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Aircraft Structural Morphing Using Tendon-Actuated Compliant Cellular Trusses

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The research described in this paper aims to develop a structural concept capable of achieving continuous stable deformations over a large range of aircraft shapes. The basic concept underlying the approach is a compliant cellular truss, with tendons used as active elements. The members of the truss are connected through compliant joints such that only modest bending moments can be transmitted from one member to another. Actuation is achieved by pulling on one set of cables while controlling the release of another, so that the stability of the structure is maintained in any intermediate position. The tendon-actuated compliant truss can be made to behave locally, and temporarily, as a compliant mechanism, by releasing appropriate cables. As a result, in the absence of aerodynamic forces, the structure can be morphed using relatively low forces. Highly distributed actuation also enables the achievement of global shape changes as the accumulation of local ones, while the use of compliant joints rather than true rotating joints eliminates binding as a significant concern. A six-noded octahedral unit cell with diagonal tendon actuation is developed for a bending-type deformation in the wing. Initial cell geometry is determined by "strain matching" to the local morphing deformation required by the application. The cell size is dictated by the available space, the morphing strain, and discretization errors in approximating a smooth desired shape. A finite element analysis is performed on a wing made of these unit cells and sized for a representative vehicle weighing 3000 lb (1360 kg). The weight of the truss wing was comparable to a conventional stiffened skin construction, although its deflections are larger. Aeroelastic concerns can perhaps be addressed through the use of active control. Several ideas for a skin, required to transfer the aeroloads to the underlying structure, are presented.

Nomenclature

B = kinematic matrix
d = vector of displacement of joints
e = vector of elongation of members
l = length of truss member
SR = stress ratio, allowable stress/actual stress
x = half the initial length of the unit cell in the x direction
z = half the initial length of the unit cell in the z direction
z_{al} = allowable space in the z direction, half the thickness of airfoil

Introduction

PRESENT-DAY fixed-wing aircraft are either designed to operate efficiently only at one speed and weight configuration, or the design is a compromise between multiple design points. Reconfigurable or "morphing" structures would make it possible for an aircraft to employ significantly different wing configurations at different speeds, enabling efficient operation over the entire flight regime. Morphing could thus enable the design of aircraft with diverse requirements such as high endurance and high speed.

Morphing can be thought of as occurring on three scales: large-scale morphing like changes in the wing area, span, or sweep; medium-scale morphing, that is, changes on the order of the wing chord, like changes in camber, thickness, twist or airfoil shape; and fine-scale morphing, that is, small changes in shape of the wing that are made locally to affect the flow over that region. Although medium- and fine-scale morphing have been found to increase the efficiency of the wing, it is large-scale morphing that promises significant benefits at different flight speeds. An aircraft could fly efficiently at low speeds with large wing span and area, thus increasing its endurance, and then decrease its wing span and area for a high-speed dash or attack or maneuver phase.

Although many researchers have considered morphing in the midscale region, not much research has been done in smooth large-scale morphing. There is a need for structures that can morph smoothly, effecting an area change of up to 50% and aspect-ratio change of up to 200%. Researchers have only recently begun to address structures capable of achieving such large changes in area. This research aims to study a structural concept capable of achieving continuous stable deformations over such a range of wing shapes.

Background

Morphing, defined as a smooth change in the shape of an aircraft surface, has been attempted in aircraft since its early stages. The Wright brothers achieved controlled flight by pulling on cables to twist the wing. As the speed of aircraft increased, the wings became stiffer, and additional discrete control surfaces were used for control and to adapt to varying flight conditions. One of the first morphing techniques used was variable sweep using hinged wings. An experimental aircraft, Bell X-5, flight tested from 1952–1955, was the first aircraft capable of sweeping its wings in flight. And since then other aircraft such as F-111, F-14 Tomcat, and the B1-B Lancer have been built with the ability to sweep back their wings for efficiency during high-speed flight. The Mach number that the airfoil sees decreases as the wings are swept back, and hence the drag caused by the compressibility effects (shocks) reduces.

Several researchers considered smoothly varying camber instead of using discrete control surfaces. Having a continuous surface lowers the drag and increases the stall angle of the airfoil. The

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Advanced Fighter Technology Integration F-111 was a joint Air Force/NASA/Boeing venture to develop smooth, variable-camber wing technology.[1] Six independent trailing-edge flap segments (three per wing) and two leading-edge flap segments provided smooth continuously variable camber using flexible fiberglass skins on the upper surface and sliding panels on the lower surface. An extensive wind-tunnel and flight-test program was performed. Significant drag reductions were observed at high lift coefficients as a result of the variable-camber concept. Spanwise lift distribution could also be changed to move the center of lift inboard to reduce the wing-root bending moments.

