A Thesis Presented to

The Faculty of Alfred University

The Exploration of Solar Sails

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Introduction

Solar sails are a form of spacecraft that achieve movement through radiation pressure from the sun. My Honors Thesis focuses on a "heliogyro type" of solar sail, which is essentially long thin blades that rotate around a central hub, very similar to that of a helicopter rotor. The following image is a conceptual view of a heliogyro type solar sail, which was created on ANSYS.

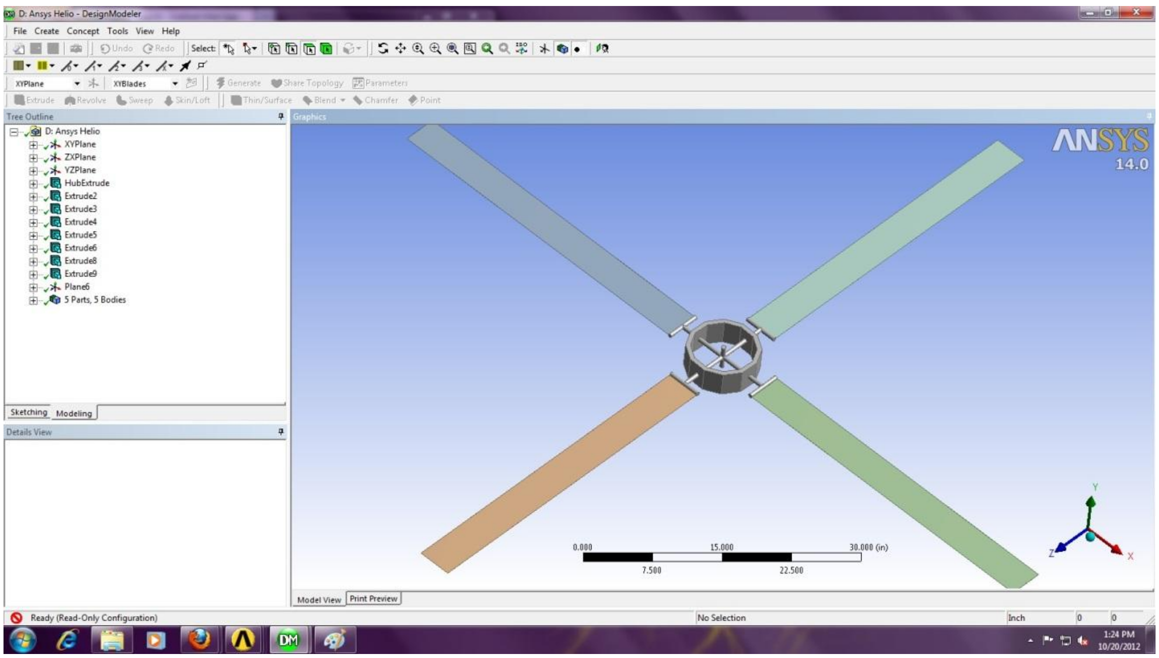

Figure 1 – Heliogyro Concept (Done in ANSYS)

ANSYS is an engineering simulation software which was used to try to simulate a solar sail. The above image depicts a twelve sided central hub with four blades. The area capacity on ANSYS is not large enough to model ideal dimensions, but to give some perspective; the ratio of blade width to length shown is approximately 1:40.

The concept of a solar sail has a rich history. "Long ago, someone stood alone on a sandy shore and gazed longingly out at the seemingly endless expanse of ocean, over a horizon suffused softly with ocean mist, musing, "I wonder, what's out there?" Then, they fashioned a boat, rigged it with a large cloth to catch the wind, and set sail. Not quite so long ago, someone stood alone on a sandy shore and gazed longingly up at the seemingly endless expanse of space, suffused softly with sparkling stars, musing "I wonder, what's out there?" Then, they fashioned a spacecraft, rigged it with a large cloth to catch the sun, and set sail" (1, Coulter). The first half of the quote has already occurred; NASA expects that the second half will take place very shortly.

Johannes Kepler observed that comet tails being blown nearly 400 years ago. He thought the cause to be solar breeze. After making this observation, Kepler postulated that ships could be made to travel to the heavens. What he did not know is that the best way to power a solar sail was actually sunlight, not solar wind. James Clerk Maxwell, a Scottish mathematical physicist, was able to demonstrate that sunlight exerts small amounts of pressure. This pressure is the basis of every modern solar sail concept (1, Coulter).

