Spring 2022

Aerodynamics Wind Tunnel Lab

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Aerodynamics Wind Tunnel Lab and Wing Design

Senior Design Project

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Introduction:

The goal for the design project is to design and develop a lab experiment for aerodynamics students utilizing the University's subsonic wind tunnel. The purpose of the lab is to introduce aerodynamics students to basic principles of lift, drag, and moment. The lab focuses on a variable aspect ratio wing and will observe how the changes in aspect ratio affect a wing's performance. There were two main parts the project was split into: designing the variable wing interface and creating the lab instructions for the students. It was essential that the design of both the physical model and the written lab was sturdy enough to last several years for use in many aerodynamics classes.

The variable wing was the more labor intensive portion of the project. In order to change the aspect ratio of the wing, the span would need to be extendable. This was the impetus for our physical design which resulted in uniform extension pieces that could be added to a base wing. These uniform extensions would allow students to see the increase in lift and moment as well as decrease in drag coefficient as the aspect ratio increased. The focus in the design would be to create a simple and easy to use interface that could be changed relatively quickly. The span of the model wing starts with the base wing and extends to the edges of the wind tunnel test chamber in order to simulate an infinite wing. A wing of infinite length is a classic problem for students, which exists to show airflow around a 2D wing. As an infinite wing has no tips, there would be no 3D vortices being generated at the ends of the wing. These vortices result in a loss of the efficiency of the wing especially at lower aspect ratios. In the wind tunnel, the wing will span to the walls of the test chamber resulting in the same effect as a theoretical infinite wing. This wing design was the heart of this project.

The lab not only introduces students to the fundamentals concepts in aerodynamics, but also lays out procedures for the wind tunnel experiment. This includes general wind tunnel usage and background information for the wind tunnel itself. It would also include the data analysis approach that students would use in order to clearly represent the measured data. By clearly organizing and presenting data, it would be much easier to make informed conclusions on the results. The final part of the lab includes a section where students will design and manufacture their own winglets in order to show the reduction of the previously mentioned wing tip vortices.

Design Procedure:

The first item designed was the wing assembly as it would be the most intensive part. The force limits of the wind tunnel were crucial to the sizing of the wing and the speed at which the experiment was run at. Improper sizing or speed would result in damage to the wind tunnel. The wing will be quite wide in its largest configuration, spanning the entire test section of the wind tunnel. All calculations were done at this largest size as the forces experienced will be at a maximum. The speed of the air in the wind tunnel had to be large enough to produce a considerable amount of lift and drag on the wing. The wing is quite heavy at max span and the drag was important as it is the main focus of the experiment.

Below are the equations necessary to theoretically calculate the normal and axial force:

Formula for Wing lift and Drag:

$$L = \frac{1}{2} * \rho * V^2 * S * C_l \qquad (2.1)$$

$$D = \frac{1}{2} * \rho * V^2 * S * C_d \qquad (2.2)$$

Where ρ is air density, V is airspeed, S is planform area, and Cl & Cd are coefficients of lift and drag respectively.

Formula for Converting Lift and Drag to Normal and Axial Force:

$$L = N * cos(\alpha) - A * sin(\alpha) \qquad (2.3)$$

$$D = A * cos(\alpha) - N * sin(\alpha) \qquad (2.4)$$

Where N is normal force, A is axial force, and α is the angle of attack of the wing.

