Aeroelastic Analysis of Wing Twist for Roll Control of a Micro Air Vehicle

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ABSTRACT

With increasing growth of micro air vehicles and flexible aircraft structures, new ways to control aircraft are needed where conventional trailing edge control surfaces are not feasible. This project performs a preliminary analysis on the feasibility for using wing twist to control the roll of a micro air vehicle. The aeroelastic effects of this wing twist are analyzed over a design space of material selection (specifically torsional rigidity) and trim velocity. The analysis is performed in ASWING software on a generic micro air vehicle developed by the Munitions Directorate of the Air Force Research Laboratory called the GenMAV. The results present a design tradeoff between the increased ability to induce a roll moment and the decreased lift-to-drag ratio as flexibility and wing twist are increased. The results are then compared with a conventional trial in which the GenMAV’s elevons are used to generate an equivalent roll moment for the same trim conditions. A comparison of these results shows an increase in performance utilizing wing twist for the trim case analyzed, and an increased capacity to generate large roll moments for rapid maneuvering.
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# Nomenclature

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_a$</td>
<td>Aileron Deflection</td>
<td>Degrees</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Angle of Attack</td>
<td>Degrees</td>
</tr>
<tr>
<td>$i$</td>
<td>Angle of Incidence</td>
<td>Degrees</td>
</tr>
<tr>
<td>$EI$</td>
<td>Bending Stiffness</td>
<td>$Nm^2$</td>
</tr>
<tr>
<td>$\bar{c}$</td>
<td>Chord Length</td>
<td>$m$</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Coefficient of Drag</td>
<td>n/a</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Coefficient of Lift</td>
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</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>$kg/m^3$</td>
</tr>
<tr>
<td>$D$</td>
<td>Drag Force</td>
<td>$N$</td>
</tr>
<tr>
<td>$q$</td>
<td>Dynamic Pressure</td>
<td>$Pa$</td>
</tr>
<tr>
<td>$\delta_e$</td>
<td>Elevator Deflection</td>
<td>Degrees</td>
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<tr>
<td>$L$</td>
<td>Lift Force</td>
<td>$N$</td>
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<tr>
<td>$M_x$</td>
<td>Roll Moment</td>
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</tr>
<tr>
<td>$\delta_r$</td>
<td>Rudder Deflection</td>
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</tr>
<tr>
<td>$G$</td>
<td>Shear Modulus</td>
<td>$GPa$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Side Slip Angle</td>
<td>Degrees</td>
</tr>
<tr>
<td>$GJ$</td>
<td>Torsional Stiffness</td>
<td>$Nm^2$</td>
</tr>
<tr>
<td>$V$</td>
<td>Trim Velocity</td>
<td>$m/s$</td>
</tr>
<tr>
<td>$S$</td>
<td>Wing Planform Area</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$b$</td>
<td>Wing Span</td>
<td>$m$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Wing Twist Angle</td>
<td>Degrees</td>
</tr>
</tbody>
</table>
2 INTRODUCTION

Wing twisting to control the roll of an aircraft has been around for over a century. In fact, the very first successful aircraft, the Wright Flyer built by the Wright Brothers, utilized wing warping to control the aircraft. Birds use wing twist to control precise maneuvers and generate propulsion. So what has led to the decline of wing twist in favor of conventional ailerons over the past century? In part, a major driver for ailerons was the use of stiffer materials for aircraft structures. As balsa and pine wood was replaced with aluminum and composites, wing flexibility was taken as a detriment and sought to be minimized rather than actively used for aircraft control. The use of ailerons, which change the shape of only a small portion of the wing in a predictable manner through rotating a hinged lifting surface, allow for precise and predictable roll control with stiffer wings. Aeroelasticity, which is the interactions of aerodynamic forces and aircraft structural dynamics, was largely an unpredictable factor that could lead to flutter, control reversal, and even buckling of the aircraft lifting surfaces if the materials are too flexible. However, modern analysis tools such as ASWING and ZAERO can be used to analyze the effects of aeroelasticity in flight. These analysis tools bring about a new phenomenon, the ability to design an aircraft to utilize aeroelasticity and flexibility as a benefit.

