CHAPTER 8

Flexible-wing-based micro air vehicles

P.G. Ifju

Mechanical & Aerospace Engineering Department, University of Florida, USA.

Abstract

This chapter describes a unique flexible wing concept as applied to micro air vehicles. This flexible wing has numerous advantages over convention wing designs including passive gust rejection, improved aerodynamic efficiency, delayed stall, the ability to be reconfigured for storage and morphing, as well as improved durability. The materials and methods used to fabricate the flexible wings will be presented along with examples of the flight vehicles. A brief framework of the approach used to perform computational fluid dynamics modeling for fluid-structure interaction of flexible membranes will be provided. Results from flight tests, as well as wind-tunnel tests, will be provided to demonstrate the benefits of the flexible-wing concept.

1 Introduction

Micro air vehicles, or “MAVs”, are a class of aircraft with a maximum size of about 6 inches and are capable of operating at speeds of 25 mph or less [1]. The concept is for a small, inexpensive and expendable platform that can be used for missions of surveillance and measurements in situations where larger vehicles are not practical. For example, they can be used for small unit battlefield surveillance, mapping out the extent of chemical/radiation spills or viral outbreaks, as well as more routine applications such as monitoring crops or wildlife distributions. Many potential uses involve launching of large numbers of MAVs to secure the necessary coverage with the intrinsically “close up” type of maneuvering allowed by a micro-sized aircraft. In some applications, MAVs could be used in swarms or sent to a pre-designated grid to collect and transmit data. Practical applications of MAVs are becoming more achievable with the ever-decreasing size and weight of the payload components that could include video cameras, chemical sensors, electronics, and communication devices. Only a few years ago, the thought of a 6-inch flying machine equipped with a functional video camera was science fiction. Today it is a demonstrated fact.

It is well known that in the Reynolds number range between 10,000 and 100,000, which corresponds to the MAV size range identified by DARPA, the aerodynamic performance of
Conventional airfoils is dramatically degraded. Figure 1 illustrates this phenomenon in a plot that describes the marked drop in the lift to drag performance as a function of Reynolds number for all smooth, rigid airfoils. This plot clearly illustrates that the design rules that have been adopted for large aircraft cannot be scaled down to the MAV scale. With smooth, rigid wings in this Reynolds number range, the laminar flow that prevails is easily separated, creating large separation bubbles, especially at higher angles of attack [2]. Flow separation leads to sudden increases in drag and loss of efficiency.

![Region of Interest - All Rigid, Smooth Airfoils](image)

**Figure 1**: Coefficient of lift divided by coefficient of drag versus Reynolds number for all smooth airfoils.

In nature, one can observe the relationship between Reynold’s number and aerodynamic efficiency in birds, where large species soar for extended periods of time while small birds have to flap vigorously (high frequency) to remain airborne. The Reynold’s numbers of the larger species are well above 100,000, whereas hummingbirds would fly at below 10,000 if they attempted to soar. Additionally, the wing loading for small birds is less than that for large birds.

Another major obstacle for flight at this small scale is the diminished stability and control characteristics that accompany the small mass moments of inertia of these tiny aircraft. Also, the velocity scale of the turbulence naturally exhibited by the atmosphere is comparable to the flight speed of these vehicles. Therefore, variations in airspeed over the wing can be large, and can even cause variations from one wing to the other, leading to difficulty in maintaining smooth flight. These factors make control of these diminutive aircraft difficult, both for a remote operator or an on-board autopilot. Other technical challenges associated with flight on the 6-inch scale include the need to provide reliable propulsion and miniaturization of components, including the electronics and actuators for the control surfaces.
In the quest to develop practical MAVs, two approaches have been employed so far. The first and most popular is to configure the airframe as a lifting body or flying wing using conventional propeller-driven thrust. In this approach, the emphasis is to increase the relative area of the lifting surface while decreasing drag, directly addressing the decrease in the aerodynamic efficiency, and ignoring issues of stability and control. In order for these designs to fly at all, active stability augmentation systems are usually required. In nature, the great optimizer, there are no examples of lifting bodies or flying wings. All birds and bats have well-defined wings and a fuselage. The second approach that has been explored on the MAV scale is the direct mimicry of birds [3–5]. By flapping, birds produce both lift and thrust. Researchers have demonstrated flapping mechanisms in the lab environment, but have yet to produce practical controlled flight vehicles. Complex control issues and high power consumption remain as formidable challenges for this type of MAV.

