# DESIGN OF A DEPLOYABLE UAV

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## ABSTRACT

This paper presents the design and analysis of deployable mechanisms for a small unmanned aerial vehicle. These mechanisms enable a large reduction in estimated packaging volume without the typical weight penalty gained by altering aircraft structure. The wings and tail are redesigned to enable the aircraft to be transported and operated by a single user.

# NOMENCLATURE

Α	Wing cross-sectional area			
b	Semi-span			
b <sub>eff</sub>	Effective semi-span			
е	Vertical wire eccentricity			
Ε	Young's modulus			
h	Body height			
Ι	Second moment of area			
I <sub>0</sub>	Original second moment of area			
l	Length of section			
L	Effective semi-span length			
m	Effective semi-span mass			
Μ	Bending moment			
$n_s$	Number of wing sections			
$t_{max}$	Maximum wing thickness			
Т	Tension			
$v_y$	Displacement in the y direction			
W	Lift per metre span			
W	Aircraft width			
$w_b$	Body width			
Wnew	New body width			
x	Distance along span			
$\mathcal{W}_{PV}$	Percentage change in packaging volume			

#### INTRODUCTION

Unmanned aerial vehicles (UAVs) can be described simply as aircraft that do not carry a pilot or their required life support systems on board. The aircraft are usually remotely piloted from a distance, with the capability to perform some autonomous functions. No possibility of loss of life and reduced operating costs due to lower weight make UAVs a sound choice for dangerous or dull military missions. The cost of procuring UAVs is much lower than manned aircraft, making them an obvious choice when military budgets are being cut. With no pilot on board the unmanned aircraft is able to perform advanced manoeuvres that would be deemed unsafe if a human attempted them. UAVs are clearly of high importance to various military forces around the world. In the American Department of Defence 2012 budget, UAV programmes received a 30% increase in funding, with most other programme funding being cut [Moe, 2012]. UAVs have also found many uses in the civilian world including search and rescue and surveillance. There have even been instances of members of the public using unmanned aircraft systems.

Unmanned aerial systems are typically smaller with better performance than the manned equivalent, which is why UAVs exist in a larger range of sizes, with wingspans ranging from 40m down to a few centimetres. Similar roles such as surveillance have been filled by a very diverse range of UAVs (although the smaller aircraft are more limited to short range missions, and aircraft with wingspans smaller than a few centimetres are of little practical use due to such short range, endurance and payload capability) [Austin, 2010].

UAVs pose a promising opportunity to integrate morphing technologies. Broadly speaking, morphing describes an ability for an aircraft to change its geometry in flight to operate more efficiently. This has become more critical with an ever-increasing drive to design more efficient aircraft that burn less fuel. Wings with the ability to change geometry parameters such as sweep, camber and span are the most common morphing component on an aircraft. Developments in materials are enabling more novel designs that synthesise structure and actuation. More promising designs include active materials that give a physical response to an electric current or particular temperature input. Structures utilising these materials can be made to efficiently fit a number of flight conditions without weight penalty. Comprehensive reviews of morphing aircraft are available [Ajaj et al, 2011], [Valasek, 2012] as well as detailed information on morphing research areas and uses such as adaptive torsion wings [Ferrero and Icardi, 2009], [Ajaj et al, 2012], [Ajaj et al, 2013] and variable stiffness spars [Nam et al, 2002].

Long wings mean aircraft require large storage volumes, usually much bigger than the body of the aircraft. Aircraft carriers became severely limited in the number and size of aircraft that could be carried. In answer to this, Northrop Grunman designed a hinge mechanism that could be used to increase the capacity of aircraft carriers by as much as fifty percent. Although not the first folding wing design, previous attempts had proved unsuccessful [ASME, 2006]. Although several different folding orientations have been investigated and utilised, very few mechanisms have been invented to achieve these. By far the most common is the hinge (sometimes combined with a universal joint to allow a greater range of orientation); in fact the author was unable to find details of any other method.