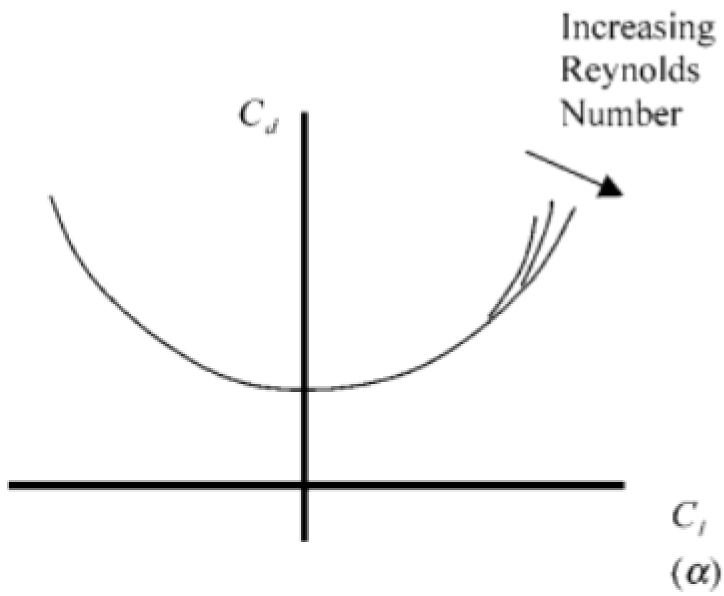
Using these equations the lift and drag force can be obtained from the axial and normal forces in the same way that will be done by students conducting the experiment. The wind tunnel max loads and all data output are given in normal and axial force. By specifying a wind speed and assuming standard atmospheric pressure, the lift force was calculated with varying S, or planform area, values. Due to the fact that the wing had a fixed span, at full extension the S value was a direct function of the chord value. The coefficient of lift and drag was set to the max values apparent in published C_l and C_d vs α plots to simulate the maximum loads the wing will experience. According to the calculations a chord length of 6 inches at a speed of 45 miles per hour would remain well below the damaging loads.

Once calculations were done with a factor of safety, 5 lbf, below max limits, a prototype wing was made to test the manufacturing method. 3D printing was the chosen method as it is versatile and cheap. The University of Akron offers 3D printing services and they were contacted to produce the wing. A rough prototype was made to test the capabilities and preciseness of the 3D printing. Once the prototype was made some changes were made to the design and a final wing assembly was printed. These changes mainly included adjusting hole diameters and the wall thickness of the prints.

Wanting a snug fit, the holes in the airfoil were intentionally slightly undersized in the CAD model. This allowed more precise tolerances to be made by drilling out the holes after printing. The snug friction fittings provide extra security to keep the wing together in the wing tunnel while undergoing loading. Once the holes were drilled out to acceptable sizes, the magnets were glued into place and the trantorque inserted. The surface of the wings were still rough from printing so they were sanded down to aid in aesthetics and aerodynamics.

The next major part to design was the lab instructions themselves. The main focus of the experiment/lab was to show the effect of aspect ratio has on the drag coefficient. This wing could be used for several different experiments, such as showing where the wing stalls and finding the zero lift angle of attack. For a focus on drag, an angle of attack of greater than zero was preferred. This is important because the aspect ratio plays a role in the lift induced portion of the drag polar equation which dictates the drag coefficient.

Figure (1): The Drag Polar Plotted



Source: Introduction to Aircraft Flight Mechanics

The instructions of the lab are based on the theoretical values for speed and angle of attack needed to prevent damage. Values beyond what are provided should not be exceeded. The experiment will begin at a low angle of attack and data will be collected for lift, drag, and moment for each aspect ratio. Two angles of attack can be run to provide more data to work with, as well as show the importance aspect ratio has in the lift induced portion of the drag polar.

The final portion of the lab includes a section for students to design their own winglets. This section only limits students' designs with the limits of the this projects' wing interface. Mainly the physical dimensions, of the wind tunnel and of the wing interface that the winglets will attach to, are the only constraints for student designs. A single basic winglet design was produced so that students have a baseline model to start from and something to compare to. Students will be left to do their own research on the most efficient and optimized winglet designs. Students will then manufacture and test their designs as the final portion of the wind tunnel lab.

Design Details:

For the wing interface, the airfoil, Clark Y, was selected as it is a very common airfoil and used on many planes. The chord length was set at 6 inches. The thickness of an airfoil is a function of its chord and 6 inches gave a satisfactory thickness to design the interface. This sized airfoil was large enough to give data at a reasonable scale, without being so large as to push the boundaries of the wind tunnel's capacity for axial and normal force. Ideally the chord would be set to a minimum to reduce the load on the wind tunnel while still giving accurate and reasonable data.

Once the chord was set, the connection interface was designed. The design included three holes throughout the span of the airfoil. The two outermost holes would hold two carbon fiber spars that would support the weight of the extension segments as well as prevent rotation. As there still may be small gaps in between the wing's extension pieces, airflow through these gaps may be enough to push the segments apart. Considering this, for added security, small quarter inch round neodymium magnets were added to the ends of each segment to provide an axial securing force across the span of the wing interface. The designed pull force between the magnets was 4.75 pounds. This is more than enough force to secure the segments together during testing even with unexpected span-wise forces due to gaps. Most airflow will be in line with the chord resulting in axial and normal forces that will not affect the positions of the extension pieces.

