Design And Numerical Analysis of Morphing Airfoil With Corrugated Geometry In The Application MAV's

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Design and numerical analysis of morphing airfoil with corrugated geometry in the application MAV's

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ABSTRACT

The main objective of the work is to enhance the aerodynamic performance during takeoff and cruise by using newly corrugated airfoil of MAV's by Morphing it at the trailing edge. In this study, the transient nature of corrugated airfoils at low Reynolds number were assumed to be the flow is laminar, incompressible and two dimensional. The newly corrugated geometry which is parameterized from the camber line using a Radial basis function (RBF) based on interpolation method positioned at the lower surface of the airfoil i.e., NACA0015. Five morphed geometries are designed using ANSYS Space claimer. The computational domain is meshed using cartesian grid, the surface meshes with quadrilateral. Numerical simulations are performed with turbulent models i.e., k-omega, k-epsilon and Spalart allmaras. In the analysis, there is an increment of coefficient of lift and decrease in coefficient of drag by varying Reynolds number. Compared to NACA0015, corrugated NACA0015 shows good results.

Keywords: Corrugation, Morphing, Turbulent models, RBF

I. INTRODUCTION

Micro Aerial Vehicle is a miniature of UAV's that has size restriction and maybe autonomous. The development of innovative adaptive structures on MAV's, such as "Morphing wings", can potentially reduce the complexity of the aviation structure. These are divided into Fixed wing MAVs, Rotary wing MAVs, Flapping wing MAVs. Fixed wing MAVs are aircraft models of size less than 200mm, controlled by remote. This can be as small as human palm. These MAVs have wing and propeller, helps them to fly.

Rotary wing MAVs are tiny helicopters, controlled by remote. They don't have wing they use rotors. These are most commonly used MAVs.

Flapping wing MAVs are most trending recent in the development of MAVs. These MAVs are most complicated then compared to other MAVs as they use the same mechanism as bird to achieve flight. As birds flap wing in different ways to achieve flight. Different birds have different ways to flap there wings, insects also have different ways to flap there wings. Now MAVs have been also designed by observing the dragonfly.

Modern craft can be as small as 5 centimetres. Most of the development of MAVs are seen for commercial, research, government and military purpose. The interest on Morphing wing has been increased due to its superior benefits. The structure that can change its geometric characteristics and also properties (stiffness and damping) according to the mission requirements or at different load conditions.[1] The main idea in positioning corrugated portion is for actuating the trailing edge. Besides, it will re-energies the flow which will helps to delay the flow from separation. The Maximum speed of a Micro Aerial vehicle would be around 10-15m/s. As we are considering a low Reynolds number. Because the boundary layer is the great deal of managing an adverse pressure without separation. The assumptions we made for this study are the flow is laminar, steady, incompressible and 2-Dimensional. MAVs have the potential to operate the missions in denser regions that near the Earth surface. Near the earth surface the airflow is turbulent. This results in turbulent intensity on the stability of the MAVs.

Most MAVs have problems during takeoff and cruise. As a result, main objective is to enhance the aerodynamics performance by using corrugated used for morphing the trailing edge. All the cases of MTE optimized airfoils have showed a significant improvement in the overall aerodynamic performance, and MTE airfoils increased the efficiency.

In this paper a computational study is done in order to investigate the aerodynamic performance of newly corrugated airfoil, positioned at 25% of the chord length from the trailing edge of the airfoil by continuously morphing trailing edge wing.

In order to increase the aerodynamic performance by morphing technology by placing corrugated design at the lower surface of the symmetric airfoil (i.e., NACA0015) and using by giving deflections of airfoil models (2deg, 5deg, 7deg, 9deg) at the trailing part of the airfoil. The airfoil is reconstructed from the camber line using a Radial Basis Function (RBF) based on interpolation method.

Performed the study by using the concept of different turbulence models (k-omega, k-epsilon and Spalart allmaras).[2]

All the three models were considered and used to analyse the newly designed aerofoil for MAVs.

Compared to all the models, k-epsilon model has interpreted the good results.

