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Use of XFOIL in Design of Camber-Controlled Morphing UAVs

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ABSTRACT: The standard curriculum for Aerospace Engineering students at the University of Cincinnati includes AEEM361 Integrated Aircraft Engineering. The goal of this course is to instruct students in the tools and methodology of aircraft design. The integrated aspects of aircraft design are underscored by introducing pre-junior (between sophomore and junior) students to the state-of-the-art morphing technology, inspired by bat and bird flight, which can enable an aircraft to adapt its shape to best suit the flight condition thereby enhancing mission performance. In this article, we present the development of unique software tools, which provide undergraduates an opportunity to design airfoils for morphing aircraft. Morphing is introduced in the form of "on demand" camber as well as sweep change with the aim of improving aerodynamic efficiency for a multi-objective (several design points) mission profile. The Global Hawk UAV mission in general and its LRN1015 airfoil in particular is in focus due to the relative long mission times spent at the two different flight conditions, namely high-speed dash and low-speed loiter. We are using several tools to virtually simulate a morphing wing including XFOIL to perform fast and relatively accurate two-dimensional steady-flow simulations of different morphed configurations using a camber-controlled morphed wing to maneuver. In this article we detail AeroMorph, the educational MATLAB-based tool developed for design of a camber-controlled morphing of airfoils with the aim of improving aerodynamic efficiency and exploration of the basic relationships between flap deflection and airfoil morphing based on a camber change. DOI 10.1002/cae.20437

Keywords: camber-morphing; XFOIL; UAVs

INTRODUCTION

Since the early 1990s, the Department of Aerospace Engineering (AsE/EM) and Engineering Mechanics at the University of Cincinnati (UC) has pursued an effort to redesign its undergraduate Aerospace Engineering Curriculum with an emphasis on teaching increased design principles and multi-disciplinary content. As a result of this effort, the Integrated Engineering/Integrated Aircraft Engineering/Integrated Spacecraft Engineering sequence (9 credit hours in all) was developed and over the past 10 years this approach has been implemented successfully. During the last two academic years, one of the co-authors of this article, Dr. Cohen, serving as instructor for the Integrated Aircraft Engineering class, introduced a project involving a morphing UAV program inspired by the bat. The main idea was to design an original airfoil which alters its geometry at different flight conditions. Furthermore, an assessment was made as to the impact of this technology on the overall mission performance and cost of the UAV. The main observations which emerged from this effort are as follows:

- Students get very excited when challenged with a state-of-the-art research problem. "*This is a new concept, which I totally had fun working on. I think including such new real world concepts in a class project was awesome*"; "*It was very interesting. Had the opportunity to put in our thoughts on airfoil design to see whether it works or not. Got to play with new software, XFOIL. Should have more on* ***Morphing Airfoil Design****. I learned a lot and it is very exciting.*"
- Students want to acquire tools which they perceive as being relevant for engineers ."*This is a good idea. It is a project/problem that could be used in the work force.*"
- Students want to **create that which never was**. "*First, I was very interested in the project itself. I was also pleased with how it was split into 3 milestones. But instead of just blending two airfoils together, I wanted to create my own morphing airfoil with whatever angle sweep producing the most L/D.*"
- Students in their pre-junior (between sophmore and junior) year have a better feel for their major. "*I feel that I have a better*

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understanding of conceptual design. Somewhat more motivated to continue on with my major."

(Note: citations in Italics are based on written feedback provided by the students taking the Spring 2008 Integrated Aircraft Engineering class at UC.)

During the past two decades, there has been a growing need for aircraft to perform effectively while flying in aerodynamically different operating regimes within the flight envelope during a single mission. Wing morphing/shape shifting technologies can empower aircraft (manned and unmanned) to adapt its aerodynamic configuration "on demand," thereby expanding their role and capabilities in the tactical arena. In recent years there has been an increasing number of academic, government, and industrial interest in morphing technology [1–7]. A fine example of effective morphing in a flying creature is the bat. Bats have very efficient wings, and they have a unique ability to morph wing camber. Morphing (changing camber and aspect ratio) makes bats far more maneuverable than birds especially at very low speeds. Bats' wings consist of long, thin, lightweight bones, held together by a skin membrane, which enables the rapid change in wing camber. Using the bat as the biological inspiration behind the proposed research program, we develop an approach for morphed camber control which enables maneuvering without the conventional control surfaces.

