Design, Analysis and Construction of a Fin for Rocket Applications

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INTRODUCTION

Designing a rocket is a careful balance between stability and performance. The fins serve the purpose to stabilize the rocket at the cost of increased drag.

OpenRocket[1] is an existing tool that can be used to size the planform of the fin. Given a value for the the span, root chord, tip chord and sweep angle, the software can output the apogee and minimum stability of the rocket. It is of interest to find the fin geometry set that will result in the most stable rocket without sacrificing aerodynamic performance. Although OpenRocket comes with an optimization tool, it was not deemed sufficient for the task, since it does not support multiple constraint functions or multiple objectives. A custom optimization script was written in Python to extend the functionality of the software.

Another area where OpenRocket falls short is the characterization of the coefficient of drag of a fin with an airfoil. To find the airfoil best suited for the mission, a computer simulation was conducted to compare the performance of the diamond airfoil to the biconvex airfoil.

With the fin planform and airfoil determined, it is now possible to construct the fin. Several methods of construction were investigated, with a focus on inexpensive manufacturing. The manufacuting techinique should be repeatable, since any difference in one of the fins can make the rocket unstable.

PLANFORM SIZING: A MULTI-OBJECTIVE OPTIMIZATION PROBLEM

The optimization problem was defined using two desirability functions[2], one for the apogee requirement (9144m) and one for the stability requirement (1.5 body calibers). The value of the desirability function approaches unity as the parameter approaches the desired quantity, and the value decreases as the parameter undershoots or overshoots the desired quantity. Next, any number of constraints can be defined. This is done to eliminate unfeasible geometries from the design space. For example, the tip chord is constraint to be smaller than the root chord.

Now that the problem is defined, it needs to be solved. A genetic algorithm was chosen for the problem. The input to the algorithm is a fin geometry set. That geometry gets passed to OpenRocket, which acts as a black box that then outputs the apogee and minimum stability. From these results, the next generation of fin geometries is created.

Due to the multi-objective nature of the problem, there is no one absolute solution. Instead, the solution is a pareto optimal front, where certain combinations of the fin planform geometries favor high apogee-low stability designs, and other combinations favor low apogee-high stability designs. It is up to the designer to pick one geometry amongst the pareto optimal for the mission, based on the material and the maximum flight velocity.

DETERMINING AIRFOIL SHAPE THROUGH COMPUTER SIMULATIONS

Two candidates were explored for the fin airfoil: the biconvex airfoil, and the diamond airfoil. The optimum design of the fin airfoil was determined using a Computational Fluid Dynamics software, Ansys FLUENT. The $K - \omega$ SST turbulence model coupled with the density based solver were employed to obtain coefficients of drag. The simulations were run at two representative Mach numbers, Mach 1.4 and Mach 0.4. The airfoils' mesh was optimized by a number of ways. This entailed using a greater concentration of divisions on the walls on the rounded leading and trailing edges, the addition of inflation layers and the overall reduction in the size of mesh elements. A standard of y+ <5 was maintained in all airfoil simulations. This ensured the successful capture of the viscous sublayer on the wall boundary layers. Capturing the viscous sublayer produced sensible coefficient of drag results. Convergence of the residuals, coefficient of drag, and volume integrals were monitored to ensure that the results were accurate. The results from the CFD experiment suggested that the coefficient of drag of the diamond airfoil in the supersonic regime is nearly 33% lower than that of the biconvex airfoil. This resulted in the final decision of the diamond airfoil being chosen for the mission.

CONSTRUCTION

A two part female mold is constructed using a CNC machine. Carbon fiber is laid onto each half of the mold, and then the air is evacuated with a vacuum. After the two halves are made, additional sheets of carbon fiber and more epoxy is applied then the mold halves are bolted together. The pressure bonds the two halves with the new sheets to form a whole fin. When the part leaves the mold, the edges need to be trimmed and sanded. This process is repeatable and ensures that the diamond airfoil is captured each time, since the pressure of the molding process pushes the fibers into the contour of the mold.

Alternative inexpensive methods of construction were also considered, but they were less successful due to the small thickness of the fin. The construction of a male mold through additive layer manufacturing was attempted, but the printer did not capture the diamond profile correctly. Next, a male mold made from a foam cutter was constructed, but the foam was too fragile to use for laying composites.

RESULTS, CONCLUSIONS, AND FOLLOW-ON WORK

This paper outlined the design, analysis and construction of a fin for use on a high powered rocket. The initial sizing was determined through a custom-written optimization script that uses OpenRocket as a blackbox for the simulation data. Given an input fin geometry, the blackbox returns flight data such as the apogee and the minimum stability. Then, based on constraints and objectives, the optimization script will find a set of fin geometries that satisfy the multiple objectives. From there, a computation fluid dynamics experiment was conducted to find the airfoil that produced the least amount of drag. The diamond airfoil and the biconvex airfoil were compared, and it was shown that the diamond airfoil has superior performance for this specific mission. The fins were finally constructed out of carbon fiber using a female mold and vacuum bagging.

In future work, the optimization software can be extended to take into account the effect of the geometry on the structural integrity of the fin. For example, fin geometries that exasterbate flutter would be heavily penalized in the algorithm. The same script can also be extended to optimize other aspects of the rocket geometry, such as the length of the nose cone and the boat tail. With the fins constructured, they can be subject to non-destructive tests to validate the analysis conducted. For instance, a torsion test should be done to determine the shear modulus. Data from the test flight and the IREC flight can be used to calculate the coefficient of drag of the rocket, and compare with the simulated values.

REFERENCES

[1]Niskanen, S., “OpenRocket,” Software Package. Ver 15.3, 2015.
[2]NIST, *Engineering Statistics Handbook*, 2012, Chap. 5.