In figures 2 and 3, the models for the base wing and the extension piece designs may be found. In figure 4, an expanded view of all components may be seen. It should be noted that the length of the extension rods in the figure are only a representation of spars' placements and not representative of their actual length (14 inches).

Figure (2) &(3): Base Airfoil Section

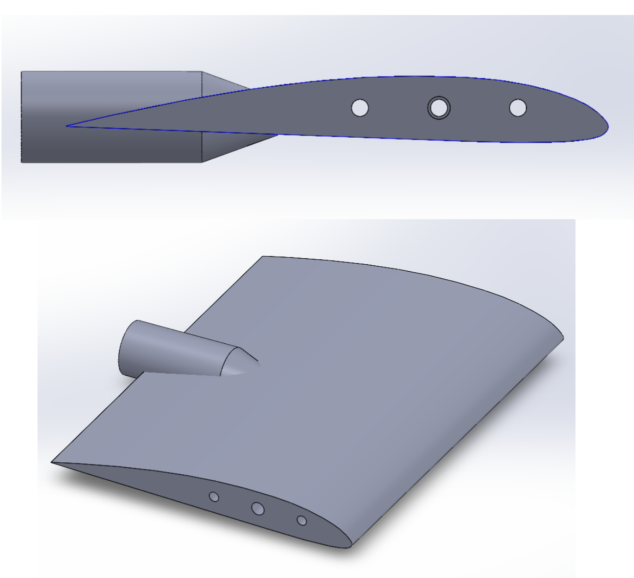
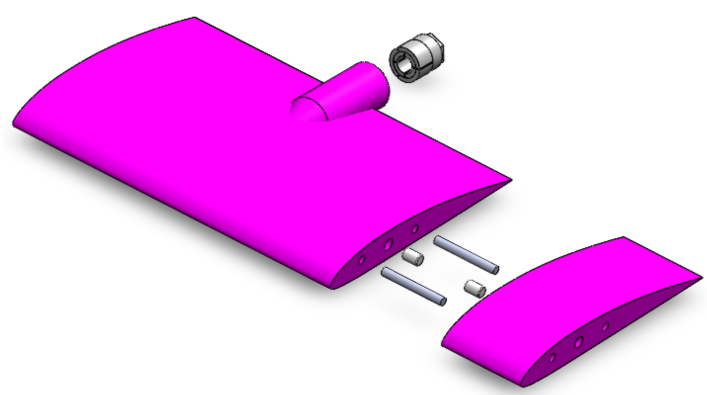


Figure (4): Expanded View with Extension



At the base of the airfoil was a cylindrical hole made to house a trantorque. This would secure the airfoil into the wind tunnel onto the sting. As the trantorque is tightened it will clamp onto the sting as well as expand into the airfoil attachment point.This allows for students to quickly attach and detach the wing interface as needed. Due to cracking in the initial prototype's mounting point, the walls of the model were strengthened by increasing the wall thickness. The strength of the new design will allow the interface to undergo much greater axial and normal forces.

For the experiment instructions, the critical angle of attack of the wing will be found. This will be initially confirmed by wind tunnel testing by the students. Then, students will move forward with the rest of the experiment. The angle of attack and airspeed would remain constant through the experiment. Other angles of attack will be used but the important factor is that it remains constant for all wing spans. Initially, the main body section would be run in the tunnel without extensions. Then, after data is collected, one segment will be attached onto the airfoil body by simply sliding the piece onto the rods. This pattern will continue until the wing spans the full length of the wind tunnel. It is important to note that the final configuration will simulate an infinite wing and the data should be viewed independently as to not skew the data.

Once data is collected at the required angles of attack it can be added to excel and converted into drag coefficient. In excel this can be easily plotted and the trends observed. As is the case with most experiments, the data collected can be compared to the theoretical numbers that will also be a part of the experiment. The students will not only gain knowledge of the effects of wing design but also experience with the wind tunnel that will prove to be useful later in their college career.

In the final portion of the lab, students will design, manufacture, and test their own winglet designs. As a part of the section, a single set of winglets was designed so students may have a baseline for how average winglets may affect the aerodynamics of the wing. Students will be familiarized with how the wing interface works from the previous sections of the lab. First, students will be given the CAD models for the wing extension sections. Then, it will be left to the students to research the most efficient winglet designs that would fit this application. Students will use this research to design their own winglet. They will use the wing extension CAD model as a basis for the general dimensional requirements necessary to join the wing interface.

