a result of global morphing being able to alter aerodynamic properties to a higher degree. As Whitcomb and many others have demonstrated, it is the net attainable performance
that is of greatest importance with respect to a certain concept. Therefore, it is global morphing that is pursued in the current work. As an additional note, combining both morphing levels into a single concept is not considered at the moment in order to keep the morphing system as uncomplicated as possible. Also, combining both morphing levels would require more complex modeling tools that entail more time to develop and validate.

The choice to pursue global morphing directly impacts the establishment of further functional requirements. Since it is global morphing being pursued, a supplementary general requirement of the system is to provide this functionality. It is important to outline this requirement as this definition, in turn, influences the design of the concept. Subsequent development of the concept can be accomplished through reviewing possible design methodologies that can be applied to the wingtip.

2.3 Design Methodology

As mentioned, the development of a versatile morphing system takes some consideration. Regarding the wingtip as a system it can be designed in two broad ways. That is to say the wingtip can be developed using a dedicated or a modular design methodology. As noted in [28], a flexible morphing system (i.e., a wing or wingtip) is expected to have varying morphing requirements between different regions along its span. As an example, the wingtip may require large cant capabilities at the root while lower cant and greater twist is required at the tip. To
address these issues one can look into the benefits of each design approach as well as examining pre-existing morphing methods.

Traditionally, as well as within many of today’s morphing concepts, approaches are developed using a dedicated methodology. This is confirmed by looking back at the history of morphing methods (Fig. 1.1) as well as viewing current methods such as those noted in Chapter 1. A dedicated methodology involves designing a system specifically to meet the current requirements imposed [28]. The result is a morphing system whose functioning mechanism is tailored and dedicated to meeting the specific requirements imposed by the system. As an example of this consider the Makhonine MAK-101 aircraft, which permits variable span morphing. The aircraft is capable of changing a single morphing degree of freedom and is therefore dedicated to 1-DOF morphing only. Furthermore, in following this design methodology, the design approach and associated analyses are valid only for a specific design case, making a change in morphing requirements a costly endeavor. Focusing on 1-DOF morphing also effectively limits the potential performance gains associated with a particular concept. The intent of a morphing system is to avoid these issues and provide as much functionality as possible without overcomplicating the design as a whole.

As an alternative a modular design methodology can be adopted. As mentioned in [28], a modular methodology has a multitude of benefits over a dedicated design approach. In particular, the morphing system can be designed to meet a variety of motion requirements including, but not limited to those that are current, ideally, encompassing all known requirements [28]. Common to [28], the wingtip can be segmented in the spanwise direction such that it is made up of sequentially stacked morphing modules. A modular system permits a higher level of versatility and supports the possibility of addressing discrete and/or multiple morphing requirements along the span of the wingtip in addition to overall morphing requirements. As in [28], a similar reconfigurable module mechanism can be employed to suit motion requirements on an as need basis. This is accomplished through the design of a base platform that is used as a high level start point for the design of motion specific modules. Therefore, a change in flight requirements can be addressed by reconfiguring modules in use accordingly, or if necessary, adding more modules. Employing this approach, the performance of the wingtip is not limited as a result of the mechanism design.
2.4 Morphing Modes

Employing a modular design it is necessary to determine the required morphing modes of the modules. In the current work, the morphing mode refers to the manner by which a particular morphing change is achieved using a mechanical system. The mode then reflects the capabilities and motion of the mechanical system providing morphing. It is easy to conceptualize the advantages of combining multiple morphing modes into a single concept, as in [5, 11]. In terms of the wingtip, if a desirable wingtip shape is known then the goal of the morphing system is to provide a sufficient number of morphing degrees of freedom to adequately emulate that shape. To fully realize the benefits of structural morphing one must consider the restrictions imposed by choosing a limited number of morphing modes as well as the modes themselves. As discussed in the previous section, aircraft similar to the Makhonine MAK-101 are characterized by a single morphing mode. This limits the potential performance benefits that can be achieved through the morphing system. The morphing modes must also be chosen such that they sufficiently imitate desirable shape changes. The goal in designating specific morphing modes is to classify a set of morphing changes that offer a certain degree of morphing functionality while retaining a level of simplicity, as to allow a particular mechanical system to be applied.

As shown in Fig. 2.2, for wingtips one may distinguish a set of six parameters (i.e., cant angle, toe angle, twist angle, sweep angle, span, and airfoil selection) that generally set one wingtip device apart from another. For example, the primary difference between a canted winglet and a raked wingtip is the degree of cant. If one were to take a canted winglet and reduce its degree of cant they would essentially end up with a wingtip device that resembles a raked wingtip. Therefore, the alteration of these parameters can dictate different types of wingtip devices. If one were to also perform a parameter sweep of these variables they would perceive a motion that reflects possible global shape changes of the wingtip. Generally these parameters are unique for each wing/wingtip combination and it is the mixture of these variables that allow a wingtip to be beneficial for a particular wing or aircraft. In traditional cases, the variables are chosen uniquely for each application and performance goal. Using a morphing wingtip device can partially eliminate this problem by being able to adapt to differing applications. A summary of the major influence of each of these variables is provided in Table 2.2, which is similar to those of Table 1.1 of Section 1.1.

Returning to the notion of morphing modes, it is a requirement of the morphing concept to sufficiently emulate each morphing motion (i.e., the motion perceived through a parameter
Cant Angle

Sweep Angle

Airfoil Selection

Figure 2.2 Wingtip parameters [29]

Table 2.2 Influence of design variables [2]

<table>
<thead>
<tr>
<th>Morphing Motion</th>
<th>Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cant</td>
<td>Lateral stability, interference drag, and wing bending moment. Increasing cant, as measure from horizontal, can increase lateral stability as well as the bending moment on the main wing. A large degree of cant can also contribute to interference drag between the main wing and the wingtip.</td>
</tr>
<tr>
<td>Span</td>
<td>Lateral stability, parasitic drag, and wingtip loading. Large winglets can increase lateral stability as well as the bending moment on the main wing. The span is most often a tradeoff between the induced drag benefit and the profile drag penalty.</td>
</tr>
<tr>
<td>Sweep</td>
<td>Stall characteristics. Increasing the sweep can be used to increase the outboard loading of the wingtip. This, in turn, provides some control over the stall characteristics of the wingtip.</td>
</tr>
<tr>
<td>Twist</td>
<td>Wingtip loading and stall characteristics. Similar to wingtip sweep, the twist can be used to tailor the load distribution along the wingtip.</td>
</tr>
</tbody>
</table>

sweep of each of the wingtip design variables). This is done by selecting morphing modes which permit each motion, ultimately, determining the modes for each morphing module. Eliminating airfoil selection and reducing toe angle to wingtip twist, the design variables can be reduced to four morphing modes (i.e. cant morphing, twist morphing, sweep morphing, and span morphing). Airfoil selection is neglected at this point due to the emphasis on global morphing for the current concept. This choice also comes from a modeling perspective as discussed in Chapter 3. It can be shown that the four morphing modes permit global shape change of the wingtip and also emulate each of the original design parameters. A depiction of each of these modes, as they pertain to the modular concept, is shown in Fig. 2.6. Further discussion on the general motion of each of these modes is provided in Section 2.6. As a final note, the choice of
these modes also stems from a mechanism point of view. The modes are chosen to be relatively simple such that a variety of mechanisms may be applied, although the mechanism of choice for the current concept is the variable geometry truss mechanism (VGMT) as developed in [5] and discussed in the next section.

2.5 Morphing Mechanism

Although the current work does not focus on the design of a morphing mechanism, it is important, for the development of the concept, to shed some light on a mechanical system that can meet the requirements of the morphing system. The mechanism that has been adopted is the VGMT as outlined by A. D. Finistauri et al. [5, 28]. The VGMT can be applied in a modular way to meet the kinematic requirements of the morphing system. Consequently, a summary of the main features of this approach is provided below.

VGMTs are slender, active structures capable of changing their geometry to perform a variety of operating tasks. Simply put, VGMTs are truss structures in which traditional truss members are replaced with a series of active and passive prismatic actuators to provide kinematic motion. The structures are capable of large, rigid displacements and possess high stiffness to mass ratios to provide both structural integrity and functional dexterity. Examples of a planar longeron-actuated and spatial double octahedral VGMT are shown in Fig. 2.3.

The VGMT structure can satisfy the requirements necessary of the morphing system. In particular, VGMTs can provide the morphing wingtip with kinematic capabilities and can also support aerodynamic and structural loading as they are sufficiently rigid. Unlike traditional VGMTs, however, any truss used for wingtip applications must be subject to considerable size

![Figure 2.3 Planar longeron-actuated VGMT (left) and spatial double octahedral VGMT (right) [5]](image-url)
constraints as a result of narrow wingtip chords. To avoid this issue VGTMs such as those presented in [5], and displayed in Fig. 2.4, are proposed. The VGTMs can comprise the morphing modules that are to make up the wingtip structure. In essence, the spar/stringer arrangement of conventional wingtips is replaced in favor of VGTMs that kinematically connect airfoil ribs. As mentioned in [28], and shown in Fig. 2.4, the truss architecture consists of seven active and passive kinematic branches. The four active branches relate to a specific morphing degree of freedom; \( q_r \), \( q_b \), \( q_\Lambda \), and \( q_\alpha \) correspond to the branch actuators that control module cant, span, sweep, and twist, respectively [28]. The design of the morphing module permits the morphing modes as developed in the previous section. That is, the VGTM modules are capable of individual or simultaneous cant, span, sweep, and twist morphing. The modules also maintain the flexibility to adapt to changes in morphing requirements through reconfiguration of the base module.

2.6 Morphing Wingtip Concept and Associated Design Challenges

Through careful consideration of the above topics the morphing wingtip concept as displayed in Fig. 2.5 is proposed. The wing and wingtip is shown in the figure with the conventional aircraft coordinate frame. To summarize, the wingtip is made up of morphing modules, capable of individual or simultaneous cant, span, sweep, and twist morphing capabilities. The modules are stacked sequentially along the wingtip span in order to define the wingtip structure. It is intended that the morphing concept be used to address particular flight requirements amongst several
differing flight regimes, entailing the wingtip to be actively reconfigured during flight. The wingtip can then be geometrically scheduled so as to optimize each segment of flight or to address particular flight concerns, such as increased stability. The design meets the need and general requirements of the morphing wingtip. In particular, the design as shown is capable of overall morphing capabilities (i.e., multidirectional geometry changes) as well as being able to meet the strength and stiffness requirements through the use of the VGTM structure.

Returning to the morphing modes of the concept, these may be further explained by considering a module segment that is enclosed by two airfoil ribs, as shown in Fig. 2.6. Each module, \( m \), is enclosed by an inboard and outboard airfoil rib, which matches the module base and module platform of the VGTM mechanism as shown in Fig. 2.4. The local coordinate frame of each rib is situated at the \( \frac{3}{4} \) chord point along the rib line with the \( y_m \)-axis directed towards the trailing edge, the \( x_m \)-axis normal to the \( y_m \)-axis within the rib plane, and the \( z_m \)-axis situated to complete the right handed system. Each of the individual morphing modes is achieved as follows. The cant mode is accomplished through rotation of the outboard rib about the \( y_{m+1} \)-axis to develop an angle \( \Gamma_{m+1} \). Positive cant is measured by positive rotation or a wingtip up motion. The span mode is the motion of outboard rib along the \( z_m \)-axis, with respect to the inboard rib station. The span is measured as the total length of the module or the distance \( b_m \). In the sweep mode, the outboard rib is translated along the \( y_{m+1} \)-axis to create the angle \( \Lambda_{m+1} \). Note also that a positive sweep is achieved through translation of the outboard rib along the negative axis direction. Finally, the twist mode and angle \( \alpha_{m+1} \), is formed through rotation of the outboard rib about the \( z_{m+1} \)-axis while keeping the enclosing ribs parallel to one another. These details become increasingly important when developing the conceptual design framework in the succeeding
chapters. This is because these details are required for the development of various modeling tools.