In 1993, the Russian Space Agency launched a craft named Znamya 2. This craft was 20 meters in diameter and consisted of multiple spinning mirrors. The goal behind the project was to collect solar power and bring it back to earth. The mission did not succeed, as the mirrors burned up in the atmosphere over Canada. Soon after, attempts at another solar craft, the Znamya 2.5 failed during deployment as well (1, Coulter).

Another craft named Ikaros was launched on May 21, 2010, at the Tanegashima Space Center. Ikaros stands for Interplanetary Kite-craft Accelerated by Radiation of the Sun, however it is ironic that the name is very similar to that of Icarus, a Greek mythological craftsman. According to the ancient Greeks Icarus escaped from Crete, the most populous Greek island, by means of wings. Icarus's father had constructed these wings out of feathers and wax. Icarus ignored others' warnings, flew too close to the sun, which melted the wax holding together his wings, causing him to fall to his death (4, "Encyclopedia of Greek Mythology: Icarus"). The story of Ikaros, however, has a much happier ending. The project goal was to demonstrate the world's first successful solar powered sail. The deployment went smoothly and Ikaros was soon completing its first mission and proving that solar sails could be guided with precision. On December 8, 2010, Ikaros flew by Venus. At one point the interplanetary vehicle came as close as 80,000 kilometers to the second planet to the sun. Ikaros snapped photographs as it flew by and transmitted them back to the International Space Station. I have not found any research on what type of missions the craft is currently taking on, but nothing I have read leads me to believe it is not still in flight today (3, "Solar Power Sail Demonstrator "IKAROS"").

When one thinks of a solar sail, it is almost like pondering magical possibilities; the idea of easily traversing across space. There are however many practical applications for the craft. Traditionally solar sailing was seen as a way to efficiently transport supplies to different planetary bodies (assuming that in the future more activity will be taking place in outer space). However, more importantly, it is thought that solar sails, due to efficient maneuvering abilities, may be able to achieve orbits that we never could before, extending the classical principles of orbital mechanics. The creation of new orbits could be very beneficial in avoiding overcrowding of satellites, which is inevitable due to the growing population and the rapidly increasing technology of our current culture (2, McInnes).

In 1967, Richard MacNeal, an employee for NASA, introduced the innovative design that received great consideration for a viable, working solar sail. MacNeal wrote multiple papers on his research and ideas. His design concept is for a solar sail that employs long, narrow blades made from extremely thin film that operates similarly to a helicopter rotor. The blades would slowly unravel from spools during deployment, which could take up to two weeks. The idea itself creates a vast number of engineering problems associated with operation, structural design and stability, which need to be addressed in order to make the project considered as a serious possibility (5, MacNeal).

Three Mechanical Engineering colleagues at Alfred University, Stephanie Chang, Cory Essington, and Chelsea Gill, chose to do their Senior Project work on the heliogyro solar sail in fall 2011. In spring 2012, I joined the project and continued work for a semester with Cory Essington and Chelsea Gill. The project was under the University supervision of Dr. Timothy Wong and progress was reported to our NASA supervisor, Dr. Keats Wilkie. Each week of the semester the group gave a presentation to Dr. Wong and the members of the Mechanical Engineering Senior class concerning the project's progress.

Heliogyro solar sail research made for a perfect Mechanical Engineering Senior Project. Each new week found me enthused and ready to pursue a new facet of the project. It entails a multitude of important engineering concepts. The concepts behind solar sails demand analyzing materials, blade movement and deformation, hub structures, ion propulsion, deployment mechanisms, and much more. As the semester continued on, a large portion of the work focused on proving the concept behind a heliogyro solar sail.

Some people consider the thought of a huge craft traveling through space in a controlled manor to be an impossibility. In my thesis I will expand upon the research my Senior Project group completed. The results showed that ideas as wild as ion propelled vehicles sailing through space can be analyzed and such a craft designed. Heliogyro type solar sails do have proven engineering concepts behind them, and are far more feasible than some may care to admit.

Methods Employed

The project of analyzing a heliogyro solar sail was a very complex endeavor, and contained many areas of study. For this reason research was drawn from a variety of areas, and many different testing methods were employed in order to analyze data and attempt to prove concepts. In this section I will document, in detailed fashion, the methods carried out in order to execute the project.

In order to analyze different hub designs for the center of the craft, I used Abaqus, a finite element program, to calculate stress, deformation, plastic strain, and other characteristics of a system under specified loading. Abaqus can run thousands of calculations in seconds. I chose Abaqus for this task because it is very easy to import parts created in SolidWorks (a three-dimensional computer aided design program), and one can apply pressures, body rotational forces, new material characteristics, and run analysis very quickly.