Once the students have acquired the CAD models for their winglet designs, they will move to manufacturing. This process will include contacting the 3D print room to have their designs printed and then post processing of their design. These final steps in manufacturing include attaching the magnets to their designs and finishing the surface of the printed pieces likely by sanding. Students will then test their new winglets, the baseline winglets, and the wing without winglets. Again, students will process this testing data into consumable results. This test will, in theory, show aerodynamic benefits increasing between the wing without winglets versus the baseline winglets and then the baseline winglets versus the students' optimized winglets.

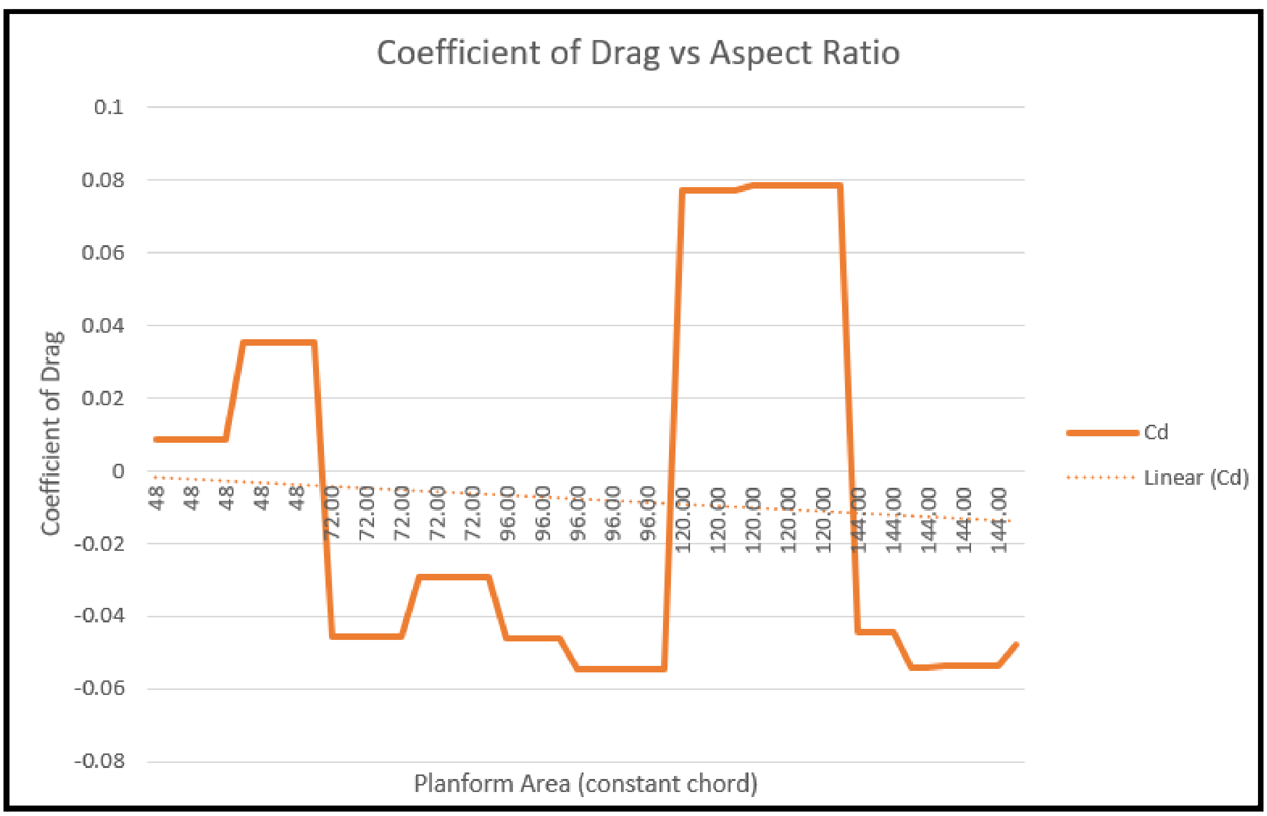
Verification:

With the wing model printed and assembled it was important to do tests in the wind tunnel to verify our theoretical calculations. First, the max load on the wind tunnel was tested. The wing was set to max angle of attack without stalling the airfoil and the speed in the wind tunnel was gradually increased. At 50 mph the strength of the spars became a major concern as the wing was visibly flexing along the span. Future tests would need to be run at 45 mph or less.