A growing market for flexible structures in aviation is the use of unmanned aerial vehicles (UAVs) and in particular, micro air vehicles (MAVs). These vehicles are often designed to take the impact of crashes regularly, and a key feature is their portability. Flexible structures enables both these goals, as flexible structures can often withstand impacts better than more brittle carbon fiber or composites, and they allow for the structure to be manipulated to take up less space for transport.

A flexible aircraft wing is often designed with a stronger leading edge to take most of the structural strength and a more flexible trailing edge section to achieve the desired camber needed for lift. This poses a problem for the use of conventional ailerons, as these are a trailing edge device that are not feasible with more flexible trailing edges. Hence the motivation for the re-emergence of wing twist for roll control, which is a key option for controlling these flexible MAVs. Wing twist can be induced in a number of methods ranging from mechanical servos to active materials that change shape as a result of an applied current. For example, a joint DARPA/AFRL/NASA study commissioned a Northrop Grumman led Smart Wing Program which has explored the use of shape memory alloys (SMA) for active wing twist [5]. Hingeless control surfaces such as the SMAs used
in the Smart Wing Study can provide improved aerodynamic performance as these devices all but eliminate the discontinuities from deployed conventional control surfaces, thereby delaying the onset of flow separation and stall characteristics.

Utilization of wing twist has additionally been studied for use on manned aircraft in the X-53 Active Aeroelastic Wing (AAW) Program, a joint effort by NASA, the Air Force, and Boeing researchers. This program modified an F-18 fighter aircraft to equip it with flexible wings from a pre-production prototype to use a combination of active and passive aeroelastic control to produce a highly flexible, light-weight control system [10]. Flight control software was developed to actively command trim settings to facilitate wing twist to minimize loads at high speeds. This project successfully demonstrated the use of actively controlled wing warping technology for aircraft roll at transonic speeds, and provides a benchmark for future aircraft designs to use this technology such as fighters, UAVs, and high altitude long endurance (HALE) aircraft [6].

This report aims to study the effects of wing twist as a method of roll control as compared with the use of a conventional trailing edge device.

3 Aeroelasticity Overview

Aeroelasticity encompasses the interaction of the structural, aerodynamic, and inertial forces that act upon an aircraft in flight. These interactions build off each other, and may have a significant impact on the control and stability characteristics of the aircraft.

Static aeroelasticity is of primary concern for this study. Static aeroelasticity focuses on the steady state deflections of flexible aircraft surfaces in a trimmed equilibrium condition. A key concern in static aeroelastic analysis is divergence, which is a structural failure due to the aerodynamic forces overcoming the restoring forces of the structure, which is most common in wing torsion [2]. With this potential adverse effect, the stiffness of the structure is a key parameter for aeroelastic analysis, since the stiffness directly relates to the restoring forces that resist deformation of the surface.

For aircraft, aeroelasticity arises when the aerodynamic forces cause structural deformation of the aircraft surfaces. The deformed surfaces have different aerodynamic properties and thus generate
different loads which in turn causes different structural deformations. In trimmed steady-state flight, this cycle continues until equilibrium is reached. This aeroelastic cycle is depicted below.

![Aeroelasticity cycle](image)

**Fig. 1. Aeroelasticity cycle.**

Aeroelastic interactions influence flight performance in many ways, including stability derivatives that affect the aircraft dynamic response to perturbations, control effectiveness and even control reversal of control surfaces, and aircraft dynamic stability to include flutter [10]. In addition, as structural weight is minimized with new composite materials being introduced and with the advent of advanced statically-unstable aircraft systems with high authority feedback control systems, aeroelastic effects are becoming even more significant. These changes tend to decrease the frequency separation between the “rigid body modes” and the “elastic modes”, which highlights the importance of aeroelastic study in the design of control systems for these systems to limit adverse effects of dynamic aeroelasticity such as flutter [9].

Clearly, aeroelasticity is an important concern as the aircraft structural materials are made more flexible. However, aeroelasticity and flexible structures, if properly understood, may be actively controlled to provide optimal performance for an aircraft. This concerns the field of aeroservoelasticity, which uses interactive flight controls to modify the aeroelastic dynamic response of an aircraft to increase performance and stability [10].
4 MODELING

4.1 GENERIC MICRO AIR VEHICLE (GENMAV)

The definition of what constitutes a micro air vehicle varies, but in general, a MAV is an aircraft that is generally the size of a bird or smaller. MAVs generally operate in low Reynolds number flight regimes due to their smaller sized wings [2]. The market for micro air vehicles has seen large growth over the past decade as these small, unmanned aircraft allow them to be particularly useful in both maneuverability and portability to accomplish missions that would be more difficult or impossible with larger platforms. The emergence of smaller sensor platforms further increases the potential of micro air vehicles for surveillance and other missions.