Abaqus was used to compare stress distribution and deformation in hubs of different materials and different geometries. I started by using SolidWorks with another colleague, Michael DiBella, to create hubs of different geometries. Next I imported them into Abaqus, chose proper material characteristics, and applied proper loads and boundary conditions. I fixed the inside of the hub, applied a body rotational force to the system, and applied pressure in specific areas to mimic the average centrifugal force of the blades. Then a mesh was created for the part, which controls exactly how accurate the analysis will be. A global seed is selected to determine how fine the mesh will be, I would recommend choosing a global seed between 20 and 80. This ensures that a proper analysis is run, but is not so complex that the program takes an unreasonable amount of time to load. I kept the program's suggested global seed of 62. Finally, an analysis was run and the results organized. The following tables (Table 1, 2, and 3) display in detail the different design variables I chose to test. When one uses Abaqus it is very important that they keep a consistent unit system. The hub parts were done in millimeters, which called for tonnes, megapascals, newtons, radians and seconds.

Geometry	***Dimensions (mm)***
Circular 4 Blader	1000 Inner Diameter, 1200 Outer Diameter, 500 Thickness, 150 Diameter of Connecting Bars
Square 4 Blader	1000 Inner Length and Width, 1200 Outer Length and Width, 500 Thickness, 150 Diameter of Connecting Bars
Hexagonal 6 Blader	500 Inner Sides, 615 Outer Sides, 500 Thickness, 150 Diameter of Connecting Bars

Table 1 – Geometry Data

I chose to analyze three different types of geometries: circular, square, and hexagonal. I kept the dimensions as consistent as I could, considering that I was dealing with different shapes.

Outward Pressure on Connecting Bars (MPa)	***Rotational Velocity (rad/s)***
0.002	5
0.21	50
21.16	500

Table 2 – Force Data

To obtain pressure data I calculated the pressure that a bar of 150 mm diameter would undergo due to centrifugal force of a Mylar blade, 5280 feet long by

1 foot wide by 1 micron thick, rotating at the specified velocities. Thickness for solar sail blades is usually thought of as being on the order of microns to keep the weight of the sail very low. This extremely small thickness means that changing the length and width would not affect the pressure calculation by much. Mylar has a density of 86.8 $\frac{lb}{ft^3}$, and is an ideal material for the blades due its reflectivity, flexibility, thinness and light weight (6, “MylarÂ®, Plastic Sheet, Polyester Film Sheet and Sheet Properties – Grafix Plastics”).

Material	***Young’s Modulus (MPa)***	***Density (Tonne/mm³)***	***Poisson’s Ratio (Unitless)***
Carbon Steel	200,000	$7.86*10^{-9}$	0.30
Titanium	110,000	$4.51*10^{-9}$	0.32

Table 3 – Material Data

I chose to test both carbon steel and titanium for the hub material. This was due to their strength and common use.

In order to explore acceleration of the craft I used the following formula reported by MacNeal:

$$a = \frac{p*A}{W},$$

where a is the acceleration of the craft in terms of earth’s g’s (9.81 m/s), p is the pressure due to solar radiation in $\frac{lb}{ft^2}$, A is the total area of the sails in ft^2, and W is the weight of the craft in lbs. I found that density and blade thickness are the underlying factors that control craft's acceleration. Graphs in terms of these variables were then generated in order to gain a better understanding of the relationship (5, MacNeal).

There is also the matter of developing an understanding of how to get the sail to accelerate in necessary directions. I used two different methods to do this. The first was analyzing MacNeal's equations for pressure in the lift direction as well as pressure in the drag direction, understanding them, and running some numbers through them. Secondly, since a heliogyro type solar sail is very much like a helicopter, I explored the principles behind helicopter controls and their similarities to controlling an interplanetary craft.

One of the most important aspects of the project was proving the concept of centrifugal stiffening. In a heliogyro solar sail, the blades are not supported; the only thing keeping them unraveled is centrifugal force. ANSYS, an engineering simulation software, was used to do this. ANSYS was also used to begin modeling the solar sail. ANSYS was chosen because although the program has a very high learning curve, it has nearly endless capabilities and can simulate many complex situations, including a multiple blade solar sail spinning around its axis under specific pressures. Unfortunately, progress was cut short because Alfred University did not renew the license for ANSYS after the spring 2012 due to limited use in other classes. Progress until that point has still been documented to the best of my abilities; however the inability to access past ANSYS files caused difficulty.

