Vertical Axis Wind Turbine Strut and Blade Design for Rural Alaska

Author: Josh Heppner

Table of Contents

Abstract

A Darrieus vertical axis wind turbine was designed with hollowed out, hook shaped airfoil blades connected to a drive shaft via T-slot aluminum extrusions. This turbine was designed for wind conditions in rural Alaska with 60 mile per hour gale force winds considered as a worst case scenario. Finite element analysis was applied to models created in SolidWorks using ANSYS to evaluate designs. The final prototype was built primarily out of aluminum with a budget of $2500 and has 36 inch long blades with a chord length of 12 inches and an overall turbine diameter of 36 inches.

<u>Introduction</u>

<u>History</u>

Vertical axis wind turbines (VAWTs) have been around since the late 19th century [1]. Due to material and computational limitations, however, VAWTs have remained largely underdeveloped since then. Horizontal axis wind turbines (HAWTs) have received further development over the past century due to easier construction and ability to model behavior.

When compared to each other, VAWTs have some advantages over HAWTs. VAWTs are insensitive to the direction of the wind so they do not require an additional mechanism to point into the wind. Theoretically, a VAWT should require fewer materials than a HAWT since a VAWT is smaller. Because VAWT generators are close to ground, they are easier to service than HAWTs. Also, VAWTs tend to produce less noise than HAWTs do.

However, there are areas where HAWTs have advantages over VAWTs. HAWTs generally face more into the wind and are more efficient as a result. In the couple millennia since Hero of Alexandria created the first horizontal axis wind powered machine [2] mankind has extensively tested different HAWT designs. Compared to the barely over a century life of VAWT designs, HAWTs have had far longer to be tested for efficacy. Current HAWT designs are highly optimized and have been proven to generate large amounts of power. Wind farms do well with HAWTs.

Commercially available materials today are far stronger and more resilient than those available one hundred years ago. In addition, numerical analysis software packages are powerful tools not available to scientists and engineers who lived one hundred years ago. As a result lots of progress has been made towards improving VAWT designs.

<u>Vertical Axis Types</u>

The two main VAWT types are Savonius and Darrieus turbines.

Savonius turbine relies on drag to spin. Savonius turbines resemble scoops. By its design, a Savonius turbine can't spin faster than the wind which limits the amount of power it can produce. However, Savonius turbines can self-start and so don't require an extra motor to start spinning and generally don't need brakes to slow down in the event of high wind speeds. Savonius turbines are also fairly easy to construct.

A Darrieus turbine relies on lift to spin. As a result, Darrieus turbines can spin faster than the wind speed and can produce more power as a result. Generally, Darrieus turbines have struts connecting airfoil blades to a shaft though some designs incorporate the strut and blade together. An extra motor and a brake are typically needed to start and stop a Darrieus turbine which introduces more cost and complexity to the final turbine design. Darrieus turbines require more engineering and more materials to construct due to the blade masses being concentrated far away from the axis of rotation.

Several different blade shapes have been used on Darrieus turbines to maximize performance. Most commonly straight blade airfoils are used. Those have profiles similar to that of

commercially available airfoils and have constant vertical cross sections. Straight blades are relatively easy to manufacture and inexpensive but aren't as efficient or robust. These are often referred to as giromills. Helical blade shapes are also used which have the advantage of producing constant torque throughout a revolution but cost more and are more difficult to construct. "Eggbeater" shape blades also exist where the blades curve outward and back from the shaft. The eggbeater shape minimizes the rotational mass at a distance from the shaft but are expensive and difficult to manufacture.

Typically straight bar struts are used to connect straight and helical blades to the drive shaft. While bar struts are simple to design, they often fail at the blade-strut interface. Some struts have an airfoil shape to mitigate drag though these struts are also more difficult to machine. Simpler designs use two sets of horizontal struts to connect the blade, one set for the top and another for the bottom of the blades. Other designs use angled struts from one hub to connect the tops and bottoms of struts to the drive shaft. The single hub design allows for only one attachment point to the drive shaft but at the cost of angled connections which increases weight for a given horizontal distance.

The majority of commercially available designs today employ some variation of giromills. Some blades may be outward convex curved in a manner somewhat reminiscent of the eggbeater design but are otherwise connected to the drive shaft via straight struts like most straight bladed designs. Eggbeater style VAWTs are more common in commercial applications where the extra cost of special blade shaping is offset by economies of scale. Due to their inherent shape, the eggbeater VAWTs are generally strut less but occasionally have supporting struts towards the ends of the blades. Helical blades are uncommon in the market.

Aerodynamics

Joukowski airfoils are common and well understood mathematically. A Joukowski airfoil is made by transforming coordinates of a circle from the zeta plane to the x-y plane via

$$z = \zeta + \frac{1}{\zeta} \tag{1}$$

This results in an airfoil shape in the xy plane. Characteristically, Joukowski airfoils have a zero degree trailing edge. The airfoil shape can then be analyzed to calculate lift and drag.

Lift can be calculated using the Kutta-Joukowski theorem

$$L = \rho_\infty V_\infty \Gamma \tag{2}$$

L is the lift per unit span. ρ is the fluid density which is assumed to be constant because the fluid is assumed to be incompressible. V is the fluid velocity far away from the airfoil. Γ is the circulation parameter and is defined by

$$\Gamma = \pi V_\infty l \left(1 + \frac{0.77t}{l}\right) \sin(\alpha + \frac{2h}{l}) \tag{3}$$

l is the chord length of the airfoil, t is the maximum thickness of the airfoil, α is the angle of attack, and h is the maximum camber of the centerline [3].

Drag is partly dependent on the Reynolds number, so the Reynolds number is calculated from

$$Re = \frac{\rho V L}{\mu} \qquad (4)$$

Using the Reynolds number the parasitic drag coefficient can be approximated by

$$c_p = \frac{0.455}{\log Re^{2.58}} \qquad (5)$$

Parasitic drag combines the effects of skin friction and form drag. The induced drag coefficient can be approximated as

$$c_i = \frac{c_L^2}{0.85\pi AR} \qquad (6)$$

In that equation, Cl represents the coefficient of lift and AR represents the aspect ratio of the airfoil which is the ratio of span to chord length. Cl can be calculated directly by

$$C_L = 2\pi \left(1 + 0.77\frac{t}{l}\right) \sin\left(\alpha + \frac{2h}{l}\right) \qquad (7)$$

Induced drag results from the airflow being directed around the airfoil and is the component of the force parallel to the free stream. The sum of the parasitic and induced drag coefficients is the total drag coefficient.