In Fig. 2.5 the wingtip is shown with an arbitrary configuration and number of morphing modules. Through careful view of this simple diagram two primary issues facing the morphing concept are revealed. That is, the question of optimal wingtip shapes and an appropriate module layout. Since the wingtip is to be morphing to address different flight requirements it is necessary to formulate a method that can discover wingtip shapes that optimize various performance parameters. Wingtips are primarily used to reduce induced drag in the climb and cruise regime. However, a morphing wingtip can be employed to address additional flight
requirements. It would, therefore, be beneficial to know which shapes can optimize supplementary flight conditions. As well, it is necessary to discretize the wingtip shapes to determine a module layout that can realize optimal configurations while suffering minimal performance losses. Generally, some performance loss is to be expected as a result of the modular design (i.e., as a result of corner flows, restrictions due to mechanism workspace etc). In summary, the current issues facing the wingtip concept can be stated as follows:

A. Formulating the optimized geometric wingtip schedules required to meet specific performance requirements

B. Determining the appropriate module spacing and density for the wingtip schedules

Stemming from (A) and (B), it is a goal of the morphing concept to sufficiently emulate desired continuous wingtip shapes. Therefore, it is necessary to first distinguish the wingtip shapes that can be used to address particular flight requirements. The shapes can then be discretized for the modular concept. The purpose of the discretization is to determine the number of wingtip modules and their respective spacing required to emulate the performance of the continuous wingtip shapes. These and other issues are addressed through the conceptual design framework as discussed in the next chapter. As a supplementary study, a series of wind tunnel tests has also been performed on the morphing concept. Results pertaining to this study can be seen in Appendix A1.
Chapter 3
Development of Conceptual Design Framework

This chapter of the thesis aims to derive and explain all aspects of the conceptual design framework. The intention of the framework is to overcome challenges (A) and (B) as outlined in the previous chapter and restated below.

A. Formulating the optimized geometric wingtip schedules required to meet specific performance requirements

B. Determining the appropriate module spacing and density for the wingtip schedules

In order to accomplish this task, three elements have been combined to make up the framework, which are all coded in the MATLAB environment. The two primary elements of the framework are a continuous shape optimization module and an aerodynamic discretization module. Each of the modules is coupled with a modified version of the well-known Tornado vortex lattice method (VLM) [31] in order to estimate critical aerodynamic parameters.

Since the primary elements are developed through an adoption of existing methods, the methods themselves are discussed first in the sequence of the conceptual design framework. Following a general discussion of these methods is an explanation as to how these techniques are applied to the task of wingtip conceptual design. Further discussion on each of these topics is provided within the chapter and an illustration of the general steps involved in the framework has been depicted below.
3.1 Flight Regime Requirements

The first stage involved in the design framework is the definition of flight regimes and associated flight requirements. As mentioned previously, it is intended that the morphing concept be used to address particular flight requirements amongst several differing flight regimes, entailing the wingtip to be actively reconfigured during flight. Therefore, it is critical to first outline the design requirements of the wingtip device within the differing stages of its operation. Then, the wingtip can be geometrically scheduled throughout the flight profile to best suit the requirements of each flight regime.

At first glance the designation of different flight regimes and their associated performance parameters may seem quite simple. This is because the general flight pattern of any aircraft can be characterized by a climb, cruise, and descent regime. However, one must also consider the subtle differences in flight conditions amongst the regimes themselves as well as differences between various aircraft and wing designs that all contribute to an efficient wingtip configuration. For instance the cruise regime can be further broken down into initial cruise, mid cruise, and final cruise. Each of these sub-regimes is categorized by slight variances in flight conditions including airspeed, altitude, and angle of attack, not to mention likely differences in aircraft weight. If the wingtip is to be effective for a particular aircraft all of these issues must be considered within the framework.

This step is accomplished in the framework by physically entering the flight conditions (i.e., Mach number, altitude, and angle of attack), baseline wing parameters, and associated
### Table 3.1 Various flight requirements and associated performance indices [24]

<table>
<thead>
<tr>
<th>Flight Requirement</th>
<th>Performance Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endurance (propeller aircraft)</td>
<td>Maximize $C_L^{3/2}/C_D$</td>
</tr>
<tr>
<td>Endurance (jet aircraft)</td>
<td>Maximize $L/D$</td>
</tr>
<tr>
<td>Range (propeller aircraft)</td>
<td>Maximize $L/D$</td>
</tr>
<tr>
<td>Range (jet aircraft)</td>
<td>Maximize $C_L^{1/2}/C_D$</td>
</tr>
<tr>
<td>Gliding angle</td>
<td>Maximize $L/D$</td>
</tr>
<tr>
<td>Rate of climb</td>
<td>Maximize $L/D$</td>
</tr>
<tr>
<td>Stall speed</td>
<td>Maximize $C_L$</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>Minimize $C_{D_0}$</td>
</tr>
<tr>
<td>Turn radius</td>
<td>Minimize $C_{D_0}$</td>
</tr>
</tbody>
</table>

Table 3.1 provides performance indices for each of the flight regimes considered. The performance indices, as estimated by the aerodynamic tool Tornado, are chosen to reflect various flight requirements. For example, the lift to drag ratio is often chosen to quantify cruise performance. Other regimes, and associated flight requirements, have similar desirable performance parameters as noted in [24] and shown in Table 3.1. In the table the variables $L$, $D$, $C_L$, $C_D$, and $C_{D_0}$ represent lift, drag, coefficient of lift, coefficient of drag and the zero lift drag coefficient, respectively. From Table 3.1 one can also note that morphing is not just a matter of adapting the wingtip to different flight conditions but rather a problem of changing the wingtip in order to focus on the relevant performance index for each flight requirement. This decision process becomes very important and can become a field of its own, and in fact is an important field in the design of traditional aircraft.

## 3.2 Continuous Wingtip Shape Optimization

The purpose of the optimization procedure is to distinguish optimal continuous wingtip configurations to effectively address issue (A) (i.e. formulating wingtip schedules to meet specific performance requirements) of Chapter 2. The procedure is carried out separately for each flight regime and is performed using the phenomenon-mimicking harmony search (HS) as originally developed by Z. W. Geem and J. H. Kim [33]. For each regime the previously defined performance indices are used to estimate wing/wingtip performance. Using this procedure, optimized configurations can be found that provide ideal effectiveness in terms of the sought performance index. The configurations can also dictate how the wingtip might be scheduled throughout the aircrafts flight profile.

It is well known that minor changes in wing/wingtip geometry can vary aerodynamic performance significantly, see Appendix A1. Appendix A1 also demonstrates how each of the four morphing modes, as mentioned in Chapter 2, can be used to change different aerodynamic
characteristics. Therefore, it is critical to analyze, or have a method to discover, wingtip geometries that provide optimal performance. As a note, the term continuous is used within this section to distinguish between smooth wingtip shapes as opposed to the modular shape shown in Fig. 2.5.

The HS is a metaheuristic optimization procedure that was inspired by the natural improvisation process of musicians. With regard to the current work, the HS is well suited as the global optimum exploration tool as the optimization problem is inherently one with a multimodal, discontinuous design space. The HS also has the following merits that present this method to be beneficial:

- the HS is free from divergence and can escape local optima
- the HS does not require initial value settings
- the HS can handle discrete and continuous variables
- the HS can explore continuous and discontinuous functions
- the HS is a coupled local and global search procedure

Referring back to the inspiration for this algorithm, the HS simulates a team of musicians playing together trying to seek the best state of musical harmony. Harmony amongst the musicians is considered to be a result of the individual notes being played by each instrument. Consequently, if the correct notes are played there is better overall musical harmony and vice versa. Each musician is considered to generate sound based on one of three options; (a) memory consideration (i.e., playing a piece of music from memory), (b) pitch adjustment (i.e., playing something similar to a known piece, that is, taking something from memory and changing it slightly), or (c) random selection (i.e., composing new or random notes). This can be equated to finding the ideal solution in a multivariable problem. In the optimization sequence, every musician corresponds to an attribute in a candidate solution and each instrument's pitch and range correspond to a decision variable and the bounds placed on that variable. Similarly, musical harmony is equated to an objective function for which a minimum or maximum is sought. That is, the global optima of the objective function can be found through careful selection of the decision variables.

Harmony, in the optimization algorithm, is often represented through a vector that is composed of the problem variables. Within the algorithm multiple harmony vectors are iteratively evaluated
where each vector is considered to be a candidate solution to the problem. The intention of the technique is to use good candidate solutions, already discovered, to influence the creation of new solutions. This is done by considering previously formed harmony vectors in a way that is similar to options (a), (b), and (c) above. New solutions are formed by formalizing these steps into three quantitative processes [34]:

1. Memory consideration: A harmony memory (HM) is used to store good harmonies (i.e., good candidate solutions). Harmonies within HM are also used based on the parameter harmony memory consideration rate (HMCR) € [0, 1] when further considering stored solutions. Decision variables within stored solutions are taken from HM with probability HMCR. The variables can be used to make up a new solution by being left as they are or by being pitch adjusted.

2. Pitch adjustment: Pitch adjustment is performed on variables taken from stored solutions. Similar to that of a local search, a variable is taken from a HM solution and is pitch adjusted based on the pitch adjustment rate (PAR) € [0, 1] so that a slightly different solution is formed. The degree to which a certain value is adjusted is based on the pitch bandwidth (BW). Therefore, there is probability PAR that a decision variable is altered and probability 1-PAR that the value is unaltered.

3. Random selection: If a solution is not selected for memory considerations then a new variable is generated randomly. This is done with probability 1-HMCR.

As shown in Fig. 3.2, steps (1), (2), and (3) can be formulated into a pseudo code that represent the HS procedure. The HS is, to some extent, a combined local and global optimization tool. The randomization of the HS increases the diversity of solutions while the pitch adjustment corresponds to a local search. Throughout literature the values of the HS parameters differ from one application to the next. However, typical values for the HMS, HMCR, and PAR are 1-100, 0.7-0.95, and 0.1-0.5, respectively. The BW on the other hand is completely dependent on the application as the pitch values themselves represent the problem variables. It is also important to know how each of these parameters generally affects the solution. Since the HMCR controls the use of information from the HM or the generation of random harmonies, it also regulates the rate of convergence of the algorithm. Similarly, the PAR controls the frequency of adjustment of decision variables selected from HM and regulates convergence of the solution as well. Since each of these values is related to convergence it is important that they are set appropriately to avoid premature or excessive convergence. Unfortunately, there is no strict guideline as to how
Figure 3.2  Pseudo code of the harmony search algorithm [33]

these variables should be selected, as their values are, once again, dependent on the application. Further discussion on the selection of each of these variables for the current application is provided in the next chapter.

