A LIQUID METAL MORPHABLE AIRFOIL WITH ACTUATED AILERONS

By:

Neil A. Sen
Master of Engineering candidate in Mechanical Engineering
Sibley School of Mechanical and Aerospace Engineering
Cornell University
23 Winding Brook Way
Edison, NJ 08820
nas75@cornell.edu
908-507-8674

Advised By:

Professor Robert F. Shepherd
Sibley School of Mechanical and Aerospace Engineering
Cornell University
Ithaca, NY 14853

Abstract

In the last few decades, aircraft designers have sought to be able to change an aircraft’s airfoil geometry midflight in order to optimize the flight characteristics for its current operating conditions. Past work included designing aircraft with variable planform geometries, but there are currently no successful designs of aircraft that can change the cross-sectional shape of their wings.

In this project, an airfoil made primarily of metal with low melting temperature is being investigated. The goal of this project is to design a wing that can be melted and reformed midflight. The airfoil’s geometry has to be controllable and has to react to the pilot’s input quickly.

The design process involved using various engineering simulation tools, namely finite element analysis (FEA) and computational fluid dynamics (CFD) to analyze and optimize the airfoil for its flight characteristics, its structural integrity, and the flow characteristics of the liquid metal of which the airfoil will be made. Engineering simulations have the advantage of providing feedback without the construction of costly prototypes.

Using these techniques, a workable design was reached. The next steps for the project is to construct and test a prototype in order to verify and validate the simulation results.

Introduction

Airfoils are designed with the generally expected operating conditions of the aircraft in mind. Despite that, aircraft may need mission-specific airfoil geometry optimization. There was already work done to address this in the past, when aircraft such as the Grumman F-14 Tomcat used variable-sweep wings in order to optimize its flight characteristics depending on its operating conditions (Subbarao).

Conventional geometry variation would involve very complex actuation systems. For that reason, an airfoil primarily made of metal with a low melting temperature is being investigated.

The goal of this project is to design a wing made of metal with a low melting temperature contained in an elastomer. When it is desired that part of the wing's geometry be altered to better suit the aircraft's present operating condition, metal can be melted and then pumped in or out of the part of the wing where the geometry needs to be adjusted. It is also important such changes can be made quickly as maneuvers have to be made as soon as the pilot wants it to happen.

The design will be optimized using computational fluid dynamics (CFD) and finite element analysis (FEA) simulation tools. The software used will be Fluent and ANSYS respectively.