During the mid-1990s and later, researchers in Germany looked at improving the transonic wings of civilian aircraft to actively adapt to varying parameters such as altitude, Mach number, and aircraft weight. Their morphing goals were to achieve spanwise differential camber and shock reduction using an adaptive contour ("bump") in the shock area.[2,3] The following advantages were expected: higher aerodynamic efficiency caused by optimized lift-to-drag ratio (L/D), higher maximum L/D, reduced wing-root loads, and improved performance at extended transonic conditions.

At about the same time, a team led by the Northrop Grumman Corporation in the United States was addressing smoothly varying camber under the Defense Advanced Research Projects Agency/Air Force Research Laboratory/NASA Smart Wing program.[4] A flexcore elastomeric skin trailing-edge structure, actuated using high-power ultrasonic motors, was developed as a hingeless trailing edge control surface. Significant benefits were observed in increased maneuverability and reduced drag at off-design cruise speed in transonic flight, accomplished by using morphing leading and trailing-edge surfaces that could take on smooth shapes that are not readily obtained with conventional control surfaces.

Another concept that has been studied is varying wing twist to increase roll performance. A semipassive morphing wing, the active aeroelastic wing was pioneered and advanced by Rockwell (now Boeing), and later supported by the U.S. Air Force Wright Laboratory and the NASA Langley Research Center. This concept used a wing, flexible in torsion, and leading- and trailing-edge control surfaces to induce wing twist. High-performance roll rates were achieved.[5] Another approach that was used to control the wing twist was using a variable stiffness spar (VSS), which controlled the wing torsional stiffness.[6] The VSS also significantly enhanced roll performance, but without multiple control surfaces. The team at Northrop Grumman obtained a spanwise wing twist of 5 deg using a shape-memory-alloy (SMA) torque tube.[7] This was done at a much slower rate to increase lift during takeoff and landings.

So far, most research has addressed the midscale region of morphing, that is to say, variable camber, twist, and in the fine-scale region of local shape control, like adaptive contour changes and oscillating surfaces to delay flow separation. Approaches to achieve smooth large-scale shape changes have only been investigated recently, especially at NASA.[8] Aircraft structures that are more flexible have also been considered for micro air vehicles. Studies developed wing shapes that are inspired from wings of birds and sharks. With minor in-flight wing tip adjustments, yaw, pitch, and roll control are expected to be accomplished.[9]

Telescoping wings have also been used to change the area and aspect ratio of wings. For example, there has been research in variable-span rotor blades.[10] In addition, Blondeau et al. designed and developed a telescopic wing with nylon fabric skins and pneumatic actuation of the spar. The telescoping wing had a lower lift/drag ratio when compared to a rigid fixed-wing specimen, because of an increase in parasitic drag caused by discontinuous seams.[11]

Concept

A morphing aircraft structure needs to be able to change its shape, carry the required load, and be light. So far designers have been able to accomplish only two of these three goals simultaneously.[12] Modern aircraft wings are highly weight efficient but are stiff and cannot be morphed. The required change in shape is achieved using articulated or sliding joints and additional surfaces. This type of construction is not as efficient as it might be.

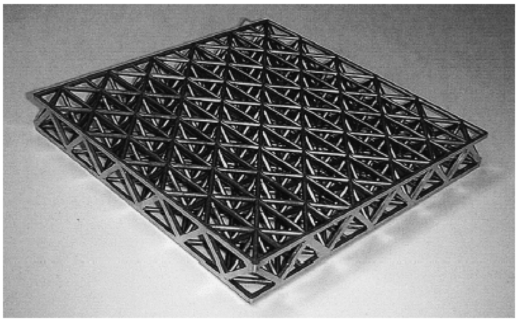


Fig. 1a Passive cellular truss.[13]

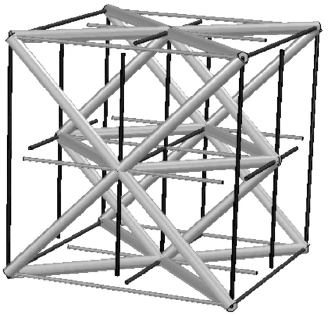


Fig. 1b Proposed unit cell, with tendons.

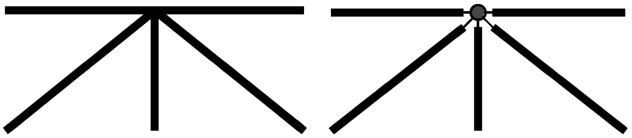


Fig. 2 Frame and compliant truss.

