

Analysis of Morphing Airfoil Structures and Experimentally Reviewing its Performance

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Abstract: This paper briefs about the morphing airfoil with variable camber and it makes use of compliant rib mechanism. Lightweight system for actuation, compliant internal structure and a flexible skin are some of the key requirements for such mechanisms. Wing morphing is a biologically inspired technique where-in, the change in shape of wings can offer various advantages compared to the conventional solutions we currently have. In this research, we have used the combination of materials such as PLA and TPU in the wing prototype. To meet desirable shape changes, stiffness can either be tailored or actively controlled to guarantee flexibility in the chord-wise (or span-wise) direction with tailored actuation forces. Hence, corrugated structures, segmented structures, reinforced elastomers or flexible matrix composite tubes embedded in a low modulus membrane are all possible structures for morphing skins.

IndexTerms – Compliant rib mechanism, elastomers, flexible skin.

I. INTRODUCTION

It was not until the late 19th Century that the concept of flight took the entire world by awe and surprise, and now it has become one of the most significant commodities that describes economies of several nations. From a recent study, conducted by the International Air Transport Association (IATA), global aviation contributes to \$2.7 Trillion (3.6%) of the world's Gross Domestic Product (GDP). Having this big of an impact on the global economy, it is only natural for airlines to set their ultimate goal to profit and/or save their finances out of this. But this procedure of saving finances/economy cannot compromise enhancement in their services. This gap between the Service sector and the economy is only bridged by the quality and performance of the aircrafts that the airlines purchase.

The expected result out of every aircraft that any airline purchases is to transport a large amount of payload, be it passengers and/or cargo, at the least possible expense incurred to the airline itself. A major portion of the expense is occupied by Fuel, followed by airport parking/ Terminal charges and maintenance/service of aircrafts. This only calls for aircrafts to be manufactured in such a way that it is highly efficient in case of fuel consumption. Thanks to the relentless advancements of technology since the early 20thth century, we, the people of the 21st century, reap the profits of highly fuel efficient aircrafts. Several manufacturers of airframes and propulsion systems, from all around the world have invested their profits into research and development organizations to improve the technology in order to enhance the fuel economy of their respective systems.

Morphing technology on aircraft has grabbed interest over the last decade because it improves the performance and efficiency over a wider range of flight conditions. Morphing wings can also be defined as wings that changes its configuration to maximize its performance at various different flight conditions and purpose. Morphing aircraft wings have requirements such as flexible skins that can undergo large strains and have low in-plane stiffness. For example, a radical change in configuration, i.e. wing geometry in flight may improve overall flight performance during take-off, cruise and landing.

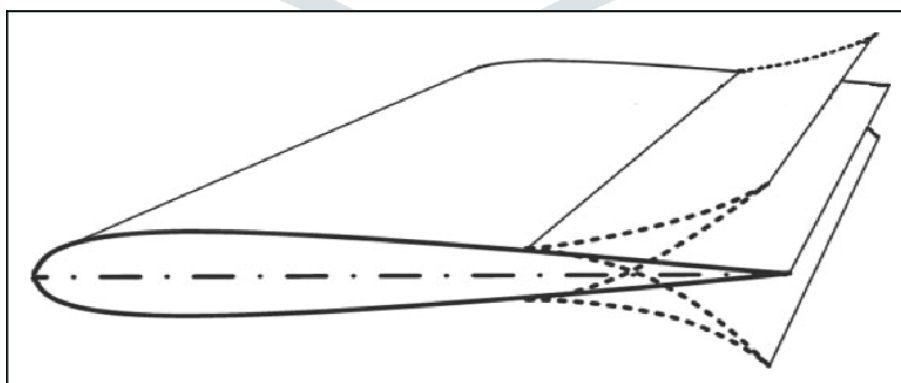


Fig. 1a. Basic Idea of a Chord-Wise Morphed Wing

II. METHODOLOGY

2.1 AIRFOIL SELECTION

Selig1223 from the Selig series, FX74MODSM from the WORTMAN series and Eppler 423 from the Eppler series of airfoils were shortlisted. Originating from the Low Speed and Low Reynolds number regime, these airfoils were analyzed and selected by means of reference scoring method.