Conventional approaches have used optimized rigid wings and accepted the need for enhanced stabilization systems or supreme pilot skill to deal with the intrinsically unsteady behavior. Of all the examples of MAVs, the most successful to date is the Aerovironment’s “Black Widow” [6], an electric 6-inch flying wing. Virtually every component on the aircraft is custom built, including a sophisticated gyro-assisted control system. Other successful examples of rigid wing designs include the “Trochoid” [7] developed by Steve Morris of MLB Company and Sander’s “Microstar. Both of these also have gyro-assisted stabilization systems. Without these enhancements, lifting bodies are difficult to control.

Previous studies, documented in Waszak [8], Shyy et al. [9–11], Smith and Shyy [12], and Jenkins et al. [13], indicate that an alternate approach, specifically letting the lifting surface move and deform, can lead to more favorable aerodynamic performance in a fluctuating low Reynolds number environment. These findings helped lead to the University of Florida’s flexible-wing concept, which we have been applying to successful MAVs over the past four years [14–17]. Flight vehicles were developed that utilize conventional propeller driven thrust in combination with an adaptive-shape, flexible wing that adapts to flight conditions and also develops a stable limit-cycle oscillation during flight.

The wings were developed to produce smooth flight even in gusty wind conditions. In order to produce the best overall flight characteristics, one must first start with an airplane that is intrinsically stable. This is accomplished via the adaptive nature of the wing as well as its natural oscillation. These aircraft can be flown by novice to average RC pilots, without the aid of gyro enhanced stabilization. Merits of the flexible wing have been demonstrated at the International Micro Air Vehicle Competition by winning the event for the last four years in a row.

2 The flexible wing micro air vehicle

The development of the flexible wing utilizes a combination of biologically inspired design and the incorporation of modern composite materials. It is thin and undercambered, as are those of small birds and bats. In previous studies [13], it was shown that thin undercambered wings are more efficient than those with significant thickness. For birds and bats on the same scale as micro air vehicles, the wings have evolved towards the ideal thin undercambered shape as can be seen in Fig. 2. The wing of the micro air vehicle that was developed is constructed with a carbon-fiber skeleton (analogous to the bone structure of the bat) and thin membrane materials (analogous to the skin of the bat wing). The overall aircraft configuration is a departure from the traditional flying wing or lifting body design. It has a distinct fuselage and wing, more similar to that of birds and bats.
Figure 2: Small bats and birds have thin undercambered wings. Bats have a bone skeleton and a skin membrane.

Figure 3: The University of Florida 6-inch wingspan flexible wing MAV is powered by an electric motor and has a color video camera on board.

The MAV shown in Fig. 3 is the product of more than three years of design iteration, using flight tests and pilot feedback as the primary method of evaluation. The planform of the wing allows for the maximum lifting surface while staying within a 6-inch diameter sphere. The 6 inch MAV weighs on the order of 65 grams and includes an electric motor, lithium polymer batteries that allow for 15 minute duration flights, two servos to control the elevator on the trailing edge of the wing, as well as the rudder on the vertical stabilizer, a FM receiver, an
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The aircraft has a range of about 1 mile and is typically flown using the video signal as the sole pilot feedback. The MAV can fly at speeds that range from 15 to 35 miles per hour.

2.1 Adaptive-wing design

The flexible nature of the wings can provide several non-obvious advantages over their conventional rigid counterparts. The wings that we have fabricated with a carbon-fiber skeleton and extensible latex rubber skin have the ability to adapt to the airflow to provide smoother flight. This is accomplished via the passive mechanism of adaptive washout. In sailing vessels, adaptive washout is produced through twist of the sail. This greatly extends the wind range of the sail and produces more constant thrust (lift), even in gusty wind conditions. In the wings that we have designed, the shape changes as a function of the airspeed and the angle of attack. The adaptive washout is produced through extension of the membrane and twisting of the framework, resulting in angle-of-attack changes along the length of the wing in response to airspeed and overall angle of attack. For example, as the plane hits a head-on wind gust the airspeed suddenly increases. The increased airspeed causes a shape change in the wing that decreases the lifting efficiency, but because the airspeed in the gust is higher, the wing maintains nearly the same lift. Once the airspeed decreases, the wing recovers to the original configuration. If there is a decrease in the relative airspeed, the angle of attack increases and the wing becomes more efficient and near constant lift is restored. The net result is a wing that flies with exceptional smoothness, even in gusty wind conditions. The adaptive washout mechanism is subtle and must be tuned into the wings in order to work effectively. We have built hundreds of wing configurations and have been able to produce many wings with remarkably smooth flying characteristics. Figure 4 illustrates the flexible nature of the wing.