Over the past 100 years of flying, we have been using the same basic idea of "steady aerodynamics" when it comes to providing lift and maneuverability. The essential component is a fixed airfoil shape, which is tapered rounded on the leading edge and thin at the trailing edge. Moreover, the fundamental flight stabilization concept based on control surfaces and stabilizers is unchanged over time although it is relatively inefficient in its lift to drag ratio, and ill-designed in its maneuverability (multi-mission flight). The question often asked is whether aeronautical engineers can learn from nature to improve flight efficiency by replacing traditional control surfaces with mission adaptive wings in a manner similar to birds. A true morphing aircraft structure should go far beyond moving one solid wing element to a different angle or location with respect to other wing components on a fixed-wing aircraft [8]. The type of geometric adjustments that DARPA proposed include a 200% change in aspect ratio, 50% change in wing area, 50% change in wing twist, and a 20° change in wing sweep [9]. Wing weight should be no greater than a comparable structure using conventional flight-control technologies. Such criteria are difficult to meet and requires adaptive or an active-aero-elastic structure, lightweight structural components, smart materials, and advanced control systems [10]. Smart materials enable creating shape-changing and multi-mission aircrafts. Different types of materials are available: shape memory alloys, electro-active polymers, piezoelectric materials that can be altered and then, through thermo-electric, electro-mechanical inputs, returned to their original form [11,12]. In a morphing system, sensor feedback is processed using a model of the dynamic system and an appropriate set of actuator commands determines the optimum morphing required by altering the geometry of the wing structure.

This effort is part of the Morphing Wing Program at the University of Cincinnati. In this program, we develop experimental and computational tools to aid in the development of aerodynamic, structural, and control technologies that allow air vehicles to maintain a safe and effective transition during in-flight morphing maneuvers in dynamic environments. The main objective of the program is to develop a computational tool that predicts the dynamic response to various control inputs, including large strain shape memory alloy actuation as well as high frequency piezo-ceramic actuators, for a morphing wing of a high-performance aircraft. The ultimate goal is to design an effective closed-loop structural–control methodology to maintain/augment maneuvers using morphing of the airfoil camber. The uniqueness of this program lies in the coupling of various morphing modes such as airfoil shape, sweep, and folding within a unified structural–control model. Upon completion of this project, it is expected to test a laboratory-based proof-of-concept wing model that morphs from one aerodynamic configuration to another and to examine the applicability and effectiveness of the developed control approach. A wing that experiences airfoil morphing is being designed and built. The detailed analysis of an auxiliary structure to implement the morphing is also being done with a finite element model (FEM) that includes large deformations. A more elaborate model that includes detailed computational structures (FEM) and fluids (CFD) will be created to capture the complexities associated with multi-disciplinary fluid-structure-control interaction. Given the multi-disciplinary nature of the project and the research team, progress in the specific discipline will be augmented with a structured approach to developing a unified model. We decided to work with the NASA developed LRN 1015 airfoil, shown in Figure 2, as a baseline which is the Global Hawk Hale UAV airfoil. The reference mission will be the Global Hawk mission. At first, XFOIL, developed by Mark Drela at MIT, is used to develop a mapping of flap deflections for the usable envelope for alpha and flap/aileron deflections. The next step will be to develop a two-dimensional rib having 4–6 rigid segments on the upper surface. Each of these segments will have a pitch and plunge capability using linear COTS piezo-ceramic actuators. The segments are covered with a tight flexible skin. The above-developed mapping system (flap defections to airfoil geometry) will then translate into segment deformations. A dynamic model of the structure-control interaction will be developed and experimentally validated using a laboratory model will COTS actuators/sensor. Important to note that if the segment is too light weight we will have structural dynamic issues. On the other hand, if it is too heavy (high inertia) then you need large actuators. A trade-off is required to optimize the control contribution. Then, a low-order model-based estimator and controller will be developed. Sensitivities to sensor noise and actuator time delays will also be considered to assess robustness.

The main objective of this article is to investigate the properties of a morphing airfoil in a flight environment. This airfoil will be morphed to mimic characteristics of static airfoils with different flap configurations using software to simulate real conditions. The goal of this project is to reach a correlation between flaps and morphing that allows a given flap setting during a maneuver to be replaced by a change in the shape of the airfoil. This will be an active system that responds in real-time to commands given by the pilot. The reasoning for this project is twofold. The first is aircraft performance. An aircraft with a morphing wing could continually operate at optimal efficiency while performing each part of its mission. The second reason is stealth. Eliminating the flaps on an aircraft could significantly reduce its radar signature.

