Flow Analyses of Adaptive Aircraft

Vijaya Lakshmi T, Santhiya S, Sharath S, Surya Prakash S, Uma Maheswari S, Dr. S. Dharmalingam

Assistant professor, UG Scholar, Department of Aeronautical Engineering, Hindusthan college of engineering and technology, Coimbatore- 641032, India.

Dean, Rathinam Technical Campus, Coimbatore.

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ABSTRACT
Morphing aircraft are multi role aircraft that change their external shape substantially to adapt to a change in mission environment during flight. This creates superior system capabilities not possible without morphing shape changes. The objective of morphing activities is to develop high performance aircraft with wings designed to change shape and performance substantially during flight to create multiple-regime, aerodynamically-efficient, shape-changing aircraft. Recent interest in morphing aircraft has motivated the study of variable planform aircraft for low-speed flight discusses the performance benefits of variable wing area and variable sweep configurations. Separate variable sweep and variable span wind tunnel models have been constructed and tested by others. This project is about the design and flow analysis of adaptive model aircraft. The unique feature of this work is about each wing can increase its span, sweep and control positive and negative twist which leads to 7 DOF experimental model. This project concentrates in predicting the change in both sweep and span of morphing wing aircraft is beneficiary regarding drag reduction.

KEYWORDS: NACA 0020, NACA 0017, UAV, Sweep angle, Planform area, Wing twist, C.G location shift.

INTRODUCTION
Airplanes come in lots of different shapes and sizes from big jets to fighter planes, their shape depends on the plane's mission. For an airplane to fly, you need to be able to lift everything on the airplane into the air. The wings help generate most of the lift to hold the plane in the air. An aircraft is a vehicle that is able to fly by gaining support from the air, or, in general, the atmosphere of a planet. It counters the force of gravity by using either static lift or by using the dynamic lift of an airfoil, or in a few cases the downward thrust from jet engines.

The energy-based economy is driving a new technology to the aircraft industry: morphing-wing technology or the ability of an aircraft to change the shape of its wings during flight, is being researched heavily by both the military/government and the private aircraft industry. The goal of the application of morphing technology is to develop an aircraft that can adapt or change its aerodynamic performance to fly dissimilar missions or dissimilar mission segments within a mission more efficiently than a fixed-wing aircraft. A prime platform for investigating morphing technology is the fighter aircraft. Currently designed fighter aircraft are being used for multiple roles, depending on the branch of the military or even country in which the aircraft is being used. The designer of a fixed-wing aircraft would find the dissimilar roles and requirements of the aircraft to be a design challenge, to say the least. Even more of a challenge would be to design an aircraft that can perform all the roles required in the most efficient manner, which has been proven to be impossible (e.g. a subsonic high-endurance reconnaissance aircraft cannot perform the role of a supersonic fighter aircraft more efficiently than the fighter aircraft, nor vice versa). Morphing technology allows a system designer to design an aircraft that can adapt to its flight conditions in order to meet the performance requirements in the most efficient manner. “Morphing wings”
is the new catch phrase in the aerospace research industry today. Morphing technology employed in aircraft wings has been proven, at least on a conceptual level, to allow aircraft to outperform their fixed-wing counterparts over the entire mission in fuel savings due to drag reduction and improved lift-to-drag ratios. "Morphing wings" can imply the ability of an aircraft to change its aerodynamic performance from a very simple morphing, such as flaps or slats, to a more extensive morphing such as variable wing length, sweep, and chord lengths. This concept has the ability fold its wings, effectively changing the flight characteristics (by varying the wetted area and aspect ratio) of the aircraft extensively to allow a mission that could include reconnaissance, loiter, and attack/low observability configurations in the same vehicle, encompassing the requirements of a hunter-killer mission.

The aerospace industry has shown a history of taking a current technology and expanding it to yield the next generation of aircraft. Often the new designs end up looking like the old designs albeit with new materials or more sophisticated electronics. The current aerospace customer needs a more affordable aircraft with expanded mission capabilities. Technologies are already being applied to wings to allow wing shape and, thus, aerodynamic performance to change depending on the requirements of the flight conditions. An early example of wing morphing, i.e. wing twisting, was used by the Wright brothers for roll control and is being "re-invented" by the active aero elastic wing (AAW) program. Currently, variable wing sweep or "swing wings" are employed on many fighter aircraft to allow better cruise endurance but without sacrificing high velocity flight performance. Low order shape control is being used on aircraft in the form of Fowler flaps and ailerons. These technologies have been hugely successful, enabling aircraft to reduce stall speeds, increase lift, etc. to perform mission segments more successfully than otherwise may have been possible. However, more extensive shape control or 'morphing aircraft structure' is desired to allow drastic wing planform area and aerodynamic performance changes during flight. In our project, the morphing technology is implemented for the considered unmanned Aerial Vehicle (UAV).

External vehicle design:

The external vehicle design provides a layout of wing, fuselage and various configurations of adaptable aircraft.

A. Wing design:

The wing airfoil sections are modified NACA 0020, and have a 7-inch chord. The modification shifts the maximum thickness closer to the center of the airfoil section to create space for internal actuators.