This study utilizes a generic micro air vehicle platform developed at the Munitions Directorate of the Air Force Research Laboratory at Eglin Air Force Base in Florida called the GenMAV [8]. The GenMAV was designed to provide a baseline platform to perform experiments on MAVs in a collaborative environment, and multiple experiments have been conducted on this MAV platform.

The GenMAV has a high wing configuration with a circular fuselage and conventional tail [8]. The horizontal and vertical stabilizers are used for control via a rudder and elevons. It is constructed predominately of carbon fiber, and has a wingspan of 61 cm and length of 42 cm. The GenMAV has a flight-ready mass of 1.02 kg and is powered by a nose mounted electric motor. The GenMAV is designed for flight speeds of around 15 m/s [1].

The experimental testing and modeling used to generate the detailed ASWING model of the GenMAV were performed previously by J. Babcock, and outlined in his Ph.D. dissertation, *Aeroservoelastic Design for Closed-Loop Flight Dynamics of a MAV* [2].

The GenMAV utilizes elevons rather than ailerons to roll the aircraft; however, ASWING treats the elevons functioning as elevators and the elevons functioning as ailerons as separate control “flaps” with separate and independent deflections. Thus, the elevons functioning as ailerons will be referred to throughout this report as ailerons, since they are functioning as such in the ASWING model.

The GenMAV model was selected for this study due to its detailed prior modeling with experimental validation and due to its flight and structural properties generalizable to many MAVs.
The geometry of the ASWING GenMAV model is shown below in Fig. 2.

Fig. 2. Geometry of the GenMAV.
4.2 **ASWING SOFTWARE**

ASWING is a software program developed by Dr. Mark Drela at the Massachusetts Institute of Technology to allow for rapid aerodynamic, control-response, and structural analysis for aircraft design and evaluation. ASWING is particularly suited for analysis of aircraft with flexible wings and fuselages with higher aspect ratio [3].

ASWING allows for the prediction of static and quasi-static loads and deformations of aircraft in a trimmed condition. ASWING utilizes a nonlinear Bernouli-Euler beam representation for surface and fuselage structures, and uses a lifting-line representation to model the aerodynamic surface characteristics with use of the Prandtl-Glauert transformation in wind-aligned axes to capture compressibility effects. The aeroelastic effects are captured through coupling of the aerodynamic and structural formulations in a single nonlinear system, which is then solved by a full Newton method [3,4].

ASWING has been validated against analytical cases in both static and dynamic cases, and has been used in many other projects for aeroelastic analysis [2]. For this reason and for its capabilities described above, ASWING was chosen as an ideal software to perform the following analysis on wing twist since it allows for rapid configuration changes and captures aeroelastic effects.

5 **WING TWIST FOR ROLL CONTROL STUDY**

5.1 **BACKGROUND**

A key area of interest in this report is the use of wing twist as a replacement for ailerons found on most modern aircraft. The feasibility of wing twist is dependent on many factors, most importantly the ability to actuate a twist in the wing. This may be performed by smart materials that change shape as a result of an applied electric current or by physical actuators. The following study does not focus on the means for twist, but rather serves as a preliminary study to assess the implications of a deformed wing shape on the trim aerodynamics of an aircraft. As previously mentioned, micro air vehicles provide an excellent platform for wing twist study due to the numerous applications of flexible wings and the relative low risk and inherent low structural factors of safety needed as compared with larger aircraft platforms.
The basis of this study is to determine how a given geometrical twist of the wing shape induces a roll moment. While rolling is a dynamic maneuver, the aircraft is analyzed in trim in a quasi-static equilibrium state such that the governing equations are solved to give a non-zero roll moment yet have a roll-rate of zero.