The basic concept underlying the present approach is a *compliant cellular truss* with *tendons* used as active elements. Depending on the application, the cell structures used could be two dimensional or three dimensional. A passive cellular truss and a candidate unit cell for a tendon-actuated cellular truss are shown in Fig. 1. The cables can be activated using electric motors, or perhaps, piezoinchworm motors, which are currently under development.

The truss members are connected through compliant joints. A compliant truss differs from an ideal truss in that modest bending moments can be transmitted from one member to another through the joints. However, such a truss differs from a welded frame in that effective member bending stiffnesses are substantially reduced in the vicinity of a joint, as illustrated in Fig. 2. In a sense, such joints are analogous to flexures in two-dimensional structures, and act as "rotational springs" at the end of each element.

One possible realization of a compliant joint is a SMA cylinder or wire. Used passively in a pseudoelastic or "superelastic" mode, SMA can be regarded as a high-strain-capable structural material. To operate in this mode, the temperature must be above the transition temperature of the material. Depending on the temperature, strains approaching 8% can be experienced reversibly.

Cables or tendons cannot carry compressive loads. A truss structure involving cables might be stiff in tension under one loading condition, but might collapse under the negative load condition. The truss and unit cell should be designed so that it is stable in any load condition, even without pretension in the cables. In such a case, different cables are active in different load conditions. A key feature of this tendon-actuated compliant truss is that, by releasing appropriate cables, the structure can be made to behave locally, and only temporarily, as a compliant mechanism, that is, the structure can change shape without storing much strain energy. As a result, in the absence of aerodynamic forces the structure can be morphed using relatively low forces. This is not possible with conventional structures, as the (highly redundant) structure absorbs significant strain energy when forced into any shape other than the nominal one.[14]

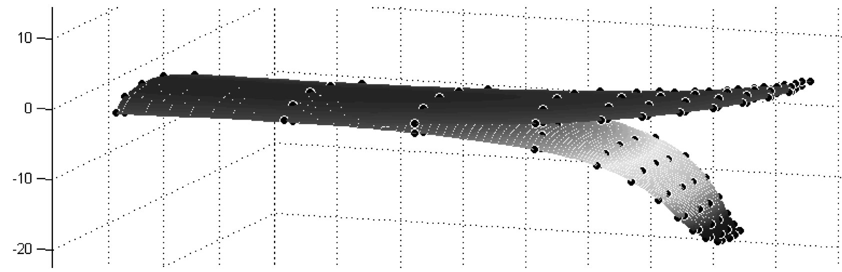


Fig. 3 Morphed and unmorphed configurations of HECS wing.

Furthermore, the use of compliant joints rather than true rotating joints eliminates binding as a significant concern. Highly distributed actuation effectors also enable the achievement of global shape changes as the accumulation of local ones. The cables are reeled in or released in a controlled manner while the structure is loaded; hence, the stability of the structure is maintained in any intermediate position.

Passive trusses are known to be efficient structures from a weight standpoint. They have been considered in the design of, for example, the high-altitude long-endurance aircraft.[15] Wicks and Hutchinson have found that the strength of optimized truss plates in bending, compression, and shear compares favorably to honeycomb core sandwich plates and stiffened panels.[16] And tendons can be made of really light and strong materials. One possible realization of cables involves high-specific-strength polymeric materials such as Spectra® (polyethylene) or Vectran® (polyester-polyarylate). Vectran, for instance, exhibits specific strength more than 10 times that of steel, whereas its specific modulus is twice that of steel.

Truss structures involving cables have so far been used in relatively low-loading conditions like deployable space structures.[17–19] Use of tendon-actuated compliant cellular trusses in aircraft structures presents a novel method for achieving a wide range of morphing shapes in aircraft wings without accruing an excessive weight penalty. Some of the promising key features of a cable-actuated truss structure are as follows: 1) truss structures are light; 2) smooth changes in the shape can be achieved because the large changes in the structure take place as the accumulation of small local changes; 3) truss structures provide nearly continuous support for a skin; and 4) cables have a large actuation capability, because the cables can be reeled in by any amount.

The hyperelliptic cambered span (HECS) wing shown in Fig. 3, and developed at the NASA Langley Research Center, provided a baseline geometry to guide the initial development of this concept. The HECS wing originated as a biologically inspired configuration that reduces induced drag.[20] Yaw, pitch, and roll control are accomplished through continuous wing morphing, especially at locations near the tip. The development of the truss structure design is approached in two ways. In the first approach, which is the focus of this paper, a cellular structure, is used. The following considerations are addressed in the development of such a structure: 1) the topology or connectivity of the unit cell, which is designed based on the strains required; 2) the strength and weight of the cellular structure; and 3) the skin design. The current paper is focused mainly on the first two issues.