![Fig. 1: 2-D view of NACA 0020 Airfoil](image1)

![Fig. 2: CAD model of the NACA 0020 Airfoil](image2)
B. Fuselage design:

The fuselage design is an interpolation between two different airfoil sections. The mid-section of the fuselage is an extruded NACA 0017 with a chord length of 12 inches. On each end, the extruded section tapers down to a NACA 0020 with a 7 inch chord. This shape creates enough space for the wings to sweep in without contacting the fuselage. Designing the fuselage as an airfoil streamlines the design, increasing the overall vehicle lift while decreasing drag.

C. Various configurations of adaptive aircraft:

The adaptive aircraft considered in this project undergoes both sweep variation and planform area of the wing. The various configurations imparting this combination is shown in Fig.3.

![Fig. 3: Configurations of Adaptive Aircraft](image)

II. Internal vehicle design:

The internal vehicle design concept provides the actuator mechanism of adaptable aircraft and actuator torque requirements for various mission requirements.

A. Actuator specifications:

The model uses two rotational actuators and five linear actuators to control the wing shape. The sweep actuators are electromechanical while all other actuators are pneumatic. Pneumatic actuators were chosen for the wing and tail extensions because for large strokes, they are lighter than hydraulic or electromechanical actuators. To control wing twist, it was necessary to have a small actuator that generated enough torque to deform a semi-rigid wing section, while still being relatively light. A small rotary pneumatic actuator was chosen to drive the twist mechanism because it could produce the high torque required at a low overall weight. The sweep design requires that the actuator directly support the aerodynamic forces against the wing. A lead screw electromechanical actuator was chosen because it is nonback drivable under load. The different subsystems include the span extension, the twist mechanism, the sweep system, tail actuation, and the control circuit.

![Fig. 4: Internal vehicle design](image)
B. Actuator torque requirements:

Airplane servos, like the one to the left, reliably move to a desired angular position, given the appropriate input. The same servos are also intended to be used in RC cars, boats, and other models. Increasingly, these servos are being applied in non-traditional ways. This is largely due to several attractive features are high Torque, accurate positioning, easy mounting, easy control and economical. However, they do have their limitations. The best way to explore this is to get one and experiment with it.

![Actuator circuit](image)

Fig. 4: Actuator circuit

Fig.4 is a block diagram, illustrating the basic idea of the servo's function. The desired position is compared to the output position of the servo shaft. A compensator adjusts this signal, and sets the input to the motor. The motor is attached to a gear head, so that the output is high torque, although at low speed. A potentiometer is attached to the output shaft to provide the feedback signal.

III. Stability characteristics:

The wings comprise a large percentage of the vehicle gross weight due to the internal actuators. The center-of-gravity (c.g.) shift that occurs when the sweep and span are changed. Considering only symmetric sweep and span variations, the x coordinate of the c.g. is

$$X_{cg} = \frac{m_w(r_w + b) \sin \theta_w}{m_{f\text{-cyl}}r_{f\text{-cyl}}}$$

where $m_w$ and $r_w$ are the mass and c.g. location of the nonmoving components, $m_w$ is the wing mass, $a_{w}+b$ represents the c.g. shift of the wing due to the span cylinder extension $r_{w}$, and $\theta_{w}$ is the wing sweep angle.

A. Effect of variable planform on drag:

This section presents a brief discussion on the approximate effects of a variable planform on drag. The effect of variable sweep and variable tail extension will then be discussed qualitatively based on the results of the variable span analysis. Consider the unswept planform geometry, the planform area can be written as

$$S = S_1 + 2\Delta b c$$

where $S_1$ is the area when $\Delta b = 0$ and $c$ is the chord length of the outer wing section. The reference area ($S_{ref}$) will be defined as $S_1$. For the planform, a simplified model for the profile drag can be written as

$$D_p = \frac{\rho S_{ref} C_{dp}}{2} \left( 1 + \frac{2\Delta b c}{S_{ref}} \right)$$

where $\rho$ is the dynamic pressure and $C_{dp}$ may be considered a 2-D profile drag coefficient (which is a function of the Reynolds number). A more elaborate profile drag model that uses lift-dependent 2-D drag polars could be used, but for the present analysis the above equation is sufficient. The induced drag for an elliptic load distribution can be written as

$$\frac{D_i}{L} = \frac{2}{\pi q b^2}$$

where $L$ is the lift force and $b$ is the total span. In the above equation a span efficiency factor (as a function of $\Delta b$) could be added to account for the effect of a non-elliptic load distribution. This is not included here because the dominant effect of span is captured in the $b_2$ term in the denominator of that equation. The total span for the unswept configuration can be written as

$$b = b_1 + 2\Delta b$$

where $b_1$ is the total span of the unextended-span, unswept configuration. Combining the above equations, the total drag can be written as

$$D = D_p + \frac{D_i}{L}$$
This equation may be used to determine the $\Delta b$ that achieves a given $L$ with minimum $D$. This is done by taking the derivative of above equation with respect to $\Delta b$ and setting it equal to zero. The resulting equation for $\Delta b$ is as follows

$$\Delta b = \frac{1}{2} \left( \frac{2L^2}{\pi \sigma_c^2 \epsilon_{dp} C} \right)^{1/3} - b_1$$