For MAVs, the wing must be flexible to cover a smooth configuration. Corrugated structure can undergo high aerodynamic loads and helps to morph the wing smoothly.[4]

II. AIRFOIL OPTIMIZATION

In order to model the airfoil, there is a method to be followed and to carry out the mesh deformation, calculate the aerodynamic coefficients and also attached the optimization models in the following sections.

2.1 Parameterization

To give the corrugated portion at lower portion of the NACA0015 airfoil, Radial Basis Function is used, explained as follows

By using above figure, the values of Radial basis function at the predicted location can be considered, as given by Φ_1 , Φ_2 , and Φ_3 , it depends on the distance between the data location. The Predictor can be estimated by taking the weighted average $w_1\Phi_1 + w_2\Phi_2 + w_3\Phi_3 + \dots$. There are different methods in it, they are Thin-Plate spline, Spline with Tension, completely regularized spline, Multiquadric function, Inverse multiquadric function. Sometimes, they don't make greater difference.

In order to design the model, Firstly, the model dimensions are collected from NACA tools from NASA website. After, five models are modelled by giving 5 deflections(0°, 2°, 5°, 7°, 9°) at the trailing edge. To actuate the deflected portion a corrugated portion is positioned at 25% of chord of 150mm.

2.2 Mesh deformation

The computational domain was meshed by using Cartesian grids. To get accurate values, refinement is also given around the surface of the deflected air foil.

Fig-A Mesh deformation at 5° deflection

2.3 Flow Solver

The analysis is done by using three turbulent models.

Spalart-Allmaras model

The One-Dimensional Spalart-Allmaras is an easy model that resolves a modelled transport equation for the kinematic eddy (turbulent) viscosity. This model is generally used for wall-bounded flows and has good outputs for boundary layer subjected to ambient pressure gradients.

In Spalart allmaras, the transported variable $\tilde{\nu}$ is similar to the turbulent kinematic viscosity except in the near-wall region.

$$[\partial/\partial t (\rho \tilde{\nu}) + \partial/\partial x_i (\rho \tilde{\nu} u_i) = G_v + 1/\sigma_{\tilde{\nu}} [\partial/\partial x_i \{(\mu + \rho \tilde{\nu}) \partial \tilde{\nu} / \partial x_i\} + C_{b2} \rho (\partial \tilde{\nu} / \partial x_i)^2] - Y_v + S_{\tilde{\nu}}] \quad \text{..... eq-1}$$

G_v is the production of turbulent viscosity, Y_v is the destruction of turbulent viscosity that happens in the near wall region because of the wall blocking and viscous damping, $\sigma_{\tilde{\nu}}$ and C_{b2} are constants, ν is the molecular kinematic viscosity and $S_{\tilde{\nu}}$ is a user-defined source term.

Note: Turbulence kinetic energy is not calculated in Spalart-Allmaras model.

The production term G_v can be modelled as

$$[G_v = C_{b1} \rho \tilde{S} \tilde{\nu}] \quad \text{.....eq-2}$$

where:

$$\tilde{S} \equiv S + (\tilde{\nu}/k^2 d^2) f_{v2} \text{ and } f_{v2} = 1 - x/1 + x f_{v1}$$

C_{b1} and k are constants,

d is the distance from the wall and

S is a scalar measure of the deformation tensor.

The destruction term is modelled as:

$$Y_v = C_{\omega 1} \rho f_{\omega} (\tilde{\nu}/d)^2 \quad \text{..... eq-3}$$

Where:

$$[f_{\omega} = g [1 + C_{\omega 3}^6 / g^6 + C_{\omega 3}^6]^{1/6}, g = r + C_{\omega 2} (r^6 - r) \text{ and } r \equiv \tilde{\nu} / \tilde{S} k^2 d^2]$$

$C_{\omega 1}$, $C_{\omega 2}$ and $C_{\omega 3}$ are constants.

Model Constants	
Cb1	0.1355
Cb2	0.622
Cv1	7.1
Cw2	0.3
Cw3	2
Prandtl Number	0.667

k-ε Standard Model

This model depends upon transport equations for the turbulence kinetic energy(k) and dissipation rate (ϵ).

