Design and Analysis of Span wise Morphing Wing to Increase the Overall Efficiency of the Aircraft

Abhilash Masane[#1],Rakesh Vaskar[#2], Shridhar Kulkarni[#3]

[#]*Department of Mechanical Engineering, Sinhgad College of Engineering, Pune, India*

***Abstract*—This paper presents design and analysis of a spanwise morphing wing to increase the overall efficiency of the unmanned aerial vehicle.The morphing wing is designed for three different mission profiles.A comparative study is carried out to show the decrease in energy consumption of a spanwise morphing wing with respect to a conventional rigid wing designed for same flight conditions. The wing is morphed telescopically from a lower aspect ratio to a higher aspect ratio according to the mission profiles. The results are interpretedthrough CFD analysis of the wing. This design can be implemented in UAV's to achieve higher efficiency and greater maneuverability.**

***Keywords*—Morphing wing, CFD analysis, UAV, Constraint diagram, Spanwise morphing.**

Nomenclature-

UAV- Unmanned aerial vehicle
AOA-Angle of attack
AR- Aspect Ratio
C_l- Coefficient of lift
$C_{l_{max}}$- Maximum lift coefficient
L- Lift generated
C_d- Coefficient of drag
$C_{d_{min}}$-Minimum Drag coefficient
k- Oswald´s span efficiency constant
v_{stall}- Stall velocity
v_{cr}- Cruise velocity
v_{to}-Take-off velocity
W/S- Wing loading
T/W - Thrust by weight ratio
v-Velocity
ρ- Density of medium

I. Introduction

The researchers have always been mesmerized by the bio-inspired flights. As a result of higher efficiency and better performance of bird-like flights, the development in bio-inspired flight has increased in a couple of years due to continuous environmental concerns and rising fuel cost. The laminar flow past a streamlined body can be improved to obtain significant drag reduction by modifying the geometry of the body according to the flow. This concept of modifying the shape of the body is known as 'morphing' [1].

A morphing wing aircraft refers to an aircraft which has the potential to adapt a certain shape depending upon the mission it has to carry out. The concept of morphing plays a very important role in the field of the unmanned aerial vehicle (UAV) and micro aerial vehicle (MAV). The morphing of the wing of an aircraft can be achieved by altering its shape in camber, span, chord, swept angle, dihedral angle etc [2].Further,this conceptcan be classifiedas active and passive morphing. Inactive morphing, energy is required to change the structure and accomplish a predefined shape. The majority of morphing including shape changing on a substantial scale falls under this class. In passive morphing, the streamlines of the wind are utilized to disfigure the structure and, in this manner, the energy is extracted from the upcoming wind streams. This requires the airframe to possess higher structural flexibility attributes to accomplish a required shape change with a given load. Passive morphing is an appealing strategy to accomplish a lightweight structure in case oflower scale geometry variations [1].

The wing with a high aspect ratio is best for gliding for a higher period with lesser consumption of energy but performs poorly at higher speed and possess lower maneuverability. The low aspect ratio wing has greatermaneuverability but generates higher drag. A spanwise morphing wing can fuse the highlights of both high and low aspect ratio wings and perform efficiently in their designed flight profiles [3]. This paper presents a spanwise morphing aircraft which can morph its shape telescopically. Various concepts of morphing are studied [1] to determine the extent of span morphing.The spanwise morphing wing is designed for flying at three different flightprofiles; gliding, cruising, and dash. Every flight profile is assigned with a particular percentage of span extension. The energy consumption for overcoming the drag is calculated for each configuration and a comparative study is carried out with a fixed wing to determine the increase in efficiency.

II. Design of Morphing Wing

For analytical purpose, themorphing wing was designed for a UAV with all up weight of 2kg. The weight of the UAV was decided by studying weight build-up schedule of different UAVs designed to perform a similar mission [3].