3.2.1 Wingtip Formulation of Optimization Procedure

HS theory can be directly adopted and applied to the problem of wingtip shape optimization. To do this the wingtip is segmented into an appropriate number of equally spanned panel partitions, \( i \), so as to emulate a continuous wingtip shape. An analogy can be made to the approximation of integrals (see Fig. 3.3). In order to approximate the integral of a continuous function on the interval \([a, b]\) the function can be partitioned into a number of smaller sub-intervals. Using rectangular areas over the subintervals the integral of the function is approximated. When the intervals are chosen to be suitably small the approximation of the integral becomes more exact. This is similar to segmenting the wingtip into a number of panel partitions. If a reasonable number of panel partitions are used the wingtip can be approximated to a continuous shape. Therefore, if the wingtip shape is highly deflected, as shown in Fig. 3.3, the panel partitions are capable of adequately approximating that shape.
Using this approach the HS can be formulated as shown in Fig. 3.4. The harmony vectors are made up of a number of decision variables that characterize the configuration of the wing and wingtip. This is accomplished by expressing the wing and wingtip partitions through global cant ($\Gamma$), span ($b$), sweep ($\Lambda$), and twist ($\alpha$). Representing the wing variables in bold, each harmony vector takes the following form:

$$\mathbf{x} = \left[ \Gamma \ b \ \Lambda \ \alpha \ , \ \Gamma_1 \ b_1 \ \Lambda_1 \ \alpha_1 , \ldots , \ \Gamma_i \ b_i \ \Lambda_i \ \alpha_i \right]$$  \hspace{1cm} (3.1)

Hence, the combination of decision variables influences the chosen objective function value. This is because the general configuration of the wing and wingtip will have differing aerodynamic properties. The objective function is formed based on the sought aerodynamic performance indices as noted in Section 3.1.
Based on equation 3.1 the HM can be represented in the following form, where $f(x)$ represents the sought objective function value:

$$
\text{HM} = \begin{bmatrix}
\Gamma^1 b^1 \Lambda^1 \alpha^1 & \Gamma_1^1 b_1^1 \Lambda_1^1 \alpha_1^1 & \ldots & \Gamma_i^1 b_i^1 \Lambda_i^1 \alpha_i^1 & f(x^1) \\
\Gamma^\text{HMS} b_1^\text{HMS} \Lambda^\text{HMS} \alpha^\text{HMS} & \Gamma_1^\text{HMS} b_1^\text{HMS} \Lambda_1^\text{HMS} \alpha_1^\text{HMS} & \ldots & \Gamma_i^\text{HMS} b_i^\text{HMS} \Lambda_i^\text{HMS} \alpha_i^\text{HMS} & f(x^\text{HMS})
\end{bmatrix} \quad (3.2)
$$

Every row of the HM represents a harmony vector and resulting objective function value. As well, the harmonies in the above matrix are each a solution within themselves; where the first row of the HM matrix represents the best solution. Since the wing variables are identical within each harmony, the goal of the search is to find the best combination of panel partition values in order to find the desired optima of the objective function. As shown in Fig. 3.4, the first step to the HS procedure is to initialize the HM. This is accomplished through the formation of HMS
random harmony vectors and sorting them to make up the initial HM. Limits are placed on each of the wingtip decision variables to avoid the generation of unreasonable wingtip configurations. Upon developing each harmony vector the performance of the associated wing/wingtip configuration is evaluated by Tornado VLM. This is carried out by assembling the decision variables into data structures that are recognized and usable by Tornado. The resulting performance of each configuration allows the harmony vectors to be recursively sorted within HM. In terms of the design framework, the performance of the wing/wingtip is chosen to reflect each flight regime and associated performance index.

Once the HM is established new candidate solutions are iteratively generated using three methods, as noted in Section 3.2 and discussed below. A uniform probability distribution and random number generator are set in the optimization coding so as to aid in the development of future harmonies. Random numbers are generated on the interval (0, 1) based on the uniform distribution. Depending on the selected random number, new harmony vectors are created through separate or combined memory consideration, pitch adjustment, or randomization.

1. Memory consideration: If the random generated number is less than the HMCR an existing harmony vector value is chosen from HM. A non-uniform probability distribution is also set so as to choose more pleasing decision variables. Therefore, it is more likely that variables within the top rows of the HM are chosen as opposed to those in lower row vectors. Upon selecting a variable, the value can be used as is or pitch adjusted to make up a new harmony vector.

2. Pitch adjustment: If the random generated number is less than the HMCR and also within limits of the PAR the selected variable is pitch adjusted. Pitch adjustment is carried out by altering the variable a small random amount within the bounds of the BW.

3. Random selection: If the random generated number is greater than the HMCR, a new harmony vector is established with random decision variables that are within their allowable range.

Within the HS coding care is taken to ensure that decision variables are not mismatched. For example, envision a variable being generated based on memory consideration. The variable being generated must match the one taken from HM. Therefore, if a panel partition cant variable is being created using memory consideration, the variable taken from HM must also be a cant variable. Similarly, the BW must also match if pitch adjustment is the method by which a new variable is being generated. Variables are then adjusted based on their own allowable range.
The HS continues to iterate through candidate solutions in this way until an acceptable stopping criteria is met. The stopping criteria can be established by considering a maximum amount of iterations of the HS procedure or can be based on suitable convergence standards. For the wingtip formulation, convergence of the performance indices and HM is used as the stopping criteria. Further details on convergence of the HM are provided in Chapter 4. As shown in Fig. 3.4, the final optimized wingtip shape is expressed through the best harmony vector. As noted at the beginning of this section the HS procedure is carried out for all flight regimes being considered within the design framework. Consequently, if \( n \) flight regimes are considered the result is \( n \) optimized continuous wingtip shapes.

3.3 Aerodynamic Discretization

The purpose of the discretization process is to discretize the continuous optimized wingtip shapes for the modular morphing concept. This is carried out to address issue (B) (i.e., determining the module spacing and density for the optimized wingtip schedules) of Chapter 2. By discretizing the wingtip configurations, an ideal number of morphing modules, \( m \), and their respective spacing can be determined. The appropriate number and spacing of modules is dependent on how close a modular wingtip can emulate the shape and performance of a continuous design. The discretization process is also carried out separately for each of the flight regimes chosen for consideration.

Aerodynamic discretization is achieved through the method as outlined in [28] using the same performance indices as originally defined for each flight regime. Although the method is used for morphing wing development in [28] it is equally applicable to wingtips. The discretization itself is accomplished through a two-step process as outline in Fig. 3.5. The method alternates between

![Figure 3.5 Aerodynamic discretization sequence [28]](image)
geometric discretization of the wingtip into morphing modules and aerodynamic evaluation of the modular wingtips performance. The wingtip is first segmented into two modules and is evaluated for its aerodynamic performance. The wingtip is then segmented into three modules and evaluated and so on until an acceptable stopping criterion is met. To begin the discretization process a known continuous wingtip shape must first be expressed in terms of a parametric curve and a parallely transported coordinate frame [28]. The curve and associated frame are situated along the quarter chord line of the wingtip and are used to distribute morphing modules. The local coordinate system is set up to match that of Section 2.6. That is, the local y-axis is directed toward the wingtip trailing edge, the z-axis directed outboard and being locally tangent to the wingtip curve and the x-axis completing the right handed coordinate system. Distribution of modules is accomplished through calculation of the total curvature of the wingtip line and allocating modules accordingly.

Parameterizing the wingtip curve on the interval $0 \leq t \leq 1$, the space curve can be represented by:

$$\mathbf{s}(t) = \{s_x(t), s_y(t), s_z(t), s_\alpha(t)\}^T$$  (3.3)

In the above, $s_x$, $s_y$, and $s_z$ are the x, y, and z scalar components of a standard space curve that, as a set, represent the position of the curve in 3D space. The additional component, $s_\alpha$, is the scalar component that describes the rotation of the coordinate frame. The components used in equation 3.3 can be any set of parametric equations that possess $C^2$ continuity on the interval $0 \leq t \leq 1$ [28]. Denoting $\dot{s} = ds/dt$ and $\mathbf{s}_X = \{s_x(t), s_y(t), s_z(t)\}^T$, the instantaneous curvature at any point $t$ along the curve can be defined using the Frenet-Serret formulas by:

$$\kappa(t) = \frac{\|\mathbf{\dot{s}}_X(t) \times \mathbf{s}_X(t)\|}{\|\mathbf{s}_X(t)\|^3}$$  (3.4)

The curvature defined above expresses how fast the unit tangent vector to the curve rotates from its local direction. Similarly, the instantaneous torsion can be defined as in equation 3.5, where the torsion is a measure of local twist that the coordinate frame experiences as it moves along the space curve.

$$\tau(t) = \frac{\|\mathbf{s}_X(t)\|}{\|\mathbf{s}_X(t)\|^2}$$  (3.5)
Using equations 3.4 and 3.5 the total curvature of the wingtip line can be defined. This is done by integrating the vector sum of the curvature and torsion over the entire length of the wingtip line. The total curvature of the 3D line is then represented through equation 3.6.

\[ \chi = \int_0^1 \sqrt{(\kappa(t))^2 + (\tau(t))^2} dt \]  

(3.6)

As noted in [28], \( \chi \) is a measure of the overall deviation of the reference wing from a straight, untwisted wing. Morphing modules are spaced such that each module spans an equal amount of total curvature. Alternatively, the equal amount of total curvature can be defined as the average total curvature for each module or \( \bar{\chi} = \chi/m \). The nodal points, denoting the beginning and end of each module, are spaced on the wingtip line to reflect the average total curvature of each module. This is carried out by sequentially solving equation 3.7 for \( t_{k+1} \) using the golden section search.

\[ \bar{\chi} = \int_{t_k}^{t_{k+1}} \sqrt{\kappa^2 + \tau^2} dt, \quad k = 0, 1, ..., m - 1 \]  

(3.7)

Since the beginning of the first module starts at \( t_0 = t_0 = 0 \), the only unknown in equation 3.7 is \( t_{k+1} \). Solving sequentially, each modules start point will always be known. Therefore, a nodal spacing vector of the form 3.8 can be determined.

\[ T = \{0, t_1, ..., t_k, ..., t_{m-1}, 1\} \]  

(3.8)

As noted in [28], the kinematics of each module must be calculated prior to aerodynamic evaluation by any flow solver as a result of meshing requirements. This is the point at which the morphing modes as defined in Section 2.6 become important. The module kinematics are solved based on the defined morphing modes. The local span of each module is the magnitude of the vector between each sequential node as shown in equation 3.9.

\[ b_m = \|s_X(t_k) - s_X(t_{k-1})\| \]  

(3.9)

Each modules local sweep and cant can be determined through equations 3.10 and 3.11, respectively.

\[ \Lambda_m = \tan^{-1}(-b_{k,y}', b_{k,z}') \]  

(3.10)
\[ r_m = \sin^{-1}\left( \frac{b'_{k,x}}{b_k} \right) \]  

(3.11)

In the above equations, \((b'_{k,x}, b'_{k,y}, b'_{k,z})\) represent the local elements of the span vector along the \(x, y, \text{ and } z\) axes. Finally, the local module twist is represented through equation 3.12, where \(x_\alpha\) and \(x_R\) are vectors determined by the orientation of the transport coordinate frame.

\[ \alpha_m = \cos^{-1}(x_\alpha \cdot x_R) - \pi/2 \]

(3.12)

Using the module kinematics the aerodynamic performance of the modular wing can be determined for each iteration of the discretization loop. The ideal number of morphing modules can be decided upon using a number of criteria, as outlined in [2, 28]:

1. If the performance of the discretized wingtip is within suitable limits of the reference wingtip performance (i.e., no more modules are required to emulate continuous wingtip performance).

2. If the performance of the discretized wingtip asymptotically approaches some maximum value and no appreciable gains are realized by adding more modules.

3. If the performance of the discretized wingtip suddenly drops when adding more modules.

4. If a maximum desired number of modules is reached and the addition of more modules would over complicate the morphing system.

The goal in deciding upon an appropriate number of morphing modules is to choose the lowest number of modules that permits an acceptable level of performance. Using fewer modules reduces the possible complexity of the morphing system as a whole. Through the above approach, morphing modules are spaced such that more tightly spaced modules are placed in areas of greater total wingtip line curvature and vice versa. Therefore, known wingtip shapes can be adequately imitated using a modular design.

### 3.3.1 Wingtip Formulation of Discretization Procedure

The modifications required to apply the discretization method toward wingtip development are rather straightforward. To adopt this technique, the discretization is restricted to the wingtip region of the wing as opposed to the methods use in [28]. Consequently, only the portion of the
wing that constitutes the wingtip is discretized. This is accomplished by defining the beginning of the parametric curve and parallel transport frame at the end of the wing section or the point at which the wingtip begins, as in Fig. 3.6.