This equation shows that for minimum drag, $\Delta b$ varies as $L^{2/3}$. Note that $C_{dp}$ is in the denominator of the equation. This indicates the expected result that as $C_{dp}$ decreases, meaning the penalty for wetted area decreases, the $\Delta b$ for minimum drag increases. The effect of variable sweep and tail extension on the drag can be approximated by considering the trends seen in the preceding analysis. For instance, assuming that sweep has little effect on the wing area, the main effect of sweep is the change it causes to the projected span (the span projected into the Trefftz plane) and the assumed load distribution. The projected span decreases with sweep, which therefore increases the induced drag. Also, if the load distribution is elliptic when the wing is upswept, the swept load distribution will be less elliptic. These factors indicate that, under the current assumptions, variable sweep is not likely to provide a drag reduction. The same can be said for the tail extension, which only increases the total area with no span increase. Thus, extending the tail increases the profile drag without decreasing the induced drag.

### B. Calculation of c.g shift:

The reference position for the center of gravity is considered to be at $0^\circ$ sweep angle. For our aircraft, let us consider the maximum sweep angle to be $30^\circ$ and hence the CG shifts aft as the sweep angle changes from $0^\circ$ to $30^\circ$. The CG shift for different sweep angles is tabulated below for UAV whose mass of the unmovable components $m_b=100$ kg, mass of the wing $m_w=60$ kg, lift curve slope $a=1$, length of the Fuselage as 21 inches, chord of the wing as 14 inches. Considering an airfoil the centre of gravity lies at 30% of the chord. Normally centre of gravity is expressed in terms of percentage of chord. Consider CG location of the unmovable components, $r_b=6.3$ inches and CG location of the wing, $r_w=4.2$ inches.

### V. Three dimensional external flow simulation of wing using solidworks:

SolidWorks Flow Simulation uses a wizard interface to setup the analysis thereby making it easy and intuitive to solve the problem. Our project concerns with external flow simulation given by pressure and velocity distribution for various combinations of sweep angles and wing twist. The wing twist denotes the variation in wing span. Both the wing twist and wing sweep of various combinations are predicted for $(15,15)$, $(15,30)$, $(-15,15)$, $(-15,30)$ respectively. Other configurations such as with and without full extension of wing as well as for sweep angle had been done for comparison.

![Fig. 5: Pressure distribution for twist=15° and sweep=15°](image)
Fig. 6: Velocity distribution for twist=15° and sweep=15°

Fig. 7: Pressure distribution for twist=15° and sweep=30°
Fig. 8: Velocity distribution for twist=15° and sweep=30°

Fig. 8: Pressure distribution for twist= -15° and sweep 15°
Fig. 9: Pressure distribution for twist -15° and sweep 15°

Fig. 10: Pressure distribution for twist=-15° and sweep=30°
RESULTS AND DISCUSSION

Evaluating for the vehicle components, the c.g. location shifts from 31.46% of the reference chord (1.81 feet) at zero sweep to 42.47% at full sweep and wing extension, a change of approximately 11% which is evident from Table. The percentage shift in CG has found out as 13.9%. The fig.12 shows that the aerodynamic center shifts aft by almost 26% for the same planform changes. Therefore, there is still a net stabilizing effect when the wings sweep, in spite of the c.g. shift. By designing the c.g. location of the nonmoving components further aft, the tail can be used as an independent agent to alter the stability margin for enhanced maneuvering when the wings are swept. Consider the zero sweep fully extended planform configuration of the adaptive aircraft as the reference. When the wings are fully extended the tail is also fully extended. As the wing is swept backward the CG position shifts aft and this has to be compensated by retracting the tail. For our UAV the tail has to be extended up to a maximum of 6.5 inches which is evident from the calculations. The capacity of the actuators that are to be used for the tail extension has to be chosen so that they provide the required extension of 6.5 inches.

Fig. 11: Velocity distribution for twist= -15° and sweep=30°

Fig. 12: $C_L$ Vs $C_D$ curve for various sweep angle
Table I: C.G. Shift for various sweep angles

<table>
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<tr>
<th>S/N</th>
<th>ANGLE OF SWEET (DEG)</th>
<th>C.G. SHIFT (INCHES)</th>
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Conclusion:

The adaptive aircraft test bed, designed and constructed for large configuration changes, is capable of five independent planform variations along with independent twist control for each wing. The vehicle undergoes a 38% increase in span, 30 degrees of sweep change, 12% change in chord length and ±20 degrees of wing twist. The c.g. location shifts from 31.46% to 42.47% of the reference chord from zero sweep to full extension and sweep. Analysis results will determine that variable planform capability allows low drag to be maintained throughout a range of lift coefficients. An approximate analysis quantified the planform changes required to maintain minimum drag. The ability to change both sweep and span was shown to be beneficial.

REFERENCES

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