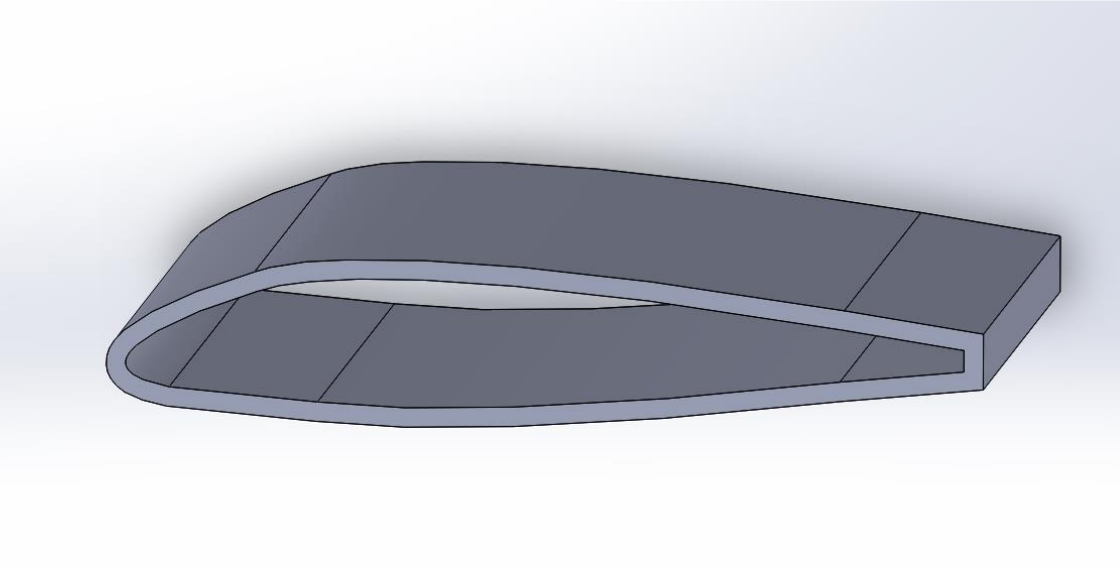
Methods

Designing an Airfoil

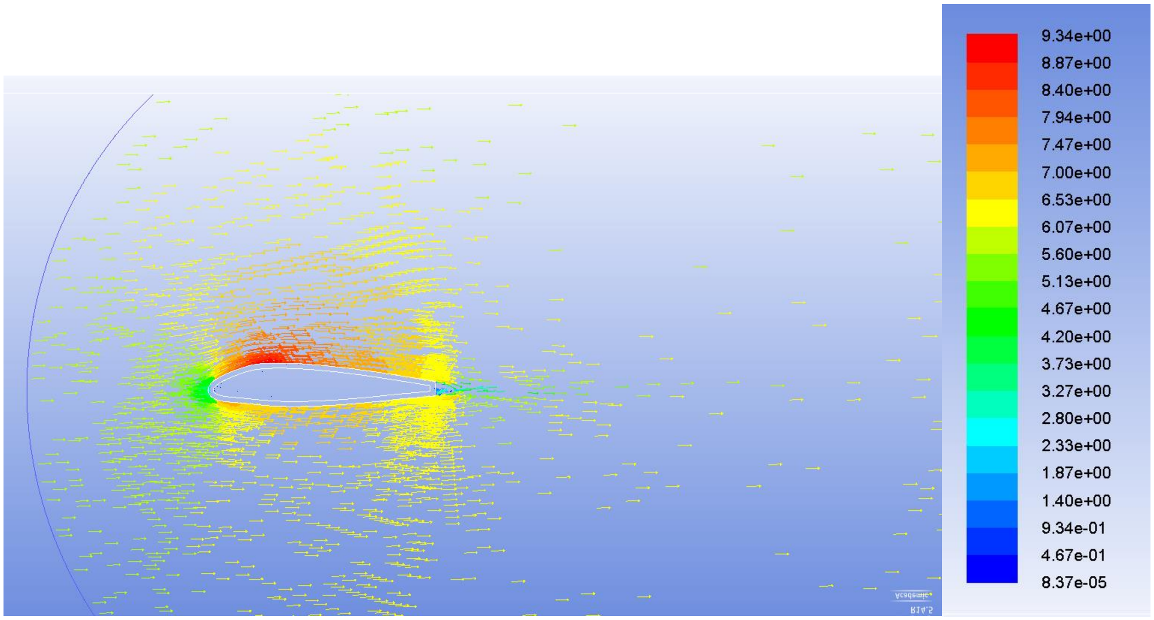
For a base airfoil, the NACA 23012 profile was selected. The NACA 5-Digit series airfoils are used for general aviation, and they have the advantages of higher maximum lift coefficient and low pitching moment (Marzocca). The NACA 23012 has seen use on small propeller aircraft like the Aero Boero AB-115 and the Aero Commander 500 Shrike. As the aircraft on which the morphing airfoil will be mounted is not expected to fly very fast, the selection of the NACA 23012 seems appropriate.

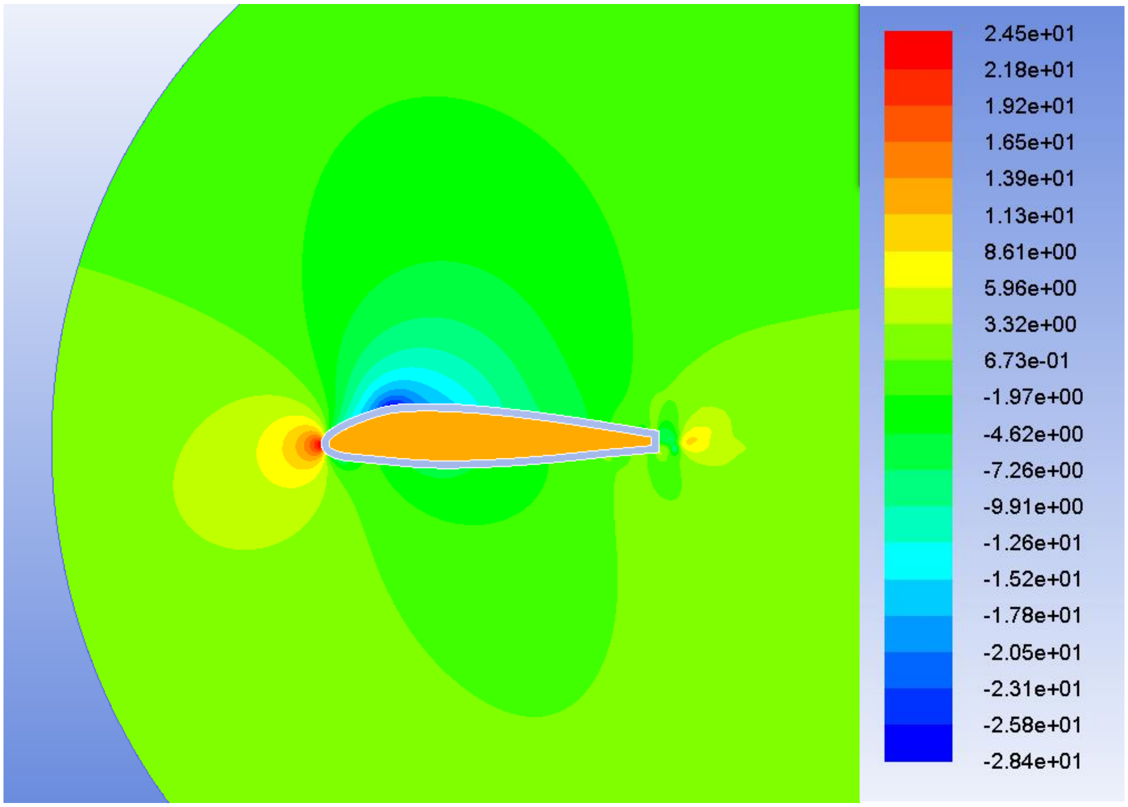
The airfoil's structure will be made with Field's Metal encased in M4601 elastomer. Field's Metal has a low melting temperature of about 64 degrees Celsius, and M4601 is a soft, durable material (Field).

A CAD model of the NACA 23012 was imported into ANSYS Fluent to analyze its flight characteristics.