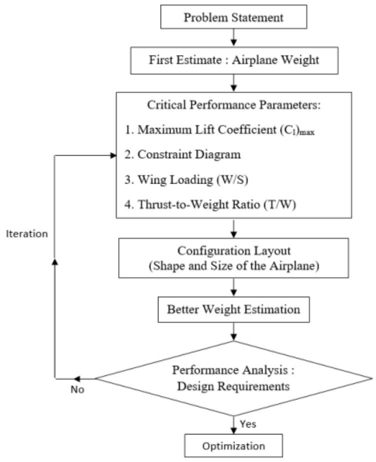

Fig. 1 Design Flow of Conventional Aircraft [5]

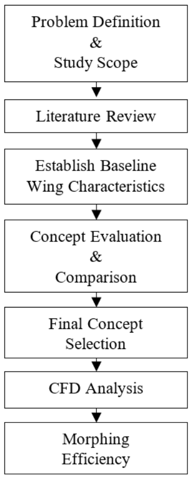

Fig. 2 Design Flow of Morphing Wing

A. *Mission Profiles-*

The morphing wing was designed to fly within three different flight profiles with variable endurance depending upon the situation and necessity. The different flight profiles were selected after analyzing several research papers [1 - 4].

TABLE 1

Mission Matrix

Mission	Speed	Duration
Loiter	12 m/s	8 min
Cruise	15 m/s	5 min
Dash	30 m/s	2 min

B. *Airfoil selection-*

The high cambered foils are less efficient at high-speed operation.It was intended to select a foil with moderate camber or semi-symmetric foil with a considerable $C_{l_{max}}$ and least $C_{d_{min}}$. For the selection of foil, the foil database of approximately 2000 foils was analyzedusing XFLR5 for Reynolds Number 50,000 to 9,00,000 with AOA ranging from -2° to 15°. The analysisyield 7 different potential airfoils, among which Eppler 397 had minimum energy consumption for the required range of Reynolds Number.The range of values of $C_l/C_d$and C_l for Eppler 397 at different angles of attack.

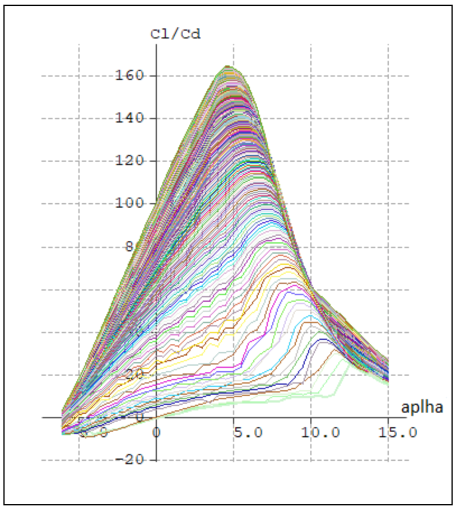

Fig. 3C_l/C_dvs. alpha for Eppler 397

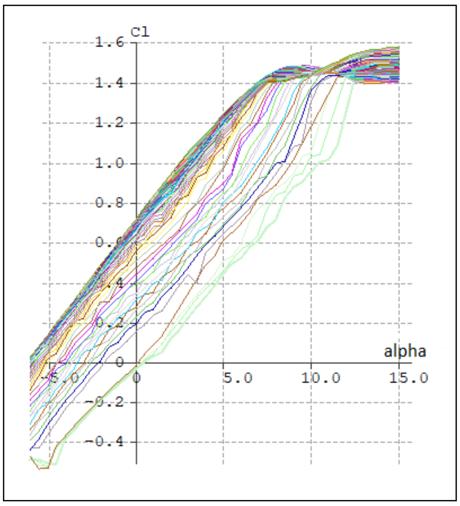

Fig. 4$C_l$vs. alpha for Eppler 397

C. Rigid Wing Design-

A best-suited rigid wing was designed to carry out a comparative study of its performance with respect to morphing wing performing the same set of missions. The design procedure included:

*1) Constraint Diagram:*Constraint diagram is a plot of thrust by weight ratio (T/W) of the aircraft to its wing loading (W/S). It gives an idea about the propulsion system and the wing area of the aircraft. The constraint diagram is a plot, usedto find the best-suited wing area for arigid wing. Dynamic equations for the preliminary conditions were used to generate the constraint diagram [4]. The three preliminary conditions for the UAV refers to take-off [4], cruise[5] and stall [5].