Typically a hinge is used to connect two sections of the forward wing spar, enabling part of the wing to fold back over the fuselage. A universal joint can be added the allow folding alongside the fuselage. The discontinuity introduced into the structure necessitates a hinge that is strong enough to transmit loads from one part of the spar to the other as well as to facilitate folding, leading to a large weight increase, and therefore performance penalty to the aircraft. For many of the larger aircraft incorporating these mechanisms, powered actuation systems also need to be installed into the aircraft, as the wing sections are too heavy to lift by hand. This extra weight penalty can be avoided by adding folding mechanisms to smaller UAV equivalents, where the sections can be lifted by hand. Many of the small surveillance UAVs are stored in a disassembled form, to reduce the risk of damage whilst being transported. Multiple cases or a large single case make transportation on foot very difficult and so a vehicle is needed. This is a sub-optimal solution to transport small light unmanned systems such as the Aerovironment Raven RQ-11. If the aircraft could be stored without being disassembled by adding folding mechanisms to the wings, then the packaging volume would be vastly reduced and the aircraft could be transported by a single person. For aircraft weighing only a few kilograms, this may be carried by a soldier as part of their regular inventory allowing for real-time surveillance very close to the target location. Smaller unmanned systems tend to have a very simplified structure. A rectangular planform wing, and a tail consisting of one or more booms are common features. To further decrease the packaging volume of the aircraft these booms may be modified with a telescopic mechanism. These mechanisms tend to be flexible due to the space between the individual sections to allow for

easy expansion and retraction. Flexibility should be minimised in order to maintain the structural integrity of the tail boom and to allow the moments generated by the control surface on the tail to be transferred to the aircraft.

Most importantly any concept to be considered must add minimal weight to the aircraft. Also of great importance is that the aerodynamic characteristics are not altered, meaning that no part of the mechanism should protrude from the wing and cause drag. Ideally the mechanism can be synthesised with the structure as discussed earlier, with active material characteristics to enable actuation from a thermal or electric input.

Whilst obvious that much research is being conducted in the area of morphing, almost none seems to have been focussed on the problems of folding wings to decrease storage volume. Possible solutions are investigated herein for a small UAV similar to the Aerovironment RQ-11 Raven. Structural Concepts

## BASE UAV DATA

The UAV consists on an un-swept and rectangular planform wing with NACA airfoil section 65(2)-215. The wing does not possess any control surfaces nor high-lift devices. The tail boom has a circular cross-section.

Parameter	Data
Length	1.1m
Wingspan	1.4m
Chord	0.23m
Height	0.25m
Mass	1.9kg
Wing Configuration	High

## Figure 1: UAV Data

# STRUCTURAL CONCEPTS

## Wing Concepts

The primary aim of the wing concepts is to reduce the width of the aircraft as much as possible, without compensating by an increase in length or height. For comparison, the packaging volumes for each concept will be compared to the volume of the fully assembled aircraft, roughly 0.385m<sup>3</sup>.



Figure 2: Raven Product Shot

Concept 1: Side Folding Sections.

Most attempts at folding wings have incorporated only one joint along each semi-span. Although optimal from a weight increase point of view, a single joint may not give the best trade-off between weight increase and packaging volume. If the joining method has a much lower weight detriment than hinges, more than one join to decrease the packaging volume will give a better result. The wings may be simply folded up next to the body as seen in figure 3. First a calculation to find the number of hinges that would be required to allow the largest decrease in width without a change in wing orientation to minimise complexity.

In order to not increase the height of the aircraft further, the length of each section must be less than or equal to the height of the aircraft.

$$b_{eff} = \frac{(2b - w_b)}{2} = 0.65 \,\mathrm{m} \tag{1}$$

$$n_s = \frac{b_{eff}}{h} = 3 \tag{2}$$

The number of sections required is actually 2.6, but rounded up to 3 for later calculations. So two full length sections and one smaller section of length 0.15m would be needed, equating to six joins along the span. It is clear therefore that the joining method between the sections will need to be very light, at least six times lighter than previous mechanisms just to equal the efficiency. The reduction in packaging volume would need to be large enough to make this concept viable despite any weight gain. The height and length remain unchanged:

$$w_{new} = 2 * n_s * t_{max} + w_b \tag{3}$$

$$\%_{PV} = \frac{(w_{new} - w)}{w} * 100 = -74.8 \%$$
(4)

Based on the NACA airfoil section used, a thickness of 15% of the chord yields a packaging volume reduction of 78.4%. This is a large reduction, however the number of joints may mean this reduction is not enough to justify any weight increase. Comparison must be sought with other concepts.