Bezier curves are chosen to represent the wingtip line to characterize the possible wide range of optimized continuous wingtip shapes. Parametric representation of the wingtip line with a Bezier curve on the interval (0, 1) is given by equations 3.13-3.15 as:

\[ s_x(t) = \sum_{i=0}^{n} B_{i,n}(t)X_i \]  \hspace{1cm} (3.13)

\[ s_y(t) = \sum_{i=0}^{n} B_{i,n}(t)Y_i \]  \hspace{1cm} (3.14)

\[ s_z(t) = \sum_{i=0}^{n} B_{i,n}(t)Z_i \]  \hspace{1cm} (3.15)

where \((s_x, s_y, s_z)\) are the scalar components of the wingtip line, \(B_{i,n}\) are the Bezier basis functions, \((X_i, Y_i, Z_i)\) are the coordinates of the Bezier control points, and \(n\) is the total number of control points. Here, the values of \(i\) and \(n\) are not to be confused with their previous usage as the number of panel partitions and flight regimes as noted in earlier sections.

Figure 3.6  Adaptation of discretization method toward wingtip development
The basis functions of the Bezier curve are given by the Bernstein basis polynomials as:

\[ B_{i,n}(t) = \binom{n}{i} t^i (1 - t)^{n-i}, \quad i = 0, \ldots, n, \]  

(3.16)

Control points for the Bezier curve are extracted from the optimization results of Section 3.2. The position of each control point is the quarter chord location at the beginning and end of every panel partition, as demonstrated in Fig. 3.6. The Cartesian coordinates of the control points are extracted based on the optimal harmony vector as found by the HS. That is to say, the geometry of the panel partitions is used to determine the control point locations.

In a similar manner the Bezier curve is also used to represent the torsion of the transport frame. Also in parametric form, the scalar component that characterizes the rotation of the coordinate frame is given by equation 3.17.

\[ s_\alpha(t) = \sum_{i=0}^{n} B_{i,n}(t) A_i \]  

(3.17)

Again, \( B_{i,n} \) are the Bezier basis functions denoted by equation 3.16. Unlike the space curve, however, the term \( A_i \) is used to represent the degree of curvature of the coordinate frame as opposed to Cartesian coordinates. The curvature points are also extracted from previous optimization results. These are developed from the degree of twist of each panel partition.

Once the parametric form of the Bezier curve is constructed, the discretization process continues as noted in Section 3.3. That is to say, the distribution of morphing modules is calculated based on the total curvature of the Bezier space curve. The module kinematics are then calculated so that the performance of the discretized wingtip can be determined. The aerodynamic model coupled with the discretization process is Tornado VLM. As mentioned in the previous section, a number of criteria are used to determine an optimal number of morphing wingtip modules. By using this approach the wingtip is not simply segmented into equally spanned morphing modules, but is discretized as determined by desirable wingtip configurations. Based on the total curvature of the desired shapes more, closely spaced modules will be put in regions of larger total curvature and vice versa. Therefore, the modular concept will be capable of more adequately emulating desired wingtip shapes.
3.4 Aerodynamic Model

As mentioned previously, the aerodynamic tool used in the current work is the well-known Tornado VLM [31], which has been developed and continually updated by Dr. Tomas Melin. Although Tornado is considered a low fidelity tool it has been selected for the current work for its computational efficiency. The VLM is fast, which is a requirement of design studies that entail a large number of function evaluations, such as the one here. More advanced aerodynamic tools are not practical for the design framework at the moment due to the considerable increase in solution times. VLMs are also quite accurate in the linear regions of flight which aircraft tend to spend a lot of their time. In the design framework, Tornado is used for the calculation of relevant aerodynamic coefficients through the computation of wing lift, induced drag, and zero lift drag. To do this Tornado has been coupled with both the optimization and discretization modules. As such, some background information is provided on this tool.

Common to all VLMs, the aerodynamic model is built based on potential flow theory. Therefore, a number of assumptions are implied; being that the flow field is incompressible, inviscid, irrotational, and lifting surfaces are considered thin (i.e. influence of thickness on aerodynamic forces is neglected). Lifting surfaces within Tornado are approximated through a set of lifting panels, as shown in Fig. 3.7.

In Tornado each panel contains a control point and a vortex-sling, which is essentially a seven-segment vortex line. The vortex-slings are oriented such that they pass through the ¼ chord position of each panel. Using the vortex-slings the spanwise and chordwise variation of lift is modeled as a set of step changes in vortex strength from one panel to the next. The strength of each bound vortex is represented by $\Gamma$, which is not to be confused with the letters usage in previous sections. The strength of each vortex is unknown and is calculated by applying a
surface flow boundary condition and solving the resulting system of equations. The boundary
condition states that there is to be zero flow normal to each panel’s surface. In essence, this
means that at the wing surface the flow must be completely parallel to the surface. The
condition is applied at the ¾ chord point along the centerline of each panel (i.e., the control point
location). To account for varying airfoil designs, the panels are sloped within the airfoil plane to
imitate the camber of different airfoil types. The normal velocity, \( V_{normal} \), surrounding each panel
of the lifting surface is composed of a free stream component and induced flow component, as
shown in equation 3.18. In the equation, \( V_\infty \) and \( W_i \) denote the free stream velocity and induced
velocity, respectively.

\[
V_{normal} = b + W_i = f(V_\infty) + W_i = 0
\]  

(3.18)

\[
W_i = \sum_{j=1}^{p} w_{ij} \Gamma_j
\]  

(3.19)

The free stream component, \( b \), in equation 3.18 is a function of the free stream velocity, which
takes into account the surrounding flow conditions (i.e., angle of attack, sideslip etc.). As
demonstrated through equation 3.19, the induced component is a function of all the vortex
strengths on the wing. The influence coefficients, \( w_{ij} \), represent the induced flow on panel \( i \) due
to the vortex on panel \( j \). Therefore, a set of linear equations can be set up which represents the
vortex strengths on all panels, \( p \). The resulting linear system of equations can be shown to
follow equation 3.20.

\[
\begin{bmatrix}
w_{11} & w_{12} & \cdots \\
w_{21} & \ddots & \cdots \\
\vdots & \ddots & \ddots \\
\end{bmatrix}
\begin{bmatrix}
\Gamma_1 \\
\Gamma_2 \\
\vdots \\
\Gamma_p \\
\end{bmatrix}
= 
\begin{bmatrix}
b_1 \\
b_2 \\
\vdots \\
b_p \\
\end{bmatrix}
\]  

(3.20)

Summarizing the above, \( w \) is the induced flow from each vortex through each panel, \( \Gamma \) is the
vortex strength which is unknown, and \( b \) is the flow through each panel as determined by the
flight condition. The strength of the vortex-slings is obtained through solution of equation 3.20.
The lift of the lifting surface can then be calculated through the Kutta-Joukowski theorem
(equation 3.21). In equations 3.21 and 3.22, \( l \) represents the width of each lifting panel.

\[
L = \sum_{i=1}^{p} L_i = \sum_{i=1}^{p} \rho \cdot V_\infty \cdot \Gamma_i \cdot l_i
\]  

(3.21)
\[ D = \sum_{i=1}^{P} D_i = \sum_{i=1}^{P} \rho \cdot V_{\infty} \cdot \Gamma_i \cdot l_i \sin \alpha_i \]  \hspace{1cm} (3.22)

Once the lift is known, the induced drag of the lifting system can be calculated through equation 3.22. This is performed by calculating the induced angle of attack, \( \alpha_i \), which gives rise to the lift induced drag. Tornado also incorporates additional features such as a compressibility correction for high subsonic Mach numbers as well as a zero lift drag prediction method, which make it a valuable tool for the current application. The compressibility correction is performed by relating flows in the incompressible plane to those in the compressible plane. This is carried out in the VLM coding through a compressibility correction factor applied to the vortex strengths as solved through equation 3.20. The correction has shown to result in higher computational accuracy, as noted in [34]. On the other hand, the zero lift drag prediction is performed by estimating the surface drag that is to be expected from the wing area. This is performed in Tornado using a coefficient of drag correction factor that is multiplied by the wetted wing area. Therefore, although the VLM is incapable of calculating viscous drag it is able to estimate induced drag, zero lift drag, and lift, which are all important factors in aerodynamic analysis.

To summarize, the conceptual design framework is a three-step process that includes the definition of flight requirements, optimization of the wingtip to meet those requirements, and discretization of the wingtip for the modular concept. To begin the framework the primary design requirements of each flight regime must be outlined. This entails the definition of expected flight conditions as well as the performance characteristics that designers wish to address within each regime. Once the flight conditions and associated performance indices are selected the framework proceeds to find optimal continuous configurations of the wingtip. This step is performed separately for each flight regime. Using the optimization results, the framework then discretizes each wingtip configuration. Throughout the entire framework process the performance indices for each regime remain constant. Therefore, if the optimization procedure looks to address \( C_L/C_D \) for a particular regime, the discretized wingtip performance is also measured using \( C_L/C_D \) for that regime. In the end a researcher or designer can select ideal module layouts for each of the wingtip configurations. The results are modular wingtip shapes that can be used to address varying flight requirements with ideal performance.

A few additional notes must be made on the conceptual design framework. First, it is important to mention that the optimization and discretization processes are intended to be independent of the actual morphing mechanism, insofar as the required morphing motion falls within the
workspace of the mechanism. Therefore, it is assumed that the configurations examined through these processes are achievable by the morphing mechanism. Secondly, as shown in Fig. 3.1 some consolidation of the discretization results is required to determine a final module layout for the concept. The discretization results obtained for each flight regime will, in general, be different from one regime to the next. Variations in these results are to be expected as different configurations will be optimal for varying flight conditions. Consequently, some method to consolidate the variety of module layouts obtained through the framework is required. Although this aspect is left untouched within this thesis it is important to note for the overall development of the concept.
Chapter 4

Design Study

The results presented in this section of the thesis demonstrate the application of the conceptual design framework toward modular morphing wingtip development. A primary goal of this research is to demonstrate the feasibility of the proposed concept. In doing so, it is anticipated that the framework will reveal modular wingtip configurations that yield improved efficiency over fixed wingtip designs. Within the chapter the framework is first validated prior to implementation in the design study. This is carried out through a comparison of the current analytical model with other research work. For the design study a hypothetical wing/wingtip combination is considered. The study is posed as an optimization problem in which a design mission composed of three flight regimes is investigated. The intent of the design mission and framework process is to distinguish optimal modular geometric schedules for each flight regime based on desired performance metrics. This is done to illustrate the steps in the process as well as to outline how the current tools overcome the challenges imposed by the morphing concept. The results are used to identify relevant morphing configurations of the wingtip and their respective module layout, as well as to demonstrate implementation issues using the current approach.

4.1 Validation of Framework

The optimization and aerodynamic modules of the design framework are compared and validated previous to implementation in the design study. This analysis is carried out to check
the legitimacy of the framework results and to examine the shortcomings of using a low fidelity aerodynamic tool.

To the author’s knowledge and with the exception of [28], no other work has been performed on the modular discretization of morphing wings or wingtips. Although other researchers are pursuing modular methods they have used equally spanned morphing modules to develop their concepts. Since the discretization process used within the framework has been adopted from [28], this aspect of the thesis work is not validated. Validation is, however, carried out on the optimization module and aerodynamic model separately, as discussed below.