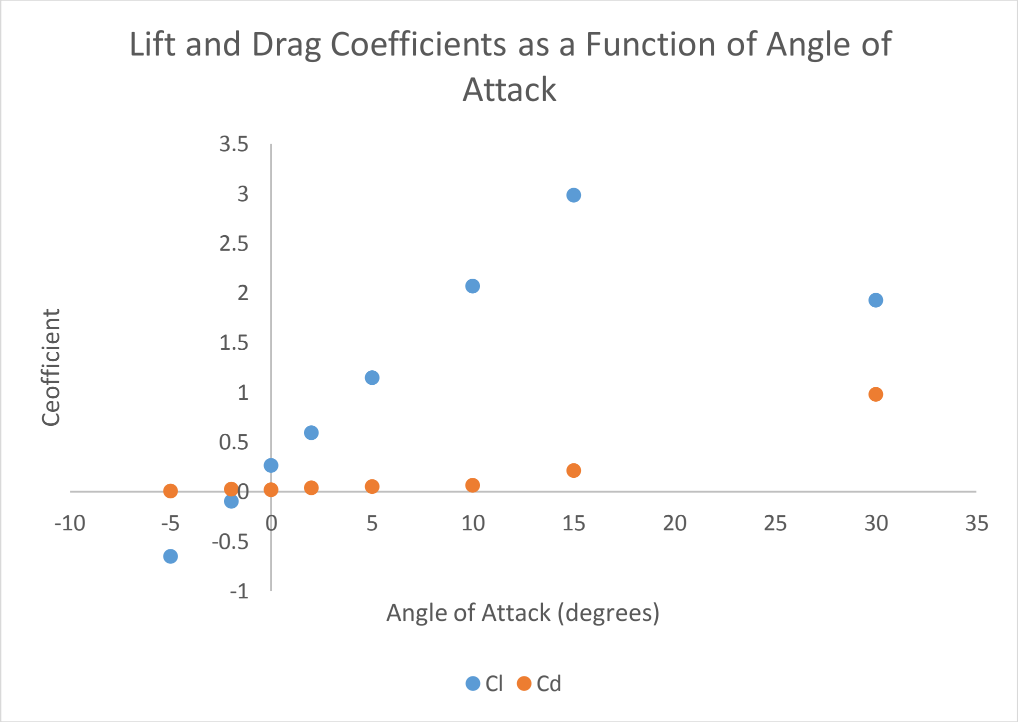
The initial test case was using an airspeed of 6 m/s, or 13.4 mph, at an angle of attack of 2 degrees. The air flows above the wing quite a bit faster than it does below the wing, and the net pressure distribution pushes the airfoil up, thus showing the airfoil to have ideal lift characteristics.





The simulation was rerun over a range of angles of attack to find how the coefficients of lift (C_l) and the coefficients of drag (C_d) vary. As expected for an airfoil used in normal flight, both coefficients increase steadily until they reach an angle of attack of 15 degrees. After that point, the coefficient of lift drops dramatically while the drag coefficient increases more dramatically, which is unsurprising as an aircraft would be expected to stall at such steep ascents. From 15 to 30 degrees, the drag coefficient increases almost 5 times while the lift coefficient sees a 35 percent reduction.

Angle of Attack (degrees)	Cl	Cd
2	0.593978	0.036583
5	1.148015	0.0533
10	2.06787	0.063972
15	2.987791	0.213168
30	1.92816	0.97923
-2	-0.09689	0.02828
-5	-0.64782	0.008046
0	0.261931	0.020678



In addition to lifting the aircraft, the airfoil has to be controllable. The aileron of the airfoil has to be actuated by pumping liquid Field's metal into its section, which would cause the aileron to bend as a result of its internal loading and the mechanics of the M4601. Before that could be done, the flow characteristics of the Field's Metal had to be understood.

Modeling the Flow of the Field's Metal

Modeling the flow of the Field's Metal as it goes through the tubes to get from one part of the aircraft to another involved generating a numerical solution to the Navier-Stokes equations. Assuming a uniform viscosity, the full Navier-Stokes equations are:

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho\boldsymbol{u}\cdot\nabla\boldsymbol{u} = -\nabla p + \mu\nabla^2\boldsymbol{u}$$

For the purposes of this project, several simplifying assumptions were made. The flow was assumed to be steady state, and thus the acceleration term went to 0. The flow was taken to be onedimensional, so the velocity vector only contained one non-zero component. Field's Metal was also assumed to be incompressible, causing $\rho \boldsymbol{u} \cdot \nabla \boldsymbol{u}$ to go to 0 as well.

The dynamic viscosity of Field's Metal has not been documented, but it can be calculated based on its material properties and its current temperature. The following equation for the calculation of the viscosity of liquid metals was derived by George Kaptay:

$$\mu = A \cdot \frac{M_i^{\frac{2}{3}}}{V_i^{\frac{2}{3}}} \cdot T^{\frac{1}{2}} \cdot \exp\left(B \cdot \frac{T_{m,i}}{T}\right)$$

Contained in the equation are several parameters. $T_{m,i}$ is the metal's melting temperature. M_i and V_i are the metal's atomic mass and molar volume respectively. A and B are constant parameters, where $A = (1.80 \pm 0.39) \cdot 10^8 \left(\frac{J}{K \cdot mol^{\frac{1}{3}}}\right)^{\frac{1}{2}}$ and $B = \ 2.34 \ \pm 0.20$. The metal's viscosity is a function of its current temperature$T$.

At a temperature of 100 degrees Celsius, the viscosity of Field's Metal was calculated to be about 0.0016 kg/m·s. When compared to results published by Hildebrand and Lamoreaux, the calculated value of Field's Metal's viscosity falls well within a reasonable ball park of what the dynamic viscosity of a liquid metal is expected to be.