#### **Concept 2: Twisting Sections**

No change in orientation of the wing or overall height of the aircraft were permitted in the previous concept, limiting the packaging volume reduction that could be achieved. The next concept makes use of the second largest dimension on the aircraft, namely the length from nose to tail. There is a much higher upper limit to how much the length of the aircraft can be shortened due to the body and tail, leaving more space for wing folding. The wing moves from the original orientation to being in-line with the tail and body by twisting around the leading edge as shown below:



Figure 3. Front view of 4 sectioned wing example at a). full expansion b). mid-contraction c). full contraction



Figure 4: folding with change of wing orientation showing a). fully assembled aircraft b). Wings twist around leading edge c). wings rotate in-line with body.

Like the previous concept neither the height nor length of the aircraft are altered by this method, however the width is further decreased. Moreover there are less joins so the weight penalty will be less.

$$w_{new} = w_b + 2 * t_{max}$$
(5)  
$$w_{PV} = \frac{(w_{new} - w)}{w} * 100 = -88 \%$$

Nearly a 10% further decrease in packaging volume over the previous concept, coupled with a much lower weight increase make this concept a lot more viable. A universal joint could be used to achieve this change in orientation with minimal complexity. In their stored orientation, the wings leave little space for the tail to be shortened, however this can be overcome by further folding the wings. There is a large space that can be utilised above the tail boom. Another joint could be added to each semi-span towards the tip, allowing space for the tail boom to be shortened with a telescopic type mechanism:



Figure 5: Adding second join to each semi-span allows for a decrease in length as well as width.

#### **Concept 3: Telescopic Sections**

The previous concepts are based on the use of joints that allow parts of the wing to fold and change orientation. Another possibility is to use a telescopic spar with a fabric skin as seen in figure 6. Like the tail, flexibility should be reduced to maintain the stiffness of the wing. The minimum length that a telescopic mechanism can contract to is equal to the size of its longest member, limiting the reduction in packaging volume that can be achieved with this method. The length of the longest member can be shortened by adding more sections to the mechanism, however this increases the flexibility. The use of the fabric skin is problematic. The wing skin can flap during flight. To prevent this, enough force needs to be applied to keep the skin tight. Wing displacement further increases the stress on the skin, increasing the likelihood of tearing. The second problem occurs when the wing is collapsed to be stored; the skin will need to be folded, causing creases that can weaken the skin. These creases will leave an uneven wing surface when extended, causing drag. More force will need to be applied to the skin to smooth out creases, increasing the likelihood of skin failure. Keeping the exact airfoil shape using fabric is difficult without using many ribs. Using more ribs alleviates this problem but increases weight and reduces the decrease in packaging volume that can be achieved with this method. An I-beam would typically be used for an aircraft spar. However a telescopic mechanism using this cross-section would be too big to fit in the in the wing, due to several sections being needed to give a large decrease in packaging volume. A circular cross-section would work best due to ease of manufacturing and large second moment of area to resist bending.

### Concept 4: Inflatable Wing

The final concept follows a very different route: using inflatable wings. Inflatable wings have been around for many decades, although their usage has been very limited. Advances in materials have enabled the usage of inflatable wings on unmanned aircraft, leading to more novel deployment options such as being fired from a gun.

Inflatable structures have inherent problems such as maintaining their shape, and inflation/deflation. Maintaining the shape of an inflated object without a rigid shell is very difficult. Many small chord-wise sections are introduced to give an airfoil shape, leaving a very uneven surface as shown in figure 7.