4.1.1 Aerodynamic Validation

As mentioned previously, the aerodynamic model is Tornado, which has been developed by Dr. Tomas Melin. The Tornado coding has been verified by Dr. Melin himself in [31, 34] as well as other researchers [19]. For conventional wing (i.e., relatively planar) and multi-wing designs the models accuracy is well within the methods assumptions. In [34], the model was verified against wind tunnel data that were gathered through analyzing an elliptical wing planform. Comparing the lift slopes of the experimental results to those of the VLM the percent difference between results was shown to be 0.9%, 0.2%, and -2% for Mach numbers of 0.3, 0.4, and 0.5, respectively. Slightly larger errors were noticed when comparing drag polars as a result of the codes inability to capture viscous effects. The percent difference between experimental and VLM results was shown to be -4%, -5%, and -4% for the three Mach numbers.

Using the VLM in the current work, the primary concern with the model is its inability to capture viscous effects. Since the current design uses a modular approach for wingtip morphing there may be significant viscous interactions between adjacent modules. This comes about through interacting junction flows at the point where one module mates up with one another. Therefore, a validation exercise is carried out on a modular wing design to quantify this error. This task is done through comparison of the VLM to a higher order numerical method.

For the current comparison case the work performed in [28] is used. The aerodynamic tool used in [28] is ANSYS Fluent, which incorporates a solver that can handle viscous effects. In [28] the discretization was performed on an entire wing while using $C_L/C_D$ as the performance index. The wing examined in the work has a taper ratio of 0.1 and is scaled such that the root chord is one thousand units in length. The points used to construct the quarter chord wing curve, also taken from [28], are displayed in Table 4.1. The flight condition for the wing is set to an AoA = 5° and a flight speed of $M = 0.3$ at standard sea level. Repeating the study using the current
aerodynamic model, one needs only to compare a few data points to demonstrate the difference in aerodynamic tools. For the four module discretization case the performance was noted to be $C_L/C_D|_{m=4} = 25.0807$ in [28]. Using the linearized aerodynamic model a performance of $C_L/C_D|_{m=4} = 31.1821$ is calculated for the same four module case. Similarly, in [28] the optimal discretization was noted to be the six module case with performance of $C_L/C_D|_{m=6} = 26.4002$. Again using Tornado the value of $C_L/C_D|_{m=6}$ is found to be 32.3323. These values result in a percent difference of 21.7% and 20.2% for the four module and six module discretization’s respectively. It is clear that the simplified aerodynamic model over predicts the $C_L/C_D$ ratio. This is to be expected as the simplified model under predicts drag. Since the percent difference is quite large for these cases it is clear that the aerodynamic tool being used in the framework is only valid for conceptual design purposes. The benefits of such low fidelity tools is in there solution times which are quite fast and highly applicable to optimization procedures. Further development of the morphing concept would require higher order tools for aerodynamic evaluation.

### 4.1.2 Optimization Validation

The test case used to validate the optimization module is taken from [19], where a four module wingtip is investigated using Tornado. A genetic algorithm is used for optimization purposes in [19]. However, results obtained from a modified version of the HS module should be comparable as long as a similar global design space is being investigated and an appropriate convergence criterion is selected. In order to perform the validation the HS module is modified to consider an augmented Airbus A320 wing planform that consists of four morphing modules, as shown in Fig 4.1.

In addition, a quasi-analytic weight prediction module as developed by Torenbeek [35] is added to the HS in order to compute an estimated wing weight. An additional five-pounds per square foot is also added to approximate the additional weight of the morphing mechanism, as suggested by [19, 12]. In [19] limits are placed on the motion of all four of the modules. The first module is restricted to cant and twist morphing only as the remainder of the modules are

<table>
<thead>
<tr>
<th>$t$</th>
<th>0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_x$</td>
<td>0</td>
<td>3.00</td>
<td>6.72</td>
<td>11.43</td>
<td>17.58</td>
<td>25.97</td>
<td>38.01</td>
<td>57.14</td>
<td>91.43</td>
<td>171.43</td>
<td>571.43</td>
</tr>
<tr>
<td>$s_y$</td>
<td>0</td>
<td>36.85</td>
<td>80.4</td>
<td>130.65</td>
<td>187.6</td>
<td>251.25</td>
<td>321.6</td>
<td>398.6</td>
<td>482.4</td>
<td>572.85</td>
<td>670</td>
</tr>
<tr>
<td>$s_z$</td>
<td>0</td>
<td>250</td>
<td>500</td>
<td>750</td>
<td>1000</td>
<td>1250</td>
<td>1500</td>
<td>1750</td>
<td>2000</td>
<td>2250</td>
<td>2500</td>
</tr>
<tr>
<td>$s_\alpha$</td>
<td>0.0227</td>
<td>0.025</td>
<td>0.0278</td>
<td>0.0313</td>
<td>0.0357</td>
<td>0.0417</td>
<td>0.05</td>
<td>0.0625</td>
<td>0.0833</td>
<td>0.125</td>
<td>0.25</td>
</tr>
</tbody>
</table>
permitted cant, span, sweep, and twist morphing. As noted in [19], restrictions are also placed on the motions of each of the three outboard modules, although the exact intervals are not revealed. For the validation case the intervals are selected as shown in the below optimization statement.

\[
\begin{align*}
\text{Max.} & \quad I_{\text{validation}} \\
\text{w.r.t.} & \quad \Gamma_1, \alpha_1, \Gamma_{2-4}, b_{2-4}, \Lambda_{2-4}, \alpha_{2-4} \\
\text{s.t.} & \quad \lambda = 0.11 \\
& \quad c_r = 6.75 \text{ [m]} \\
& \quad -5^\circ \leq \Gamma_1 \leq 5^\circ \\
& \quad b_1 = 5.15 \text{ [m]} \\
& \quad \Lambda_1 = 32.5^\circ \\
& \quad -2^\circ \leq \alpha_1 \leq 2^\circ \\
& \quad -5^\circ \leq \Gamma_{2-4} \leq 60^\circ \\
& \quad 0.875 \text{ [m]} \leq b_{2-4} \leq 0.9250 \text{ [m]} \\
& \quad -2^\circ \leq \Lambda_{2-4} \leq 2^\circ \\
& \quad -1.5^\circ \leq \alpha_{2-4} \leq 1.5^\circ 
\end{align*}
\]

The scalar function, \( I_{\text{validation}} \), to be optimized is the specific air range (SAR) as outlined by the Breguet range equation below.

\[
\text{SAR} = \frac{V_\infty \cdot (L/D)}{W \cdot \text{sfc}} \quad (4.1)
\]

In equation 4.1, \( V_\infty \), \( L \), \( D \), \( W \), and \( \text{sfc} \) are the freestream velocity, lift, drag, aircraft weight, and specific fuel consumption, correspondingly. For the optimization the initial cruise regime of
Figure 4.2  Left: Optimization module validation results, Right: Optimization results of [19]

AoA = 3°, M = 0.78 and altitude of 10,668 [m] is used. The stopping criteria is chosen to reflect convergence of the objective function values and wingtip shape variables as stored in HM. Consequently, the HS stops when the objective function values and wingtip shape variables are within a tolerance of $1 \times 10^{-4}$ and $1 \times 10^{-1}$, respectively.

Performing the optimization using the current model provided similar results (Fig. 4.2) to those shown in [19]. As shown in Fig. 4.2 the wingtip is characterized by a large degree of cant in the outboard modules. The inboard module also has a slight degree of cant, which resembles the results shown in [19] for the initial cruise regime. Small differences are to be noted between the two configuration results. This could be a consequence of several factors (i.e. convergence criteria, variable restrictions etc.) that cannot be addressed without further knowledge of the optimization procedure used in [19]. Unfortunately, the exact values of cant, span, sweep, and twist for each module are not directly expressed in [19]. The wingtip shapes, however, are considered alike thus validating the optimization module.

4.2 Design Study Problem Definition

Table 4.2 outlines the three flight regimes and associated performance indices that are considered for the design study. The flight profile consists of three distinct flight regimes namely climb, cruise, and descent. Additional flight regimes are not considered due to the computation time required to complete a full run of the framework. Although somewhat arbitrary, the conditions within each of these regimes reflect those that a typical commercial airliner might encounter. For each regime pertinent performance indices are distinguished for optimization, which relate to desirable performance requirements.
Table 4.2  Flight regimes and associated performance indices

<table>
<thead>
<tr>
<th>Flight Regime</th>
<th>Altitude [m]</th>
<th>Mach Number</th>
<th>Angle of Attack [deg]</th>
<th>Performance Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Climb</td>
<td>500</td>
<td>0.3</td>
<td>10</td>
<td>max (R/C &amp; θ_c)</td>
</tr>
<tr>
<td>2. Cruise</td>
<td>10,000</td>
<td>0.8</td>
<td>3</td>
<td>max (C_l/C_D)</td>
</tr>
<tr>
<td>3. Descent</td>
<td>0</td>
<td>0.2</td>
<td>6</td>
<td>max (C_{Lmax} &amp; C_l^{3/2}/C_D)</td>
</tr>
</tbody>
</table>

For the climb regime, rate of climb (R/C) and climb angle (θ_c) are the sought performance indices. These are chosen as they dictate how quickly an aircraft can ascend to its cruise altitude, where the aircraft generally operates most efficiently. As well, climb characteristics are essential if an aircraft needs to climb to a higher altitude to avoid bad weather or turbulence. Consequently, climb characteristics are not only important for the climb regime but also the cruise regime. For steady, unaccelerated climbing flight the rate of climb (R/C) and climb angle (θ_c) are given by equations 4.1 and 4.2, respectively.

\[
R/C = V_\infty \left[ \frac{T}{W} - \frac{1}{2} \rho_\infty V_\infty^2 \left( \frac{W}{S} \right) \right]^{-1} C_{D,0} - \frac{W}{S} \frac{2K}{\rho_\infty V_\infty^2} \tag{4.1}
\]

\[
θ_c = \sin^{-1}\left[ \frac{T}{W} - \frac{1}{2} \rho_\infty V_\infty^2 \left( \frac{W}{S} \right) \right]^{-1} C_{D,0} - \frac{W}{S} \frac{2K}{\rho_\infty V_\infty^2} \tag{4.2}
\]

As shown in equations 4.1 and 4.2, the R/C and θ_c are essentially dependent on thrust (T), drag (in the form of zero lift drag, C_{D0}, and drag due to lift, K), weight (W), and wing loading (W/S).

Considering the altitude and engine thrust to be constant in the above formulas, the wingtip can be configured to optimize the drag and wing loading for the flight condition to realize ideal climb characteristics.

For regime 2, the coefficient lift to drag ratio (C_l/C_D) is chosen due to its influence on various flight parameters related to the cruise regime. For instance, range and endurance both heavily rely on the lift to drag ratio or alternatively the C_l/C_D ratio. Endurance for jet propelled aircraft can be represented through equation 4.3. Assuming the thrust specific fuel consumption (c_t) and weight ratio (W_0/W_1) remain constant, endurance can be optimized by maximizing the C_l/C_D ratio.

\[
E = \frac{1}{c_t C_D} \frac{W_0}{W_1} \ln \frac{W_0}{W_1} \tag{4.3}
\]

Finally, for the descent regime the maximum coefficient of lift (C_{Lmax}) and the ratio C_l^{3/2}/C_D are
chosen as the performance indices. These metrics are selected as they can be used to characterize requirements that stipulate descent performance. In particular, maximizing $C_{L\text{max}}$ decreases the stall velocity of the aircraft whereas maximizing $C_{L^{3/2}}/C_D$ corresponds to a lower minimum sink rate. Both of these parameters become important when considering passenger comfort upon landing. For example, landing speeds are typically just above the stall velocity. By decreasing the stall velocity lower landing speeds can be used. Similarly, maximizing the $C_{L^{3/2}}/C_D$ ratio, the aircraft can descend more slowly. This allows the aircraft to slowly touchdown on landing.