Using the method outlined by Kirby, the fluid flow was discretized in the direction going across the flow, the differential equation was transformed into a series of linear algebraic equations, and translated into a MATLAB solver that solves for the "cell center" values of the liquid metal's speed.

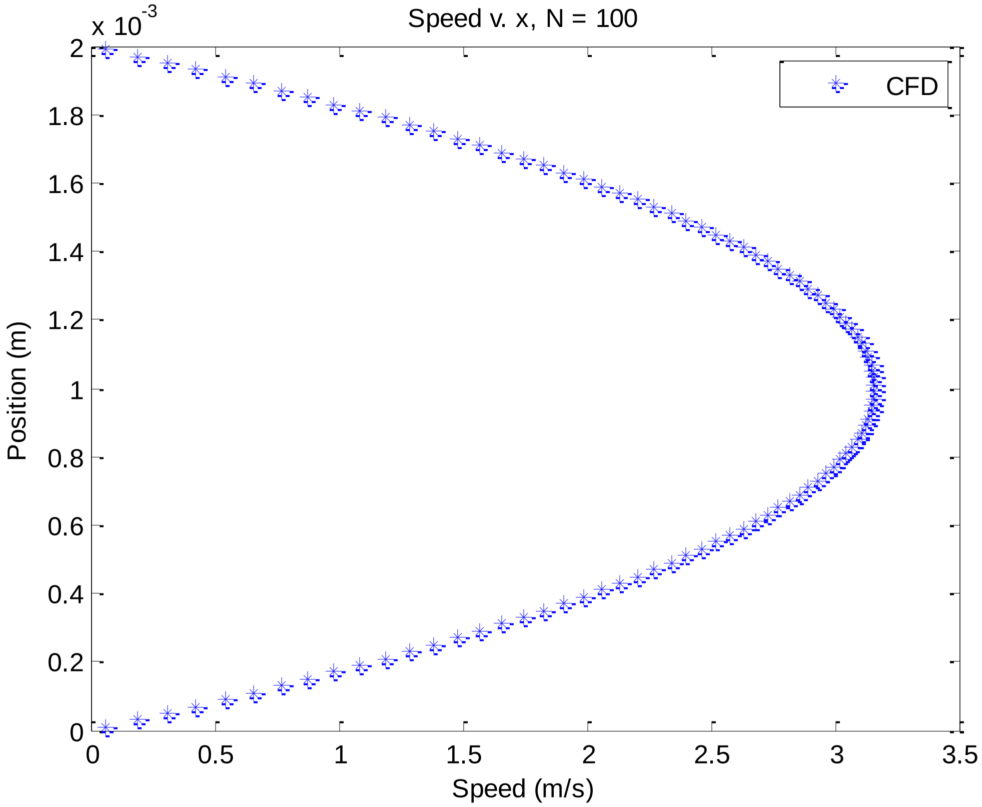
The user can input the number of divisions, depending on the desired fineness of the mesh, the Field's Metal's temperature, the width of the channel the Field's Metal will be flowing through, and the expected pressure gradient that would be driving the Field's Metal.

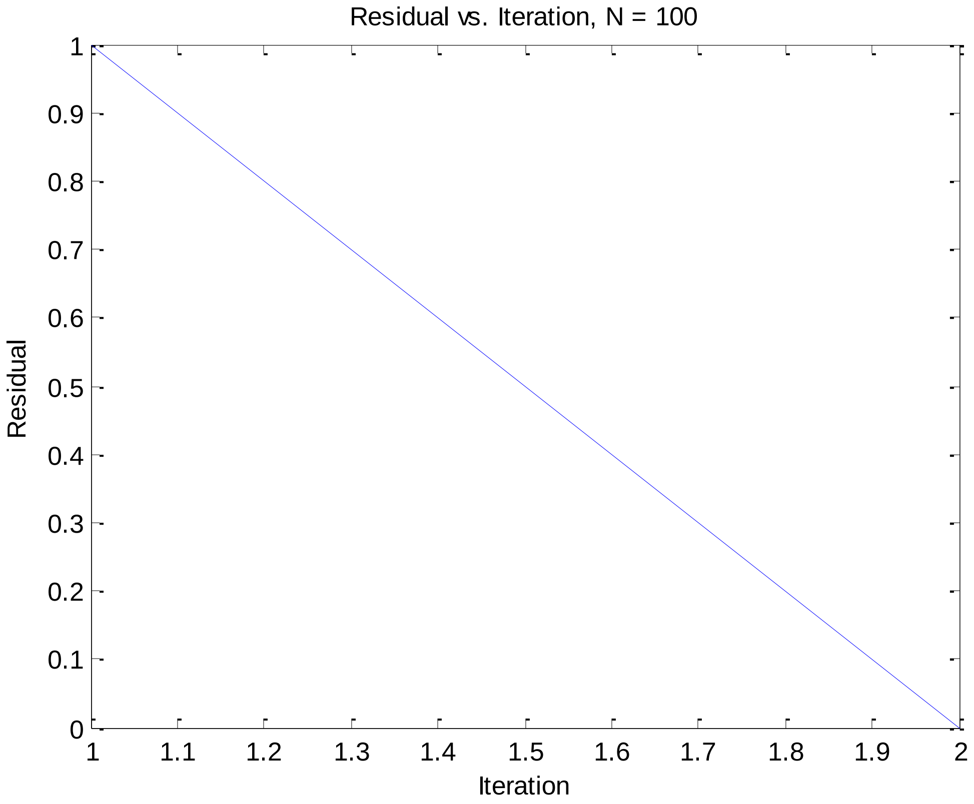
One of the assumptions made is the no-slip condition. The model will return a laminar velocity profile, which is reasonable given the material properties of the Field's Metal and the speeds it is expected to flow.