Figure 7: Inflated wing for UAV

This surface causes drag and flow separation. A second problem arises due to the inflation. The aircraft will be carried in a deflated form, and then inflated when near to its target location. If this UAV was to be carried by a soldier as part of their regular inventory, would compressed gas canisters also be required. These canisters are heavy and the soldier may not have the time to inflate the wings by hand [Cadogan et al, 2003]. The thickness of the wing skin and the air pressure inside the wing dictate the stiffness. Therefore a thicker skin increases the stiffness but also the weight of the wing. Like the fabric wing skin considered previously, creases will form when the wing is deflated. Polymer skins retain creases more than fabric skins, and can be very difficult to get out reducing the life of the material. Temperature can also have an effect of the flexibility of the skin, increasing the probability of failure during hot and cold weather [Harris, 2011]. Any packaging volume calculation would need to include the volume of the compressed air cylinders to inflate the wings, and more than one set of cylinders may be needed if multiple flights occur in one mission.

# **Tail Concepts**

The hollow tail boom doesn't contain any pull/push rods, giving sufficient space for a mechanism. The most obvious choice to use is a telescopic mechanism, although there are several factors to be considered. The first is the number of sections that will be included in the telescopic mechanism, each additional piece adds flexibility and it is not yet known how much the mechanism will need to contract. Wing concept 2 involves a change in orientation for the wing, reducing the length by which the tail can be shortened. A telescopic mechanism running the length of the whole tail would add excess flexibility and carry a weight penalty. Nevertheless, a telescopic mechanism would be compatible with all wing concepts.

A second possible mechanism is a collapsible cross-section boom. The mechanism has three sections, two of which are rigid. The middle section is flexible due to small hinges around its circumference, this enables the section to collapse, allowing it to fit inside the two rigid parts of the tail boom. The collapsing section has an extra manufacturing complexity due to the 6 small hinges required. Compliant hinges would work well for this mechanism, reducing the weight added to the tail boom. Difficulty lies in predicting the packaging volume saving due to the tail boom modifications as the change in length is dependent on the orientation of the wings. Although concept 2 allows for the greatest reduction in width, the tail boom becomes restricted in its movement due to the orientation of the wings. A combined packaging volume saving evaluation is performed below:

	Wing Concepts			
Tail Concepts	1	2	3	4
1	79.4	90.2	63	-
2	78.5	89.7	71	-

Figure 8: Combined packaging volume reduction percentages

## CONCEPT SELECTION

The combination of wing concept 2 and tail concept 1 give the largest decrease in packaging volume, and theoretically offer the minimum weight penalty. During storage, the orientation of the wings gives a good opportunity for the wings and tail to be locked together, reducing the risk of damage during transportation.

## ANALYSIS FOR THE SELECTED CONCEPT

Now that viable concepts have been chosen to greatly reduce the packaging volume of the aircraft with minimal weight increase, detailed design and analysis of the wings and tail can begin. Selecting the correct materials will further minimise the weight penalty inherent to these concepts. Usually, a composite skin and ribs, along with a foam/honeycomb wing filler, would be used for such small wings.



Figure 9: Staged diagram showing tail boom collapsing cross-section

#### Aerodynamic Analysis

The estimation of aerodynamic parameters will use the Tornado Vortex Lattice Method program. The vortex lattice method is a linear aerodynamics code that models the wing as a number of panels with zero thickness. A set of vortices are arranged in a horseshoe on each panel, with the horseshoe from the quarter-chord point to infinitely downstream. The vortices create downwash that, combined with the boundary conditions set in the free stream, can be used to solve for the vortex strength. Then employing the Kutta-Jukovski theorem, the force acting on each panel can be computed [Melin, 2000], [Anderson, 2011]. Tornado runs in MATLAB, requiring wing geometry and flight conditions as inputs. The number of span-wise and chord-wise panels are specified for the computation. The results for all of the panels are given in matrix form, as well as the total lift and drag components which are given below in figure 8. In figure 9 the wing planform plot is shown in Tornado. The centre of gravity and reference point are located at the origin for simplicity in the model. Tornado has many airfoil sections saved in the program, so the geometric data for the selected airfoil was readily available. The drag value estimated by Tornado is comparatively small so is excluded in analysis