Take-off run: $$T/W = \frac{v_{to}^2}{2gS} + \frac{\rho v_{to}^2 C_{D_{to}}}{W/S} + \mu\left(1 - \frac{q\,Cl}{W/S}\right)$$ …..Eq. 1

Cruise condition: $$T/W = \frac{1}{2} \cdot \frac{\rho {v_{cr}}^2 C_{D_{min}}}{W/S} + \frac{k\,(W/S)}{1/2\rho {v_{cr}}^2}$$ …..Eq. 2

Stall condition: $$T/W = \frac{\rho C_{l_{max}} {v_{stall}}^2}{2}$$ …..Eq. 3

The equations were modified depending upon the requirement of the UAV and a MATLAB code was prepared to plot the curves to define the solution region of the design.

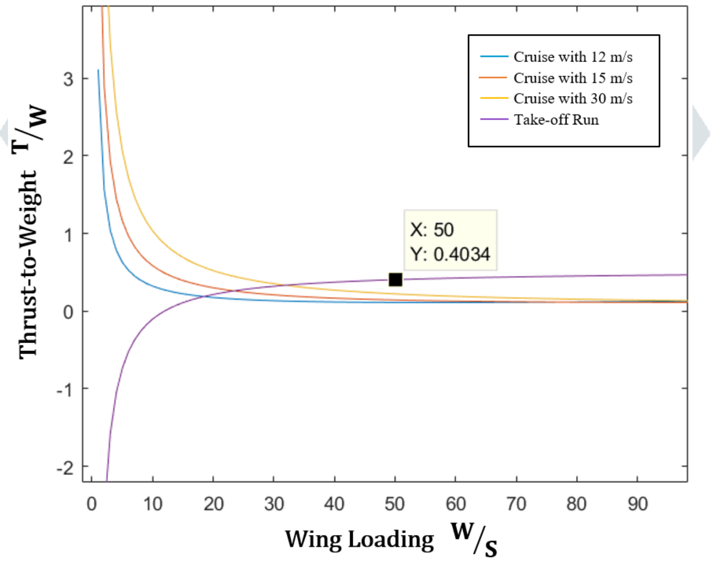

Fig. 5 Constraint Diagram

*2) Wing Area:*The wing loading of50 N/m^2 was optimum design coordinate of the solution region. The wing area was calculated to be 0.391m^2. The aspect ratio of 6 and rectangular wing planform satisfied the mission conditions [5]. The rigid wing was modelled in XFLR5 to analyzeits performance. The table below shows the energy consumption of a rigid wing for overcoming the generated drag.

TABLE 2

ENERGY CONSUMPTION FOR RIGID WING CALCULATED USING XFLR5

Mission	Velocity (m/s)	C_d	AREA (m^2)	FORCE (N)	POWER (W)	ENERGY (J)	Total
LOITER	12	0.044	0.394	1.529035	18.34842	8807.243	30260.435
CRUISE	15	0.027		1.466049	21.99074	6597.222	
DASH	30	0.019		4.126658	123.7997	14855.97	

D. Morphing Wing Design –

The purpose of the morphing wing was to reduce the extensive energy consumption required to overcome the drag of the fixed wing without altering the mission profile. The main two aspects of morphing are the type of morphing and extent of morphing. A spanwise morphing wing generates a greater increase in efficiency as compared to other morphing techniques [3]. The extent of morphing was determined by generating various iterative models in XFLR5 and analyzing the increase in efficiency corresponding to change in morphing extent. Initially, the wingspan was morphed up to 20% but the increase in efficiency was analyzed to be 11%. Hence, the wingspan was morphed further up to 40%to achieve a23% increase in efficiency. The following table shows the corresponding area and energy consumption of the morphing wing 40% morphing.