The lift to drag ratio is the ratio of the lift force to the total drag force. Taking the ratio of the lift and drag coefficients will result in the same ratio [3].

The effective angle of attack is the angle of the centerline of the airfoil relative to the oncoming flow. The value of the angle of attack is dependent on the physical orientation of the airfoil relative to the flow and also dependent on the amount of camber in the airfoil. Higher camber corresponds to an effective higher angle of attack. The increase in the effective angle of attack from the camber can be calculated as $\frac{2h}{l}$. For some angle of attack there is a maximum lift to drag ratio called the critical angle of attack. This angle typically falls between 10 to 15 degrees above the free flow.

Tip speed ratio of turbine blades is of concern when trying to achieve maximum power generation. The tip speed ratio is the ratio of the speed of the rotor tip to wind speed, expressed as

$$\lambda = \frac{\omega r}{V} \qquad (8)$$

where λ is the tip speed ratio, ω is the rotational speed of the rotor, r is the radius of the blade from the rotor, and V is the wind speed. For optimal performance, the tip speed ratio can be approximated as

$$\lambda_{optimal} = \frac{4\pi}{n} \qquad (9)$$

where n is the number of rotor blades in the system. Most systems use three blades so the optimal tip speed ratio is generally $\frac{4\pi}{3}$. The power available in the wind is

$$P = \frac{1}{2}\rho S V^3 \qquad (10)$$

where P is power, ρ is density, S is the cross sectional area of the turbine, and V is wind velocity. The power coefficient is defined as

$$C_p = \frac{P_{turbine}}{P} \qquad (11)$$

and cannot exceed the Betz limit of 59.26%. In practice, most wind turbines have efficiencies around 45%. Due to inefficiencies present in real systems, the optimal tip speed ratio for turbines is higher than expected by the simple correlation above. Empirical data suggests that the optimal tip speed ratio of about 5.8 will produce a maximum power coefficient of 0.36 for a Darrieus turbine [4].

Project Statement

The intent of this project is to design straight airfoil blades with struts so that a Darrieus turbine will have a long life cycle in rural Alaska. The final product will have hooked shape turbine blades to allow self-starting behavior. Also, the struts connecting the blades to the drive shaft will be selected to maximize resistance to bending stress and to minimize rotational mass.

Project Scope

For this project, a prototype will be built that can withstand forces induced by wind speeds of 60 miles per hour. All materials will be purchased with a $2500 budget.

The limitations of this project are system size and capacity. While commercial models may have blades that are tall as 360 feet [5], the project budget only allows for blades that are around a percent of that size. Consequently, a reduction in blade size corresponds to a reduction in system capacity as well, due to the amount of lift generated being directly proportional to the span of the blades.

Methods

Design

After initial research into existing designs, several ideas were sketched in a design notebook. The best of those design ideas were selected for implementation.

Time was spent researching which materials would be used for this project. The three main materials for consideration were steel, aluminum, and carbon fiber. Aluminum was selected over steel due to aluminum's lighter weight and aluminum was selected over carbon fiber due to aluminum costing less, its higher availability of fasteners, and its ability to be shaped easily without specialized equipment.

Several general assumptions were made in the design process. Due to the low wind speeds the turbine would likely encounter, air was considered to be inviscid, incompressible, and have constant properties. Also assumed was that the fatigue strength of the aluminum alloy used was about the same as the yield strength. Therefore, metal fatigue wouldn't likely wouldn't become a factor as long as none of the turbine parts yield mechanically.

To determine turbine blade parameters, MATLAB code was written to calculate the lift to drag ratio, the optimal angle of attack for varying initial conditions, and other code was modified to model flow around the airfoil [6]. The turbine blade was approximated as a Joukowski airfoil for purposes of calculation. While the airfoil used in the design wouldn't be a Joukowski airfoil, its characteristics would be similar enough for determining close approximations for lift and drag coefficients.

The MATLAB code data suggested that the effective angle of attack could come solely from the camber in the airfoil with no additional angle of attack necessary. The lift to drag ratio was approximately 6.3514. Flow around the airfoil was smooth and was consistent with theory on flow around a Joukowski airfoil.

A NACA 2415 airfoil was selected as the basis for the turbine blade based on the relatively high camber of the NACA 2415 airfoil. A larger amount of camber corresponds to a higher angle effective angle of attack [7] and also gives more area to insert ribs.

In order to reduce blade mass, it was decided that instead of using an entire airfoil profile part of the bottom edge would be cut out. This resulted in a hook shaped airfoil. In addition to decreasing the amount of rotational mass, the concave interior of the airfoil acted as a means to more easily self-start the turbine by catching wind via drag.

Analysis

A SolidWorks part of the NACA 2415 airfoil was made and was then modified to remove the majority of the lower edge. The dimensions of the airfoil were 36 inches height, 12 inch length, and the initial thickness of the airfoil was 0.0156 inches. 6061 alloy aluminum was used designated as the material. This part was then loaded into ANSYS Workbench. Fluid dynamics tests were ran using CFX in order to find velocity and pressure contour plots for the highest wind speed the airfoil would likely encounter, in this case 60 mph. The velocity profile closely

resembled that of an ordinary airfoil and the pressure was highest at the center of the leading edge, at about 235 kPa.

Using the static structural analysis tool in Workbench, various airfoil thicknesses were tested with triaxial loading to determine the safety factor. The inside face of the hooked portion was designated as a fixed support. A vertical load of 100 N was used to simulate weight from the blade and additional parts and ice, a 150 N axial load was used to simulate the lift force, and a 60 N force along the chord of the blade to simulate the drag force. A drag coefficient of 1.28 was assumed for these calculations. A safety factor of at least 4 was desired for the final design. The initial thickness of 0.0156 inches failed and the thickness was repeatedly increased using values from a steel gauge conversion table. 0.190 inch thickness resulted in a safety factor of 15 but was far too thick to bend into shape and had too much mass.