5.2 Trim Conditions
The GenMAV aircraft is trimmed in the ASWING software for straight-and level flight with one major exception: the aircraft’s elevons are constrained to zero deflection and the roll moment ($M_x$) is left unconstrained. The elevators and rudder are constrained to give zero angular acceleration about the y and z axes, respectively, as is desirable for straight and level flight. The full trim conditions of the GenMAV for this study is detailed below in Fig. 3. In Fig. 3, each variable in the top row is constrained by a given trim variable in the left-hand column, linked by a white square. To read the chart, follow the column from each constrained variable in the top row down the column until a white square is reached. Then follow the row which contains the white square to the left side to reach the constraining variable and its value.

Fig. 3. Trim conditions for wing twist study.
5.3 Design Space

The design space covered ranges in material flexibility from nylon to extremely stiff and ranges in trim velocity from 10 – 30 m/s as the wing was twisted up to 4 degrees at the tip. The velocity was increased in 2.5 m/s increments, and the stiffness of only the wing is varied. The wing was twisted in a linear fashion with the root at zero twist angle relative to the fuselage, and the tip twisted to an angle ($\theta$) up to 4 degrees in 1 degree increments. The wings were twisted in an equal-and-opposite manner with the local angle of incidence ($i$) of the wing along the span varying by the following equation, with $y$ as the distance along the y-axis and the wing span as $b$.

$$i(y) = \frac{\theta y}{b}$$

[1]

The wing was twisted in this manner to emulate a simple servo device which twists the tip of the wing while the root is attached rigidly to the fuselage. The wing was twisted about an elastic axis taken at the mid-chord. Wing twist induced by an active material or other means may take a different twist distribution along the span, and alternate distributions may be addressed in future work. The twist angle was limited to maximum 4 degrees of variation since, as to be shown in Section 6, further deflection angles generate too large a roll moment to be compared reasonably with ailerons.

The trim velocity range was chosen to capture off-design trim performance since higher and lower airspeeds play an important role in the aeroelastic forces generated, and a key concern to the feasibility of flexible wings is the ability to retain performance in off-design conditions for take-off, landing, or maneuvering flight. The GenMAV’s design trim for best lift-to-drag ratio is around 18 m/s, and as will be shown, the lift-to-drag ratio drops more rapidly as the aircraft is slowed from this value than if the airspeed is increased. Thus, the 10 – 30 m/s range was chosen to capture a large performance spectrum, particularly in terms of the lift-to-drag ratio.

The material flexibility was selected as a design variable since the flexibility of the aircraft is paramount to this study, and variations in material torsional stiffness provide a benefit to the aircraft designer wishing to use these results for material selection. Only the torsional stiffness is varied in this study in an effort to separate the effects of torsional and bending stiffness and focus solely on torsional stiffness effects. The bending stiffness is kept at an extremely high value ($EI = 1000 \text{Nm}^2$) to give an essentially stiff wing in bending. The torsional stiffness values were chosen.
to approximate that of actual materials. The original GenMAV model of predominately carbon fiber was scaled based on the shear modulus ($G$) to achieve the desired torsional stiffness ($GJ$) input for the ASWING model. These design points are detailed below in Table I.

**Table I: Material Design Space for Wing Twist Study [7]**

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>Shear Modulus ($GPa$)</th>
<th>Scale Factor</th>
<th>GJ ($Nm^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NYLON</td>
<td>4.1</td>
<td>0.12</td>
<td>0.0398</td>
</tr>
<tr>
<td>Tin</td>
<td>18</td>
<td>0.55</td>
<td>0.17455</td>
</tr>
<tr>
<td>Aluminum 6061-T6</td>
<td>24</td>
<td>0.727</td>
<td>0.23273</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td>33</td>
<td>1</td>
<td>0.32</td>
</tr>
<tr>
<td>Titanium Grade 5</td>
<td>41</td>
<td>1.24</td>
<td>0.39758</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>77</td>
<td>2.34</td>
<td>0.75861</td>
</tr>
<tr>
<td>Stiff</td>
<td>n/a</td>
<td>n/a</td>
<td>1000</td>
</tr>
</tbody>
</table>

5.4 **Performance Criteria and Process**

The main performance factor used to evaluate the trial results is the lift-to-drag ratio. This parameter was chosen since it is commonly used as a design parameter in wing design and this study is intended as a preliminary study to analyze the effects of wing twist as a design tool. The steps of this study are outlined in the following figure.