Parameter	Data
Lift	89N
Drag	4N

Figure 10: Total lift and drag values at 10° attack angle and the aircraft's maximum velocity of 22.5 m/s

#### **Materials Selection**

For this wing, the composite wing skin takes almost all of the loads. The main purpose of the filler is to give some support to the skin and to add stiffness. Therefore the most important criteria for selection is density, as this filler makes up a large volume fraction of the wing. As seen in figure 12 a study using material selection software CES Edupack. Each blob on the graph represents a material that could possibly work for this use. The composites are sized by stress and not strain. The PVC cross-linked foam shown on the graph has a very low density with a relatively high Young's Modulus, making this material the best choice for a wing filler. Using PVC cross-linked foam, the mass of the wing filler for the wing is 0.19 kg. The selection of composite for the wing skin is performed in the same way, by choosing the material with the highest Young's Modulus-to-mass ratio (YMM). Displayed graphically in figure 9 are possible materials. Again, mass is the most important criteria and so the composite with a low density is selected. Both the polypropylene with 10% carbon fibre (PP 10% carbon fibre) and the polymethylpentene (PMP) have similar YMM's, however the PMP materials have poor UV resistance. Therefore the PP with 10% carbon fibre is chosen as the wing skin material. The wing can now be dimensioned.



Figure 11: Geometry plot in Tornado



Figure 12: Filler selection using CES Edupack



Figure 13: Composite Selection using CES Edupack

## WING DIMENSIONING

Due to the size of the baseline UAV, the structure of the wing is vastly simplified compared to that of larger aircraft. Sizing methods, such as those detailed in [Howe, 2004] are applicable to the more complex structures of larger aircraft. Instead, making an initial estimation of wing skin thickness at 2mm and then using multiple finite element analysis iterations to reduce the wing structure. As a factor of safety of four had already been applied to the flight loads, a factor of safety is not needed in determining the structure, so the factor target is one. Iterations were performed until a factor of safety of one was achieved for the failure of the structure, figure 11 shows a skin thickness of roughly 1mm is needed to resist flight loads with safety factor of four. These simulations are model each semi-span as a cantilever beam, fixed at the root and free at the tip, with a uniformly distributed load acting on the underside of the wing. The wing is assembled from the skin and foam filler in Solidworks, then material properties are applied, along with fixtures, and the assembly is meshed.

Iteration of the skin thickness shows that a skin thickness of about 1mm is needed to withstand loads, giving a total wing mass of about 40% of the total aircraft mass, a more reasonable value. However this neglects any mass added due to mechanisms and composite wing section caps. Once the original wing has been designed, a second design iteration could be performed to account for the tension in the wires and the affect this has on the skin sizing, although further analysis of the tension needed in the wires would need to be done first. This will not be included herein. The various methods by which sections can be hinged and locked together are now investigated for the chosen wing concept.

## WING-TO-WING, BODY-TO-WING AND BODY-TO-TAIL CONNECTIONS

As discussed previously, metal hinges have been the most common method of connecting two wing sections together. Any hinge needs to align the two sections, and lock both sections together to ensure a good transmission of loads across the wings. A possible solution is to use two separate mechanisms to perform these tasks, therefore enabling any hinge-type mechanism to be smaller. Some active materials have the ability to revert from a deformed shape to a pre-set shape when a stimulus such as a temperature change or electric current is applied. Temperature actuated active materials may be difficult to use as their immediate environment will need to be temperature controlled, to prevent unnecessary actuation. This would be overly complex and would certainly increase the weight. The electronically activated versions would be more suitable for the application. However these materials are too expensive to be used for this application [Lagoudas, 2007].