While there were not any in the model used in this project, the code was written in anticipation of future modification to account for possible nonlinearities in the fluid flow. The solver would start with an initial guess value in the cells, solve the equations and calculate the residual, the discrepancy between the updated guess and the previous guess values:

$$R = \sqrt{\frac{N\Sigma_i\left(u_i - u_{g,i}\right)^2}{\Sigma_i u_i}}$$

The code would iterate the values until the residual falls below 10^{-6}, the criterion at which round off error typically ceases to be significant.


Speed v. x, N = 100
x 10^-3
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Position (m)
CFD
0
0.5
1
1.5
2
2.5
3
3.5
Speed (m/s)

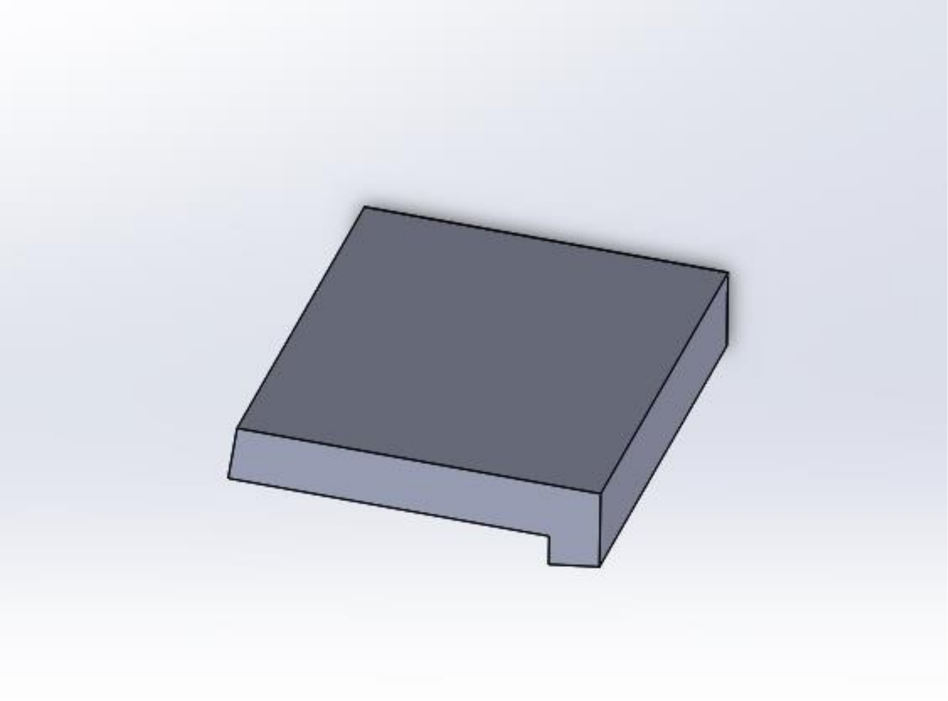

Residual vs. Iteration, N = 100
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Residual
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
Iteration

Designing the Ailerons

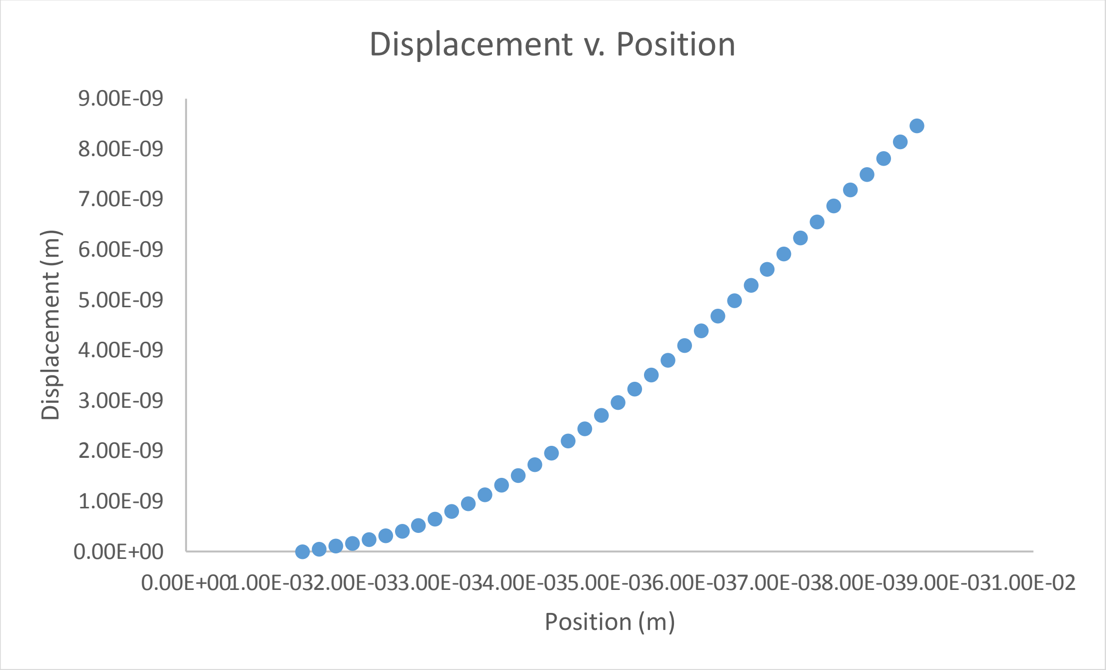
The proposed design of the ailerons is pumping Field's Metal into a series of cells made of M4601 elastomer. M4601 is much less stiff than Field's Metal. The two materials have elastic moduli of 720 kPa and 6.2 GPa respectively. The elastomer only has to hold the Field's Metal, keep it from leaking, and flex as it gets filled, while the Field's Metal bears the brunt of the aileron's structure.