![Fig. 4. Wing twist study process flow chart.](image-url)
5.5 **RESULTS**
First, the effect of trim velocity on lift-to-drag ratio over varying wing twist angles and torsional stiffness were studied. The results of these trials are shown below.

![Fig. 5. Plots depicting lift-to-drag ratio as a function of trim velocity over design space.](image-url)
First to be noted, the results for nylon differ greatly from the other results. With this highly flexible scenario, as the wings are twisted, the aerodynamics forces deform the wings a large amount which leads to large deflections that have detrimental effects on the aerodynamic properties of the wing including the lift-to-drag ratio. Thus, a nylon wing is not recommended for this specific aircraft, which with very thin wings has a low torsional stiffness. The following analysis will thus exclude Nylon. Nylon still may be a suitable material for an aircraft with thicker wings.

A few key trends are readily evident. First, as the trim velocity is decreased from the design speed of roughly 18 m/s, the effects of wing twist on lift-to-drag ratio decreased and the results begin to converge over the four twist angles. This relationship is largely independent of the torsional stiffness. The convergence may be primarily due to the fact that with decreasing airspeed, the dynamic pressure \( q \) decreases, and lift and drag then decrease as they are proportional to this dynamic pressure. Therefore, as the trim velocity decreases, the aerodynamic forces resulting from the wing twist decrease resulting in wing twist having less of an effect on the lift-to-drag ratio. The relationship between the aerodynamic forces, dynamic pressure, and trim velocity is shown below in Eq. 2 through Eq. 4. The wing planform area \( S \) remains unchanged and the coefficient of lift and drag are largely a function of the airfoil and angle of attack, which only varies locally up to the maximum 4 degrees.

\[
q = \frac{1}{2} \rho V^2 \tag{2}
\]

\[
L = C_L qS \tag{3}
\]

\[
D = C_D qS \tag{4}
\]

Another trend stemming from this relationship is the increased negative effects of wing twist at trim velocities higher than the design velocity. The plots show that as wing twist is increased, the lift-to-drag ratio decreases at a faster rate for higher velocities. Also evident is that this rate of decrease of the lift-to-drag ratio increases with decreasing torsional stiffness. These effects are summarized in the following table.
### Table II: Effects of Design Variables on Lift-to-Drag Ratio

<table>
<thead>
<tr>
<th>Action</th>
<th>( V &gt; V_{\text{design}} )</th>
<th>( V &lt; V_{\text{design}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Effect on Lift-to-Drag Ratio</td>
<td>Effect on Lift-to-Drag Ratio</td>
</tr>
<tr>
<td>Increase V</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Increase GJ</td>
<td>↑</td>
<td>↔</td>
</tr>
<tr>
<td>Increase ( \theta )</td>
<td>↓</td>
<td>↔</td>
</tr>
</tbody>
</table>

Next, the effects of torsional stiffness and trim velocity were analyzed separately for each value of wing twist. The results of these trials are shown as follows.

![Plots depicting lift-to-drag ratio as a function of trim velocity and torsional stiffness.](image)

**Fig. 6.** Plots depicting lift-to-drag ratio as a function of trim velocity and torsional stiffness.
Key trends evident from the plots again compliment the previous results that for a given angle of twist, the most pronounced decreases in the lift-to-drag ratio occur at higher velocities and with more flexible materials, as is expected. What these plots provide over the previous results is a sense of the relative weights of changes of torsional stiffness and changes in trim velocity on the lift-to-drag ratio. The lift-to-drag ratio changes more drastically over the velocity design space than it does over the torsional stiffness design space. Thus, an incremental change in trim velocity of 2.5 m/s carries more effect on the lift-to-drag ratio than an incremental change in torsional stiffness between the materials. In fact, from a torsional stiffness of $GJ = 0.759$ to a torsional stiffness of $GJ = 1000$, the lift-to-drag ratio only changes by 0.12 in its worst-case of maximum wing twist (4 degrees) and maximum trim velocity (30 m/s). This result is important for designers, since it indicated above a certain threshold of torsional stiffness, material selection doesn't have a sizable effect on the lift-to-drag ratio and other design factors can drive the material selection such as price and ability of the shape to be deformed at a desired rate or magnitude. However, as shown by the previous results for nylon, as the torsional stiffness becomes very low the effects of torsional stiffness do dominate the performance parameters such as lift-to-drag ratio.