TABLE 3

ENERGY CONSUMPTION FOR MORPHING WING CALCULATED USING XFLR5

Mission	Velocity (m/s)	C_d	AOA	AREA (m^2)	FORCE (N)	POWER (W)	ENERGY (J)	Total
LOITER	12	0.03	0º	0.47	1.24362	14.92344	7163.251	23299.717
CRUISE	15	0.023	0º	0.38	1.204481	18.06722	5420.166	
DASH	30	0.018	-2º	0.3	2.97675	89.3025	10716.3	

III. ANALYSIS OF MORPHING WING

At the initial stage, the morphing wing was analyzed using XFLR5. XFLR5 [6] is an Xfoil based solver, capable of performing various functions pertaining to foil as well as wing analysis. It uses the Vortex Lattice Method (VLM) to predict coefficients for 3D lifting surfaces. The principle of VLM is to model the perturbation generated by the wing by a sum of vortices distributed over the wing's planform. The strength of these vortices is calculated to meet the boundary conditions on the surface of the panels. The limitation of the VLM method is that the analysis is inviscid, and therefore interpolates the viscous drag coefficient C_d for the aircraft from the polar values generated from the 2D airfoil. The accuracy is therefore affected around the angle of attack close to stall angle, and hence cannot be considered for later stage [7 - 8].

Therefore, the computational fluid dynamics (CFD) analysis of the morphing wing were validated on ANSYS FLUENT. For low-speed subsonic flows, ANSYS FLUENT uses a pressure-based solver to solve the governing integral equations for conservation of mass and momentum.

A. *Pre-processing -*

The morphing wing was modelled for three configurations on SOLIDWORKS. A bullet-shaped fluid domain was used to replicate the experimental wind tunnel to increase the accuracy and precision of the result. Tetrahedral elements along with fine mesh sizing were used to mesh the domain. The mesh quality depends upon the value of smoothness which defines the rate of change of cell size. The value of smoothness has been set to medium to ensure a better mesh quality [9].

The Standard K-epsilon model was used for analysis. It is a 2-equation model which represents the turbulent properties of the flow. The first equation gives the turbulent kinetic energy of the flow which is represented by symbol K whereas the second equation gives the turbulent dissipation rate in the flow which is represented by symbol Є. Second order upwind scheme is selected for spatial discretization of the Reynolds Average Navier Stoke (RANS) equations as well as energy and turbulence equations [9]. Converged results are obtained after the residuals were found to be less than the specified values. A converged result renders velocity residual below 10^{-6}, and turbulence kinetic energy and turbulent dissipation rate residuals being below 10^{-3}.

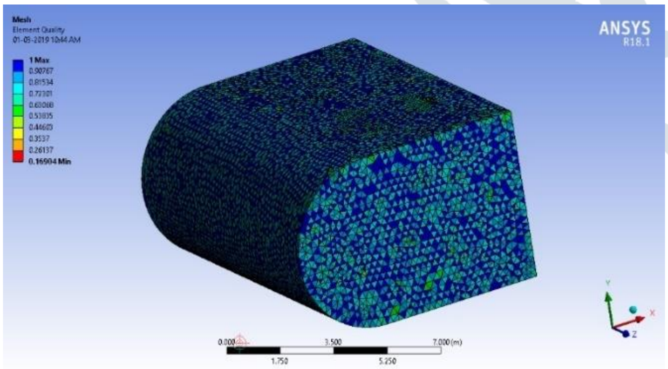

Fig. 6 Mesh Quality of Bullet Domain

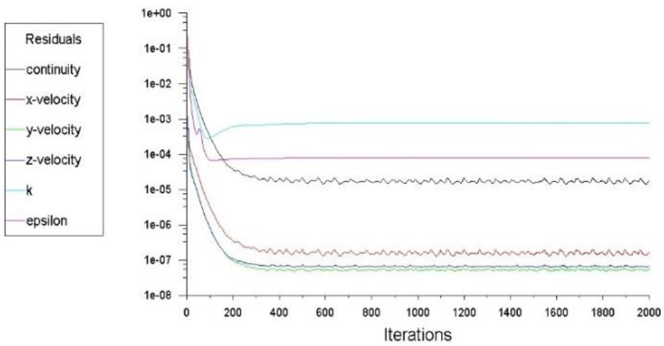

Fig. 7 Residuals Falling Below 10^{-3}

B. *Processing –*

Residuals for continuity, velocity, k and epsilon are set to 0.001 and a first order initial solution is obtained. Following this, the residual condition is changed to 10^{-6} and all quantities are represented by a second order equation. Iterations were performed until convergence was reached.