Results

Extensive testing was done in Abaqus to explore solar sail hub options. The following images (Figure 2, 3, and 4) display the three different hub geometries with loading conditions.

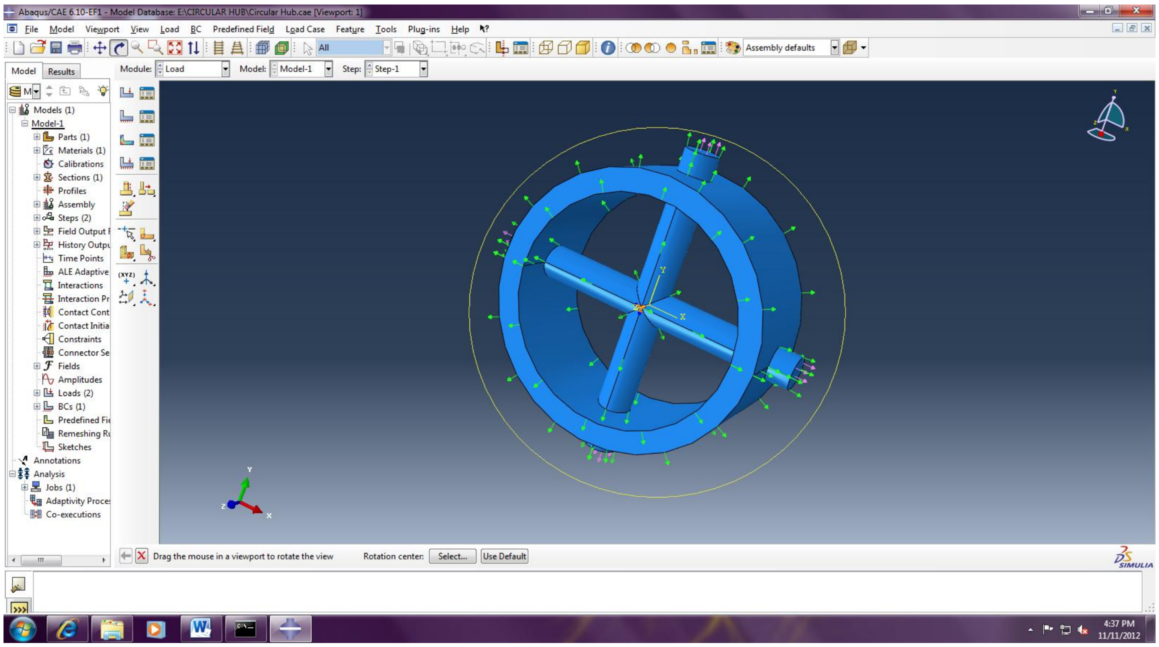

Figure 2 – Circular Hub with Loading and Boundary Conditions

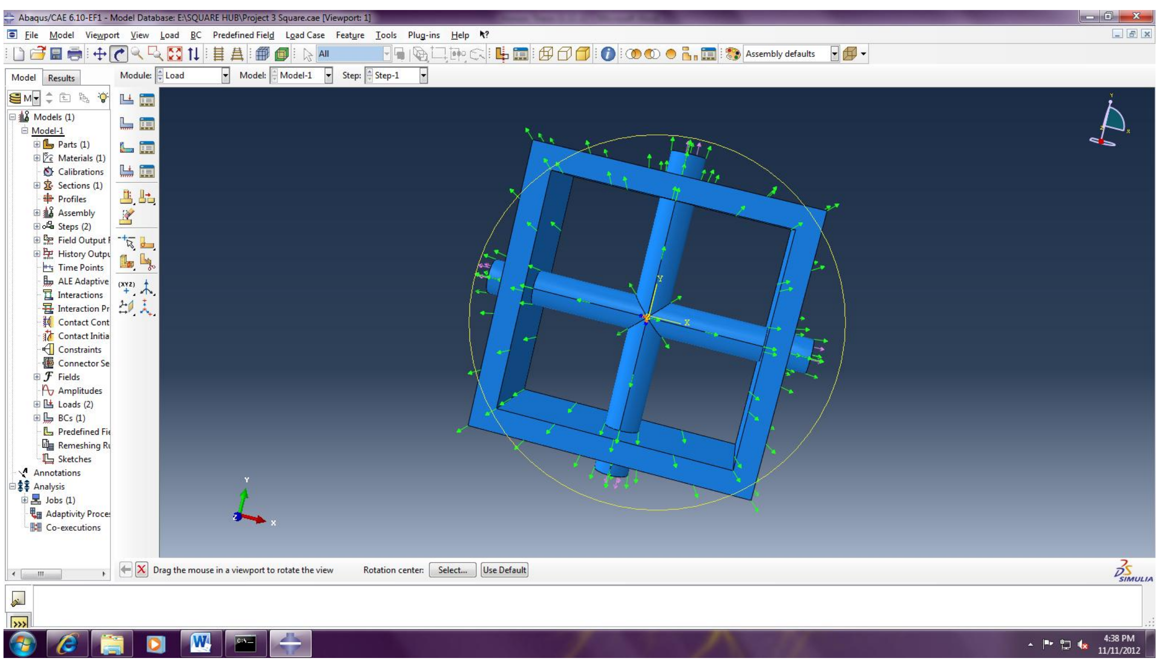

Figure 3 – Square Hub with Loading and Boundary Conditions

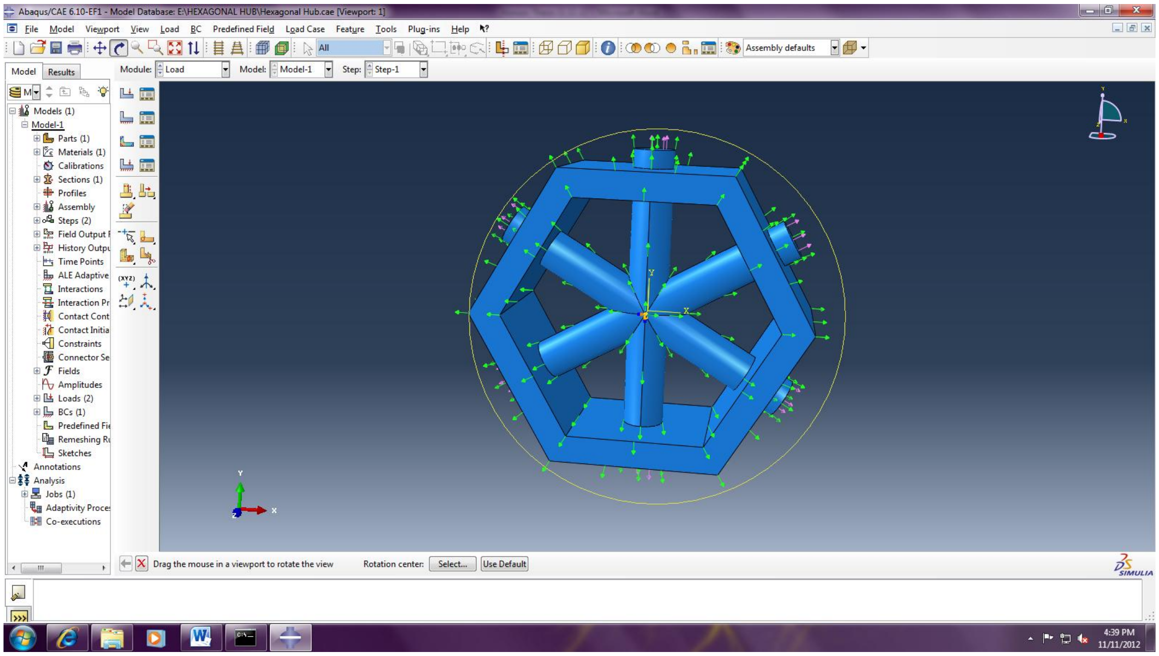

Figure 4 – Hexagonal Hub with Loading and Boundary Conditions

The above images (Figures 2, 3 and 4) display the different geometries tested as well as the loads and boundary conditions applied to them. The green arrows represent a body force due to rotational velocity, the purple arrows represent an applied pressure, and the small orange triangles in the center are the boundary conditions, the center axis is fixed. The yellow circle behind each figure is simply due to the fact that the screen is in Rotate View Mode.

The following screen shots (Figure 5, 6, 7, 8, 9, and 10) display the maximum principal stress and deformation results the program came up with. I input only a few screen shots, and then compiled the rest of the data into Table 4. This is due to the excessive amount of screen shots it would require to represent every different variable tested. In the following figures maximum principal stress results are reported in MPa and deformation results are reported in mm.