The second approach is to design using structural optimization. In this approach an initial layout or "ground structure" of three-dimensional frame elements is used to build one section of the wing. Then the topology is optimized to determine the best placement of struts and active tendons, as well as to identify elements that could be omitted. Given the discrete nature of the element placement problem, a genetic algorithm is used in the pursuit of structural improvement. This approach is discussed in greater detail in a paper by Bharti et al.[21]

Octahedral Unit Cell

A design of a cellular truss structure with fewer cables is preferable to one having a large number of cables. Because cables cannot carry compressive loads, they have to be placed in such a way that they are counteracting. Increasing the number of cables in a unit cell increases the complexity of the unit cell and the number of actuators required. If a pin-jointed statically determinate unit cell is chosen as a starting point, removing one member would render the unit cell a mechanism, allowing it to deform without storing strain energy. The simplest statically determinate unit cell, with the fewest members, is the tetrahedral unit cell with six members. The next simplest is the octahedral cell with 12 members. A tetrahedral unit-cell structure can only have a shear mode of deformation using one member as a cable. The octahedral unit cell, however, can be used to obtain effective expansive, compressive or shear strains.

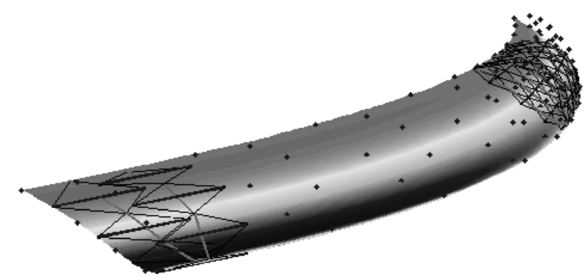


Fig. 4 Cellular truss structure for HECS wing.

In the HECS wing, the primary mode of deformation is spanwise bending, with some twist near the tip. Figure 3 shows the HECS wing in both the unmorphed and morphed configurations. The morphed and unmorphed configurations, as defined by sets of three-dimensional points on the surface, were provided by NASA Langley Research Center. The data for a finer mesh of points were obtained by interpolation. The approximate strain, defined as the change in length caused by morphing over the original length, in surface and thickness directions in the wing coordinate system was calculated from the interpolated data. The ratio of the chordwise to the spanwise strains varies over the surface. Over most of the top surface, this ratio is positive, suggesting the use of a material with an effective negative in-plane Poisson's ratio. Over most of the bottom surface, the ratio is negative. The normal and shear strains through the thickness were much smaller than the surface strains.

An effective way of accomplishing the required deformation is to use a layer of octahedral unit cells for each of the top and bottom surfaces as shown in Fig. 4. In the figure, the projections of the corresponding unit cells on the top and bottom surfaces are shown. The orientation and configuration of each unit cell is determined by the local morphing strain requirements.

The basic unit cell used for the top surface, an octahedral unit cell with a central cable, is shown in Fig. 5. In the figure, the thicker blue lines represent truss members, and the lighter red lines represent cables. The cables provide the actuation. If the cable connecting nodes 5 and 6 is shortened and the remaining cables are lengthened simultaneously, then the the points 2 and 4 will move further apart. The ratio of these strains can be changed by varying the lengths of truss members in the y-z plane and the x-z plane. A bench-top demonstration model of the top-surface unit cells is shown in Fig. 6. The in-plane cables in the model have been replaced by one central cable for ease of construction.

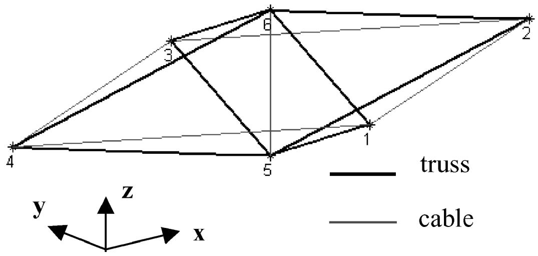


Fig. 5 Unit cell for top surface of HECS wing.

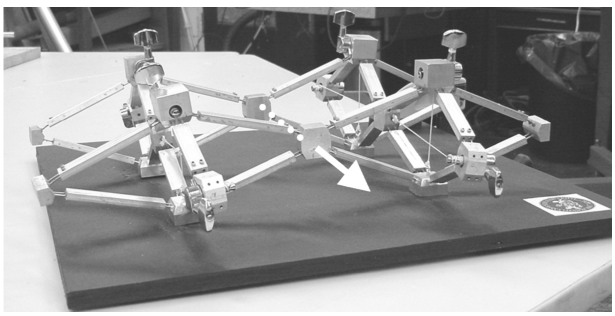


Fig. 6 Bench-top demonstration model.