Additional details regarding the geometry of the wing and baseline wingtip can be seen in Fig. 4.3. The wing planform is arbitrarily chosen such that the wingtip begins at the outboard 70% of the wingspan. For optimization purposes, the aircraft was chosen to have a thrust to weight ratio of 0.3571 and a maximum takeoff weight of 17,622 [kg]. Discussed within the next section are details regarding how the framework is implemented for the design study. The purpose of the framework is to distinguish optimal modular wingtip configurations for the hypothetical aircraft.

### 4.3 Implementation of Conceptual Design Framework

Prior to implementation, a grid convergence study of the baseline wing geometry was performed with Tornado. This was carried out using the cruise regime as noted in Table 4.2. The appropriate amount of vortex panels was determined through a coefficient of drag and coefficient of lift grid convergence study. The convergence criterion was chosen to be a change of less than 0.5% between simulations. As a result, a minimum of ten chordwise and twenty-five spanwise vortex panels are used for each evaluation made by Tornado for either the optimization or discretization processes. As an additional note, for each of these processes the
passive wing section remains constant and the wingtips performance is estimated as part of the entire wing.

As shown in Fig. 3.1 the second step in the framework is continuous wingtip shape optimization. For the HS procedure, twenty wingtip partitions are used to emulate a continuous wingtip shape. A larger number of wingtip partitions are beneficial in terms of achieving smooth wingtip shapes. However, this would result in greater convergence times for the HS process. For the process to be implemented by Tornado, the boundaries of the partitions are chosen to coincide with those of the vortex panels. Therefore, on each partition exists a vortex panel resulting in a total of ten chordwise and thirty-five spanwise vortex panels being used for aerodynamic evaluation.

As noted in Section 3.2.1, the design variables for each wingtip partition are the cant angle ($\Gamma$), span (b), sweep angle ($\Lambda$), and twist angle ($\alpha$). The passive wing section is also represented through these variables, though they remain fixed in HS process. For the three optimization statements the scalar function, $I$, to be maximized or minimized is formed based on the chosen performance metrics. In the cruise regime, $I$ is chosen to be merely the performance metric itself since only one index is chosen for optimization. The function takes the form of equation 4.4 where $x$ is a vector containing the design variables as denoted by equation 3.1.

$$\text{max}. I_{\text{cruise}} = \max \left( \frac{C_L}{C_D} \right), \text{where } I_{\text{cruise}} \text{ is some } f(x) \tag{4.4}$$

Alternatively, a multiobjective formulation is used to create the scalar function for the climb and descent regimes as multiple metrics are defined for analysis. In these regimes, $I$ is formed using a scalarizing function as outline in [34]. Since neither of the two performance metrics, for either the climb or descent regime, are favored over the other the weights used in the scalarizing function are equal for both indices. The function to be minimized is the sum of relative differences of individual objectives. That is, the scalar function takes the following form for the climb and descent regimes, where superscripts ‘1’ and ‘2’ denote harmony vectors from the first and second row of HM.

$$\text{min}. I_{\text{climb}} = \min \left( \left\{ \frac{(R/C)^2 - (R/C)^2_1}{(R/C)^2_1} \right\} + \left\{ \frac{(\theta_c)^2 - (\theta_c)^2_1}{(\theta_c)^2_1} \right\} \right), \text{where } I_{\text{climb}} \text{ is some } f(x^1, x^2) \tag{4.5}$$
\[ \text{Min. } I_{\text{descent}} = \text{min. } \left( \left( \frac{(C_{L_{\text{max}}})^2 - (C_{L_{\text{max}}})^1}{C_{L_{\text{max}}}^1} \right)^3 + \left( \frac{(C_{L_{\text{max}}}^3/C_{D})^2 - (C_{L_{\text{max}}}^3/C_{D})^1}{(C_{L_{\text{max}}}^3/C_{D})^1} \right)^3 \right) \]

where \( I_{\text{descent}} \) is some \( f(x^1, x^2) \) \hspace{1cm} (4.6)

It can be noted from equation 4.1 and 4.2 that \( R/C \) and \( \theta_c \) differ only through the freestream velocity \( V_\infty \). Although this is the case the multiobjective formulation as shown through equation 4.5 is used to combine these metrics into a single function.

For each optimization statement a number of practical constraints are also introduced to limit excessive cant, sweep, and twist angles. This is done to avoid peculiar wingtip shapes, such as configurations that result in stall and drag divergence issues that may not be accurately analyzed by the linearized aerodynamic code. The span of each partition is also restricted so as to enforce continuity between the total wingtip span amongst optimization runs. The statements for each regime are as follows:

<table>
<thead>
<tr>
<th>Climb Regime</th>
<th>Cruise Regime</th>
<th>Descent Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. ( I_{\text{climb}} )</td>
<td>Max. ( I_{\text{cruise}} )</td>
<td>Min. ( I_{\text{descent}} )</td>
</tr>
<tr>
<td>w.r.t. ( \Gamma_{1,i}, \Lambda_{1,i}, \alpha_{1,i} )</td>
<td>w.r.t. ( \Gamma_{1,i}, \Lambda_{1,i}, \alpha_{1,i} )</td>
<td>w.r.t. ( \Gamma_{1,i}, \Lambda_{1,i}, \alpha_{1,i} )</td>
</tr>
<tr>
<td>s.t. ( \sum_{i=1}^{i} b_i = 6 ) [m]</td>
<td>s.t. ( \sum_{i=1}^{i} b_i = 6 ) [m]</td>
<td>s.t. ( \sum_{i=1}^{i} b_i = 6 ) [m]</td>
</tr>
<tr>
<td>( \lambda = 0.1 )</td>
<td>( \lambda = 0.1 )</td>
<td>( \lambda = 0.1 )</td>
</tr>
<tr>
<td>( c_t = 0.75 ) [m]</td>
<td>( c_t = 0.75 ) [m]</td>
<td>( c_t = 0.75 ) [m]</td>
</tr>
<tr>
<td>(-10^\circ \leq \Gamma_{1} \leq 30^\circ )</td>
<td>(-10^\circ \leq \Gamma_{1} \leq 30^\circ )</td>
<td>(-10^\circ \leq \Gamma_{1} \leq 30^\circ )</td>
</tr>
<tr>
<td>(-15^\circ \leq \Lambda_{1} \leq 60^\circ )</td>
<td>(-15^\circ \leq \Lambda_{1} \leq 60^\circ )</td>
<td>(-15^\circ \leq \Lambda_{1} \leq 60^\circ )</td>
</tr>
<tr>
<td>(-1^\circ \leq \alpha_{1} \leq 1^\circ )</td>
<td>(-1^\circ \leq \alpha_{1} \leq 1^\circ )</td>
<td>(-1^\circ \leq \alpha_{1} \leq 1^\circ )</td>
</tr>
<tr>
<td>(-2^\circ \leq \Gamma_{2,i} \leq 2^\circ )</td>
<td>(-2^\circ \leq \Gamma_{2,i} \leq 2^\circ )</td>
<td>(-2^\circ \leq \Gamma_{2,i} \leq 2^\circ )</td>
</tr>
<tr>
<td>(-2^\circ \leq \Lambda_{2,i} \leq 2^\circ )</td>
<td>(-2^\circ \leq \Lambda_{2,i} \leq 2^\circ )</td>
<td>(-2^\circ \leq \Lambda_{2,i} \leq 2^\circ )</td>
</tr>
<tr>
<td>(-0.5^\circ \leq \alpha_{2,i} \leq 0.5^\circ )</td>
<td>(-0.5^\circ \leq \alpha_{2,i} \leq 0.5^\circ )</td>
<td>(-0.5^\circ \leq \alpha_{2,i} \leq 0.5^\circ )</td>
</tr>
</tbody>
</table>

For the shape optimization procedure the HMS, HMCR, and PAR rate are chosen to be 15, 0.85, and 0.35-0.85, respectively. These values are chosen based on typical settings for these parameters found throughout literature, as well as what has been observed to work well for the
current problem. Higher values of the HMCR and PAR have been observed to produce premature convergence, in which wingtip configurations that do not exceed the performance of the baseline wingtip are discovered. The convergence criterion is chosen to incorporate a minimum number of iterations as well as convergence of the HM. A minimum of ten thousand iterations must be performed so that the HS thoroughly searches the design space. Once ten thousand iterations have been completed, the stopping criteria then relies on convergence of the HM. Convergence of the HM is chosen to reflect convergence of the performance indices as well as the wingtip shape variables. Corresponding performance indices and design variables in HM must be within a tolerance of \(1 \times 10^{-4}\) and \(1 \times 10^{-1}\), respectively. This method has shown to yield improved results. Premature convergence has been observed when the criteria are chosen to only reflect the performance indices. This is because several differing wingtip configurations have similar performance. Using both the performance indices and design variables, the optimization procedure has shown to converge towards a single wingtip configuration for each optimization run.

Implementation of the discretization module is carried out using the results from the optimization procedure, as noted in Section 3.3.1. The required wingtip curve is constructed using a twentieth order Bezier curve assembled from twenty-one control points. From Chapter 3, the Bezier curve takes the form of equations 3.13, 3.14, 3.15, and 3.17. Once the kinematics of the morphing modules is calculated using the Bezier curve the performance of the discretized wingtip is approximated using Tornado. Again, the boundaries of the vortex panels are enforced to conform to the edges of the morphing modules. Therefore, as more modules are used in the discretization more vortex panels are applied over the wingtip. The performance indices used in the discretization procedure correspond to those used in the optimization process. For instance, \(C_L/C_D\) is also used to measure discretized performance for the cruise regime. Additionally, the maximum number of modules to be considered for the discretization is taken to be fifteen. Generally fifteen wingtip modules would overcomplicate the wingtip system. However, fifteen modules are selected to provide sufficient data on how the performance of the wing varies as more modules are added. The final module layout is then determined based on the discretization results, as discussed in the next section.

### 4.4 Results of Study

The results presented in this section illustrate the continuous wingtip shapes and their associated discretized performance. Performing the continuous shape optimization procedure three distinct wingtip configurations, as shown in Fig. 4.4, are revealed. Again, the purpose of
the optimization procedure is to address issue (A) of Section 2.6, which is determining ideal wingtip shapes that can address specific performance requirements. For the climb regime the wingtip is characterized by a large sweep angle and a small cant angle, somewhat similar to a conventional raked wingtip. The schedule for the cruise regime reflects more a conventional wingtip being distinguished primarily by cant angle. Finally, for the descent regime a unique wingtip shape, which resembles a drooped wingtip, is found. The descent wingtip schedule somewhat emulates the configuration of a bird's wing upon landing.