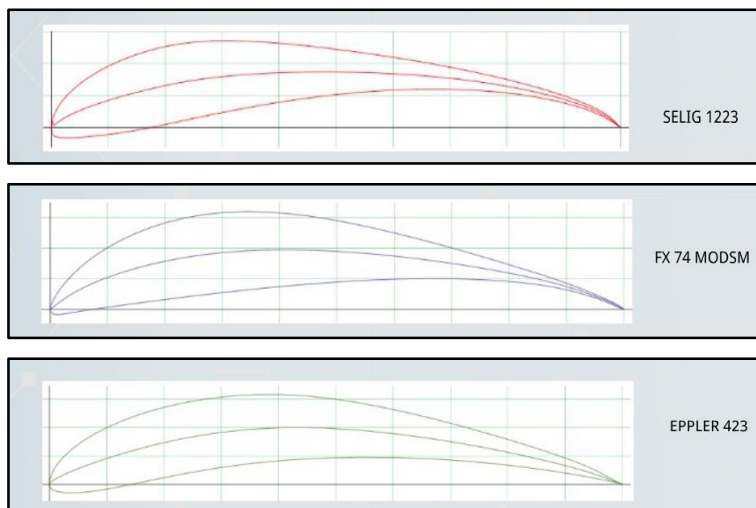


Fig. 2a. Airfoil Profiles

The parameters considered were $C_{l_{max}}$, $C_{d_{min}}$, Stall angle, C_l/C_d and ease of fabrication. The airfoil with the most favourable outcome of the listed parameters would be scored a maximum of 3 and the airfoil with the least favourable outcome would be scored a minimum of 1.

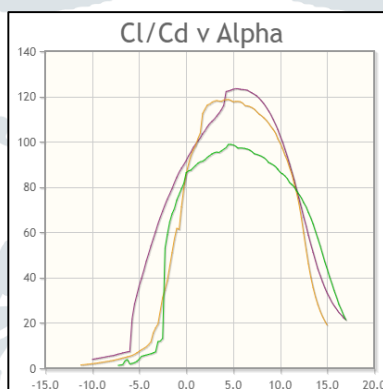


Fig. 2b. Graph of C_l/C_d vs. AOA

The airfoil characteristic plots such as C_l vs. AOA, C_l vs. C_d , C_m vs. AOA and (C_l/C_d) vs. AOA at $Re = 500,000$ were studied and the reference scoring method was employed to choose the best out of all three airfoils. The plot above shows the Lift coefficient trend with respect to angle of attack. We further observe that S1223 has the best stall performance followed by E423. But we also observe that FX74modsm has the highest lift coefficient.

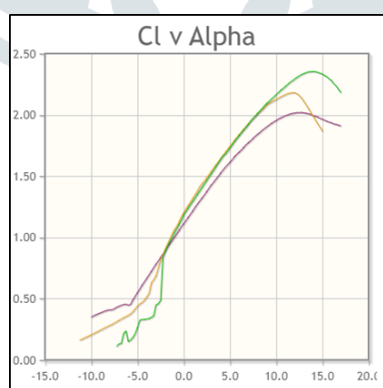


Fig. 2c. Graph of C_l vs. AOA

The plot above shows us the variation of lift coefficient with respect to drag coefficient. We further observe that E423 has the least drag coefficient followed by FX74modsm. We also observe that the S1223 has the highest drag coefficient value out of all the three airfoils. Hence we give E423 the highest score of 3 followed by 2 for FX74modsm and the least favourable score of 1 to S1223.

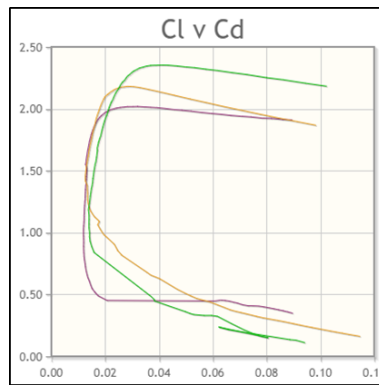


Fig. 2d. Graph of C_l vs. C_d

The figure 2b shows the variation of aerodynamic efficiency, that is the ratio of C_l to C_d versus angle of attack. We observe that the E423 has the highest C_l to C_d ratio at approximately 5° followed by FX74modsm and then the S1223 has the least C_l to C_d ratio relative to the other two. Hence, E423 gets the highest score of 3 and S1223 gets the least score of 1.