Figure 4: Due to the light wing loading during flight, it was necessary to incorporate an extensible membrane to achieve adaptive washout.

For aircraft with very small inertia, as in the case of MAVs, changes in wing loading can immediately affect the flight path. As the aircraft becomes smaller and lighter the need for
suppressing the effects of wind gusts becomes more critical, especially if it is to be used as a camera platform. Additionally, as the airspeed of the vehicle decreases, wind gusts become a larger percentage of the mean airspeed of the vehicle. For example, our 6-inch aircraft flies between 15 and 35 mph. On a typical day, the wind speed can vary by more than 10 mph. For rigid wings, the lift can vary by 50% or more over the short period of time during the gust. To make matters more critical, gusts are not always head-on. Since control of these aircraft is one of the most important hurdles, it is critical to suppress unwanted and sudden changes in direction, elevation and orientation.

In nature, birds and bats display a similar form of adaptive washout. This passive mechanism can be observed on windy days by large soaring birds. The feathers at the wing tips flap to accommodate sudden changes in airspeed. To some extent, our design approach has been biologically inspired. We have observed both birds and bats and have designed our wings to have similar characteristics. As mentioned earlier, the adaptive washout mechanism is subtle, therefore the location and stiffness of the carbon fiber skeleton members and thickness of the latex membrane are critical. In order to define the design space for our flexible wing, we built numerous prototypes to learn how the geometry of the carbon fiber skeleton affected flight performance. We also varied the relative stiffness of the different parts of the skeleton. Shown in Fig. 5 are 24 of the designs that were successfully flight-tested. We were able to make observations in the field in order to qualitatively rank their performance. Using this relatively crude trial and error process, we were able to down-select the configurations that provided the best performance. These designs were then tested using more rigorous means via additional flight tests and wind-tunnel tests.

### 3 Aircraft construction methods

In order to implement the flexible-wing concept on these small vehicles, traditional materials such as balsawood, foam and monocoat were not appropriate. Instead, the use of high specific strength and high specific stiffness materials in combination with flexible membrane materials was required [15]. For the skeleton, carbon fiber unidirectional and cloth prepreg materials were used. These are the same materials used for structures that require fully elastic behavior yet undergo large deflections. The fishing rod is a classic example of such a structure. For the membrane, extensible material was chosen to allow deformation even under very small loads, such as the case for lightly loaded wings. Latex rubber sheet material was used in this case.

During the development of the flexible-wing concept, and in the absence of mature computational capabilities, the effort was primarily driven by trial and error. This required an efficient and repeatable construction process that produced durable aircraft. Durability was extremely important since the aircraft were flight tested numerous times in the process of trimming them for level flight. Each flight ended in a crash landing during this process. If the aircraft structure was compromised during this process, trimming would be impossible. Additionally, even when the aircraft was trimmed properly and in the absence of landing gear, every flight ended in a crash. Our motto was “every crash is a landing and every landing is a crash”. With the use of carbon fiber/latex rubber wings and a carbon-fiber fuselage, we were able to produce durable and yet lightweight aircraft that could survive multiple crashes without compromising flightworthiness. In retrospect, the construction methods that we developed were the enabling technology that allowed us to explore the flexible wing concept. Typically, the construction process requires only five man-hours to build an entire MAV.
Figure 5: Numerous skeleton configurations were initially flight tested in order to narrow the design space.

Figure 6 illustrates the fabrication process. The first step in the fabrication process is drawing a wing-frame template that shows the location and thickness of each rib. This drawing is affixed to the wing tool, which is made from sheet metal and bent to the desired airfoil shape. Next, the wing is laid up on the wing tool using fine strips of unidirectional carbon-fiber prepreg (carbon fiber pre-impregnated with epoxy resin). Multiple layers are used where high stiffness or strength is required. The covering material for the access hatch and hinge material is integrated with the prepreg. The fuselage is made of a 0–90 bias carbon fiber cloth weighing 5.6 oz/yd². The cloth is wrapped around a hand-shaped foam male tool. It is then placed on the wing tool next to the wing so both parts mate perfectly when assembled. These parts are then vacuum bagged and subject to a five-hour cure cycle in the autoclave where they reach a temperature of 270°F.