The maximum performance achieved through the continuous wingtip configurations is $\theta_c = 17.9439$ [deg] and $R/C = 31.7902$ [m/s] for climb, $C_L/C_D = 28.9792$ for cruise, and $C_{L_{max}} = 1.4610$ and $C_L^{3/2}/C_D = 24.6819$ for descent. This was achieved through 55,492, 43,630, and 23,561

\begin{figure}[h]
\centering
\begin{subfigure}{0.45\textwidth}
\includegraphics[width=\textwidth]{climb_configuration}
\caption{Climb}
\end{subfigure}
\begin{subfigure}{0.45\textwidth}
\includegraphics[width=\textwidth]{cruise_configuration}
\caption{Cruise}
\end{subfigure}
\begin{subfigure}{0.45\textwidth}
\includegraphics[width=\textwidth]{descent_configuration}
\caption{Descent}
\end{subfigure}
\caption{Optimized wingtip configurations for the climb, cruise, and descent regimes}
\end{figure}
Table 4.3  Comparison of wingtip performance characteristics

<table>
<thead>
<tr>
<th>Flight Regime</th>
<th>Performance Index</th>
<th>Continuous Wingtip (CW)</th>
<th>Span Extension (SE)</th>
<th>Canted Winglet (CaW)</th>
<th>% Change CW-SE</th>
<th>%Change CW-CaW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Climb</td>
<td>R/C [m/s] θ_c [deg]</td>
<td>31.7902 17.9439</td>
<td>31.7581 17.9258</td>
<td>31.6975 17.8916</td>
<td>0.1%</td>
<td>0.3%</td>
</tr>
<tr>
<td>2. Cruise</td>
<td>C_L/C_D</td>
<td>28.9792</td>
<td>28.2905</td>
<td>26.8072</td>
<td>2.4%</td>
<td>7.8%</td>
</tr>
<tr>
<td>3. Descent</td>
<td>C_{Lmax}</td>
<td>1.4610</td>
<td>1.4035</td>
<td>1.3048</td>
<td>4.1%</td>
<td>11.9%</td>
</tr>
<tr>
<td></td>
<td>C_{L^{3/2}/C_D}</td>
<td>24.6819</td>
<td>23.6092</td>
<td>21.1565</td>
<td>4.5%</td>
<td>16.7%</td>
</tr>
</tbody>
</table>

Table 4.3 summarizes the performance values associated with each configuration for the climb, cruise, and descent regimes, respectively. The performance values are compared to conventional wingtip designs. In the table, the span extension is a planar extension of the wing while the canted winglet is taken to have a cant angle of 75° from horizontal and a sweep angle of 38°, reflecting the winglet originally developed by Whitcomb [1]. Significant performance improvements are realized through optimization of the wingtip based on the chosen performance indices. On average the optimized wingtip configurations show a percent improvement of 2.2% and 7.4% over the span extension and canted winglet, correspondingly. Hence, the results of Table 4.3 illustrate the effectiveness of the optimization procedure in terms of addressing issue (A). The table also demonstrates the efficiency of conventional wingtip devices in the climb regime. Since conventional wingtips are primarily design for climb, the percent improvement is much lower than within other regimes.

Proceeding with the discretization procedure the results as shown in Fig. 4.5 are obtained. To reiterate, the discretization process aims to overcome challenge (B) of Section 2.6, which is to determine the ideal module spacing and density of the optimized wingtip configurations. Two discretized wingtips for the cruise regime are also shown in Fig. 4.6, where only half of the wing is shown for clarity. In Fig. 4.6 the boundaries of the modules are also shown in bold to demonstrate the discretization process.

The results of Fig. 4.5 exhibit a general trend of the procedure. That is, the performance of the discretized wingtip generally increases as more modules are added to the discretization process. This is notable for each flight regime examined. The discretization trends resemble somewhat of an asymptotic/linear relationship. These trends are anticipated since additional morphing modules can more closely imitate the continuous wingtip shapes, which are regarded to have optimal performance. For the regimes the maximum values of discretized performance are \( \theta_c |_{m=14} = 17.8958 \) [deg] and \( R/C |_{m=14} = 31.7050 \) [m/s] for climb, \( C_L/C_D |_{m=14} = 28.9728 \) for cruise, and \( C_{L_{max}} |_{m=15} = 1.4570 \) and \( C_L^{3/2}/C_D |_{m=15} = 24.5281 \) for descent.
Figure 4.5  Discretized wingtip performance for the climb, cruise, and descent regimes
These values of performance occur at the fourteen, fourteen, and fifteen module discretizations for the climb, cruise, and descent regimes, respectively. It is clear from the discretization results, as compared to the continuous wingtip results, that some performance loss is to be expected through the discretization process. These performance losses accrue as a result of the modular design. The modular wingtip attempts to imitate the continuous shape. Therefore, there are geometric differences amongst the continuous shape and the modular shape which arise as dissimilarities in aerodynamic performance. These performance losses will likely increase when using a more advanced flow solver as a result of interacting boundary flows between adjacent modules. These flow mechanisms are not taken into account using the current linearized aerodynamic tool. It is important to note that only induced drag and zero lift drag are estimated using Tornado.

Although the results discussed above are promising, generally fourteen or fifteen morphing modules are too many. Ideally, a larger number of morphing modules would be desired to
closely imitate the continuous wingtip shapes with minimal performance losses. However, one must also consider wingtip complexity as well as acceptable performance losses amongst each of the flight regimes, not to mention the size constraints imposed by using many morphing modules. As more morphing modules are used the spanwise length of each module becomes shorter. At some point the modules are too short to house the VGTM mechanism. Therefore, it is critical to determine an appropriate number of modules for each regime.

As discussed in Section 3.3 a number of criteria can be used to find the optimal number of morphing modules. For instance, (1) if the discretized performance is within suitable limits of the attainable continuous wingtip performance, (2) if the discretized performance asymptotically approaches some maximum value and no appreciable gains are realized by adding more modules, (3) if the discretized performance suddenly drops when adding more modules, and (4) if a maximum desired number of modules is reached and the addition of more modules would overcomplicate the system. Take the cruise regime and criteria (1), for example. If an allowable performance difference of 0.5% is chosen, then a six module layout may be selected as the optimal modular configuration. The performance of this discretization is shown to be $\frac{C_L}{C_D}|_{m=6} = 28.7254$ in Fig 4.5. In fact, the performance of the six module layout also exceeds that achieved through the span extension and canted winglet which provided performance data of $\frac{C_L}{C_D} = 28.2905$ and $\frac{C_L}{C_D} = 26.8072$, respectively. Therefore, a percent improvement of 1.5% and 7.2% is still realized through the modular wingtip as compared to the span and canted designs.

Optimal module layouts can also be chosen in this way for the climb and descent regimes. Using the same criteria and allowable performance loss, any of the discretizations, ranging from the two module case and up, can be chosen for the climb regime. Unfortunately for the descent case, no discretization meets this performance criterion. Hence, another suitable method must be used to determine the optimal module layout for this case. This is a consequence of the discretization results being different amongst the various flight conditions. Although a certain module layout might be optimal for one regime it may not be the best choice for another.

Challenges in interpreting the discretization results can be further illustrated by choosing the six module discretization to be the optimal module layout for each case. Even though a similar number of modules are chosen the spacing of the six module discretization’s are not necessarily the same for each regime, as note in Table 4.4. Table 4.4 demonstrates the global module characteristics for the six module discretization for all flight regimes considered. Here, the
Table 4.4  Nodal point distribution and morphing module kinematics

<table>
<thead>
<tr>
<th>Flight Regime</th>
<th>Module (m)</th>
<th>Module Distribution</th>
<th>Cant mode ($\Gamma_m$) [deg]</th>
<th>Sweep mode ($\Lambda_m$) [deg]</th>
<th>Twist mode ($\alpha_m$) [deg]</th>
<th>Span mode ($b_m$) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climb</td>
<td>1</td>
<td>0</td>
<td>4.9</td>
<td>29.2</td>
<td>-1.0</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.07</td>
<td>3.4</td>
<td>30.9</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.13</td>
<td>1.7</td>
<td>32.7</td>
<td>1.2</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.19</td>
<td>0.5</td>
<td>34.3</td>
<td>1.6</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.34</td>
<td>1.3</td>
<td>34.3</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.76</td>
<td>2.3</td>
<td>32.4</td>
<td>2.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Cruise</td>
<td>1</td>
<td>0</td>
<td>19.8</td>
<td>18.7</td>
<td>-1.0</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.08</td>
<td>19.3</td>
<td>16.4</td>
<td>-0.5</td>
<td>0.5</td>
</tr>
<tr>
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<td>17.2</td>
<td>14.9</td>
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<td>0.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.28</td>
<td>14.6</td>
<td>14.3</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.39</td>
<td>11.9</td>
<td>14.1</td>
<td>0.7</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.77</td>
<td>10.3</td>
<td>15.1</td>
<td>0.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Descent</td>
<td>1</td>
<td>0</td>
<td>26.4</td>
<td>7.8</td>
<td>-1.0</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.09</td>
<td>22.7</td>
<td>7.7</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
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<td>0.22</td>
<td>19.1</td>
<td>6.6</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
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<td>4</td>
<td>0.38</td>
<td>15.2</td>
<td>6.7</td>
<td>1.7</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
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<td>0.52</td>
<td>11.2</td>
<td>7.3</td>
<td>2.0</td>
<td>0.7</td>
</tr>
<tr>
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<td>0.67</td>
<td>8.9</td>
<td>8.0</td>
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<td>1.6</td>
</tr>
</tbody>
</table>

module distribution represents the nodal point allocation of the modules along the wingtip curve. The first nodal point represents the junction between the wingtip and wing. As demonstrated in the table each six module discretization has a different module distribution. This indicates that consolidation of the discretization results is a necessary step that must be added to the design framework. In order to realize a final morphing design there must be a fixed number of modules. It is also necessary that the number of modules chosen be capable of realizing the optimal wingtip configurations with minimal performance losses.

The global joint variables associated with each module are also shown in Table 4.4. Using results such as these the module kinematics, required to realize each of the optimal wingtip schedules, are known. The kinematics of each configuration can then be used to schedule the wingtip geometry throughout flight to achieve each of the optimal wingtip shapes. Moreover, the kinematics of the discretization can be compared to the VGTM workspace to ensure that the configurations are actually attainable by the morphing mechanism. The discretization process has demonstrated to be a viable tool in the conceptual design of the morphing concept. The process effectively addresses issue (B), even though it is clear that consolidation of the results...
is required to end up with a final wingtip module layout. Using optimal morphed configurations can allow the aircraft to operate at higher efficiency during each flight regime.

The design framework and associated optimization and discretization procedures have shown to be effective tools in the design of the morphing concept. Employing these methods, the design variables associated with the morphing concept are effectively reduced. The feasibility of the modular concept is also demonstrated through the results of the design study. First, results obtained through the optimization procedure have shown to be promising in that ideal wingtip configurations, which outperform traditional wingtip designs, can be determined. Secondly, performance results obtained through the discretization procedure also demonstrate the concept feasibility. Although performance losses accrue as a result of the discretization process, modular designs can be chosen which still outperform traditional wingtip designs. Therefore, differing modular wingtip configurations can be used to improve aircraft multiphase operation. The framework has shown to be beneficial in addressing the concerns with the morphing concept. Namely, the framework can address the issues of shape optimization and modular discretization. Nevertheless, some implementation issues are present which arise as a result of the low fidelity aerodynamic tool and the required consolidation of the discretization results.
Chapter 5

Conclusion

Within this thesis the feasibility of a novel morphing wingtip concept is explored. As opposed to traditional wingtips, morphing wingtips have the ability to reconfigure during flight leading to a multiphase improvement in efficiency over static devices. The concept investigated in this thesis relies on the use of variable geometry truss mechanisms (VGTMs) to permit wingtip morphing. The wingtip is divided into a number of morphing modules, composed of VGTMs, which permit individual or simultaneous cant, span, sweep, and twist morphing modes. The scope of the thesis work was to prove the concept’s viability and establish a mathematical model that can aid in the concept’s development. This was carried out through establishing and demonstrating a design framework that first distinguishes optimal wingtip configurations and then proceeds to discretize them for the modular concept. The results of the framework are optimal modular wingtip configurations that can be used to address differing flight requirements, as defined by the researcher or engineer. Conclusions drawn from the thesis effort as well as areas of possible future work are discussed below.

5.1 Thesis Conclusions

As mentioned throughout the thesis, two of the greatest issues currently facing the concept are (A) identifying geometric wingtip schedules that can be used to address particular flight requirements, and (B) determining the optimal module spacing and density of the known wingtip shapes. These issues have been addressed in the thesis through the optimization and discretization modules.
The framework has been demonstrated in Chapter 4 and the results obtained from the design study are quite promising. The framework proved to be effective in addressing issues (A) and (B) above. In the design study, the framework procedure demonstrated the ability to distinguish ideal modular wingtip configurations that can be used to outperform traditional wingtip designs. It is clear, through viewing the framework results, that some performance losses are to be expected between the continuous wingtip shapes and their modular counterparts. This is to be anticipated as the modular design can only imitate the continuous wingtip configurations. Therefore, there are some geometrical differences between the continuous and modular wingtips, which result in aerodynamic performance losses. Although this is the case, the framework results have shown that modular wingtip designs can still outperform traditional static devices depending on the module layout selected. This has also confirmed the feasibility of the morphing concept. The morphing design can absolutely compete with existing wingtip configurations. To further the morphing concept several areas of future work are conveyed below.