In order to ameliorate the problem of thickness and weight, five ribs a quarter inch thick each were added to the airfoil for reinforcement. Two ribs were placed on the top and bottom of the airfoil, one was placed in the center, and the remaining two were positioned a set distance from the center airfoil. The top surfaces of the second and fourth airfoil were designated as fixed supports. The static structural analysis ran again with the same triaxial loads applied and the airfoil having a thickness of 0.0156 inches. A safety factor of 9.4 was obtained which was deemed satisfactory for this application.

Next, struts had to be selected to connect the airfoils to the drive shaft. Several existing profiles were selected for analysis. SolidWorks models were obtained and each of those models were ran in ANSYS Workbench with a static structural analysis. A general trend observed was that all of the struts were far stronger in tension than in bending, by factors between 60 and 160. Therefore various struts were examined primarily for resistance to bending. After testing several designs, a 1" x 1" T-slotted aluminum extrusion was selected based on its relatively light weight and resistance to bending. Though it had a low safety factor of 1.22, it was still selected on the basis that there would be two struts per blade so therefore the safety factor would effectively be doubled.

Assembly

Drawing part files were submitted to a local machine shop. The airfoil ribs were water jetted out of ⅜" aluminum sheet and the airfoil shape was bent out of 0.025" aluminum sheet. Rib thickness was increased to facilitate positioning fasteners in the ribs. Using threaded fasteners the ribs were joined to the airfoils to form the blade assemblies. Triangular shaped hubs were also machined. Struts were bolted to the ribs and hubs using special T shaped bolts to fix everything in place. A 1 ¼" hollow shaft with a ¼" wall was used as the drive shaft. Pipe flanges were used to connect the hubs to the drive shaft.

Conclusions

The prototype vertical axis wind turbine has been designed to withstand wind speeds up to 60 miles per hour. All the turbine blades have the hollowed out hook section as proposed. From existing extruded aluminum profiles available on the market now, the one that had the best weight and strength characteristics was selected. Based on these criteria, the prototype met the criteria laid out in the project statement.

This vertical axis wind turbine provides a novel way to lower the startup torque required for power production. As a result it obviates the need for a motor for starting up the turbine. The lack of a startup motor reduces system complexity and reduces the number of parts needed to manufacture the turbine system. Consequently, this particular turbine system is less resource intensive to bring to market and therefore can be priced more competitively.

To ensure proper performance, every component will have to be analyzed again when building a full sized model. Due to the nonlinear nature of aerodynamics, it cannot be simply assumed that loading behavior will increase linearly. It is likely that different struts will have to be used in order to support the vertical loads of larger turbine blades.

Project Schedule

Task Name	Duration	Start	Finish
Obtain Dimensions	1 day	Fri 1/30/15	Fri 1/30/15
Research	21 days	Fri 1/23/15	Fri 2/20/15
Design	21 days	Thu 2/12/15	Thu 3/12/15
Analysis	21 days	Thu 2/12/15	Thu 3/12/15
SolidWorks Drawings	7 days	Thu 3/12/15	Fri 3/20/15
SolidWorks FEA	7 days	Fri 3/20/15	Mon 3/30/15
Design Tweaks	5 days	Mon 3/30/15	Fri 4/3/15
Fabrication Drawings	3 days	Fri 4/3/15	Tue 4/7/15
Order Materials	10 days	Tue 4/7/15	Mon 4/20/15
Machine Parts	5 days	Mon 4/20/15	Fri 4/24/15
Assemble Machine	1 day	Mon 4/27/15	Mon 4/27/15
Test Machine	1 day	Mon 4/27/15	Mon 4/27/15

Project Budget

The project budget was $2500. This funding came from the Dr. Alex Hills Engineering & Civic Engagement Award.

The cost breakdown was:

Quantity	Item	Cost
1	48"x96" 0.025 5052 H32 Aluminum Sheet	$38.96
1	6061-T6 1 ¼" Pipe	$46.00
2	1 ¼" Aluminum Base Flange	$31.28
1	Permanent Magnet Generator, FuturEnergy PMG406	$500
2	T-Slotted Aluminum Extrusions, 15S,97 LX1.5H	$147.40
1	Water Jetted Parts	$365.00
	Total	$1128.64

For this project, SolidWorks 2014 and ANSYS Workbench 15.0 were used extensively to model parts and perform finite element analysis on them. MATLAB 2012a was used to model flow around a Joukowski airfoil and to determine the critical angle of attack.

The University of Alaska, Anchorage College of Engineering computer labs were used for the majority of the software tasks.

University of Alaska, Anchorage Professor Peng was the faculty advisor and provided assistance to answer technical questions.

References

1. Croll, Kirsteen, 2012, "Papers of James Blyth," From

   http://www.strath.ac.uk/archives/iotm/march2012/

2. A.G. Drachmann, "Heron's Windmill", *Centaurus*, 7 (1961), pp. 145-151

3. Currie, I.G., 2013, Funamental Mechanics of Fluids, 4th ed., CRC Press, Boca Raton, FL.

4. Ragheb, M. 2014, "Optimal Rotor Tip Speed Ratio," from

   http://mragheb.com/NPRE%20475%20Wind%20Power%20Systems/Optimal%20Rotor%20Tip%20Speed%20Ratio.pdf

5. Turnbull, A., 2009, "World's Tallest Vertical-Axis Wind Turbine," from

   http://googlesightseeing.com/2009/08/worlds-tallest-vertical-axis-wind-turbine/

6. Brock, J.M., 2014, "Joukowski Airfoils and the Joukowski Transformation," Bachelor of Science in Engineering Program, University of Alaska, Anchorage, Anchorage, AK.