BACKGROUND

The airfoil that will be used for the main development of this project is the LRN 1015, the airfoil used on the Global Hawk

UAV. This particular airfoil was chosen because its current mission involves varied operating conditions which could benefit most from an airfoil capable of morphing mid-flight. The first two digits give the design lift coefficient in hundredths and the last two digits describe the approximate maximum thickness ratio in hundredths. It was developed by NASA for low Reynolds numbers. The NACA four-series 0009 and 2412 will be used for data verification, as they have been much more thoroughly tested since their development. The LRN 1015 was tested by NASA in a 2 × 2-foot transonic, variable speed, ventilated wall, continuous flow wind tunnel at the NASA Ames Research Center. An 82-tube drag rake was placed 1.75 chords downstream, and the gaps between the airfoil and the wall were sealed to improve the two-dimensionality of the test [13]. The LRN 1015 was then tested for aerodynamic characteristics at various mach and Reynolds numbers. In the final step, the wind tunnel data were compared to data received from three software packages: ISES, LBAUER, and ARC2D.

XFOIL

XFOIL is a program originally written by Mark Drela at MIT in 1986. It combines high-order panel methods and the fully coupled inviscid/viscous interaction method first used in ISES. XFOIL uses a text x- and y-coordinate file to model two-dimensional airfoils. The user may input an airfoil from a file or select a NACA four- or five-series airfoil and XFOIL will build the appropriate coordinate file. The user may then make changes to inviscid/viscous properties such as Mach number and Reynolds number (*Re*). XFOIL will then use the user data to simulate flight at many angles of attack and return lift coefficient (C_l), drag coefficient (C_d), and moment coefficient (C_m) in the form of a saved polar file and generate C_l versus α and C_l versus C_d plots.

XFOIL was chosen for this project because it gives results much more quickly than more advanced CFD programs and still provides results accurate enough to be a good design tool, and because it allows the user to simulate the effects of adding plain flaps to an airfoil. When XFOIL is combined with AeroMorph, it allows us to simulate all the configurations required to build a mathematical relationship between flap deflection and camber change. The limitations of XFOIL are that it works for two dimensions only, and it is only effective at low Reynolds numbers and incompressible flows.

DATA VERIFICATION

In order to ensure that the results we are obtaining from XFOIL are accurate when compared to industry accepted data, we have acquired wind tunnel data from NASA on two NACA airfoils, the 0009 and 2412. The first step we took was to confirm that XFOIL generates accurate data for the NACA 2412 airfoil. We chose the NACA 2412 because it is an airfoil in common usage with readily available wind tunnel data. We compared reference data [13] regarding pressure coefficient (C_p) as a function of the chord (c), C_l versus α, C_l versus C_d, and C_l versus C_m to data generated by XFOIL. For this comparison the Mach number was set at 0.2 and the Reynolds number was set at 500,000 to match the data recorded by NASA in Ref. [13].

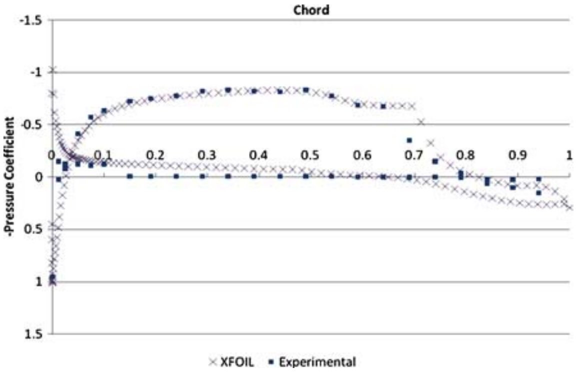


Figure 1 Pressure coefficient versus chord. NACA 2412, Mach number 0.2, Reynolds number 500,000.

Figure 1 shows that while XFOIL generates relatively accurate results, it has trouble accurately predicting the pressure coefficient around locations where separation bubbles form. This is most visible in the large spikes at the leading edge and $>0.7c$. The small discrepancies on the C_p versus c plot may be a contributor to the fact that the C_l versus C_m data acquired from XFOIL is skewed from the wind tunnel data. It is possible that the way XFOIL calculates the pressure at the leading edge and other areas of flow separation are the cause of the discrepancy.