5.2 Recommendations for Future Work

The morphing concept and design framework established within this thesis has only considered a few aspects of morphing wingtip design. Consequently, there is a lot of room to improve and expand on the current work. Some of the possible ways in which this can be done are discussed below.

Firstly, the concept itself can be expanded on. In developing the concept little regard was given toward skin options that could cover the wingtip and allow morphing. Undoubtedly, work such as this would be a thesis within itself. The skin material required to permit morphing, while maintaining some level of structural integrity and aerodynamic consistency, is anticipated to be quite complex. Several options within literature exist which range from different material options (i.e., smart memory allows and metal rubbers) to sophisticated layered skins. Therefore, this is definitely an area in which the current concept can be expanded on. Furthermore, no information was provided on how the morphing concept could be implemented into service. Since the concept is in the early stages of design, it is not known whether the concept would be more beneficial as a retrofit to existing wings or if an entire redesign of a wing is required. The concept could also be further developed by considering how the various systems, associated with the wingtip can be amalgamated with existing aircraft systems. The wingtip, as developed within this thesis, requires some source of actuation energy (i.e., hydraulic, pneumatic, electric, etc.) and some method of monitoring the wingtips movements. Therefore, an outline of how
these systems can be integrated into an aircraft becomes quite important; especially since aircraft systems are so condensed already.

Next, the framework itself can be improved upon in several areas. The shortcomings of the linear aerodynamic model used in the framework have been discussed on numerous occasions throughout the thesis. Consequently, one way to expand on the current work would be to couple a more sophisticated aerodynamic tool to the optimization and discretization modules. Using a more advanced model various drag mechanisms, which are not accounted for by the linearized model, can be accurately characterized. One of the greatest concerns in analyzing the current concept is drag which accumulates due to interacting junction flows between adjacent modules. One way to improve the framework results would be using an aerodynamic tool that can account for these flow interactions. The low fidelity tool is, however, justified at the moment due to its speedy calculation of aerodynamic coefficients. This is a requirement of design studies that entail a large number of function evaluations such as the one here.

As discussed within the thesis, a method to further expand the framework would be to add a consolidation module. It was shown that discretization results generally differ from one flight regime to the next. Thus, some method of consolidating the discretization results is required to end up with a final module layout for the concept. Finally, additional tools could be added to the framework to incorporate more areas of design including weight prediction, stability, and fluid-structure interactions. The addition of such tools would greatly aid in the development of the concept as well as in determining the concepts feasibility in comparison to other design choices. In augmenting the wingtip geometry there are also changes in aerodynamic wing loading, wing weight distribution, as well as dynamic effects that result from the wingtip being actively reconfigured throughout flight. These are all areas in which the current work could be expanded.
References


Appendix A1: Wind Tunnel Prototype

The significance of different aerodynamic shapes is well known throughout the aeronautics industry. In developing any new concept, whose efficiency heavily relies on aerodynamic characteristics, it is critical to explore the effect of geometry on performance. As part of the conceptual design process, and as an accompaniment to the thesis work, a wind tunnel prototype was designed, manufactured, and tested. The work completed in this area was carried out at Ryerson University and had the following goals in mind:

1. Establish aerodynamic data to validate the modular morphing concept.

2. Establish a database of aerodynamic load data for later testing of a structural VGTM prototype, which is to be carried out by the author’s colleagues.

Expanding on (1) above, the goal of the experimental testing was to show that small changes in wingtip geometry could lead to significant changes in aerodynamic performance. As well, to validate the concept it was critical to analyze whether or not the modular design would result in any odd flow phenomena that could be potential hazardous if the concept were to be implemented. The study is, however, restricted to low flow conditions as a result of the capabilities of the wind tunnel that has been used. Therefore, the experimental results have not been connected to the optimization study that has been presented within the thesis. Additionally, the results of the study are limited in that only four configurations are analyzed. This is a consequence of the developmental costs associated with constructing each wingtip prototype.

In developing the prototype, three single variable morphing motions were chosen for analysis. As a result, four wingtip models were manufactured that were dubbed the cant, sweep, twist, and initial configurations. The fourth configuration (i.e., the initial configuration) was used as a baseline from which the remaining models could be compared. Figure A1.1 represents the baseline wingtip planform for the wind tunnel models, which was constrained by the size of Ryerson’s wind tunnel. The experimental models were representative of a four module VGTM wingtip with two morphing modules in between two fixed modules, as shown in Fig. A1.2.
As presented in Figs A1.1 and A1.2, modules 2 and 3 were considered as morphing modules as modules 1 and 4 were regarded as fixed modules. Therefore, modules 1 and 2 were identical in geometry for each of the wingtip configurations examined. The choice to use two fixed and two morphing modules came from a manufacturing point of view such that the fixed modules could be used amongst the different models to reduce manufacturing costs. The models were rapid prototyped with a NACA 0015 airfoil, as an abundance of data exists for this airfoil type. The global morphing characteristics of the four wingtip models are shown in Table A1.1.
Table A1.1  Wind tunnel model values

<table>
<thead>
<tr>
<th>Prototype Configurations</th>
<th>Morphing DOF</th>
<th>Module 1 (fixed)</th>
<th>Module 2 (morphing)</th>
<th>Module 3 (morphing)</th>
<th>Module 4 (fixed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cant [deg]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Span [m]</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.1016</td>
</tr>
<tr>
<td></td>
<td>Twist [deg]</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1. Initial</td>
<td>Cant [deg]</td>
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<td>15</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Span [m]</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.1016</td>
</tr>
<tr>
<td></td>
<td>Twist [deg]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2. Cant</td>
<td>Cant [deg]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Span [m]</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.1016</td>
</tr>
<tr>
<td></td>
<td>Sweep [deg]</td>
<td>11.565</td>
<td>0</td>
<td>5</td>
<td>11.565</td>
</tr>
<tr>
<td></td>
<td>Twist [deg]</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3. Sweep</td>
<td>Cant [deg]</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Span [m]</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.1016</td>
</tr>
<tr>
<td></td>
<td>Sweep [deg]</td>
<td>11.565</td>
<td>15</td>
<td>5</td>
<td>11.565</td>
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<td>Twist [deg]</td>
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<td>0</td>
</tr>
<tr>
<td>4. Twist</td>
<td>Cant [deg]</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Span [m]</td>
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<td>0.1524</td>
<td>0.1524</td>
<td>0.1016</td>
</tr>
<tr>
<td></td>
<td>Twist [deg]</td>
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<td>-3</td>
<td>-8</td>
<td>-8</td>
</tr>
</tbody>
</table>

Wind tunnel testing was performed in Ryerson’s 3’ (0.9144 [m]) x 3’ (0.9144 [m]) low speed tunnel. This tunnel is an unventilated closed circuit system with a chamfered square test section. It can achieve a maximum Mach number of approximately 0.10. The tunnel was equipped with a fork shaped model mount, the top of which was connected to a force balance located above the test section. The force balance is capable of measure both lift and drag forces within a resolution of one tenth of a pound. Operation of the tunnel was performed using an external panel that permit speed control and monitoring of internal temperature as well as lift and drag forces.

The model mount protruded through the top of the tunnel so that the models were held equidistant between the tunnel floor and ceiling. The model mount consisted of an enclosed, steel, forked shaped strut connected to a NACA 0015 base module with a 0.254 [m] chord and a 0.2032 [m] span. Each winglet configuration was then connected to the mount via the base module. Angle of attack adjustment was made possible through removable sections of the strut cover. The test set-up for the four prototype configurations can be seen in Fig. A1.3.
The testing was performed over a range of Reynolds numbers (based on the mean aerodynamic chord of the baseline configuration) and angles of attack ranging from 50,000 to
430,000 and 0-12°, respectively. The upper Reynolds limit was primarily determined by the maximum speed of the wind tunnel whose utmost operating freestream velocity was approximately 36.6 [m/s]. Each model was mounted, one at a time, at mid-height in the test section via the support strut. After mounting each model in the test section a load balance was performed to zero all loads read by the force monitor. Upon completion of start-up procedures, each model was run for the range of Reynolds numbers and angles of attack. The force balance was continually zeroed after changing the angle of attack for a particular configuration. For each angle of attack and model configuration, lift and drag measurements were taken at intermediate airspeeds up to the tunnels maximum speed. After arriving at each speed increment the tunnel was run for approximately 10 seconds before the force measurements were recorded. This was done to avoid transitional turbulent airflow within the tunnel. Each test was then repeated to ensure the validity of the data. Additionally, airflow patterns were examined using tufts of yarn attached to each model during testing.

The coefficient of lift and coefficient of drag data obtained through the wind tunnel testing are summarized in Figs. A1.4-A1.11. This data was obtained through the conventional lift and drag formulas applied to the force measurements taken from the wind tunnel force balance.

![Figure A1.4](image)

Figure A1.4  $C_L$ vs. $Re$ curves for the initial configuration
Figure A1.5 $C_L$ vs. Re curves for cant configuration

Figure A1.6 $C_L$ vs. Re curves for sweep configuration
Figure A1.7 $C_L$ vs. Re curves for twist configuration

Figure A1.8 $C_D$ vs. Re curves for the initial configuration
Figure A1.9  $C_D$ vs. Re curves for the cant configuration

Figure A1.10  $C_D$ vs. Re curves for the sweep configuration
It can be seen, through Figs A1.4 - A1.11 that $C_l$ and $C_D$ converge towards specific values as higher Reynolds numbers are encountered. This was to be expected and is attributed to the laminar stability of the airflow. At low Reynolds numbers the data is somewhat scattered as a result of the resolution of the wind tunnel data acquisition system. The load data used to develop Figs A1.4 - A1.11 is sufficient to be used for future testing of the structural VGTMM model.

Figs A1.12 and A1.13 demonstrate the validity of the morphing concept, which show that a small change in wingtip geometry can lead to significantly different aerodynamic characteristics. Although this is a somewhat well known fact, the data also expresses how the lift and drag coefficients change with each morphing degree of freedom. For instance, in Fig. A1.13 the twist configuration has a much lower drag value than other configurations. This is to be expected as the twist model is washed out (i.e. the twist is reduced outboard) creating less drag. A twist configuration such as this could be used to address drag requirements during flight. As seen in Fig. A1.12, all of the morphing modes can be used to decrease the lift coefficient. Similarly, the drag coefficient can be altered both positively and negatively, as defined from the initial configuration, through differing morphing modes, as in Fig. A1.13. Therefore, these modes can be used to tailor the lift and drag coefficients in various beneficial or detrimental ways. It would be beneficial to analyze a parameter sweep of each of these variables to determine exactly how each morphing motion affects aerodynamic characteristics. However, this was not performed due to the associated developmental costs for each prototype.
The concept was also validated based on the flowfield patterns generated through the different wingtip configurations. Tufts of yarn were used to visualize the flowfield patterns, which were quite normal for all wingtip configurations analyzed. The tufts showed laminar flow over the configurations, with the exception of the 12° angle of attack data in which some flow separation at the outboard portion of the wingtip was observed for all configurations. The modular concept did not, however, shown any unusual flow patterns that would deem the concept invalid.

Figure A1.12 $C_L$ data for an AoA of 12°

Figure A1.13 $C_D$ data for an AoA of 12°
List of Contributions