After wet-sanding the fuselage with fine grit paper and removing sharp edges from the wing frame, the two are assembled with cyanoacrylate glue (CA). To prevent the glue joint from breaking, Kevlar thread is used to lash critical points. The motor and camera holes are then drilled and the vertical stabilizer is installed. Alignment of the stabilizer is critical, as on this scale even a misalignment of 1/16th of an inch can deteriorate flight performance. At this stage, the latex-wing skin is glued to the wing frame. First, a mist of spray adhesive is applied to the wing frame. Then the frame is pressed on a sheet of stretched latex. Finally, the latex is secured with a thin bead of low-viscosity CA along every rib. The final part of the assembly process involves installing the servos, motor, and control linkages. The servos are fixed to the fuselage with conventional servo tape and then lashed in place with Kevlar thread. The motor is glued in place with CA at a thrust angle of seven degrees from the mean chord line. The control horns are bent from brass rod, and the control rods are made from 1/64” piano wire. These control rods are supported by guide holes in the fuselage to prevent buckling.
Figure 6: Steps to fabricate a 6-inch MAV.

- a) Design
- b) Prepreg cutting
- c) Tool preparation
- d) Prepreg layup
- e) Fuselage
- f) Vacuum bagging
- g) Assembly
- h) Component installation
4 Wind-tunnel tests

Wind-tunnel tests were conducted in the Basic Aerodynamics Research Tunnel (BART) at NASA Langley Research Center [14,16]. The purpose of the test was to collect a variety of data to aid in the study of the dynamics and control properties of the UFMAV concept. The data consist of aerodynamic force and moment measured with an external 6-component strain-gauge balance, static wing-deformation data from a projection moiré interferometry (PMI) system [18], and flow visualization using smoke. Figure 7 depicts an early version of the flexible-wing MAV mounted in the wind tunnel.

Data was collected for a rigid wing and three different batten/membrane arrangements over a range of operating conditions determined by dynamic pressure, power setting, vehicle attitude, and control-surface deflection. The different batten arrangements are depicted in Fig. 8. More flexibility and larger membrane stretch characterize the one-batten design. The two-batten design is, by comparison, stiffer and exhibits less membrane stretch under aerodynamic load. Both wings were tested using a 4-mil latex membrane. The six-batten wing was covered with an inextensible monofilm membrane that further increased the stiffness of the wing and exhibited less membrane deformation and vibration. The rigid wing was constructed of a two-batten frame covered with a graphite sheet.

The static aerodynamic data were collected using a 6-component strain gauge balance and resolved into lift, drag, side force, pitching moment, rolling moment, and yawing moment. PMI was used to collect mean static deformation over a large fraction of the wing surface and the variance of the motions about the mean shape. Flow visualization was collected using digital video. Two methods were used: smoke flow and helium bubbles. The flow-visualization data provide insight into the underlying flow phenomena, and can be correlated with the aerodynamic and structural data.
4.1 Aerodynamic performance

Aerodynamic performance characterized by L/D is summarized in Fig. 9. These results represent L/D of the UFMAV with the propeller restrained from rotation (i.e., pinned) for several wings with varying levels of stiffness. The maximum L/D of approximately 3.0 is relatively independent of wing configuration. However, maximum L/D occurs at incidences of approximately 7.5 degrees for the rigid wing and roughly 10 degrees for the other wing configurations.

Figure 8: Three versions of the flexible wing were tested against a nominally rigid version. The rigidity of the wing increases from a) through c).

Figure 9: Lift divided by drag versus angle of attack for the four wings. The flexible wings show increased aerodynamic efficiency at high angles of attack.

Figure 10 depicts the lift curves for the various wing configurations. For small angles of attack, all the wings demonstrate similar lift characteristics with the stiffer wings having
slightly higher lift coefficient. However, it is clear that the membrane wings stall at much higher angles of attack than the rigid wing. In fact, the most flexible wing configuration has double the stall angle of the rigid-wing configuration (35 degrees and 15 degrees, respectively). This could be a key factor in enhancing the range of operation and agility of micro aerial vehicles.