The table below is the integral representation of the reference scoring methodology employed to choose one Airfoil. The scores for individual parameters are distributed and then the Airfoil's total score is computed.

Table 2a. Reference Scoring Chart

Airfoil	S1223	FX74MODSM	E423
Parameter			
$C_{l_{max}}$	3	2	1
$C_{d_{min}}$	1	2	3
α_{stall}	3	1	2
Cl/Cd	1	2	3
Ease of Fabrication	1	2	3
Total Score	9	9	12

2.2 ANALYSIS OF MORPHED CONTROL SURFACE

The primary task, to be able to define any analysis was to figure out a method to modify the E423 airfoil. It is a highly tedious task to be changing the co-ordinates of the airfoil empirically to replicate a morphed trailing edge. To avoid this, we imported the airfoil co-ordinates into CATIA Generative Shape Design.

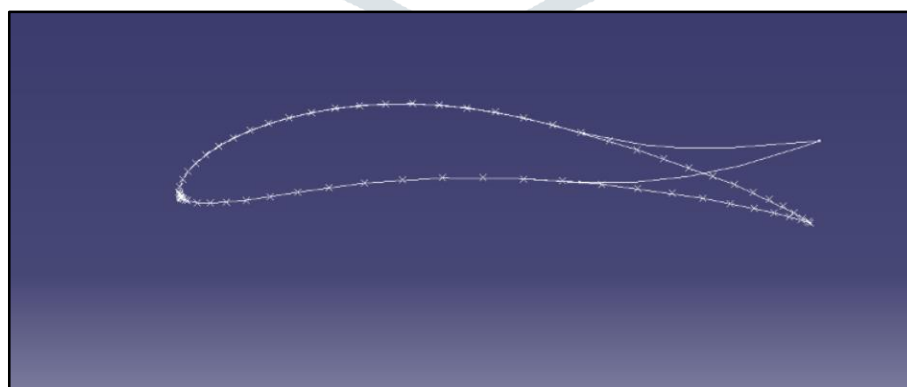


Fig. 2e. Imported Airfoil Co-Ordinates

The airfoil profile was extruded to form a surface. This airfoil surface was deformed to imitate a control surface deflection by using the SHAPE MORPHING tool. And once the surface was morphed, a 2-D profile of the morphed airfoil was projected. This morphed airfoil profile was used to create a 2-D surface which was then imported into the ANSYS Workbench.

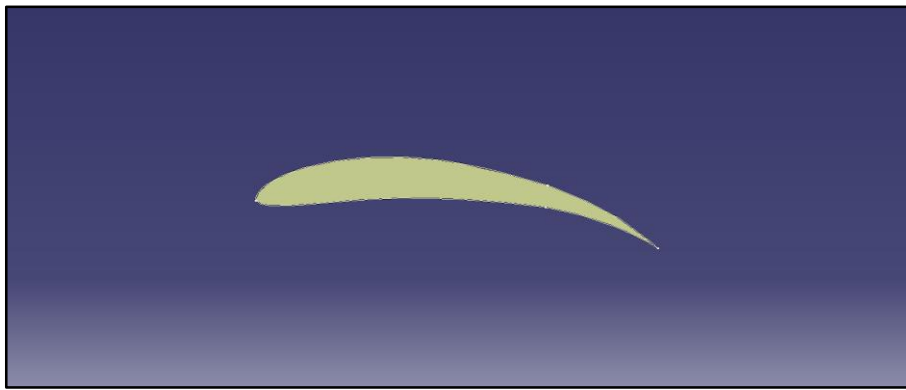


Fig. 2f. Morphed Airfoil Surface

The airfoil surface was saved in .igs format and was then imported into ANSYS Fluent. The Geometry of a test section was sketched and the airfoil surface was removed to create the impression of the airfoil cavity using Boolean tool.



Fig. 2g. ANSYS Geometry

A fine Mesh with a sufficient inflation layers was created in the test section with 28715 nodes and 48591 elements.