The final trial for this study was to analyze the generated roll moment for a given wing twist. This result is important since the purpose of the wing twist is ultimately to roll the airplane via a roll moment. The results of this trial are shown below.
Fig. 7. Plots depicting roll moment as a function of design space variables.

The plots illustrate three important relationships. First, holding all other factors constant, increasing the wing twist leads to a rather large increase in the generated roll moment. Second, the roll moment increases with increasing trim velocity as expected, since again higher velocities lead to a greater lift (and drag) force which generates a larger roll moment. This effect is exacerbated as the wing twist increases because the angle of attack of the wing tip will be larger than the local angle of attack at the root by a value equal to the wing twist angle. The larger the wing twist, the greater the wing tip angle of attack is relative to the aircraft angle of attack and thus a greater lift force at the tip which generates a larger roll moment due to the large moment arm from the center of gravity to the wing tip. These relationships are shown below in the following equations.

\[ \alpha_{\text{local}} = i_{\text{local}} + \alpha_{\text{aircraft}} = \frac{\delta_y}{b} + \alpha_{\text{aircraft}} \]  
\[ L_{\text{local}} = C_{L_{\alpha}} \alpha_{\text{local}} + C_{L_{\delta e}} \delta_e + C_{L_{\delta a}} \delta_a + C_{L_{\beta}} \beta \]  
\[ M_x = \sum_{y=0}^{b} L_{\text{local}} y \]
Further evident from these results is that as the torsional stiffness is decreased, the rate at which the roll moment increases with velocity changes from predominantly linear to predominantly quadratic. Essentially, as the material is made more flexible, you get a bigger “bang for your buck” in terms of roll moment for a given trim velocity and wing twist.

5.6 **Wing Twist Study Conclusions**
As with all design problems in aerospace engineering, this study shows an important tradeoff. As the material is made more flexible, there are reductions in lift-to-drag ratio which are exacerbated at larger wing twists. However, the ultimate goal of wing twist is to achieve a desired roll moment, and both increasing wing twist and decreasing the material torsional stiffness result in higher roll moment for a given trim velocity. Increasing flexibility can even increase the roll moment to such an extent that less wing twist is needed to achieve a desired roll moment. Thus, the designer must carefully weigh the relative contributions of trim velocity, torsional stiffness, and wing twist angle to achieve an optimal design. This selection will of course vary for each aircraft configuration; however, the trends still apply within a reasonable design range and should aid the designer in material selection for wing twist design. Selecting a trim velocity close to the design velocity in an effort to limit the adverse effect of flexibility on lift-to-drag ratio while allowing for moderate flexibility such as with Tin may provide an optimal tradeoff for the GenMAV model. This trim condition is compared to a baseline aileron roll generation in the following section to evaluate the relative cost-benefit of using wing twist over ailerons for roll control.

6 **Baseline Roll Comparison with Conventional Ailerons**

6.1 **Background**
In an effort to evaluate the benefit of utilizing wing twist for roll control, the trim condition described above is compared with the similar trim condition using ailerons. Specifically, the trim condition is as follows.

\[ V = 17.5 \, \text{m/s} \quad \text{Material: Tin (} GJ = 0.17455 \, \text{Nm}^2 \) \]
Under this condition, the following roll moments were generated using wing twist.

**TABLE III: ROLL MOMENTS AND LIFT-TO-Drag RATIO DUE TO WING TWIST AT TRIM CONDITION**

<table>
<thead>
<tr>
<th>WING TWIST (DEGREES)</th>
<th>GENERATED ROLL MOMENT (NM)</th>
<th>LIFT-TO-DRAG RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>10.41</td>
</tr>
<tr>
<td>1</td>
<td>0.09027</td>
<td>10.40</td>
</tr>
<tr>
<td>2</td>
<td>0.18200</td>
<td>10.33</td>
</tr>
<tr>
<td>3</td>
<td>0.27540</td>
<td>10.20</td>
</tr>
<tr>
<td>4</td>
<td>0.37050</td>
<td>10.01</td>
</tr>
</tbody>
</table>

To compare the use of ailerons to this wing twist case, it is necessary to find the relationship between aileron deflection and generated roll moment. Once this is found, the aircraft is then trimmed for that given aileron deflection, and the lift-to-drag ratio is found.