7. Beri, H., Yao, Y., 2011, "Effect of Camber Airfoil on Self Starting of Vertical Axis Wind Turbine," Journal of Environmental Science and Technology, **4**(3),pp 302-312.

   http://scialert.net/abstract/?doi=jest.2011.302.312

Figure 1: A rendering of the hollow airfoil shape

Figure 2: A rendering of the turbine blade assembly with ribs
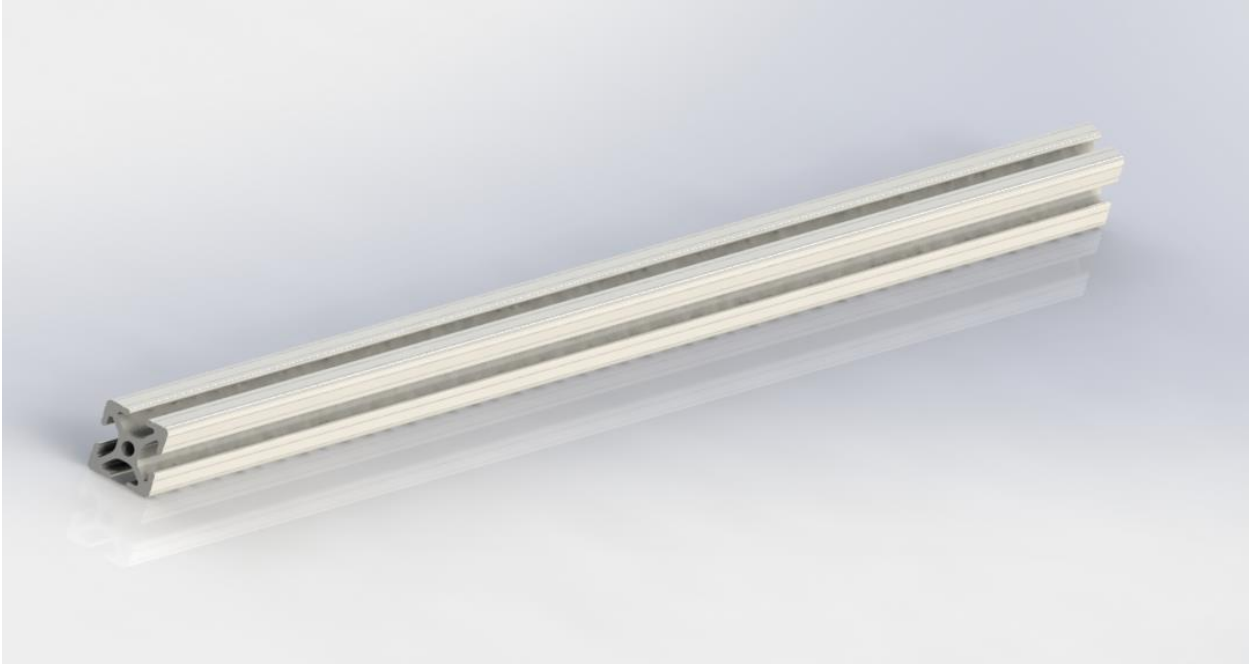
Figure 3: A rendering of the T-slotted aluminum extruded strut
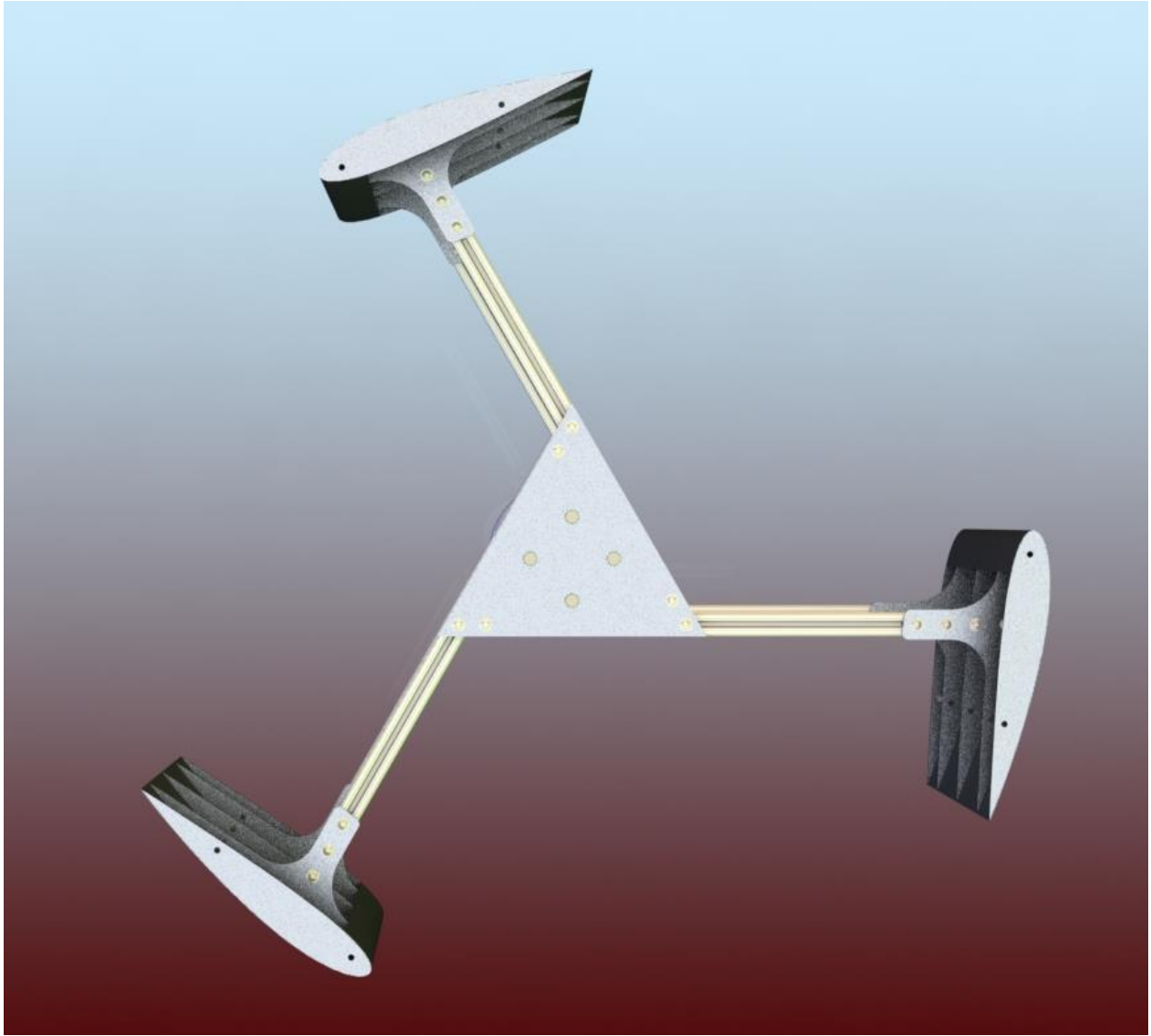
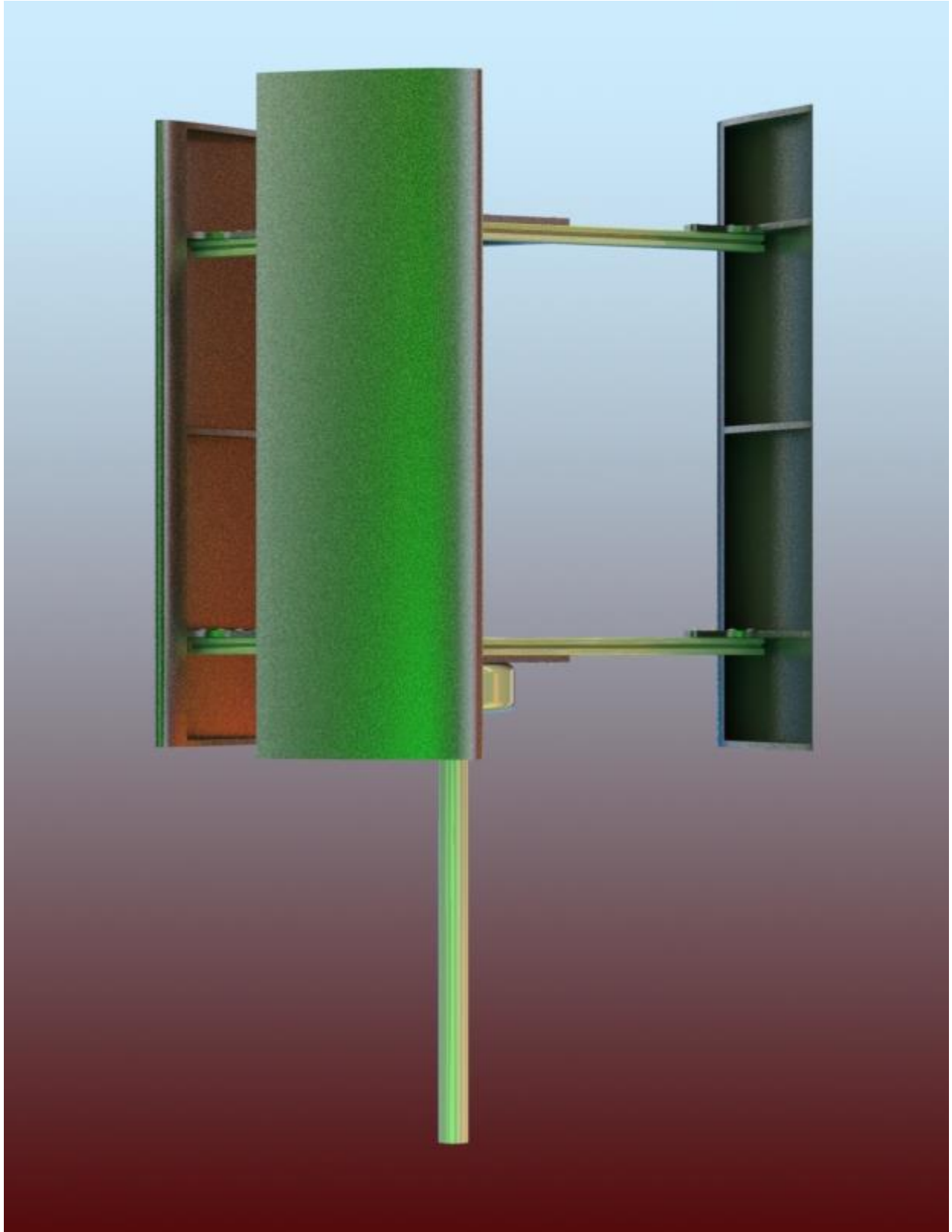Figure 4: A top down view of the complete turbine