As we are primarily using C_l versus α (see Fig. 2) and C_l versus C_d (see Fig. 3) data to develop a relationship between flap deflection and camber change, it was vital to show that XFOIL generates good results for those plots. For this the NACA 2412 results generated by XFOIL were compared to three different sets of data from Ref. [13]. In their report, NASA compared wind tunnel data and data generated by two computer simulations, ISES and LBAUER. To this we added the XFOIL data. We used XFOIL to calculate the lift coefficient at an interval of 1° over the interval [−3, 6]. This is a similar interval to the ISES and LBAUER data. XFOIL does a good job predicting C_l over the linear part of the C_l versus α plot. This is important as we will be trying to match C_l versus α data between a certain flap deflection and a camber change due to morphing. XFOIL follows the wind tunnel data well, better than ISES at positive angles of attack. The C_l versus C_d plot shows similar results. The drag predictions from XFOIL show good correlation with both the wind tunnel data and ISES and LBAUER. This shows that XFOIL is predicting both lift and drag coefficients within an acceptable range or accuracy.

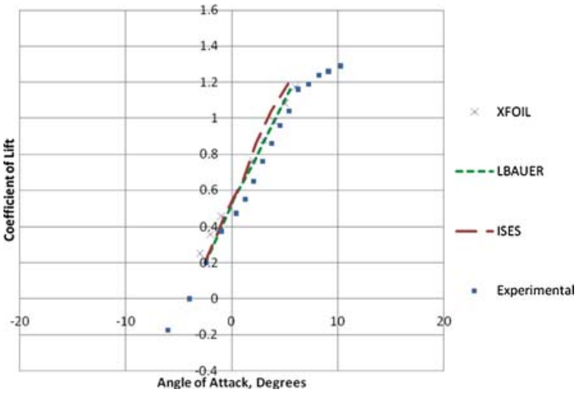


Figure 2 Lift coefficient comparison. NACA 2412, Mach number 0.2, Reynolds number 500,000. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

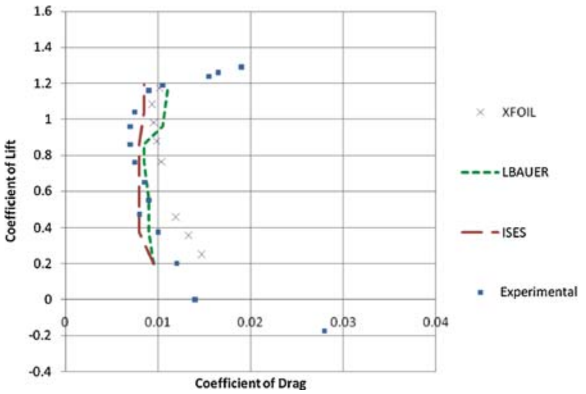


Figure 3 Drag coefficient comparison. NACA 2412, Mach number 0.2, Reynolds number 500,000. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

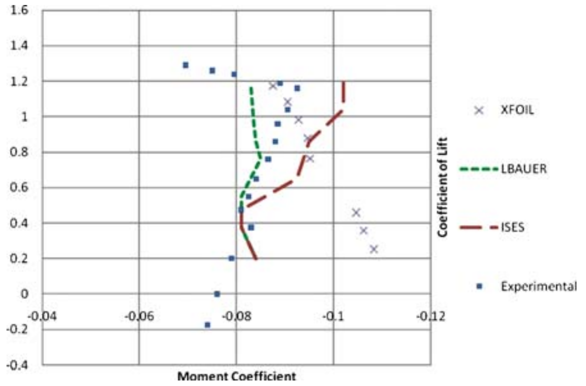


Figure 4 Moment coefficient comparison. NACA 2412, Mach number 0.2, Reynolds number 500,000. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The next comparison is C_l versus C_m (see Fig. 4). The predictions XFOIL makes for moment are not as good as for previous comparisons. At higher lift coefficients, XFOIL matches the wind tunnel data, but at lower lift coefficients XFOIL diverges. This is possibly caused by the calculation method used by XFOIL which generates large pressure spikes at the leading edge at small lift coefficients. In Figure 1, the data generated by XFOIL show an abnormal lower surface pressure spike that is several times larger than the corresponding spike in the wind tunnel data.