### 6.2 TRIM CONDITIONS

Similar to the wing twist trials the aircraft is trimmed for straight and level flight with one key difference. In this trial, the aileron is trimmed to give a desired roll moment corresponding to the values in Table III. The trim case is shown below in the same format as for the wing twist case.

![Fig. 8. Trim conditions for aileron study.](image-url)
6.3 PERFORMANCE CRITERIA AND PROCESS

Again the main performance factor used to evaluate the trial results is the lift-to-drag ratio. This allows for a direct comparison with the wing twist results for generating the same roll moment. The process is illustrated below.

![Fig. 9. Aileron study process flow chart.](image)

6.4 AILERON SENSITIVITY ANALYSIS

To match the generated roll moment between the two cases, the roll moment generated for a given aileron deflection at the trim condition was found and is plotted below.

![Fig. 10. Roll moment for a given aileron deflection.](image)
Neglecting other factors that are not changed in the trim case, the roll moment for a given aileron deflection ($\delta_a$) is related by the slope of the above plot ($C_{m\delta a}$) as follows.

\[ M_x = C_{m\delta e}\delta_e \]  

This follows the relatively linear ($R^2 = 0.9986$) relationship shown in the plot, with the slope $C_{m\delta a} = 0.0056$ from the trendline. This generated roll moment is also related to a given wing twist as shown in Table III. Thus, the aileron deflection and wing twist can be related through the roll moment each generates. This relationship is plotted below.

![Wing Twist vs. Aileron Deflection](image)

Fig. 11. Wing twist – roll moment relationship.

Since both aileron deflection and wing twist are linearly related to roll moment, it follows that they are linearly related to each other. This plot reveals a key benefit of wing twist over ailerons: a small wing twist generates a roll moment that would require a large aileron deflection. In fact, for the GenMAV, every degree of wing twist is equivalent to roughly 16 degrees of aileron deflection. This will play an important role in the lift-to-drag ratio, as to be discussed.

A caveat, this relationship is specific to the GenMAV which has aileron (elevons) with a low aileron effectiveness of $C_{m\delta a} = 0.0056$. Aircraft with a higher aileron effectiveness will not need to deflect the ailerons as much to achieve the same roll moment for a given wing twist. However,
this study is intended to be focused on aircraft similar to the GenMAV where flexibility is key and elevons are much more feasible than ailerons which may have a larger effectiveness.

6.5 RESULTS
The results of the aileron study is shown below in Table IV.

<table>
<thead>
<tr>
<th>AILERON DEFLECTION (DEGREES)</th>
<th>GENERATED ROLL MOMENT (NM)</th>
<th>LIFT-TO-DRAG RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>10.41</td>
</tr>
<tr>
<td>14.93</td>
<td>0.09027</td>
<td>9.79</td>
</tr>
<tr>
<td>30.91</td>
<td>0.18200</td>
<td>8.01</td>
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<tr>
<td>49.13</td>
<td>0.27540</td>
<td>5.35</td>
</tr>
<tr>
<td>66.53</td>
<td>0.37050</td>
<td>3.56</td>
</tr>
</tbody>
</table>

The results from Tables III and IV are combined to compare the lift-to-drag ratios for both cases. This is plotted as follows.

The plot reveals a result that the lift-to-drag ratio decreases much more rapidly to generate an increasing roll moment for the aileron case than the wing twist case. This is largely due in part to the large deflections the ailerons must undergo to achieve the desired roll moment as compared
with the wing twist. This indicates a major lift-to-drag savings for using wing twist over ailerons to generate larger roll moments.

A word of caution, however. The drag calculated due to aileron deflection is not modeled entirely in an accurate manner in ASWING. ASWING models drag in vector form as follows [4].

$$\vec{D} = \frac{1}{2} \rho |\vec{V}| \vec{c} c_{df} + \frac{1}{2} \rho |\vec{V}_{\perp}| \vec{c} c_{dp} + \frac{2 \rho \vec{V}_{\perp}}{|\vec{V}_{\perp}|} (\vec{V} \cdot \vec{n})^2 c_p \vec{c}$$  \[9\]

In Eq. 9, $V_{\perp}$ is the perpendicular component of the velocity, $\vec{n}$ is the unit normal, and $c_{dp}$ is the coefficient of pressure drag, and $c_{df}$ is the coefficient of skin friction drag. With the pressure drag a key component to the drag force, the pressure drag is calculated as follows [4].