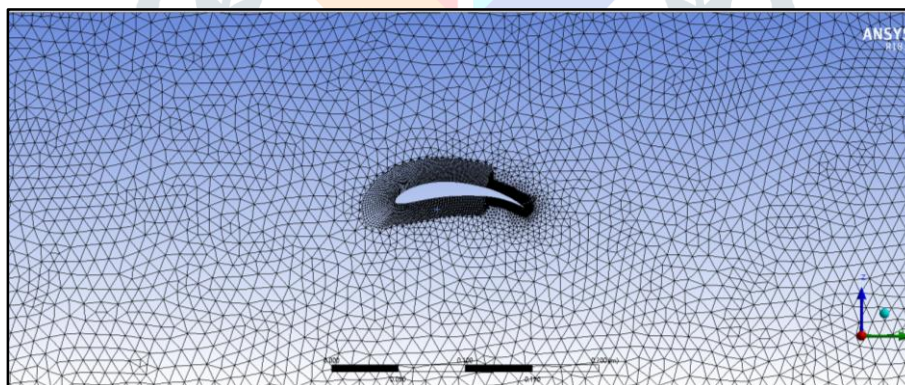


Fig. 2h. ANSYS Mesh

Named sections of the Inlet, Outlet, Wall and Airfoil walls were created in order to help set up the analysis. The model was set up to compute in steady state, pressure based results of the airfoil with a constant flow of air at 20m/s inlet velocity. The model was Hybrid Initialized and was run for calculations. The set-up also involved reporting the drag and lift coefficient plots at the solution.

The morphed airfoil was analyzed and the pressure and velocity contours were obtained along with the lift and drag coefficients. The above steps were repeated with a hinged airfoil and the corresponding results were obtained.

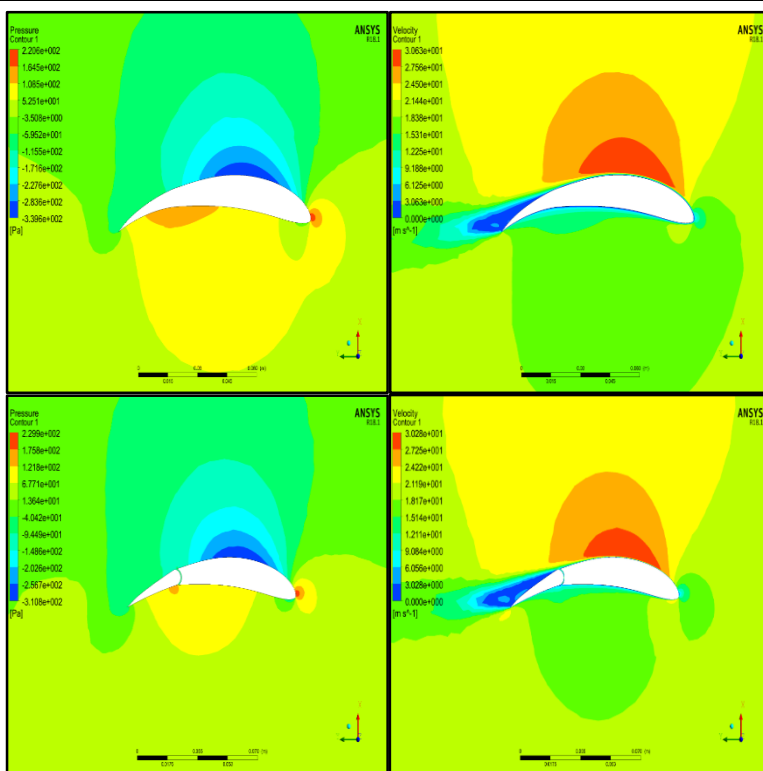


Fig. 2i. (a) Pressure Contour of Morphed (Top Left), (b) Velocity Contour of Morphed (Top Right), (c) Pressure Contour of Hinged (Bottom Left), (d) Velocity Contour of Hinged (Bottom Right)

The table below shows us the lift and drag coefficients along with the aerodynamic efficiency of morphed and hinged airfoil profiles.

Table 2b. Airfoil Parameters Comparison

Parameters	Hinged	Morphed
C_l	0.4481	0.5527
C_d	0.026	0.0273
C_l/C_d	17.2346	20.2454

III. PRELIMINARY DESIGN

3.1 DESIGNING THE PROTOTYPE

The goal was to keep the monolithic structure as the rib design and a strong leading edge region. The resulting design was generated as shown below.