The assumptions made for the flow are turbulent and effects of molecular viscosity are negligible. Therefore, this model is suitable only for turbulent models.

The turbulence kinetic energy k and dissipation rate can form as follows:

$$[\partial/\partial t (\rho k) + \partial/\partial x_i (\rho k u_i) = \partial/\partial x_j [(\mu + \mu_t/\sigma_k) \partial k/\partial x_j] + G_k + G_b - \rho \epsilon - Y_M + S_k] \quad \text{..... (4)}$$

$$[\partial/\partial t (\rho \epsilon) + \partial/\partial x_i (\rho \epsilon u_i) = \partial/\partial x_j [(\mu + \mu_t/\sigma_\epsilon) \partial \epsilon/\partial x_j] + C_{1\epsilon} \epsilon/k (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \epsilon^2/k + S_\epsilon] \quad \text{..... (5)}$$

Where

G_k - is the generation of turbulence kinetic energy,

G_b means the generation of turbulence kinetic energy,
 Y_m is the contribution of the fluctuating dilatation on compressible turbulence to all dissipation rate,
 $G_{1\varepsilon}$, $G_{2\varepsilon}$ and $C_{3\varepsilon}$ are constants,
 σ_k and σ_ε are the turbulent Prandtl numbers for k and ε ,
 S_k and S_ε are the terms for source.
 $\mu_t = \rho C_\mu k^2/\varepsilon$; μ_t is turbulent viscosity, C_μ is constant

k- ω Standard Model

The standard empirical model that depends on the model transport equations for the turbulence kinetic equation and specific dissipation rate.

The transport equations of turbulence kinetic energy and the specific dissipation rate are derived below

$$[\partial/\partial t (\rho k) + \partial/\partial x_i (\rho k u_i) = \partial/\partial x_j (\Gamma_k \partial k/\partial x_j) + G_k - Y_k + S_k] \dots\dots\dots [6]$$

$$[\partial/\partial t (\rho \omega) + \partial/\partial x_i (\rho \omega u_i) = \partial/\partial x_j (\Gamma_\omega \partial \omega/\partial x_j) + G_\omega - Y_\omega + S_\omega] \dots\dots\dots [7]$$

The effective diffusivities for the k- ω model are described as:

$$[\Gamma_k = \mu + \mu_t/\sigma_k \text{ and } \Gamma_\omega = \mu + \mu_t/\sigma_\omega] \dots\dots\dots [8]$$

Where,

σ_k and σ_ω are the turbulent Prandtl numbers for k and ω , respectively.

The result of turbulent viscosity μ_t is produced by combining k and ω as follows:

$$[\mu_t = \alpha * \rho k \omega] \dots\dots\dots [9]$$

The production of turbulence kinetic energy G_k maybe given by:

$$[G_k = -\rho u_i' u_j' \partial u_j / \partial x_i] \dots\dots\dots [10]$$

To evaluate G_k in a manner consistent with the Boussinesq hypothesis: $G_k = \mu_t S^2$. The production of ω is given by:

$$G_\omega = \alpha (\omega/k) G_k \dots\dots\dots [11]$$

The dissipation of k is giving by:

$$Y_k = \rho \beta * f_\beta * k \omega \dots\dots\dots [12]$$

The dissipation of ω is giving by:

$$Y_\omega = \rho \beta * f_\beta \omega^2 \dots\dots\dots [13]$$

Y_k and Y_ω are the dissipations of k and ω , and defined identically as in the **standard k- ω model**.

2.4 BOUNDARY CONDITIONS

The assumptions made for the flow are Laminar, Incompressible, steady and 2-Dimensional. The outlet domain is set be pressure-outlet and gauge pressure are zero.