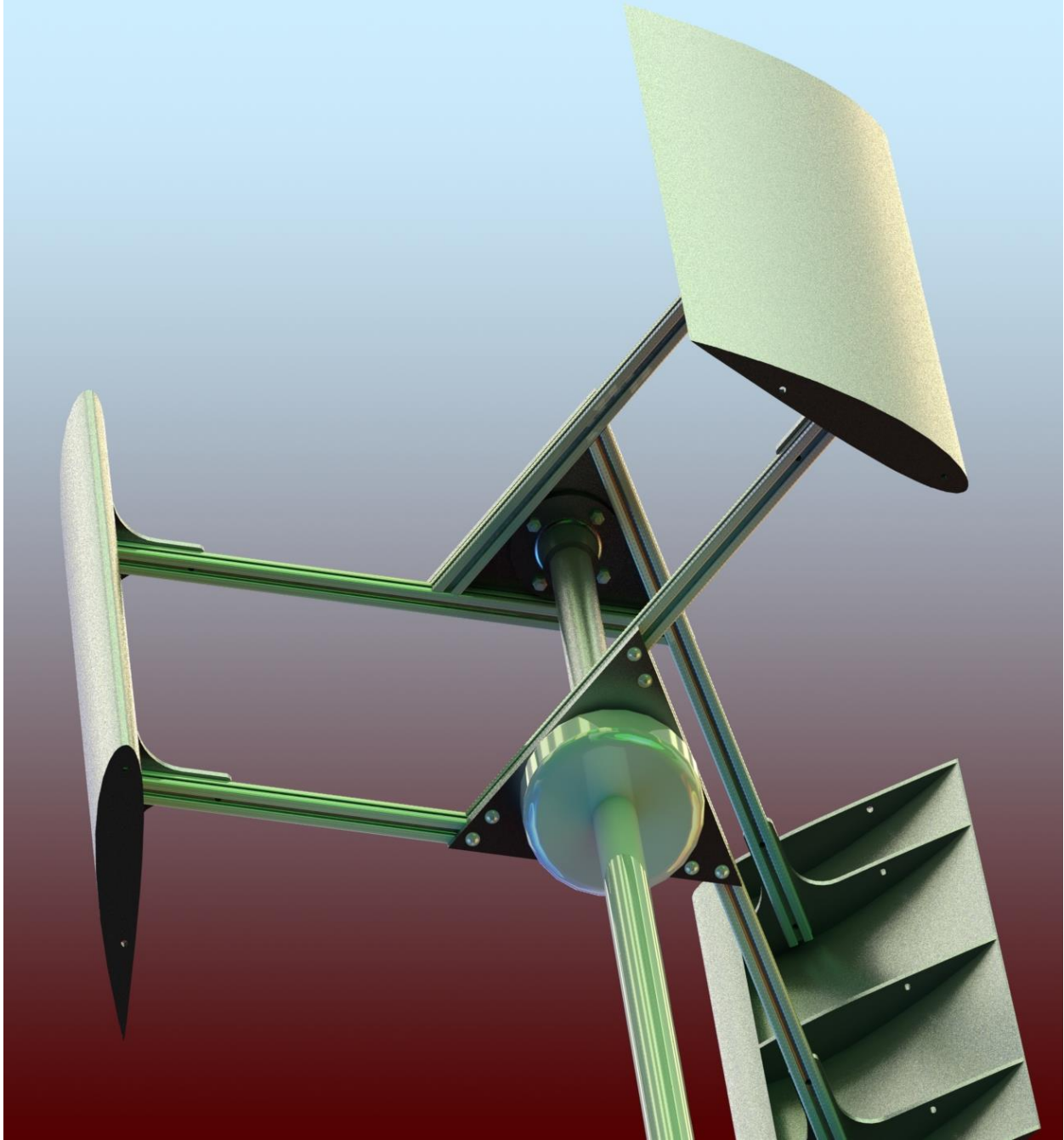Figure 5: A side view of the complete turbine assembly