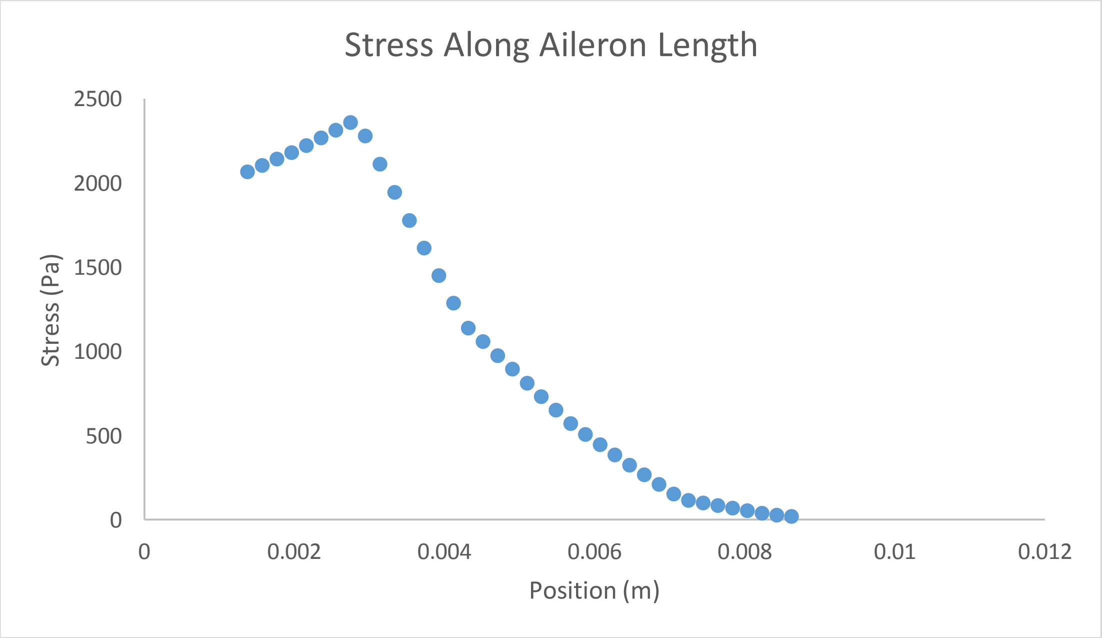
While M4601 is an elastomer, test data shows that it behaves like a linear elastic material when subjected to small deformation. For that reason, the elastomer was treated as an isotropic linearly elastic material when its data was entered into ANSYS.

An example aileron was simulated in ANSYS, subjected to a pressure of 22 Pa acting at an angle of 30 degrees. In the initial Fluent simulation, 22 Pa was calculated to be the maximum pressure the airfoil would expect to encounter, and a Boeing 737 is known to be able to deflect its ailerons at a maximum angle of 30 degrees.

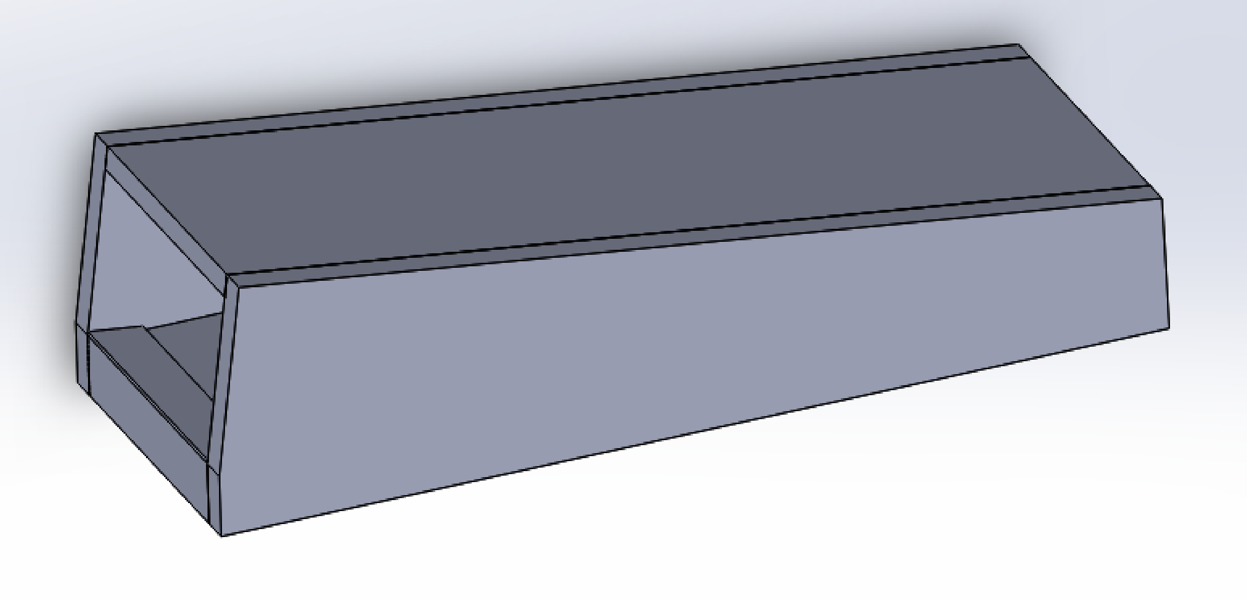


The variation of stress and displacement were found to both be well within acceptable limits. The maximum displacement was found to be on the order of nanometers.