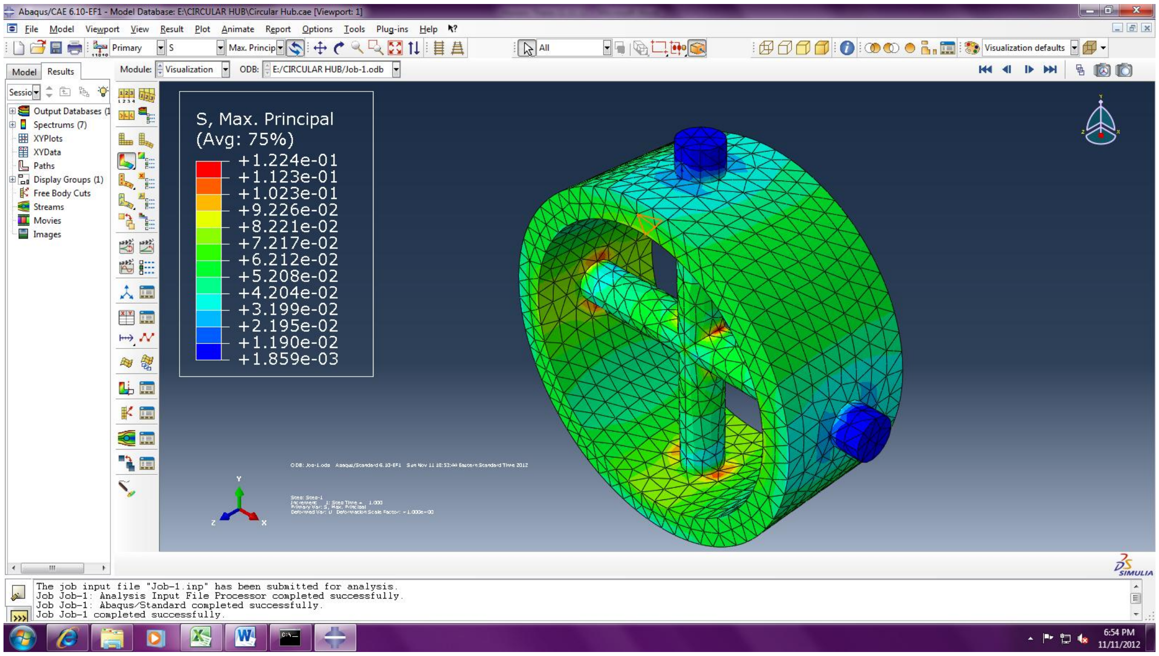

Figure 5 – Maximum Principle Stress for Circular Hub with Carbon Steel Properties Rotating at 5 rad/sec

Figure 5 reports a maximum principal stress of 0.1224 MPa. This maximum stress occurs at the edges of the intersection of the connecting bars with themselves and with the inside of the circular hub.

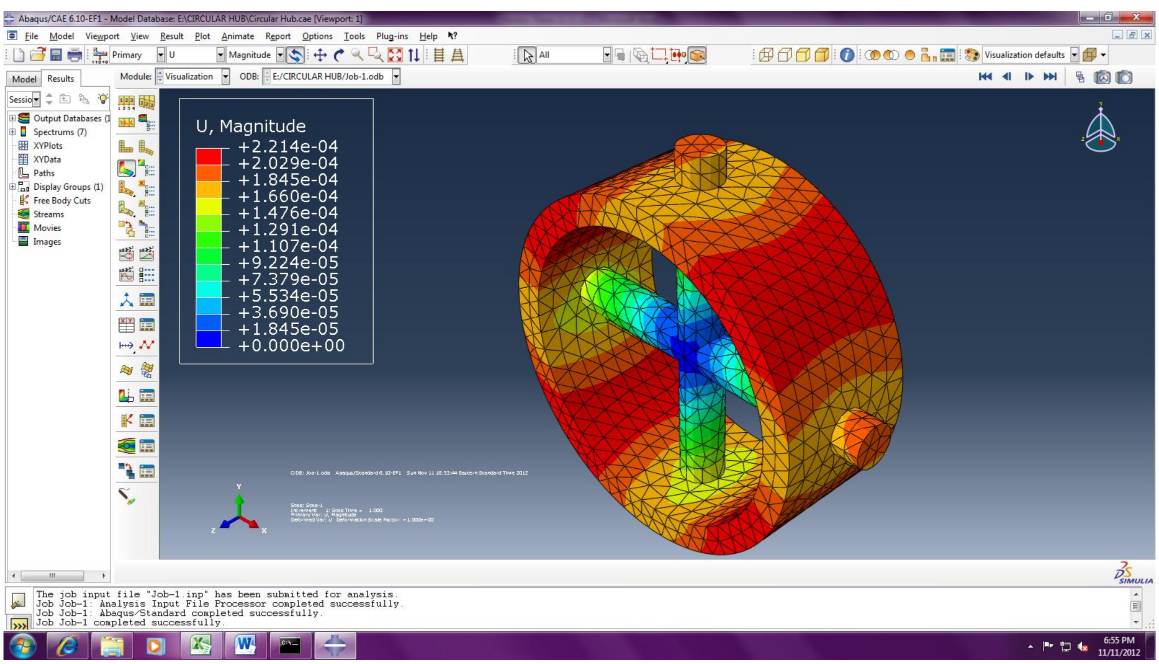

Figure 6 – Deformation for Circular Hub with Carbon Steel Properties Rotating at 5 rad/sec

Figure 6 reports a maximum deflection of 2.214*10^{-4} mm. This maximum deformation occurs in the circular hub halfway in between each set of connecting bars.