The NACA report WR L-663 [14] is a wartime report covering wind tunnel testing of many airfoil/flap conditions. It contains wind tunnel data on the NACA 0009 airfoil with a $0.3c$ sealed-gap plain flap. We chose this report and airfoil flap configuration because it allows us to verify that XFOIL provides accurate simulation of flap addition on airfoils. This particular airfoil flap configuration was chosen for several reasons. One reason is that the NACA 0009, as a NACA airfoil, is widely known and tested. Another reason is that XFOIL can only model plain flaps with a sealed gap. This limitation is not an issue because basic flap simulation is all that is required for this initial investigation into matching flaps and camber changes. The wind tunnel data for the NACA 0009 airfoil with a $0.3c$ plain flap with a sealed gap was chosen as this best matches the capability of XFOIL. In order to provide the most accurate results, XFOIL was calibrated to match the NASA report, operating at a Mach number of 0.1, and a Reynolds number of 2.7×10^6 [14,15]. This was done to ensure that no environmental variables skewed the data generated by XFOIL. To ensure the accuracy the data received from XFOIL, flap deflection angles of 0°, 5°, 10°, 15°, and 20° were compared in Figure 5.

MANEUVER COMPARISON OF FLAP VERSUS CAMBER-CONTROLLED

An important goal of this project is to find the mathematical link between flap deflection and camber change. The first step toward this goal is to determine if there is a link to be found. In order to

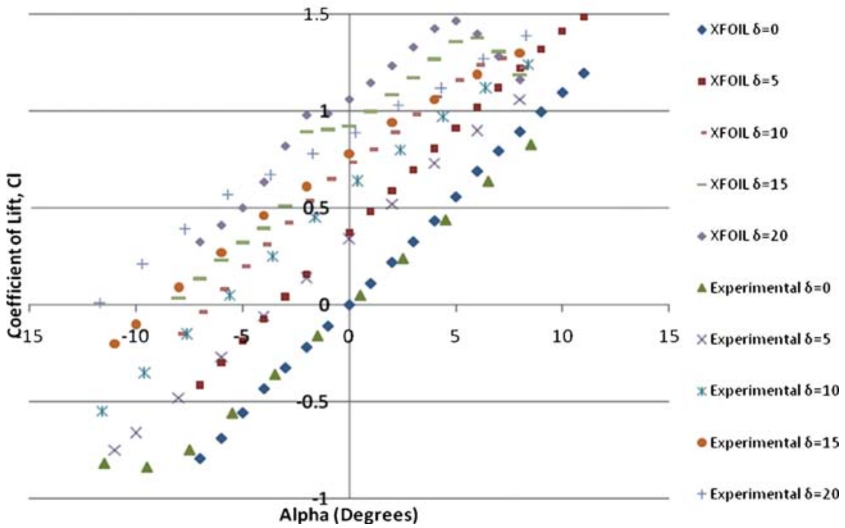


Figure 5 NACA 0009 flap comparison. NACA 0009, Mach number 0.1, Reynolds number 2,700,000. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

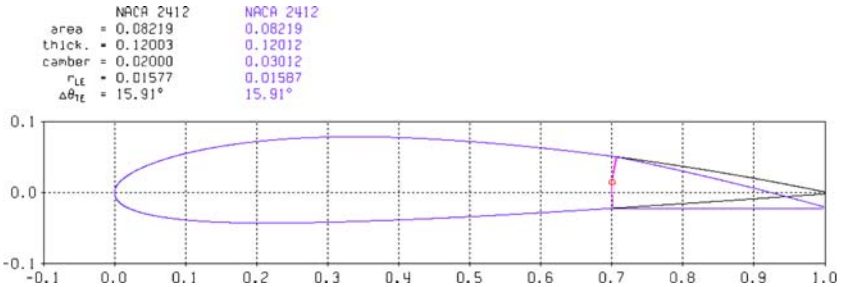


Figure 6 NACA 2412 with 4° flap deflection. The NACA 2412 airfoil with a 30% chord plain flap hinged at 50% relative height vertically, deflection angle (δ) 4°. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