C. *Post-processing –*

The model of the morphing wing was analyzed for three different configurations at three different velocities and angles of attack (AOA). The pressure and velocity contours were plotted for every configuration to study their variations at different sections of the morphing wing.

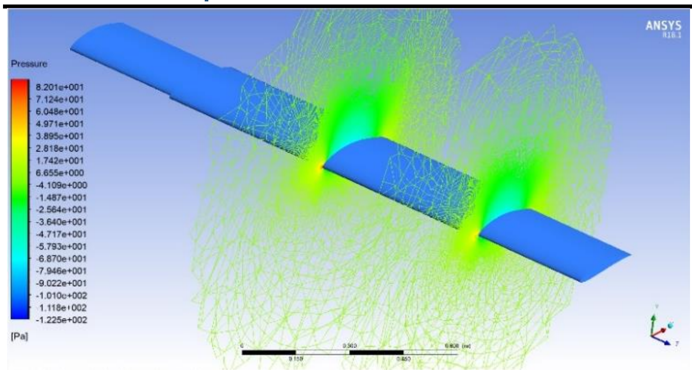

Fig. 8 Pressure Contour of 40% Span Extension Configuration for Loitering at 12 m/s and 0º AOA

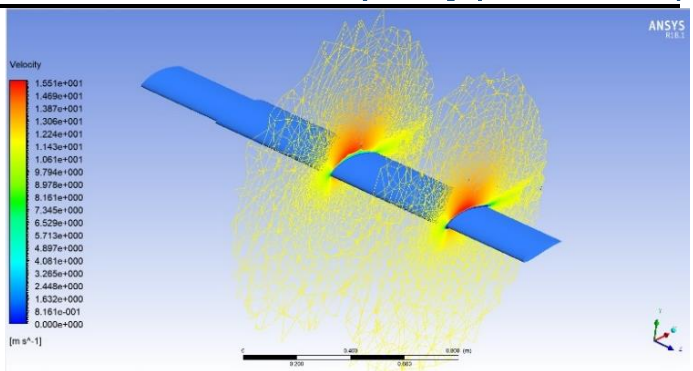

Fig. 9 Velocity Contour of 40% Span Extension Configuration for Loitering at 12 m/s and 0º AOA

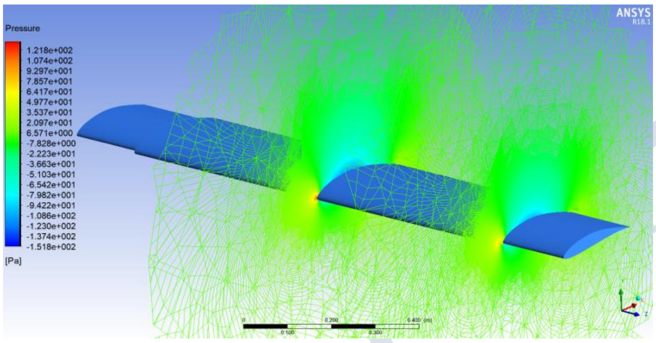

Fig. 10 Pressure Contour of 20% Span Extension Configuration for Cruising at 15 m/s and 0º AOA

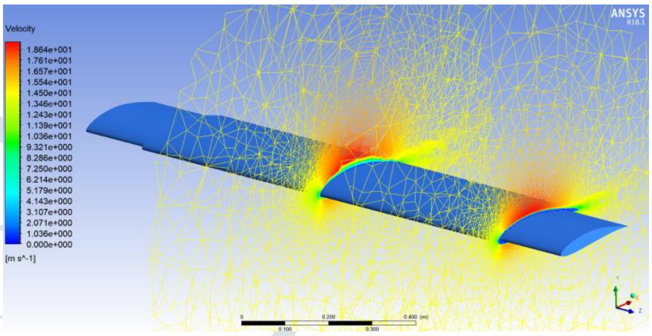

Fig. 11 Velocity Contour of 20% Span Extension Configuration for Cruising at 15 m/s and 0º AOA