TABLE-1 Boundary conditions at V=12.5m/s

Dynamic viscosity(μ)	$1.81 \times 10^{-5} \text{ kg/(m}\cdot\text{s)}$
Density	1.23 Kg/m ³
Inflow velocity(U_{∞})	12.5m/s
Reynolds number	127417.1271

TABLE-2 Boundary conditions at V=14.5m/s

Dynamic viscosity(μ)	$1.81 \times 10^{-5} \text{ kg/(m}\cdot\text{s)}$
Density	1.23 Kg/m ³
Inflow velocity(U_{∞})	14.5m/s
Reynolds number	147803.8674

III.RESULTS AND DISCUSSION

This section gives the info about the numerical simulation results for the aerodynamic performance of the Morphing trailing edge of NACA0015 at velocities 12.5m/s and 14.5m/s.

3.1 Aerodynamic performance analysis during MTE

To study the influence of Angle of attack(α) and Deflection (θ) on the aerodynamic characteristics of Morphing trailing edge (MTE), the 5 air foils listed in fig- 1 were simulated. The deflection angles of the 5 air foils are measured as $0^{\circ}, 2^{\circ}, 5^{\circ}, 7^{\circ}, 9^{\circ}$. The range of α is set be 0° to 20° with interval 2° . The Mach number and Reynolds numbers at 12.5m/s are 0.21 and 127417.1271 and at 14.5m/s are 0.25 and 147803.8674.

Figure 2: shows the simulation results of the 5 stable states of the Morphing at 12.5m/s and 14.5m/s .

Figure-2(a) $\theta = 0^\circ$, Velocity=12.5 m/s

Figure -2(b) $\theta = 2^\circ$, Velocity=14.5 m/s

Figure-2(c) $\theta = 5^\circ$

Figure-2(d) $\theta = 7^\circ$

Figure-2(e) $\theta = 9^\circ$

Fig- 2(f) C_L Combined graph

Fig 2(g) C_D Combined graph

Fig-2(h) C_L/C_D Combined graph

The C_L vs α graph results in morphing trailing edge depicted in the above fig-2 are used for evaluating the aerodynamic performance.

In Fig.2(a) Deflection $\theta = 0^\circ$ at velocity 12.5m/s and 14.5m/s, the maximum coefficient of lift occurs at 12° angle of attack (AOA), there the flow get separated. Here, $C_{L \max}$ difference is around 5%.

In Fig 2(b) Deflection $\theta = 2^\circ$ the maximum coefficient of lift at velocities 12.5m/s and 14.5m/s occurs at AOA 14° . The maximum coefficient of lift between the two velocities is about 2%.

In Fig.2(c) Deflection $\theta = 5^\circ$ at angle of attack 18° the maximum coefficient of lift occurs with the velocity 12.5m/s and 14.5m/s. $C_{L \max}$ difference is about 2%.

In Fig.2(d) Deflection $\theta = 7^\circ$ at velocity 12.5m/s the maximum coefficient lift occurs at 14° angle of attack, whereas at 14.5m/s velocity it occurs at 12° angle of attack. The maximum coefficient of lift between the two velocities is about 7%, the value has increased.

In Fig.2(e) Deflection $\theta = 9^\circ$ the maximum coefficient of lift at velocity 12.5m/s and 14.5m/s occurs at 12° angle of attack. $C_{L \max}$ difference is around 7.1%.