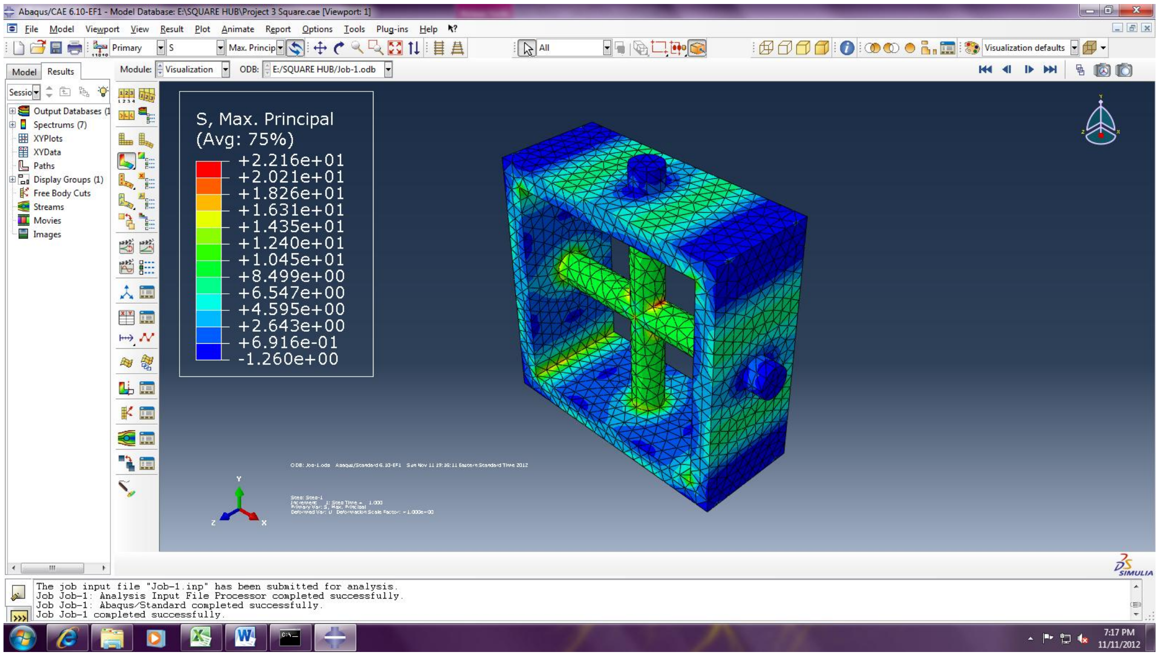

Figure 7 – Maximum Principle Stress for Square Hub with Titanium Properties Rotating at 50 rad/sec

Figure 7 reports a maximum principal stress of 22.16 MPa. This Maximum stress occurs along the inside edges of the corners of the square, as well as the edges where the connecting bars intersect. This is a much larger value than the circular case due to it experiencing ten times the rotational velocity.