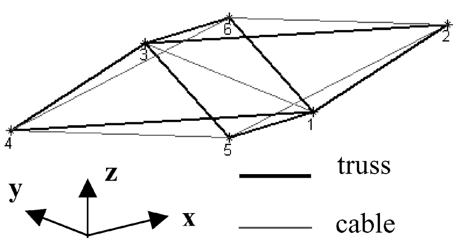


Fig. 7 Unit cell for bottom surface of HECS wing.

The unit cell used for the top surface is shown in Fig. 7. Here the strains in the x and y direction increase or decrease simultaneously when the cables are actuated.

Mechanism Modes

The structure formed by the octahedral unit cells, just described, can have an inextensional mode of deformation, that is, it can distort without any change in the length of the members, even though a unit cell is statically determinate by itself. For example, the structure in Fig. 6 can fold hinging about the axis denoted by the arrow. The existence of the inextensional modes is verified using the method provided by Pellegrino and Calladine.[22] The equations of kinematics of small displacements of the assembly are written as follows. For each bar there is one equation relating its elongation e to the components of displacements of the joints d at either end; and the resulting equations can be written as

$$B \cdot d = e \tag{1}$$

The null space of the kinematic matrix B gives the inextensional modes of the structure, that is, a set of vectors of the displacements at nodes that do not cause the extension of members. This method does not account for cables being slack under compression. In this approach the unit cell is formed by taking a unit cube and placing the octahedral unit cell in the center and adding additional members appropriately. A cable or a truss is added following the octahedral truss pattern, after calculating the mechanism modes and observing the mode of deformation. The unit cell required to form a stable single-layer truss plate includes additional members along the top and bottom surface of the unit cell, as shown in Fig. 8. The bottom-surface unit cell shown in Fig. 6 is seen in the center of the cell in Fig. 8.

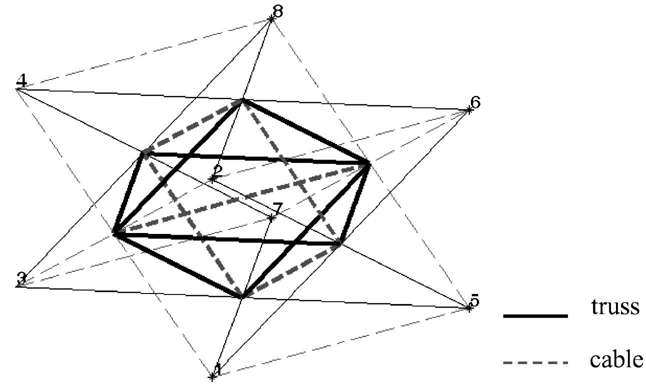


Fig. 8 Unit cell that is integrated into the structure.

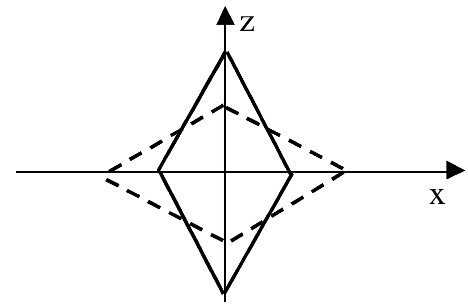
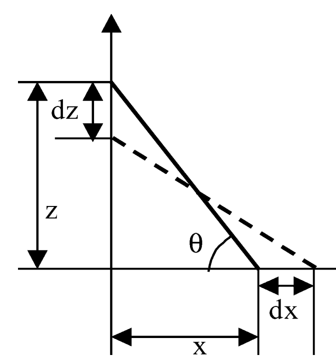


Fig. 9 Deformation of the parallelogram of truss members of an octahedron.

Fig. 10 Large movement in the x and z directions.



The solid lines are truss members, and dashed lines are the cables. The inner octahedral cell is represented using thicker lines for clarity.

Size of Unit Cells

The size of the unit cell in the three directions can be limited by the morphing strain required and the available space. Consider the parallelogram formed by the truss members in the x-z plane of Fig. 6. Two configurations of this parallelogram are shown in Fig. 9: the solid lines show the initial configuration, and the dashed lines show the configuration after deformation. The expansive or compressive strains in the unit cell are caused by the change in lengths of the diagonals of the parallelogram in the plane.