TABLE – 3 C_L AND C_D VALUES WITH RESPECT TO α AT VELOCITY 12.5m/s

	Case-0- Without MTE		Case-1- MTE-2deg		Case-2- MTE-5deg		Case-3- MTE-7deg		Case-4- MTE-9deg	
	velocity at 12.5m/s		velocity at 12.5m/s		velocity at 12.5m/s		velocity at 12.5m/s		velocity at 12.5m/s	
AOA	Cl	Cd	Cl	Cd	Cl	Cd	Cl	Cd	Cl	Cd
0	-1E-06	0.00313	0.0226	0.0039	0.014	0.003	0.062	0.0039	0.075	0.0043
2	0.032	0.0032	0.0546	0.0041	-0.018	0.004	0.093	0.0044	0.1	0.0048
4	0.063	0.0038	0.0855	0.0045	0.046	0.004	0.12	0.0053	0.13	0.0056
6	0.094	0.0048	0.114	0.005	0.077	0.004	0.14	0.0066	0.15	0.0069
8	0.11	0.0067	0.139	0.006	0.1	0.0049	0.16	0.0085	0.17	0.0087
10	0.13	0.0096	0.16	0.008	0.133	0.006	0.18	0.01	0.18	0.01
12	0.14	0.013	0.168	0.01	0.155	0.007	0.185	0.014	0.196	0.013
14	0.13	0.02	0.172	0.013	0.172	0.009	0.18	0.019	0.194	0.018
16	0.12	0.028	0.166	0.018	0.182	0.011	0.16	0.027	0.18	0.025
18	0.123	0.038	0.154	0.026	0.184	0.015	0.159	0.04	0.17	0.036
20	0.13	0.049	0.143	0.012	0.176	0.02	0.162	0.054	0.17	0.052

TABLE – 4 C_L AND C_D VALUES WITH RESPECT TO α AT VELOCITY 12.5m/s

Case-4- MTE-9deg			Case-3- MTE-7deg		Case-2- MTE-5 deg		Case-1- MTE-2deg		Case-0- Without MTE	
velocity at 14.5m/s			velocity at 14.5m/s		velocity at 14.5m/s		velocity at 14.5m/s		velocity at 14.5m/s	
AOA	Cl	Cd	Cl	Cd	Cl	Cd	Cl	Cd	Cl	Cd
0	0.1	0.0054	0.085	0.0052	0.015	0.003	0.023	0.003	-0.0000018	0.004
2	0.14	0.0061	0.12	0.0058	-0.018	0.003	0.055	0.003	0.044	0.0042
4	0.18	0.0072	0.16	0.007	0.047	0.003	0.086	0.004	0.086	0.0049
6	0.2	0.0089	0.19	0.0087	0.078	0.004	0.115	0.005	0.12	0.0063
8	0.24	0.011	0.22	0.011	0.108	0.0047	0.139	0.006	0.16	0.0089
10	0.258	0.014	0.24	0.014	0.135	0.005	0.158	0.008	0.18	0.012
12	0.267	0.018	0.25	0.019	0.158	0.007	0.17	0.017	0.19	0.018
14	0.264	0.023	0.24	0.025	0.174	0.008	0.174	0.013	0.18	0.027
16	0.249	0.033	0.22	0.037	0.184	0.011	0.169	0.017	0.16	0.038
18	0.23	0.048	0.213	0.054	0.186	0.014	0.155	0.002	0.164	0.0511
20	0.22	0.07	0.21	0.074	0.178	0.019	0.15	0.003	0.174	0.067

3.2 Flow field Analysis

As shown in fig-3 the pressure contours of 5 deflections at 12.5m/s and 14.5 m/s. The maxima and minima pressure on the airfoils is verified by the intensity of the colour. The pressure beneath the airfoil is darker, it means there is an increase of C_L when the deflection is increasing. From all the pressure contours, 9° deflection has maximum C_p on the basis of intensity of colour beneath the airfoil. As, the increase in deflection the C_p is also getting increased, C_L values are also getting increased.

Figure-3(a) $\theta = 0^\circ$, $\alpha = 12^\circ$ at 12.5m/s

Figure-3(b) $\theta = 0^\circ$, $\alpha = 12^\circ$ at 14.5m/s

Figure-3(c) $\theta = 2^\circ$, $\alpha = 12^\circ$ at 12.5m/s

Figure-3(d) $\theta = 2^\circ$, $\alpha = 14^\circ$ at 14.5m/s

Figure-3(e) $\theta = 5^\circ$, $\alpha = 18^\circ$ at 12.5m/s

Figure-3(f) $\theta = 5^\circ$, $\alpha = 18^\circ$ at 14.5m/s

Figure-3(g) $\theta = 7^\circ, \alpha = 14^\circ$ at 12.5m/s

Figure-3(h) $\theta = 7^\circ, \alpha = 12^\circ$ at 14.5m/s

Fig-3(i) $\theta = 9^\circ, \alpha = 12^\circ$ at 12.5m/s

Fig-3(j) $\theta = 9^\circ, \alpha = 12^\circ$ at 14.5m/s

Velocity Contours-

As shown in fig-4 the velocity contours of 5 deflections at 12.5m/s and 14.5m/s. From the analysis, for $0^\circ, 7^\circ, 9^\circ$ the flow gets separated at the AOA 12° , for 2° deflection the flow gets separated at the AOA 14° and for 5° deflection the flow gets separated at 18° at 12.5m/s. Therefore, the above results shows that 5° deflection is suitable for takeoff for MAVs in case of 12.5m/s.