$$c_{dp_{net}} = c_{dp} + c_{da} \delta_a + c_{de} \delta_e + c_{dr} \delta_r$$ \[10\]

This linear approximation is intended to model drag devices such as spoilers rather than conventional trailing edge surfaces such as ailerons, since these trailing edge devices have a profile drag that is roughly quadratic with surface deflection rather than linear. However, since the trailing edge devices, namely the elevons, were constrained to zero (for roll considerations-antisymmetric), the linear drag factors are zero such that the linear vs. quadratic relationship is a non-factor in the pure roll case. Inaccuracies in drag from the elevons do show up in the pitch consideration; however, the inaccuracies in approximation play into both the elevons and the wing-twist case in pitch only and thus can be neglected since the key difference between the two is analyzed only in the roll axis.

### 6.6 AILERON STUDY CONCLUSION

Even with these inaccuracies in the modeling of drag due to aileron deflection and the limited scope of the direct comparison of ailerons to wing twist, the results do pose important qualitative results. First, wing twist has the potential to perform as well if not better than ailerons in terms of lift-to-drag ratio for high roll moment scenarios. Second, wing twist can be used to generate a relatively large roll moment for a small wing twist. Therefore, wing twist would be ideal for MAVs that are designed to be highly maneuverable and undergo large roll rates. An example of such a
vehicle would be a MAV modeling a bat, where flexible wings and high maneuverability are desirable.

7 CONCLUSION

These studies revealed that there may be a benefit to the use of wing twist over elevons for this specific aircraft configuration. Ultimately, there are many more design factors (to be discussed in Section 8) to be considered before making an absolute determination on the benefit of wing twist. However, this study does show that wing twist may be beneficial to achieve larger roll moments with small deflections, especially as material stiffness is decreased. Key trends in the studies showed that decreased material stiffness does not linearly relate to changes in roll moment and lift-to-drag, but instead has a larger effect when varied from “flexible” to “very flexible”, as shown from the Tin vs. Nylon results, than from “stiff” to “moderately stiff”, as shown with the Stiff vs. Carbon Fiber results. Decreasing the torsional stiffness was further shown to increase in a linear manner to increasing in a quadratic manner with trim velocity as the torsional stiffness is decreased. However, this positive effect of decreased torsional stiffness comes at a decrease in lift-to-drag ratio, and it is ultimately up to the designer to balance this trade-off with other factors such as actuator power required to select the best use of wing twist for roll control for a more flexible aircraft.

8 FUTURE WORK

This is a preliminary study on the effects of torsional stiffness on a MAV model, the use of which is intended to be beneficial in the use of wing twist for roll control. As such, there is much room to expand the design space, performance parameters, and overall aircraft configurations. For example, the torsional stiffness distributions may be changed to a non-constant model along the span to analyze the effects of changing material or thickness along the wing span. The range of material stiffness may be expanded on to include the range of stiffness between that of Tin and Nylon that still may converge for the given GenMAV model. Additionally, differing performance metrics other than lift-to-drag ratio may be analyzed based on the designer’s goals. To fully understand the effects of aeroelasticity, future work should include a study of the combined effects
of varied torsional and bending stress together on not only on the wing surfaces but on the empennage as well. Experimental validation of the results may be achieved through wind tunnel testing of the GenMAV model and physical twisting of the wings to match the configurations in this study.

While this analysis is geared towards that of a small MAV, aeroelasticity and the use of wing twist for roll control can apply to larger aircraft, especially high-altitude long endurance (HALE) aircraft. Thus, the Reynolds number can be varied to analyze the aeroelastic effects on these larger configurations.

Additionally, alternative methods for twisting the wing may be studied. This report used a linear twist; however active materials may result in non-linear twisting along the span and these distributions may yield differing results than those presented in this report. Following these computational results, designing a controller to control wing twist using actuators or active materials would be a logical next step. A trade study on the relative cost-benefit of using wing twist that incorporates actuation limitations and weight and power costs should be investigated before a complete design decision is made.

Finally, this analysis can be expanded to investigate the utilization of wing or even vertical and horizontal tail twist to control yaw and pitch in addition to roll.
9 REFERENCES