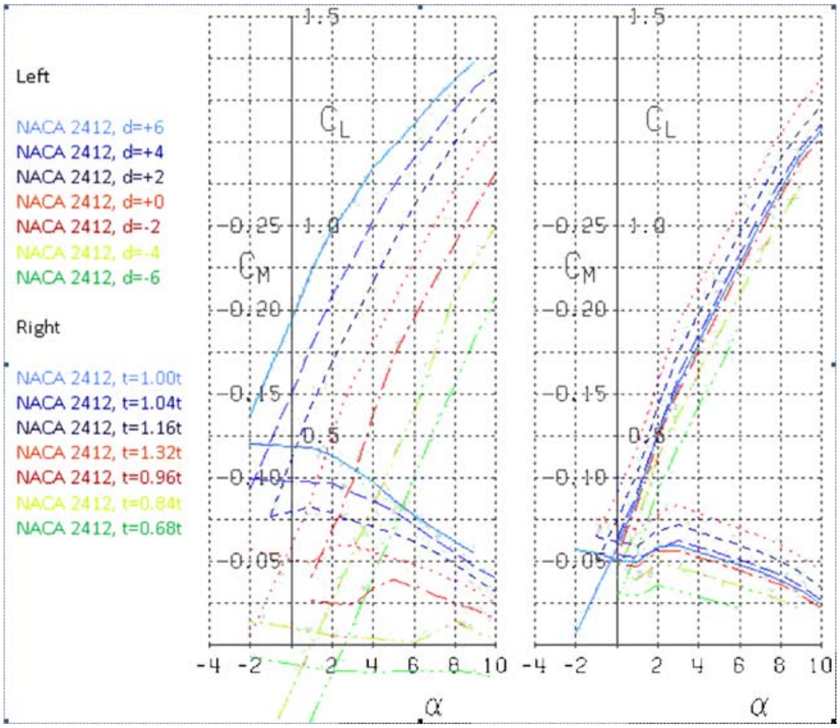


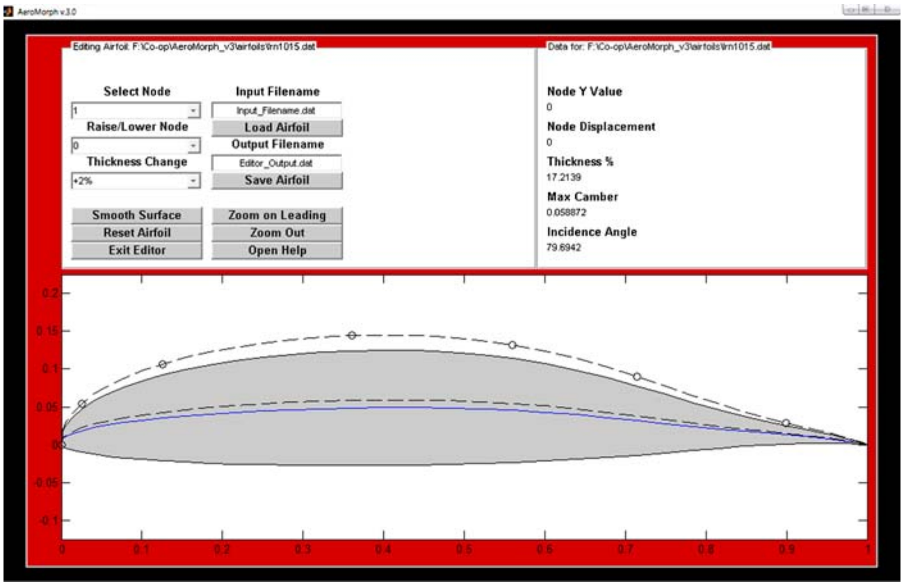
Figure 7 XFOIL flap-camber change comparison. C_l versus α for the deflection angle (δ) interval [6, 4, 2, 0, −2, −4, −6] (left), and C_l versus α for small camber changes (right). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

do this we used the NACA 2412 airfoil, shown in Figure 6, to plot several different flap configurations and camber changes.

The NACA 2412 airfoil was modified using XFOIL [16] to include a trailing edge flap. XFOIL only has the capability to model plain flaps with a sealed gap. The Global Hawk, and therefore the LRN1015, has more advanced flaps, but plain flaps are sufficient for this initial investigation. The flap was hinged at 70% chord, 50% relative height, and deflected over the interval [6°, 4°, 2°, 0°, −2°, −4°, −6°] as illustrated in Figure 7. The positive deflection direction in XFOIL is down, so a deflection of 4° in XFOIL is $\delta = -4$. The camber of the NACA 2412 airfoil was changed using AeroMorph, an indigenous Matlab [17]-based airfoil editor detailed in the next section. Since AeroMorph only changes the thickness of the upper surface, it effectively changes the mean camber line, and therefore the max camber.