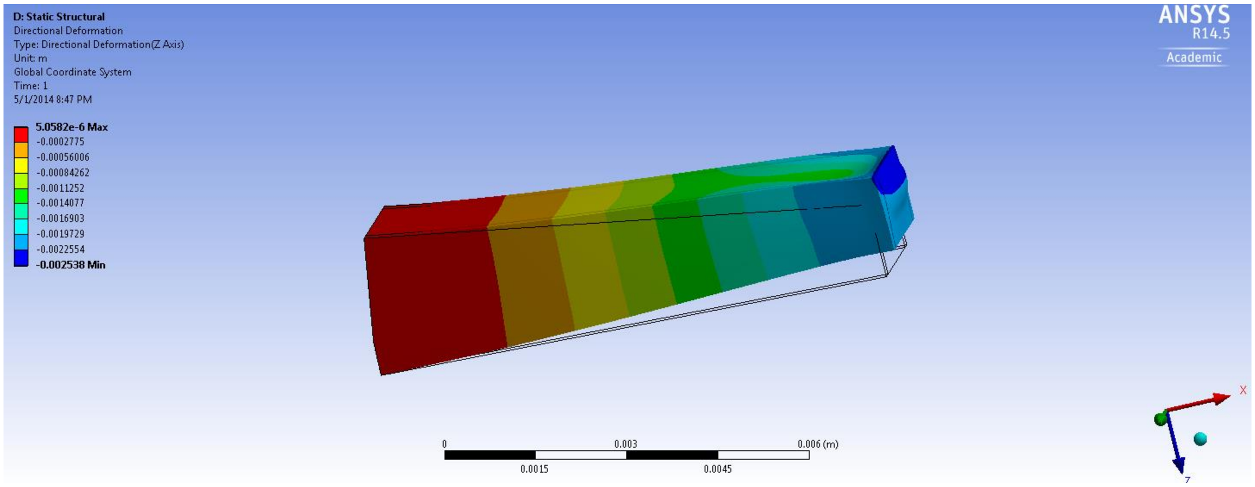




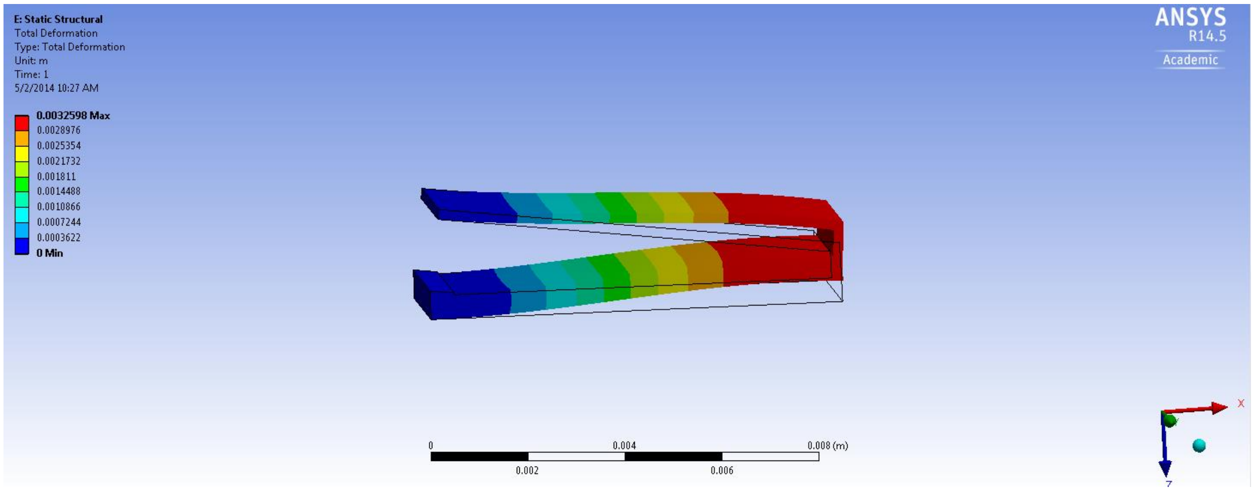
When it was found that the Field's Metal would be more than able to stand up to the aerodynamic pressure it would be subject to, the pressure needed to inflate the ailerons had to be found. The cells would have elastomer walls 0.25 mm thick, except at the bottom where it would be 0.5 mm thick. One proposed cell was then analyzed in ANSYS.



A pressure of 200,000 Pa, or 29 psi, was applied to the inside surface at the trailing end of the cell. Most of the cell's stiffness came from the side walls due to their heights' contributions to their area moments of inertia.



When the same aileron was analyzed without its side walls, it could deflect 3.25 mm with an applied load of only 20,000 Pa, or 2.9 psi. Despite the tradeoff that comes with increased stiffness, the side walls are necessary to contain the Field’s Metal.