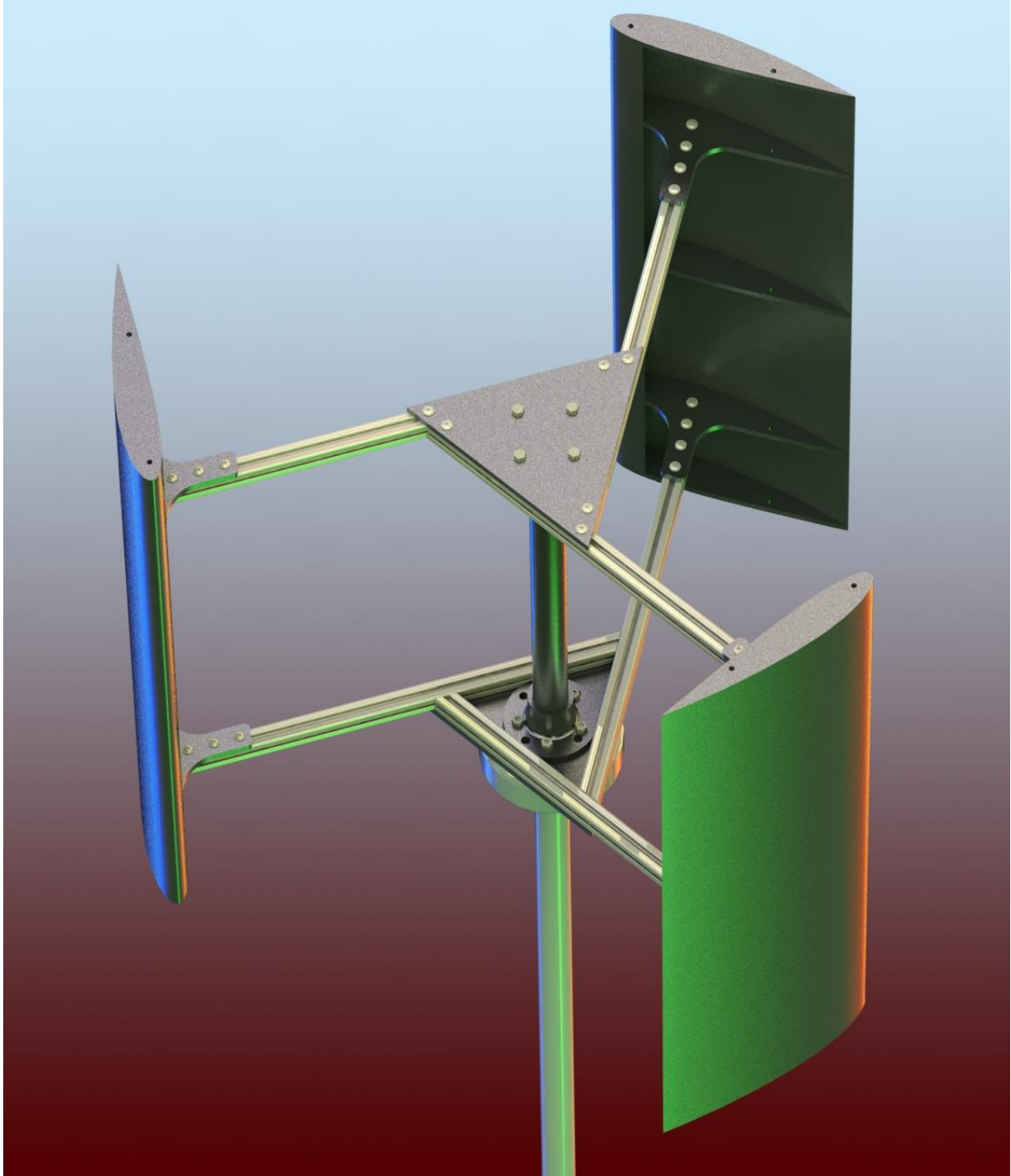Figure 6: A bottom-up view of the complete turbine assembly