In this deformation, the length of the truss members is fixed. Depending on the initial slope of the truss member with respect to the x axis (Fig. 9), the effective strains in the x and z direction vary. For small deformations, Eq. (2) holds.

$$x dx = z dz \tag{2}$$

For large deformations, the deformations dx and dz, as shown in Fig. 10, are related by the following equation:

$$(x - dx)^2 + (z + dz)^2 = l^2 \tag{3}$$

A change in cell size (the distance between opposite vertices of the octahedron) in one direction also results in some change in cell

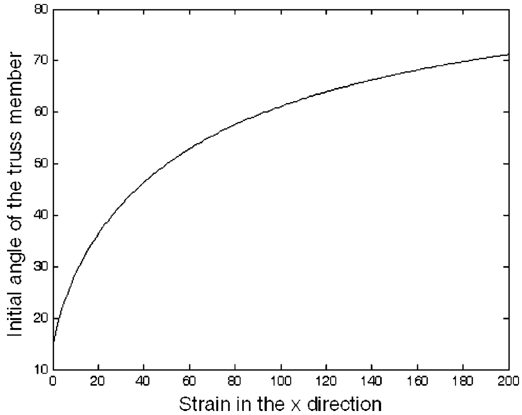


Fig. 11 Initial angle required for a given strain.

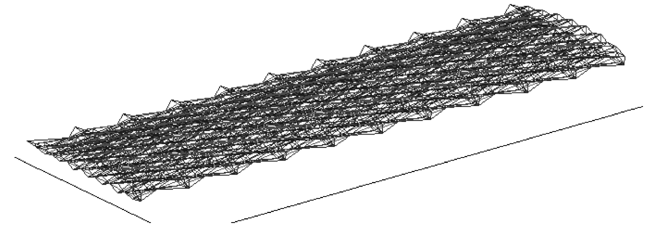


Fig. 12 Wing made of the octahedral unit cells.

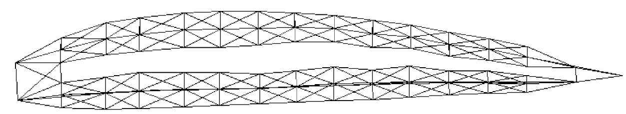


Fig. 13 Cross section of the wing structure.

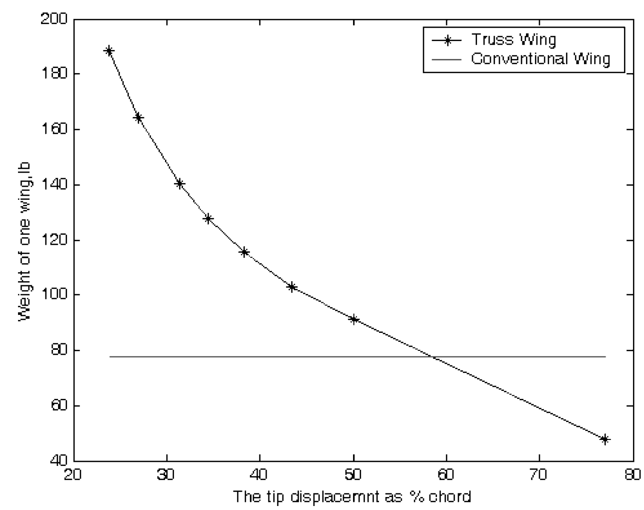


Fig. 14 Weight comparison of truss wing and conventional wing.

size in the other directions. If the size of the cell is limited in the thickness or z direction, then the maximum change in length in the other directions can be obtained as the change in z direction goes from the limit length z_{al} to 0. When z is 0, x is equal to l (length of the truss member). However, the structure would lose its shear stiffness if the angle of the truss member is allowed to go 0. Hence, the final angle is limited to 15 deg.

$$\varepsilon = \text{change in length/original length} = [l\cos(15) - x]/x$$

$$\Rightarrow \varepsilon = l\cos(15)/x - 1$$

$$\Rightarrow x/l = \cos\theta = \cos(15)/(1+\varepsilon)$$

$$\Rightarrow \theta = \cos^{-1}[\cos(15)/(1+\varepsilon)] \tag{4}$$

This relation is plotted in Fig. 11. The figure shows that for a 15% strain, as is required by the HECS wing, the initial angle of the truss member should be 30 deg. Therefore, if the maximum thickness of the airfoil is 4 in., the allowable displacement in the thickness direction z_{al} for a unit cell in the top surface would be 2 in. With the initial angle of the truss member as 32 deg, the size of the unit cell in x direction is $[z^*_{\mathrm{al}}\cot(32)] = 3.2$ in. The size of the unit cell just obtained is acceptable for the HECS wing because the maximum strain of 15% is only seen in a small area near the tip. Hence there would be a reasonable number of unit cells in the wing. However, if the required strain is large, say, 100%, then the size of the unit cell is 1 in., and a large number of such cells would be required per unit area. Hence, to minimize the number of actuated tendons, the octahedral unit cell is most effective when the strains are not too large. Another aspect that could limit the size of the unit cell is the accuracy of the airfoil geometry approximated by the unit cells.