AEROMORPH

As this project is investigating morphing airfoils, we needed to find a way to easily and quickly morph any airfoil. We chose to develop our own application to do this. We also wanted to be able to use the software as a learning tool. The software was presented to the students for use in developing new airfoils for their final project. AeroMorph (see Fig. 8) is an application by the author written in Matlab that allows the user to make fast changes to airfoil coordinate files and then use those files in XFOIL or any other two-dimensional simulation program that requires *x*–*y* coordinate files. AeroMorph allows manipulation of the upper surface of the current airfoil either by a leading-edge to trailing-edge thickness change or by individual node changes. The graphical interface, as shown in Figure 8, allows changes to be made with drop-down menus and


AeroMorph v.3.0

Editing Airfoil: F:\Co-op\AeroMorph_v3\airfoils\lrn1015.dat

Select Node: 1

Raise/Lower Node: 0

Thickness Change: +2%

Input Filename: Input_Filename.dat

Output Filename: Editor_Output.dat

Data for: F:\Co-op\AeroMorph_v3\airfoils\lrn1015.dat

Node Y Value: 0

Node Displacement: 0

Thickness %: 17.2139

Max Camber: 0.058872

Incidence Angle: 79.6942

Figure 8 AeroMorph user interface. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

instant visual confirmation of any changes made. There are three main parts to AeroMorph: The editor box, the data box, and the plot box.

The editor box contains everything needed to make changes to the current airfoil. The Thickness Change dropdown menu will perform a leading- to trailing-edge displacement change based on a percentage of the chord length. For example, if a 5% thickness increase were accomplished on the LRN1015 airfoil, which has a thickness of 15% of the chord, the new airfoil would have a thickness of 20% of the chord. In order to make changes to an individual node, the node must first be selected in the Select Node dropdown. The nodes are shown as black circles in Figure 8. Choosing a node will also refresh the Data box to show information on the selected node. Note that the leading-edge and trailing-edge nodes (1 and 8) are not moveable. Once a node has been selected, its vertical displacement can be modified using the Raise/Lower Node dropdown. Nodes can be moved up or down. In order to maintain a smooth surface the panels between the nodes are able to rotate. When a node is raised or lowered, the panels to the right and left of the selected node rotate about the adjacent nodes. The Smooth Surface button uses the polyfit function in Matlab to generate an 18th order polynomial describing the upper surface of the current airfoil. It then uses that polynomial to remap the upper surface. This has the effect of smoothing the distortions caused by manipulating the airfoil, especially individual node changes. This should be used only as needed because it can cause distortion at the leading- and trailing-edges of the airfoil. The Smooth Surface button has very little effect on airfoils that contain more than 150 coordinates, such as those output by XFOIL. The Reset Airfoil button returns the current airfoil to its original configuration, deleting any unsaved changes.

The data box displays information about the current airfoil. The data will automatically refresh whenever the airfoil is changed. Under Thickness %, it displays the thickness of the current airfoil in percentage of the chord of the airfoil. This will change whenever a thickness change is performed using the Thickness Change dropdown. Under Max Camber it displays the value corresponding to the maximum displacement of the mean camber line from the chord of the airfoil. Under Node *Y* value it displays the overall displacement of the currently selected node from the chord line. Under Node Displacement it displays the relative displacement of the currently selected node from its original position.

The airfoil plot displays the current airfoil as well as the original airfoil. The original airfoil is displayed with a gray fill and a solid black border. The current airfoil is displayed with a dashed line. The individually moveable nodes on the airfoil are displayed as black rings along the upper surface of the airfoil.

RESULTS

An important milestone of this project is to find a mapping of a given flap-based maneuver to an equally or more effective morphing-based maneuver. In the case of two-dimensional analysis such as this, ailerons and elevators are treated as flaps and therefore noted as such. It is important that it can be shown both that morphing maneuvers are a viable alternative to flap maneuvers, such that one can achieve the same lift differential as using a conventional flap/aileron approach. Several different configurations were chosen to be compared side by side. The desired configurations were obtained using an iterative process, taking into account the normal operating configurations for the Global Hawk aircraft. The Global Hawk, as it loiters over its target, may make a series of wide figure-eights involving very small lift differentials in order to have the camera "hover" over a designated point. Therefore, small flap deflections were chosen for matching. The flaps chosen for this comparison are plain flaps hinged vertically centered, at 0.7 chord. The configurations chosen are flap deflections (δ) of 0, -1, -2, and -3, as well as morphed configurations of -2% thickness, and -4% thickness. It is shown in Figure 9 that a thickness change of -2% of the chord results in a similar lift coefficient profile to a -1° flap configuration. Similarly, a thickness change of -4% of the chord results in a similar lift coefficient profile to a -3° flap configuration.