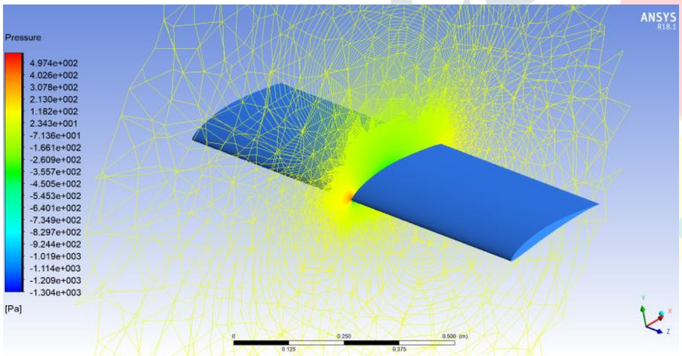

Fig. 12 Pressure Contour of Fully Retracted Configuration for Dash Profile at 30 m/s and -2º AOA

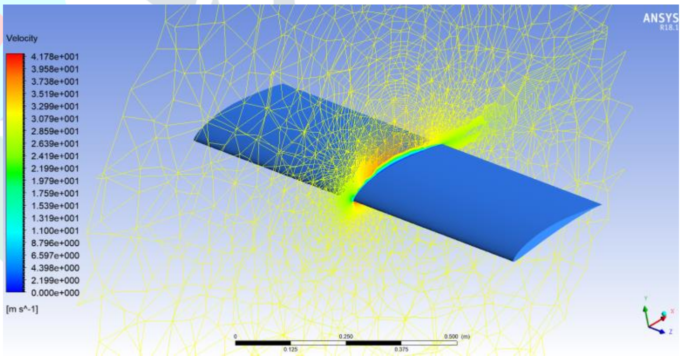

Fig. 13 Velocity Contour of Fully Retracted Configuration for Dash Profile at 30 m/s and -2º AOA

IV. Results

The results obtained from ANSYS Fluent were used to validate the results of XFLR5 to calculate more precise value of percentage increase in efficiency of morphing wing with respect to the conventional rigid wing.

TABLE 4

COMPARISON OF ENERGY CONSUMPTION FOR MORPHING WING CALCULATED USING XFLR5 AND ANSYS FLUENT

Mission	Velocity (m/s)	AOA	XFLR5 Lift (N)	XFLR5 Drag (N)	% Increase in Efficiency using XFLR5 Results	ANSYS Fluent Lift (N)	ANSYS Fluent Drag (N)	% Increase in Efficiency using ANSYS Fluent Results
Loiter	12	0º	20.0249	1.24362		20.14512	1.35312	
Cruise	15	0º	23.84008	1.204481	23 %	25.48149	1.67762	9.29 %
Dash	30	-2º	47.2898	2.97675		50.78906	4.47442	

V. Conclusion

This paper presents designing and analysis of a spanwise morphing wing to increase the overall efficiency of an unmanned aerial vehicle (UAV). The test model was designed on SOLIDWORKS and then analyzed on XFLR5. Then the results were validated using ANSYS FLUENT. The spanwise morphing wing with 40% span extension, when compared with the rigid wing designed for same mission profiles, shows an increase in efficiency. The results obtained from XFLR5 showed a 23% increase in efficiency. The XFLR5 results when validated using ANSYS FLUENT showed 9.29% increase in efficiency.

In the development of further work, it would be possible to conduct a wind tunnelanalysis by fabricating a scaled-down prototype to validate the results obtained from software with experimental values. Further, it is possible to manufacture entire micro aerial vehicle (MAV) capable of spanwise morphing to analyze flight performance of a span-morphing aircraft in the real world.

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