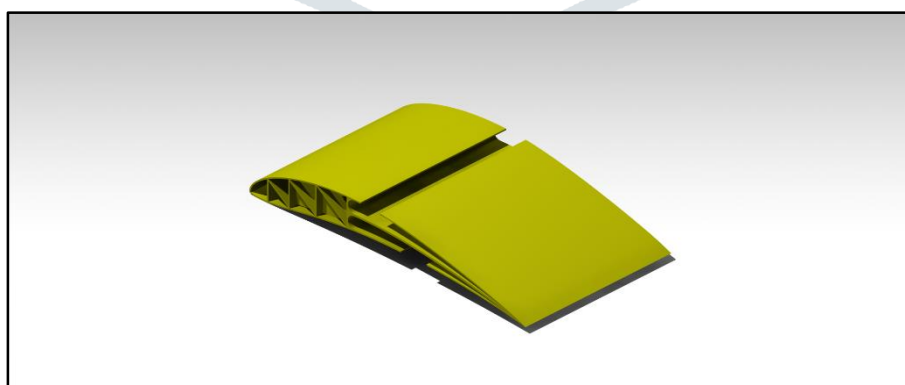


Fig. 3a. Inner Compliant Core

The figure above shows the structure to possess the leading edge truss and a compliant structure along the mean camber line after 45% of the chord all the way up until the trailing edge. Corrugations were preserved and were moved further upstream.

The two part wing structure was put through a Structural Analysis Test for Maximum Elastic Von-Mises Strain. The Steps followed are as mentioned below.

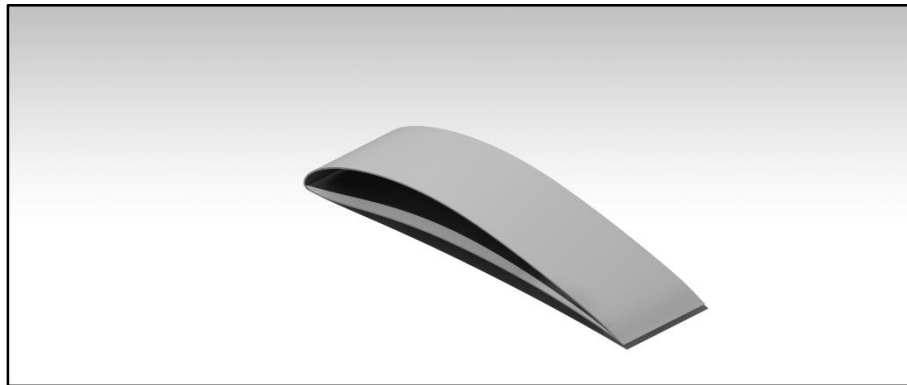
- The product was converted to “.iges” format and imported into Ansys Work bench static Structural Geometry Window.
- The mechanical properties of the materials used was saved at the Engineering Data tab as follows.

Table 3a. Mechanical Properties of PLA and TPU input at Engineering Data Tab

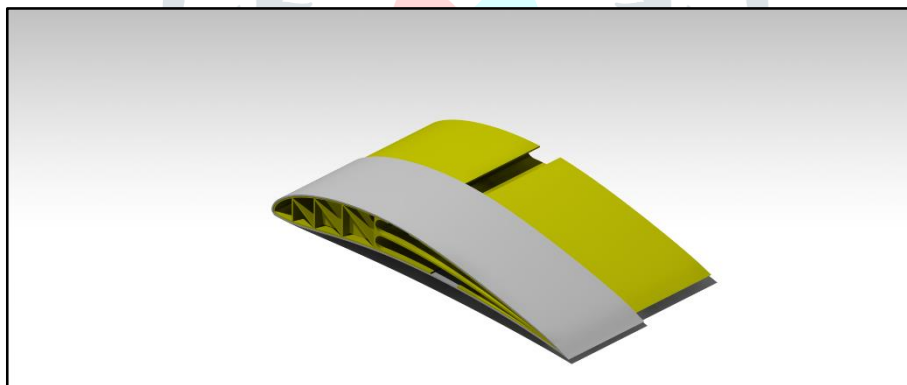
Material	Density (kg/m ³)	Young's Modulus (MPa)	Poisson's Ratio
PLA	1260	2454	0.33
TPU	1350	12	0.38

- The saved material data was assigned to their respective parts.
- The model was meshed and refined to the second order. This was done to increase the number of nodes thereby facilitating an accurate result.

The Inner Core Element, 3D printed out of PLA, was to be covered using a flexible skin which also shares the same profile as that of the chosen airfoil. This Skin was 3D printed using TPU filament and was done to keep a smooth surface exposed to the air (fluid). The following figure represents what the skin will look like.