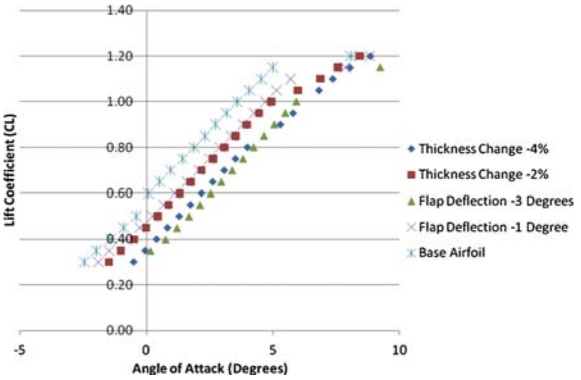


Figure 9 Lift coefficient versus angle of attack. LRN1015 with both flap and morphed configurations, Mach 0.2, Reynolds number 500,000. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

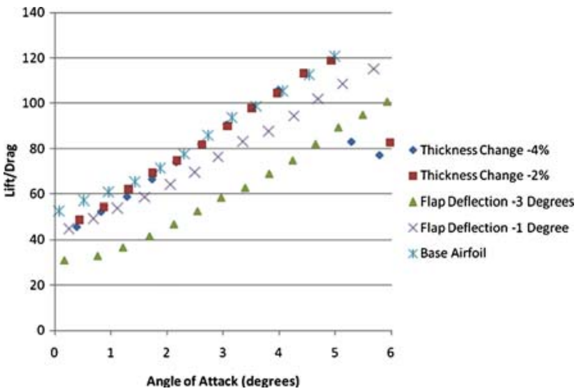


Figure 10 Lift/drag versus angle of attack. LRN1015 with both flap and morphed configurations, Mach 0.2, Reynolds number 500,000. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The next step of the project was to show that there is a potential benefit to using a morphed configuration over a flap-based configuration. This was found when the lift/drag efficiency was compared for different configurations. An important factor in the capability of the Global Hawk is its ability to loiter over a target for many hours. A factor that directly contributes to how long the aircraft can maintain its position is its efficiency. An increase in efficiency directly translates into more hours over the target and lower costs for operation, both in fuel and the number of aircraft required to cover a target for a specified period.

When comparing the efficiency of the flap-based configurations to that of the morphing configurations in Figure 10, a clear trend can be shown. Whereas the flap-based configurations showed as much as a 35% drop in efficiency compared to the baseline LRN1015 airfoil over small angles of attack, the morphed configurations showed almost no drop in efficiency. This is very important as it shows that the morphed configurations have a great potential to increase the efficiency of aircraft maneuvers. In the future, a more detailed investigation will be made into maximizing the efficiency of the airfoil in every flight condition, potentially leading to a double-digit increase in overall efficiency.

CONCLUSION

This article covers but the first step in our project to increase aircraft performance through the use of thickness-based camber-morphing technology. We have proven through our initial investigation that we have developed effective tools and that morphing can be a viable alternative to flap-based maneuvers. Initially, we compared the predictive capability of XFOIL to that of several other CFD programs, including ISES and LBAUER, and also to experimental results recorded by NASA for the NACA 2412 airfoil. The CFD programs were used by NASA in their report. After verifying its accuracy with unmodified airfoils, we used data from a NACA wartime report on the performance of the NACA 0009 airfoil with flaps to determine the capability of XFOIL to predict the changes in performance made by flap usage. We were again successful in showing XFOIL's capability. We then used the NACA 2412 airfoil to demonstrate that morphing can provide a similar lift differential to that created by a flap change in a maneuver. Finally, we demonstrated that an aircraft using the LRN1015 airfoil can achieve the lift differential required to perform a maneuver while maintaining higher efficiency than an aircraft using flaps to perform the same maneuver. In the future, we will map both flap and morphed configurations in an effort to develop an algebraic relationship between the two. We plan on having our results tested in a wind tunnel, to verify the accuracy our results. In parallel, we will also begin to examine the structural and control aspects of the morphing aircraft problem.

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