![Graph showing coefficient of lift versus angle of attack](image)

*Figure 10: Coefficient of lift versus angle of attack shows that the rigid wing stalls at around 13 degrees, whereas the flexible wings stall at much higher angles of attack.*

While these results are similar to the results for other low aspect ratio, low Reynolds number wings, there are important differences. At low angles of attack, the aeroelastic wings behave like rigid wings with similar aspect ratio. The lift curve slope for the UFMAV is approximately 2.9. The lift curve slopes of similar rigid wings at comparable Reynolds number and aspect ratio (Re=70,000, AR=2) are approximately 2.9 as well. However, these wings have stall angles between 12 and 15 degrees. The stall angles of the aeroelastic wings are between 30 and 45 degrees (i.e., stall angle of the vehicle plus the wing incidence angle) and are similar to that of much lower aspect ratio rigid wings (AR=0.5 to 1.0). However, the very low aspect wings exhibit lower lift curve slopes of 1.3 to 1.7. The aeroelastic wings appear to exhibit the stall behavior similar to rigid aspect ratio 0.5 to 1.0 wings and the lift-generating capability of rigid aspect ratio 2.0 wings.

### 4.2 Structural deformation of aeroelastic wing

It was shown previously that the flexible wing is able to operate over a wider range of angles of attack without stalling. Understanding how this is accomplished requires determining how the wing responds to changes in the flow conditions. PMI was used because it is noncontacting and requires no surface preparation. This is especially important for the small highly flexible wing of the UFMAV where it is difficult, if not impossible, to use typical sensors (e.g. accelerometers, strain gauges) without altering the dynamics of the wing.

PMI uses optical methods and digital image processing to create contour maps of the surface of an object [18]. The maps represent mean quasi-static deformation of the surface. In addition, it is possible to determine the variance of the deformation about the quasi-static
shape. The measurement accuracy depends on the resolution of the digital image and the field of view. In this case, very fine details of the wing shape could be obtained. Analysis of the PMI data is ongoing but some preliminary results are presented here.

Figure 11: Wing deformation at three span-wise locations for various angles of attack.

Figure 11 shows the mean chordwise deformation of the wing at three spanwise locations, inboard, midspan and outboard. The results shown are for the two-batten latex configuration.
The wing leading edge is near a chordwise location of 4 inches. The chordwise deformation is presented relative to the wing at \( q=0 \) psf, i.e., wind-off zero (WOZ). The deformation data is determined at \( q=1.6 \) psf and trim power setting at four angles of attack: 0, 10, 20, and 30 degrees.

It is clear from these plots that the wing undergoes significant deformation. The maximum displacement of the membrane is approximately 0.25 inches at 30 degrees of vehicle incidence. The effect is to gradually reduce the camber of the wing as angle of attack increases. The degree to which the camber is reduced increases with span. Thus, though the vehicle may be at 30 degrees incidence, the wing sees a much smaller local angle of attack.

4.3 Flow visualization

Smoke and helium bubbles were used to perform simple flow visualization of the UFMAV for different wing configurations and flight conditions. Figure 12 shows a sample of the smoke-flow video. Several qualitative aspects of the aerodynamics of the vehicle were identified.

The wing-tip vortices appeared to be much weaker for the more flexible one-batten and two-batten latex membrane wings than for the more rigid wings. The latex membrane wings also exhibit a billowing of the membrane between the battens, especially at high angles of attack. It was also observed that the flow over the horizontal tail and elevons was very consistent across the entire range of angle of attack. The flow did not appear to separate from the upper surface of the tail, even at angles of attack near stall. This observation is consistent with the relatively linear behavior of the control effectiveness and insensitivity to changes in angle of attack.

4.4 Summary of wind-tunnel tests

The results indicate that the elastic membrane wing allows the vehicle to achieve higher angles of attack without stalling. This fact coincides with significant static deformation of the wing under load, particularly at higher angles of attack. It appears that the deformation allows the wing to see a smaller effective angle of attack at high vehicle attitudes. The deformation
also appears to contribute to weaker wing-tip vortices. It is likely that there is some link between the vortex strength and structure, membrane billowing, and the stall resistance of the latex membrane wings. In addition, the static deformation is accompanied by extensive membrane vibration.