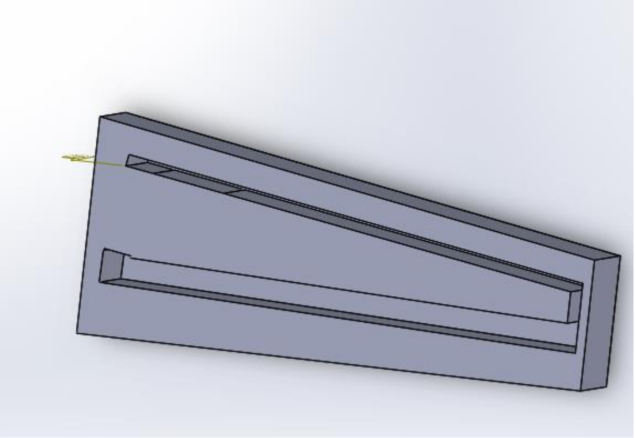
With this internal loading, the elastomer cell was found to deflect 2.5 mm upward at the trailing edge. Compared to a net length of about 8 mm, this would indicate a deflection of 18 degrees. A pressure of 200,000 Pa would mean a fluid flow of 7 m/s. Assuming the Field’s Metal is flowing through a pipe 2 mm in diameter, the cell should be filled in less than 0.0014 seconds. Such a flow would also require a pressure gradient of 4500 Pa/m in the direction of the flow.

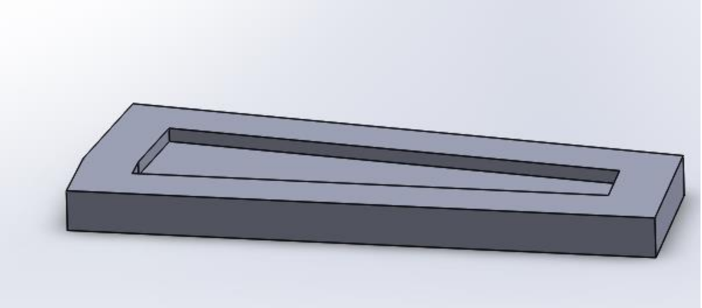
Making the Airfoil

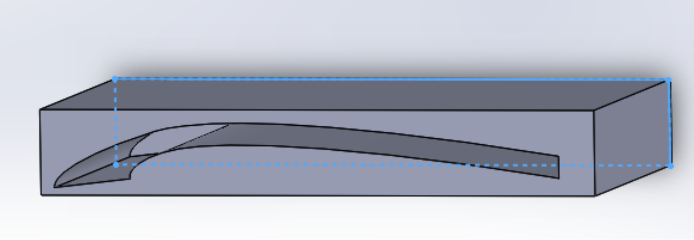
The elastomer cells that will contain the Field’s metal will be poured into molds, which will be 3D printed. A primary structure will be sealed off on the sides with walls with a thin layer of elastomer. Once the cells are put together, they will be injected with Field’s metal in order to make up the airfoil’s base structure. The cells will then be cemented together with more thin layers of elastomer.

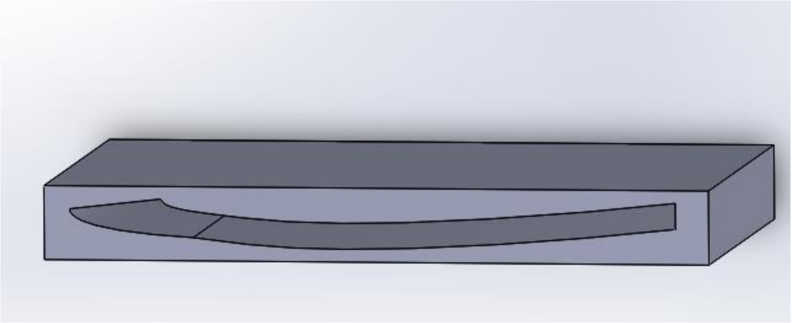
Given the geometry of the airfoil components, the elastomer will very likely stick to the molds as it cures. For that reason, it is recommended that the molds have a nonstick coating to facilitate extracting the elastomer.

Once the elastomer has been cured, it has to be thoroughly checked for weaknesses so it does not pop when inflated.









Conclusions

Based on the simulation results, this design of an airfoil appears to be one that should satisfy the requirements of an airfoil that can morph to suite the mission's needs midflight. The Field's Metal can flow at a high speed, which is critical for the wing to respond quickly to the pilot's input. The ailerons are also able to flex with reasonable amounts of pressure.

At the same time, it is absolutely necessary to build and test a prototype of this wing. The prototype would first have to be tested in a wind tunnel to measure the pressure distribution over a range of angles of attack to verify the simulated lift and drag coefficients.

The model for the Field's Metal's flow is under the assumption the metal stays at a constant temperature. In reality, it is expected the metal will cool down as it travels through the airfoil, which would result in increased viscosity. The Field's Metal's viscosity and speed would need to be empirically measured because there could be terms in the Navier-Stokes equations the model did not take into account. From the measurements, the model would need to be updated so the energy equation would be coupled to the Navier-Stokes equation through the viscosity equation.

The elastomer will also need to be tested. As elastomer structures have a tendency to pop when subjected to internal pressure, the integrity of the M4601 cells will need to be verified.

Once a physical model has been found to match what the simulations dictated, then this design is a good start to developing a morphable airfoil.

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