**Fig. 3b. Flexible Outer Skin**

The figure below shows us how the Compliant Inner Core easily slides into the Flexible Outer Skin.

**Fig. 3c. Wing Structure of the Prototype**

3.2 STRUCTURAL ANALYSIS

A structural analysis was conducted and the steps mentioned below were followed.

- Engineering Data was updated with mechanical properties of PLA filament and the Inner core was imported into geometry window.
- This was further meshed and the analysis settings were updated as follows.
- The entire truss leading edge region was identified as a fixed support and a force of 100N was applied at the control horn in the pulling direction which makes the control surface deflect down.
- The figure below shows the location of the fixed support and the location where the load is applied and also the direction of the load.

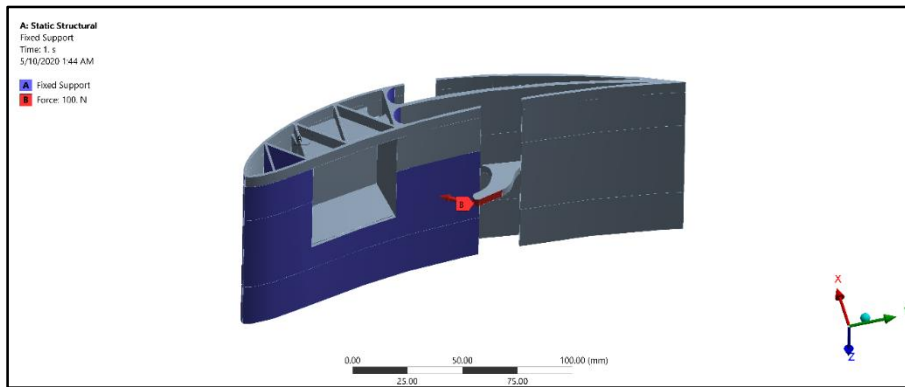


Fig. 3d. Locations of Fixed Support and Load Application

- The model was analyzed for Equivalent Von Mises Strain and Total Deformation.
- The following figure shows us the maximum deformation to be recorded at 16.252mm and the maximum strain at the control horn to be 0.03203mm/mm and at the maximum strain at the upper mean camber line to be 0.00711 mm/mm.