Elastomers, due to their high flexibility are possible candidates to act as hinges. However elastics are prone to be broken by excess tension, and can thin after repeated usage. So the hinge would need to be large enough to prevent this happening. Increasing the size of the hinge would solve this problem by spreading tension over a larger area, but would increase the weight. Moreover a thicker hinge would be more difficult to manipulate. Any elastic material will spring back to its previous form when the deforming force is removed, necessitating locks to keep the aircraft in its folded shape. If these locks were to fail, then the aircraft wings would be forced to deploying its packaging, possibly causing damage to the aircraft. Most elastomers have a low Young's Modulus, possibly too small to take the wing loads.

Hinges, in their traditional sense, have been very inefficient in the wings. There is, however, a new area of design into compliant mechanisms, which are movable structures made from a single part, rather than many parts made into an assembly. A thin strip of the same material is used to connect parts. Because the wing is small and light the hinge will only need to be very small. Making the hinge out the same material as the part of the wing it is connected to means that there are no joints to speak of, only a thinning in the material. Thicker hinges increase are not an option due to reduced flexibility, so compliant hinges are not suited for this use.

A possible method of both hinging and locking sections together would be to use wires. These wires would run the length of the wing, possibly originating from the root, with a mechanism at the wing tip to tighten and loosen the wires for assembly/disassembly. This would provide a very lightweight and inexpensive method to decrease the storage space needed for the aircraft, and so deserves further analysis.

### Number of Wires and Chord-Wise Positioning Study

The chord-wide position of the wire(s) is important to ensure tension is distributed evenly across the airfoil section end cap. If all wiring connects to the centre of the cross-section, a large bending moment and displacement will result as shown in figure 15.





Figure 14: Wing end cap tension study showing the reduction in deformation by using multiple wires



Figure 15: Conceptual wire-hinge designs



Figure 16: Wire-hinge design

As displayed in the finite element analysis above, using multiple wires has several advantages over a single wire:

- Reduced wing tip cap deformation due to the distribution of the tension holding wing sections together.
- In the case of a wire breaking, other wires in the same wing provide a fail-safe against the wing unlocking and failing. However this will require redundancy in the wire sizing, increasing weight.

To ensure transfer of torsion, rib locking mechanism are needed. These locks ensure the individual wing sections cannot rotate will respect to one another by forming a lock and key type fit between two sections. The shape of the rib male lock or 'key' is important, different shapes will have different manufacturing complexities and weight increases. In order to transmit bending and torsion along the



Figure 17: Male and female components of rib locking mechanism.

wing, the top and bottom surface of the male key need to be as large as possible, as these surfaces will have the most contact with the inside of the adjacent section. Two lock ribs are in the adjoining section to prevent the rectangular key section cutting into the foam filler during flight. The wires pass through the space between the rib lock and the leading/trailing edge.

Two wires provide both of the above advantages whilst being lightweight, and so will be used to provide both locking and hinging for wing sections.

Connecting the wings to the body of the aircraft is complicated due to the wires running from the tip to the root. Tensioners could be added to the wing tips for each wire, however this adds mass at the wing tips, resulting in poor aeroelastic performance. Therefore the wires need to run through to the body of the aircraft to be tensioned. As the wing undergoes a change in orientation with disassembly, a restrictive hinge will be used at the leading edge connection to the body to prevent over-rotation of the wing, causing damage to the wires, see figure 16, 17. By connecting the wires to the telescopic mechanism in the tail, tension may be applied to the wires by extension of the tail during assembly. A spring in the telescopic mechanism reduces the increase in wire tension due to wing deflection as shown in figure 18. All four wires from the wings are connected together in the tail, to ensure tension is applied evenly to all wires. The wires in the wing would apply tension perpendicular to the wing tip, with the tension acting as a follower force along the chord line down the span, on the original neutral axis.



Figure 18: Tail spring connection to wires

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#### **Formula Derivation and Evaluation**

The addition of wires to the wing stiffens the wing and decreases the displacement by supplying a counter-acting moment to that caused by the lift. An estimation of the reduction gained is evaluated using Euler-Bernoulli beam theory.