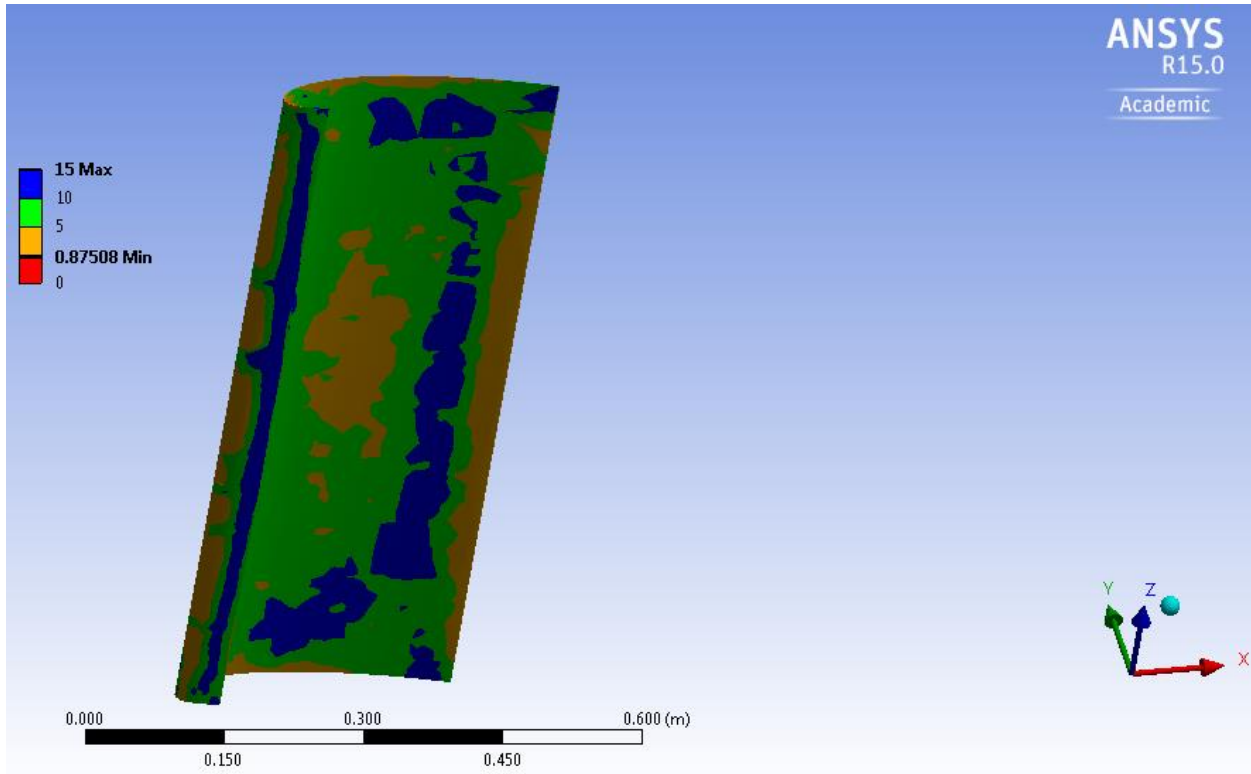Figure 7: An isometric view of the complete turbine assembly

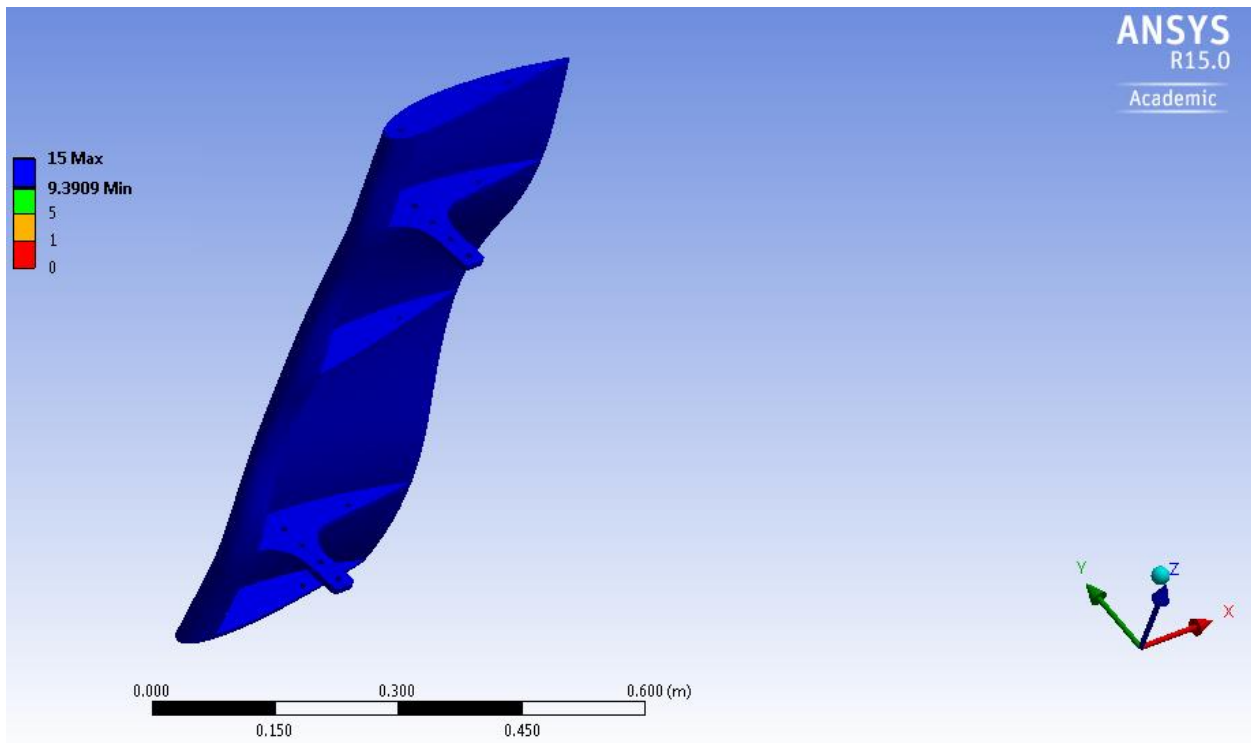Figure 8: 0.0156" Airfoil failing in static structural test