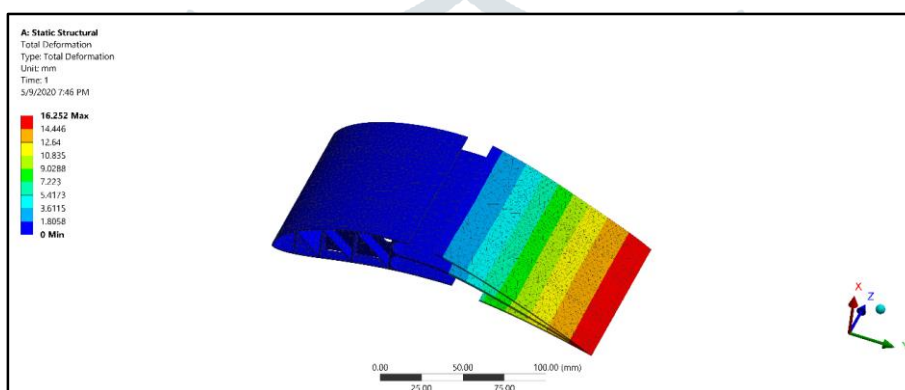


Fig. 3e. Total Deformation

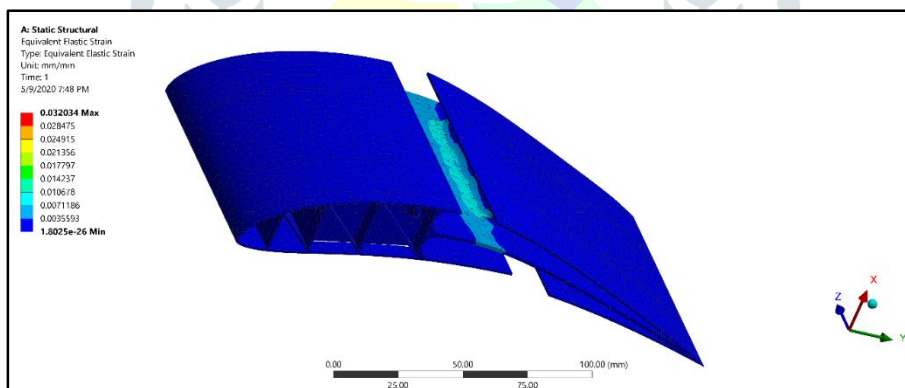


Fig. 3f. Maximum Strain at Upper Mean Camber Line

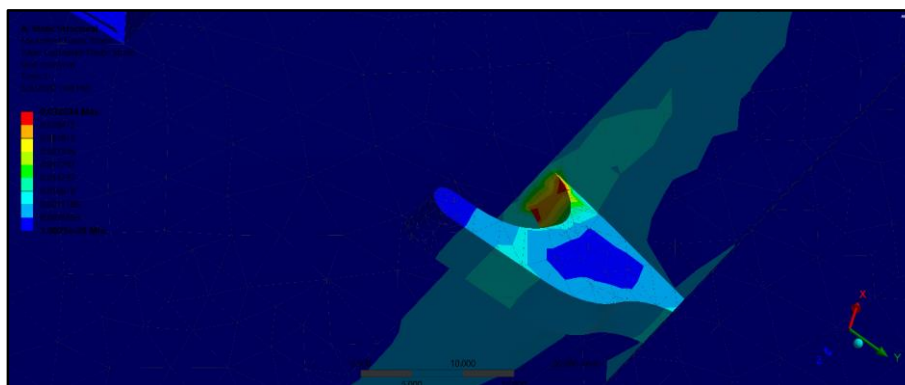


Fig. 3g. Maximum Strain at Control Horn

IV. RESULTS AND DISCUSSIONS

The mechanism was tested and proven for enhancing aerodynamic as well as structural efficiency. The design was fabricated and the structural analysis was experimentally verified.

The following results were observed during the experimental testing of the assembly after 3D printing the model.

Parameters	Computational	Experimental
Max Down Deflection	16 mm	20mm
Max Up Deflection	14mm	18mm

The model was extensively tested for fatigue by means of recording the operational time and the number of cycles of Neutral-UP-Down-Neutral Sequence. The following were the results of this experimental test to determine the Optimum number of operational cycles.

Cycle Sequence	Cycle Duration	Number of Cycles	Average Down Deflection	Average Up Deflection
N-Up-Down-N	300s	84	19mm	15mm
	600s	200	23mm	19mm

As and when the duration of run time of the Inner Core was increased, it was observed that there was a slight increase in the deflection values. This experimental test was conducted in a rather primitive arrangement and helped us empirically determine the maximum number of times it would be safe to operate this compliant mechanism. It was determined that any more number of cycles after the 300 mark would result in a partial structural failure, therefore considering a FOS of 0.5, it was empirically established that 150 cycles within a time frame of 800s was the optimum number of cycles.

V. CONCLUSION

This concept of morphing airfoils could bring about a radical enhancement of efficiency to the aviation industry. The right combination of structural members and their materials is crucial to develop morphing mechanisms that can be certified air worthy. This report gives a comprehensive solution to determine the material combination and manufacturing process of such compliant structures which allow controlled deformations for scaled models and experimental models only. To be able to develop such technology for real aircrafts, it would require the elimination of the empirical assumptions made in this report. Although, there have been Industries like FlexSys Inc. who have successfully achieved morphing for real passenger planes like the Gulfstream G650. This, however, still does have a comprehensive number of tests to undergo before being certified Air worthy by the FAA.

In conclusion, it is observed that morphed wings can be proved to be more aerodynamically efficient thereby bringing about a drastic change in the way we usually fly. It brings us a step closer to the efficiency with which the birds we see around us fly at.

VI. ACKNOWLEDGMENT

We thank the writers whose research papers we referred and developed the baseline for our research work, which we were able to change and deliver good results according to our requirements. Our mentor, Dr. R Rajendran, we are grateful to him for his helpful feedback. We extend our gratitude to Flexfoil (by FlexSys Inc.) for the inspiration. The variable surface controls of FlexFoil, geometrically reflect a major change over traditional aircraft flaps. The FlexFoil control surface adjusts wing cambers as they are moving rather than utilizing the heavy and bulky system of the regular wing assemblies, by leveraging the inherent elasticity of aviation grade materials.

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