While running the experiment the results of increasing the aspect ratio were as expected. The coefficient of drag was decreasing with increasing the aspect ratio. One problem that arose was the imperfection of the wing causing contact on the side of the wind tunnel. This will greatly affect the forces detected by the wind tunnel and make the data point unreliable.

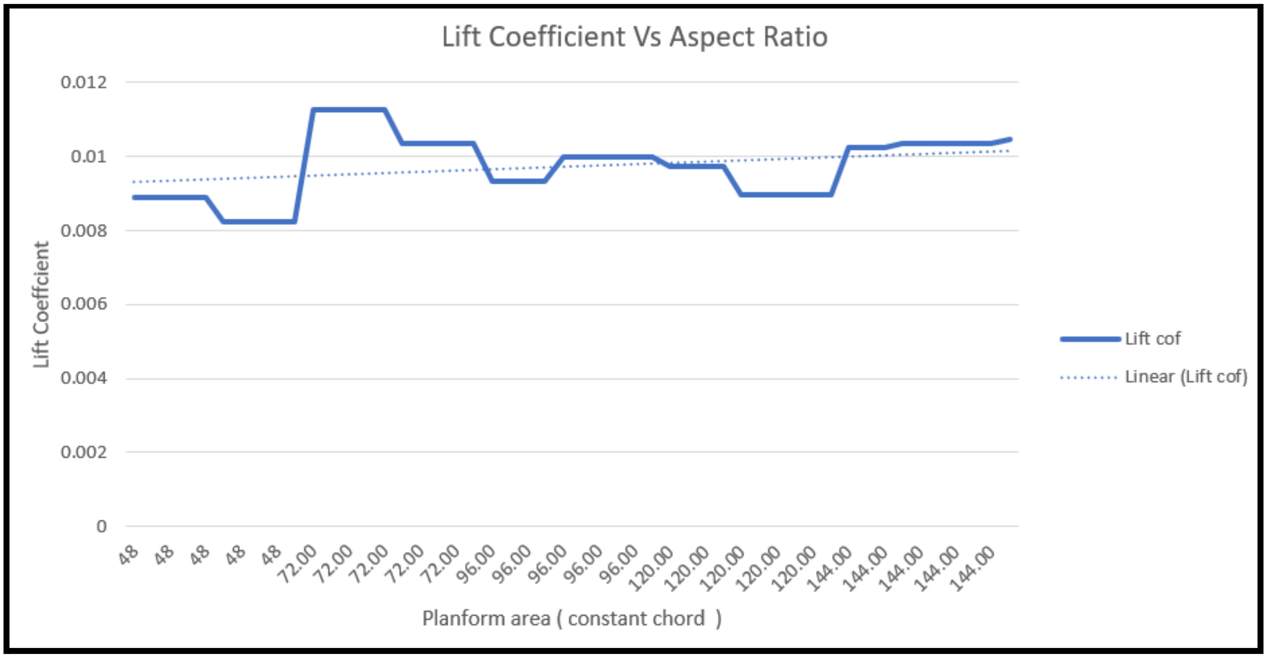
During the test the spar rods were left at full length and values were recorded at each aspect ratio. While the data was erratic, fitting a trend line to the data does show a very slight decrease in the drag coefficient. The data was not 100% reliable and another test should be performed to get data in a more accurate way. Human error, by the wind tunnel operator, likely caused much of the error leading to the unexpected and inaccurate data. This accounts for a large part of the uncertainty of the results and could be easily avoided in future testing.

Figure (5) Drag Coefficient vs Aspect Ratio:



From figure 5 it can be seen that the drag coefficient did in fact decrease except for one data set. The drag coefficient is also negative at times which indicates that there is an error.

Figure (6): Lift coefficient vs Aspect Ratio



The above figure shows the lift coefficient vs aspect ratio. The coefficient value increases with aspect ratio at a constant chord. This is expected and adds some reliability to the results. Again there are the same errors as described in the drag coefficient graph.