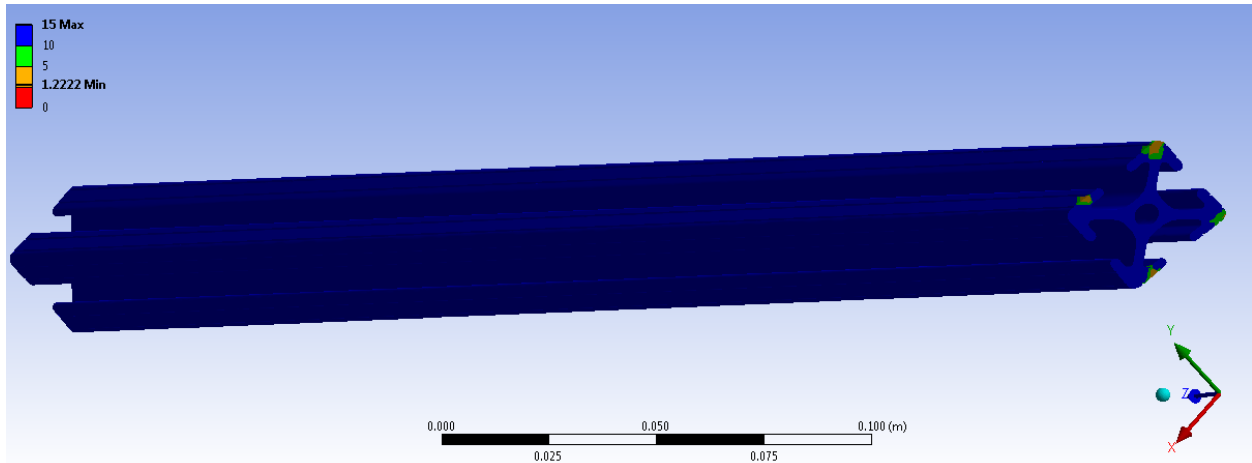Figure 9: 0.0156" Airfoil with 5 ribs passing static structural test

Figure 10: Strut passing static structural test

Specimen	Max Tension Force (N)	Max Bending Force (N)	Max Bending w/ Mesh Refinement (N)
Al 45 R4 18 in 1.77x1.77	25000	420	N/A
AL EX 1 18 in. 1.5 x1.5	26100	520	565
Al EX 6 18 in. 1.5x1.5	29000	530	400
Al Tube 18 in. 0.5 OD x 0.065 in Wall	2700	17	16
Al Tube 18 in. 0.75 OD x 0.083 in Wall	5230	47	52
Al Tube 18 in. 1 OD x 0.095 in Wall	5230	51	53

Table 1: Comparison of various strut profiles with loading

Airfoil Thickness, Inches	Safety Factor	Blade Mass, lbs
0.051	0.27	2.68
0.0641	0.365	3.06
0.0808	0.571	3.57
0.1019	0.875	4.2
0.125	1.294	4.89
0.16	2.089	5.91
0.19	13.163	6.76

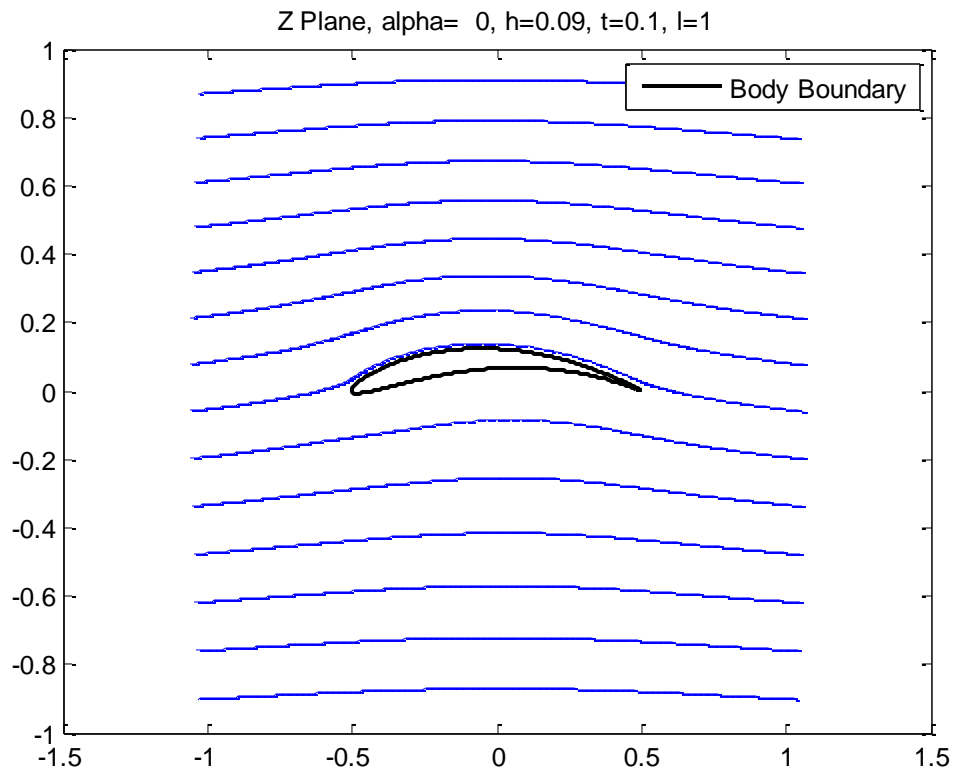Table 2: Data for loads of 100 N vertically, 60 N along the drag vector, 500 N in the lift vector

Figure 11: MATLAB Plot of flow around Joukowski airfoil