![Figure 13](image_url)

Figure 13: Frequency of pilot input illustrates that high-frequency input, associated with unstable aircraft, is minimized by the flexible wing.
5 Flight tests

The research effort to develop the flexible-wing-based micro air vehicle relied extensively on flight tests to determine the relative merits of various wing designs. For the most part our early conclusions were dominated by direct pilot feedback, which typically included qualitative language. Remarkably rich data on flight quality can be derived from such tests and thus this is an irreplaceable component in the design process. This method is very effective for getting planes to fly and trimming them out, however, it is not very scientific and lacks quantitative measure. Our challenge was to develop a quantitative method to assess flight quality. A method was developed to record pilot input on the two control axes, namely roll and pitch. From experience, we noted that when experienced pilots fly RC planes over a set course, the frequency of feedback is higher for poorly behaved aircraft. The converse is true for well-behaved or easy to fly aircraft. For unstable aircraft, high-frequency corrections to the flight path are required to maintain the course, making the pilot quite busy. By recording the input and plotting the results in the frequency domain, we could characterize how well an aircraft flew. High-frequency input was direct evidence of poor flight quality.

On a common fuselage, we tested four configurations to verify this method of assessing flight quality. A flexible wing was tested against a nominally rigid wing fabricated from a continuous sheet of carbon fiber with an undercambered configuration of the same shape as the flexible wing. The flexible wing was tested in three conditions; a forward center of gravity (CG) on a calm day, a forward CG on a windy day, and an aft CG on a calm day. Typically an aircraft with a forward CG will be stable and one with an aft CG will be erratic. The baseline, rigid wing was set to maximize its stability by setting the CG forward.

Figure 13 shows the spectral decomposition of the pilot input. It can be seen that the high-frequency pilot input was far less for the forward CG flexible wing on the calm and windy day than that for the other two configurations. This was the case for both the roll and pitch commands. This method confirms in a quantitative sense the qualities that our test pilots have been reporting about the flexible-wing concept. The flexible wing is easier to fly and more forgiving in windy conditions than nominally rigid versions.

6 Computational modeling

For a rigid wing, the pressure distribution is determined by the wing shape and free-stream flow properties. For a flexible wing, its shape changes under aerodynamic load, and consequently, the angle of attack and surface-pressure distribution will change along with the flight environment. In order to shed light on the aerodynamic characteristics of the flexible membrane wing, one needs to solve coupled fluid-solid dynamics to track both the shape change and the pressure distribution on the wing shape.

Even though the importance of the viscous effect on membrane-wing aerodynamics has been recognized for quite some time [19], little has been published that address the issue. To date, most of the work in membrane-wing aerodynamics is based on simplified fluid and structure models [20]. The first use of Navier–Stokes equations as the flow dynamics model in a membrane-wing theory appears to be the work of Smith and Shyy [21]. In their work a computational procedure is presented that models the interaction of a two-dimensional flexible membrane wing and laminar, high Reynolds number steady fluid flow. Results from the viscous-flow-based membrane-wing model were compared with a potential-flow-based membrane-wing theory. Unsteady laminar flow surrounding the membrane wing has been reported by Shyy and Smith [22], and a corresponding turbulent flow computation by Smith and Shyy [23]. Recently, Jackson reported an analysis to address the aerodynamics of high
aspect ratio membrane wings of conical shape using the lifting-line and thin-airfoil theories. Aerodynamics and optimization of low Reynolds number flexible wing are reported in [9, 24–26]. In the following, we use the CFD simulations to highlight the aerodynamics of a representative wing.

The Navier–Stokes equations for incompressible fluids, written in three-dimensional curvilinear coordinates [27], are solved using a multi-grid-block, pressure-based, moving grid technique [11, 26]. To facilitate the solution of such moving boundary problems, we have implemented an automated regridding procedure to ensure that the grid system not only matches the geometric changes but also is smooth and not excessively skewed.

Obviously, the goal is not only to compute and analyze the dynamics of the coupled fluid and structure systems, but also to use the knowledge gained to improve the design capability. Accordingly, shape optimization has also been conducted based on the CFD solutions. To facilitate such an optimization task, we adopt a gradient-based search technique [28]. From the initial condition and the gradient information obtained in the course of computation, the shape is progressively modified toward the estimated optimal target. Such procedures require the generation of a series of new grid systems based on the new geometries. The present moving-grid technique can perform this task effectively because the remeshing process can be handled with exactly the same procedure as the moving-boundary problem, and with the same automation. The 3-D flexible wing aerodynamics and shape optimization efforts are ongoing.