Strength and Weight Considerations

If they are to see use in practice, such structures must be capable of satisfying all of the design requirements for primary aircraft structure: carrying basic structural loads, as well as those associated with active morphing.

A model wing structure is sized for a vehicle weighing 3000 lb, representative of a military unmanned air vehicle. The wing is made of the octahedral unit cells described in the preceding section. Different configurations of the unit cells are used for the top and bottom layers. The negative in-plane Poisson's ratio unit cells (Fig. 5) are used in the top layer, and the positive in-plane Poisson's ratio unit cells (Fig. 7) are used in the bottom layer. The top and bottom layers are connected with truss members near the leading edge and trailing edge. The structural layout is shown in Fig. 12, and a cross section of the wing is shown in Fig. 13.

The wing is designed for a loading condition with a limit load factor of ±4 and a factor of safety of 1.5. The load is distributed spanwise using the Schrenk's approximation[23] and chordwise using the pressure distribution of the Clark Y airfoil. The wing structure is analyzed using linear finite element analysis. The truss members are assumed to be tubular, made of aircraft-grade aluminum alloy, and the cables are made of a high-strength polymer like Spectra. During the finite element analysis, the stiffness of any cable having a compressive load is set to a small value to effectively eliminate such cables, and the analysis is repeated. This process is continued until the same set of cables is carrying compressive loads as calculated in the preceding iteration.[24] The areas of the truss members are adjusted so that local buckling of cross section or column buckling or material failure occurs at the ultimate load, and the areas of the tendons are adjusted so that the material failure occurs at the ultimate load. The stiffness of the structure and hence the stress in the members change as the areas of the members are changed. The stresses in the members are recalculated, and the members are sized again. This process is repeated a few times until the sizes and stresses converge. The areas of the members thus calculated were found to be reasonable even at the root where the members see the maximum load.

If the members are sized only to prevent local failure under the applied loads, the deflections are relatively high, that is, the overall structure is relatively soft. To increase the stiffness, the cables and truss members are resized by multiplying the failure load (ultimate strength or buckling load) of each member with a factor (stress ratio, SR > 1). The sizing process is repeated for different values of SR, and the weight of the wing is calculated each time. To represent the weight of the nodes, an additional 18 lb is added to all of the configurations uniformly, based on the assumption that the nodes are solid and spherical. The weight of the actuators and skin is not included.

Figure 14 shows the results in terms of weight of the wing vs maximum displacement. Also plotted in the figure is the weight of a conventional stiff wing of a light fighter aircraft, designed for the same loading conditions, that is, a gross weight of 3000 lb, load factor of 4, and factor of safety of 1.5. It has the same size, same planform, and no variable sweep capability. This weight was obtained using the statistical weights method[25] and does not include the weight of the control surfaces or the actuators. This weight is an estimate of the weight of a nonmorphing conventional stiffened-skin wing. The optimal weight of the truss wing is not known because the limiting deflection affects the weight of the truss. However, this analysis shows that the weight of the truss wing can be comparable to the weight of a conventional wing at this geometric scale.

Although the deflection of the wing of the fighter aircraft is not known, it is likely small compared to those obtained for the truss wing. The control surfaces on a typical fighter aircraft are hinged, and large deflections of the wing would cause the hinges to bind, making the control surface inoperable. This acts as one limiting factor for the deflection of such a wing. In the truss wing concept, however, this is less of a concern because the whole wing can morph to provide control.

Torsional stiffness has not been addressed explicitly in the preceding calculations. The truss wing is torsionally soft compared to a conventional wing, leading to lower divergence and flutter speeds. However, the truss wing is highly adaptable; it could be actively morphed to avoid divergence, for example, by washout. Flutter could also be suppressed through the use of high-bandwidth active control.[26] The lateral shear stiffness of the structure decreases as the angle of the truss members decreases. However, even in the fully extended configuration, truss members are at a small angle. The unit cells in the preceding analysis are closer to the fully extended configuration.

As just noted, the weight of the truss wing does not include the weight of the skin. The details of the skin have not yet been established. The skin in a morphing truss wing will not add significantly to the bending stiffness of the wing; however, it needs to transfer the air loads to the underlying truss structure. If the skin is made of a lightweight polymer like Vectran (200 denier, 50 × 50 plain weave), the additional weight of a skin is around 0.7 lb. If segmented skins (discussed in the following section) are used, the additional weight could be somewhat higher.