Despite the data showing errors it does show that the coefficient of drag will decrease with aspect ratio. With a proper single file wind tunnel test and minor changes to wing design the test can be accurately repeatable. The ability to run the test at higher speeds will show a greater variance in the coefficient values as both lift and drag vary directly with velocity squared. After some small manufacturing changes and experiment alterations, this experiment could be easily repeated to find more accurate results.

Costs:

Figure (7): Cost Analysis

Cost Analysis			
Materials:	Price Per Unit:	Amount:	Total:
1/4in. Round Neodymium Magnets	1.50$	50 magnets	75$
4mm x 1000mm Carbon Fiber Rods	5$	2 rods	10$
Gorilla Super Glue Gel (20g bottle)	7$	1 bottle	7$
ABS Plastic (3D Printing)	22$	2 kg	44$
Trantorque Mini 3/8in	60$	1 unit	60$
Services:	Price Per Unit:	Amount:	Total:
3D Printing	15$	30 hrs	450$
Wind Tunnel Testing Time	150$	10 hrs	1500$
Labor:	Price Per Unit:	Amount:	Total:
Engineer's Salary	40$	70hrs x 2	5,600$
		Total Estimated Project Cost:	7,746$

The costs of this project were relatively low overall. By far the largest contribution to the total estimated cost was incurred through the engineer's salary. Obviously, these are only estimates and not actual expenses to be concerned with. The other two large costs in the project were 3D printing and wind tunnel testing. Traditionally, wind tunnel testing is rather expensive, thankfully however, this project is focused on the university's own wind tunnel. The cost included in the table is a mere estimate that also includes an hourly rate for the TA in charge of assisting students with the wind tunnel. In addition, the university's own 3D printing services were used so there were no actual costs incurred by wind tunnel testing, 3D printing services, or 3D printing material. The actual costs incurred by this project were limited to the materials used in the attachments of the wing. These included: super glue, magnets, carbon fiber rods, and the trantorque. The trantorque was borrowed from the mechanical engineering department, so the glue, magnets, and rods were the only parts that led to real expenses. These items were also relatively low cost, which bodes well if there are to be future iterations on this project.

Conclusions:

There are several changes that can be made to this design to improve its performance. The main change would be stiffer spars throughout the span. This would allow greater speeds in the wind tunnel. An unexpected obstacle was the flexing of the spar as more lift was produced. While the loads on the wind tunnel were well below limits the flex in the wing was too much. A stiffer material would produce less flex and keep the wing straighter. One thing to consider is the weight of the material. Carbon fiber is lightweight and strong but stronger materials like steel would be a significant increase in weight of the wing. This increase in weight makes calculations more difficult as it will alter the normal force detected by the tunnel and therefore affect the lift. A carbon fiber roll wrapped tube may be a suitable candidate as a spar. They do exist in the correct dimensions online for the current configuration. This may increase the overall material cost. If the stiffness greatly improves from a new spar, then the benefits of the improved experiment would much outweigh the costs.

In the current design the spars extend the whole span of the wing. This produces a lot of drag and can affect the data. An improvement to mitigate this flaw is to have several spars of varying lengths that can be swapped out with every extension piece added. This will provide a more accurate representation of the change in the drag coefficient by eliminating the drag caused by the rods protruding.

In future iterations of the lab, different airfoils may be selected to be built in the same or similar configuration to this one. In preparation of this, the RG-15 8.9% airfoil has been modeled in Solidworks in the same interface configuration as shown in this report. If this configuration for the interface holds into the future, then the lab could easily be expanded using this model. Even if the configuration does need to be updated, this could be easily done by editing the pre-existing models. The ease of manufacturing by 3D printing allows for quick iterations if necessary.

The wing model design provided is a good base and can achieve the experiment desired. Many changes can be made to improve performance and aesthetics of the wing. Testing of the proposed project showed favorable and mostly expected results. With new changes would come increased costs and time but yield better results. The provided wing is a good base point of the desired wing design. With one or more iterations on the wing design it can be a reliable model for the aerodynamics class for many semesters. With its ease of manufacturing by 3D printing any damaged pieces can be replaced quickly.

References

Yechout, T. R., Morris, S. L., Bossert, D. E., Hallgren, W. F., & Hall, J. K. (2014). *Introduction to aircraft flight mechanics: Performance, static stability, dynamic stability, classical feedback control, and state-space foundations*. American Institute of Aeronautics and Astronautics, Inc.