From the analysis on the wing only, it was found that substantial three-dimensional pressure distributions on both sides of the wing are present. The distribution largely follows the geometric definition of the wing. It is well known [29, 30] that the rates of change of the lift and drag coefficients with angle of attack are strongly affected by the aspect ratio of the wing. Specifically, existing evidence, all based on high Reynolds number testing, indicates that the wings of various aspect ratios have about the same angle of attack at zero lift, but the slope of the lift curve increases progressively with increase of aspect ratio.

Streamlines at an angle of attack of 6° are shown in Fig. 14. Detailed flow structures including trailing vortex lines are clearly visible. The aerodynamic assessment has demonstrated that at the designated Reynolds number range, the lift is sufficient to support the current design. With the flexible-wing technology, the lift can be maintained with reduced influence from the unsteady flight environment.

Figure 14: Streamline representation obtained from computational fluid dynamics model.
7 Reconfigurable and morphing wings

Flexibility can be used for purposes other than flight-quality improvement. These include shape manipulation and reconfiguration for both improved maneuvering and storage. Traditional control surfaces such as rudders, elevators, and ailerons have been used almost exclusively for flight control. This method has proven to be effective, albeit limiting, for very aggressive maneuvers, and for flight regimes where agility is required. By morphing or reshaping the wing using distributed actuation such as piezoelectric and shape-memory material, preferred wing shapes can be developed for specific flight regimes. Such reconfiguration, however, would required an inordinate amount of authority and thus energy if the wings were nominally rigid. The flexible nature of the wing allows for such distributed actuation with orders of magnitude less authority. For example, the individual battens on the wing can be made from shape-memory alloys or piezoelectric materials. Or traditional actuators such as servos can be used to pull, via thread, on various portions of the wing to affect the shape. This idea is as old as powered flight itself, with the first use of wing warping credited to the Wright Brothers. They used wing warping for directional control on their very first flights.

At the University of Florida we have just begun to investigate using wing warping for control. Our initial work utilizes conventional servos and a string that “pulls” on various parts of the wing to affect the shape. Figure 15 shows one of our models with a thread connecting...
the wing tips to a servo in the fuselage of the airplane. As the thread is tightened on one side of the aircraft, the angle of attack of the wing increases, thus acting in a similar manner as an aileron. The roll rate developed by the actuation was considerably higher than that from the rudder. Additionally, it produced nearly pure roll with little yaw interaction.

An additional benefit of the flexible wing is the ability for it to be reconfigured for storage purposes. Figure 16 illustrates an 11-inch wingspan foldable wing MAV that can be stored in a 3”-diameter canister. In some military applications where a MAV is deployed from fast-moving larger manned or unmanned aircraft, the MAV must be packed into a small container. The container is deployed from the aircraft and parachutes towards the ground. It then opens and the MAV is released to perform the desired surveillance mission. This technology allows the MAV to be deployed for remote sensing and surveillance missions.
Figure 16: A foldable wing was developed in order to enhance MAV portability.

The wing utilizes a singly curved shell structural element on the leading edge. This allows for the wing to readily collapse downwards for storage yet maintain rigidity in the upwards direction to react the aerodynamic loads. The effect is similar to that of a common tape measure, where the curvature in the metallic tape is used to retain the shape after it has unspooled from the casing, yet it can be rolled back into the casing to accommodate the small-diameter spool. The curvature insures that the positive (straight) shape is developed after it is unwound from the case and can actually be cantilevered for some distance. The curvature of the leading edge of the wing acts as the curvature in the tape measure.

8 Summary

The flexible-wing concept developed at the University of Florida may be one of the enabling technologies that will lead to the mass deployment of flying machines known as micro air vehicles. Borrowing from nature, flexibility provides for smoother flight than conventional wings, especially in turbulent wind conditions. They also have the potential to achieve more aggressive maneuvers as a result of the delayed stall angle. A combination of flight tests, wind tunnel experiments and computational models has been used to document the physics behind the beneficial characteristics of the flexible wing. Further research into morphing technology, as well as increasing the sophistication of the computational model, is underway. This will lead to more advanced vehicles in the future.

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