The truss structure made of octahedral unit cells could be heavier than a conventional design but has the ability to provide smooth and continuous deformations. Although it might not be very effective to design an entire wing made from such cells, they could be used in sections of the wing where morphing is especially important. For example, in the HECS wing the truss structure can be used mainly in a small spanwise section near the tip to bend and twist the wing tip, the wing tip itself being a stiff structure that acts somewhat like a control surface. Deciding exactly where to place morphing structure could be addressed more generally through a comprehensive trade study that compares the benefits of morphing with the weight and complexity penalties.

Skin Design

The development of a skin system that can accommodate large shape changes while carrying and transferring aerodynamic loads is an essential element of aircraft morphing technology, posing perhaps one of the most difficult technical challenges.

Low (or releasable) membrane stiffness is desirable in order to reduce morphing actuation requirements, whereas high lateral stiffness is desirable in order to maintain an aerodynamic shape while transferring load effectively. Several approaches to morphing skin structure are being explored.

High-strain-capable materials offer the possibility of directly accommodating or withstanding the required morphing strains. Depending on the magnitude of these strains, such materials might include superelastic SMA, high-strength elastomeric composites, and impermeable or tensioned fabrics. Low stiffness membranes, although attractive in principle, might require closely spaced lateral support in order to minimize lateral deflection under pressure loads. Those that are especially stiff, such as SMA, might be best considered when inextensional skin deformation (bending only) is a possible morphing deformation.

Folded inner skins might provide lateral support for a very flexible outer skin as shown in Fig. 15. These would be designed to expand or contract with the main load-bearing structure. Similar approaches have been considered for deployable space membranes.[27]

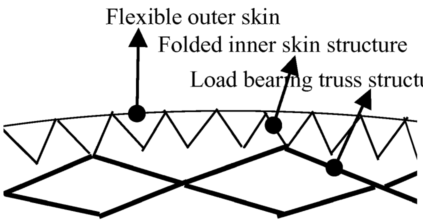


Fig. 15 Folded skin structure.

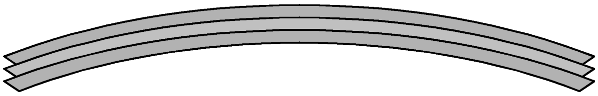


Fig. 16 Multilayer skins carry membrane loads with low bending stiffness.

Multilayered skins consisting of multiple thin layers of conventional materials that are not bonded together, as illustrated in Fig. 16, could be used for bending-type deformation. Such a skin, in which transverse shear stresses are not transmitted from one layer to another, can carry the same membrane loads as a monolithic skin having the same thickness, but can withstand much higher bending curvatures. Because of reduced bending stiffness relative to a monolithic skin, however, a multilayered skin would probably need to be supported over distances smaller than typical rib and stringer spacing.

Segmented skins, made of multiple discrete elements that slide relative to one another as the structure deforms, somewhat like fish scales or feathers, offer the possibility of high local lateral stiffness in combination with low-force membrane deformation. Individual elements would be fairly stiff, capable of transmitting aerodynamic forces to the underlying structure. This approach seems particularly suited for use with a compliant cellular truss, in that each segment might be attached naturally to the nodes of a cell. A significant concern in such a construction would be maintaining aerodynamic smoothness at the discontinuities.

Conclusions

A tendon-actuated compliant cellular truss is proposed as a means of realizing morphing aircraft structures. An octahedral unit cell is developed for bending-type deformation and considered for use with the hyperelliptic-combered-span wing aircraft. Initial cell geometry is determined by strain matching, adjusting the size and orientation of cells to the required local morphing deformation. The limiting size of the unit cell is dictated by the required deformation and the available thickness of the wing section. Actuation and release of appropriate tendons are used to adjust the geometry of individual cells and the overall structure. The compliant joints are implemented as cylindrical elements of superelastic shape memory alloy. Additional cell shapes need to be investigated for larger changes in area; a topology optimization approach will be used to develop new unit cells.

A wing is also designed for a representative vehicle weighing 3000 lb using the octahedral cells. The weight of a stress-sized wing is comparable to that of a conventional wing, although its deflections are larger. Aeroelastic concerns can perhaps be addressed through the use of active control.

Several concepts for a morphing skin were also presented. The tendons are made of a high-specific-strength polymer like Vectran or Spectra. Tendon actuators are presently under development. The tendons could be actuated locally or combined to be actuated from a remote location, such as the root of the wing.

Numerous technical challenges remain before morphing airframes capable of exhibiting large, rapid, and smooth shape changes become reality. Nevertheless, the potential for combined persistence and rapid response in a single aircraft makes the continued pursuit of this technology important.

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