The moments due to the horizontal and vertical components of tension are accounted for in the second moment of area equation. Equation 13 gives the standard moment from a cantilever beam under distributed load. Equation 15 gives the modified second moment of area term to account for the changing position of the neutral axis. The axial compression applied by the tension in the wires alters the position of the neutral axis. The neutral axis is estimated to lie on the chord line before tension is added:

$$M = \frac{w}{2}(x^2 + L^2) - wxL + Te$$
 (6)

$$\frac{d^2 v_y}{dx^2} = \frac{M}{EI} \tag{7}$$

$$I = I_0 + \frac{I_0^2 T^2}{A(M)^2}$$
(8)

The solution for the displacement equation can be assumed to have a fourth-order polynomial form:

$$v_{y}(x) = A_{0} + A_{1}x + A_{2}x^{2} + A_{3}x^{3} + A_{4}x^{4}$$
(9)

The second differential of this solution form:



Figure 19: Wing free-body diagram

Inputting the assumed solution form and multiplying both sides by the right side denominator gives the following equation to solve:

$$(2A_2 + 6A_3x + 12A_4x^2)E(I_0A(M)^2 + I_0^2T^2) = MA(M)^2$$
<sup>(11)</sup>

Solving is achieved by expanding both sides and collecting coefficients of powers of x with  $A_0$  and  $A_1$  equal to zero due to boundary conditions, giving the final equation:

#### 15

$$v_{y}(x) = \frac{8e^{3}AT^{3} + 12e^{2}wAL^{2}T^{2} + 6ew^{2}ATL^{4} + w^{3}AL^{6}}{4(4EI_{0}^{2}T^{2} + 4e^{2}AEI_{0}T^{2} + 4ewAEI_{0}L^{2}T + w^{2}AEI_{0}L^{4})}x^{2} - \frac{wL}{6EI_{0}}x^{3} + \frac{w}{24EI_{0}}x^{4}$$
(12)

The tension applied to the wing must be limited to prevent buckling. A buckling analysis is performed to find maximum tension that can be applied, the results are shown in figure... The finite element analysis simulation shows the buckling load to be about 1700N, so the maximum

load with a safety factor of 1.5 is about 1160N, so the results for equation 19 with be plotted up to this limit

Plot type: Buckling Displacement1 Mode Shape : 1 Load Factor = 1.5047 Deformation scale: 1e-005



Figure 20: Solidworks finite element buckling analysis



Figure 21: Effect of tension on normalised wing tip displacement



Figure 22: Effect of tension on extreme load cases

As displayed in the graph, when the tension in the wire reaches a certain value, the displacement in the wing becomes zero. Beyond this point the wing is displaced downward as the moment due to the vertical component of the tension is larger than the moment due to the lift. Placing wires in the wing is a lightweight method of reducing the wing displacement during flight as well and providing a folding mechanism for the aircraft.



Figure 23: Difference in results between the analytical method and finite element method for a lift equal to weight flight condition



Figure 24: Difference in results between the analytical method and finite element method for a 400% maximum lift flight condition

As is clearly shown in figure 23, 24 there is some error in the data between the two methods. One causes of this would be the Young's Modulus value chosen for the analytical method. This method treats the wing as a beam structure, with a constant Young's Modulus over the whole structure, whereas the finite element analysis allows simulation of the actual full size structure with all of its parts. Another causes of the error is the analytical method only accounts for the contribution of bending moment to wing displacement. The simulation program used is able to be more accurate by accounting for shear force as well. The error averages out at 0.48. This is large, however as Euler-Bernoulli Beam Theory is basic, a large error is expected. Nevertheless, both methods show a tension applied to the wing along the original neutral axis can reduced wing bending.

# **CONCLUSIONS AND FUTURE WORK**

Using wires to provide both a hinge and locking mechanism is a very lightweight and relatively simple method of reducing the volume of the aircraft for storage by over 93%. The tension in the wing has been shown to reduce the wing displacement greatly. Experimental verification of the methods devised herein are needed to fully prove the theory. With the wing displacement reduced by applying tension, further study in how this can be used to reduce wing structure and therefore weight can be done. Further study into how the vertical eccentricity affects the wing displacement would be needed. The method of applying tension to a wing to reduce wing bending may be studied for use on larger aircraft to reduce wing structure and weight.

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