For 14.5m/s velocity, At $\theta = 0^\circ, 7^\circ, 9^\circ$ the flow gets separated at 12° AOA, $\theta = 2^\circ$ flow gets separated at 14° , $\theta = 5^\circ$ flow gets separated at 18° .

Figure-4(a) $\theta = 0^\circ, \alpha = 12^\circ$ at 12.5m/s

Figure-4(b) $\theta = 0^\circ, \alpha = 12^\circ$ at 14.5m/s

Figure-4(c) $\theta = 2^\circ, \alpha = 12^\circ$ at 12.5m/s

Figure-4(d) $\theta = 2^\circ, \alpha = 14^\circ$ at 14.5m/s

Figure-4(c) $\theta = 5^\circ$, $\alpha = 18^\circ$ at 12.5m/s

Figure-4(d) $\theta = 5^\circ$, $\alpha = 18^\circ$ at 14.5m/s

Figure-4(e) $\theta = 7^\circ$, $\alpha = 14^\circ$ at 12.5m/s

Figure-4(f) $\theta = 7^\circ$, $\alpha = 12^\circ$ at 14.5m/s

Figure -4(g) $\theta = 9^\circ$, $\alpha = 12^\circ$ at 12.5m/s

Figure -4(h) $\theta = 9^\circ$, $\alpha = 12^\circ$ at 14.5m/s

IV. CONCLUSIONS

- Since the first week of confirming of topic chosen, research has been done through journals and reference books in internet and library. Lift is found to be the most important aerodynamic parameter for flight.
- Numerical flow analysis has been done for morphing airfoil with required boundary conditions and using flow models.
- The improved design Corrugated morphed trailing edge - performed much better in higher lift and lower drag as compared without morphing NACA0015 at different Angles of Attacks (AOA).
- By comparing graph C_L and C_D versus AOA at different deflections (i.e, 0° , 2° , 5° , 7° , 9°) it shows as deflection is increasing, the C_L is also increasing.
- But, from all the results, it is observed that for take-off at $\theta = 50$ (deflection) suitable. As, the flow is separating at 18° AOA.

Observations:

- From all the results, aerodynamic efficiency has improved. The design objective is to increase the Lift-to-Drag ratio while take-off and Cruise.
- For take-off 5° deflection is suitable. Because it delays the flow till 18° AOA. Morphing trailing edge concept designed and numerically analyzed in this work.
- This work has been done for steady model characteristics of aerodynamics with different various conditions α and deflections between corrugated without morphing and with morphing.
- The corrugated shape introduced to help for mechanism in future geometries. By increasing of (θ) deflection the c_l and c_d increases accordingly varying with angle of attack (α). When increasing at small α in different flights conditions then MTE provides to enhance the lift in a flight condition i.e., during takeoff and cruise.
- The MTE concept has increased performance compare to without MTE morphing and as well as increases CL and reducing drag in different deflection of MTE, therefor at same flight conditions, the overall aerodynamic efficiency of MTE is improved than the without corrugated.
- At stall point due to MTE it suppresses the flow separation and reduces the vortices, there is more advantage in large deflection conditions.
- The project will be continued by fabricating the 2-dimensional models using 3d printing and testing has been done by using Low Speed Subsonic Wind-tunnel.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article with appropriated citations.

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Contributions

The contribution of the authors to this work is equivalent. All authors read and approved the final manuscript.

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Ethics declarations

Competing interests

The authors declare that they have no competing interests.