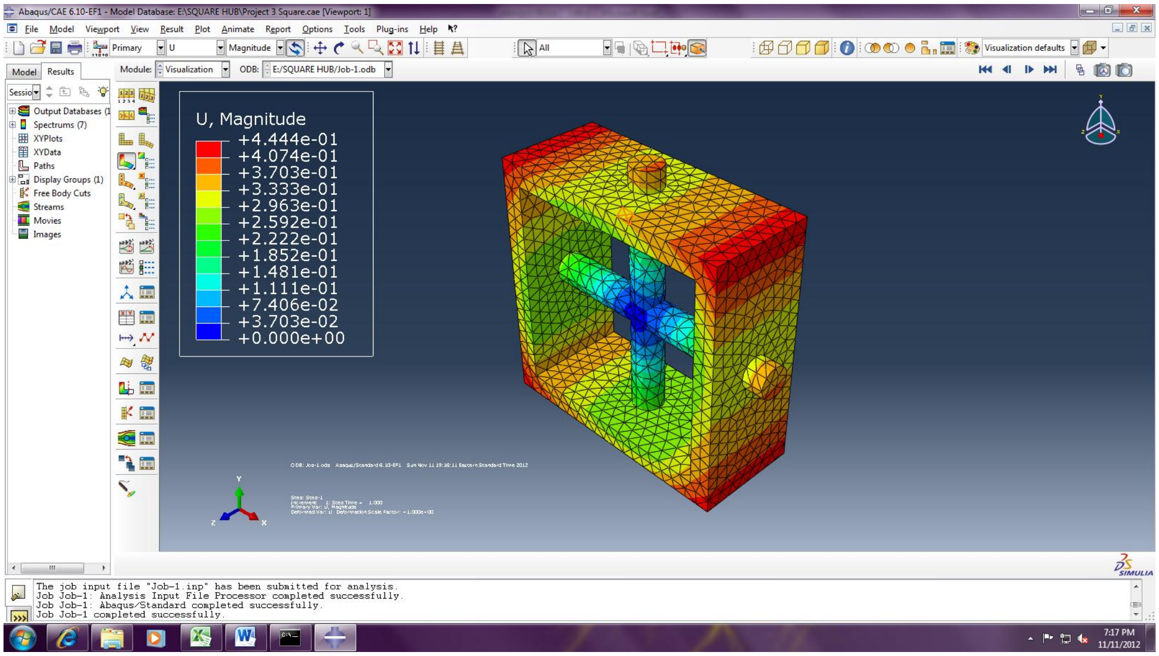

Figure 8 – Deformation for Square Hub with Titanium Properties Rotating at 50 rad/sec

Figure 8 reports a maximum deflection of 0.4444 mm. This takes place at the four corners of the square hub. This is a much larger value than the circular case because it is experiencing ten times the rotational velocity.

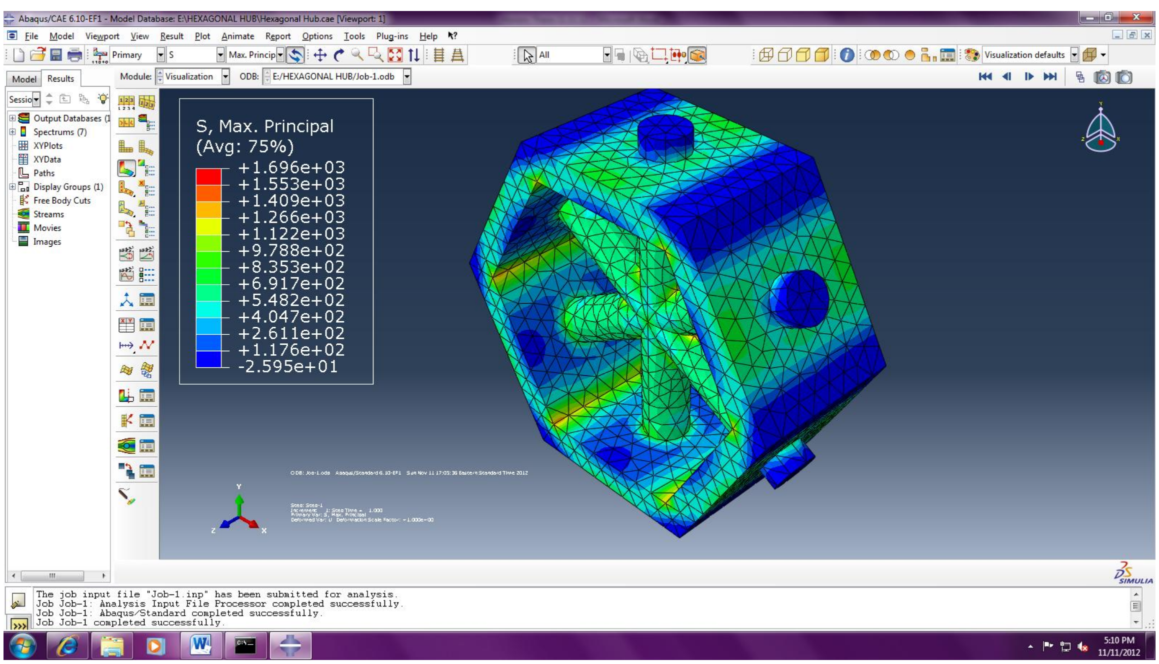

Figure 9 – Maximum Principle Stress for Hexagonal Hub with Carbon Steel Properties Rotating at 500 rad/sec

Figure 9 reports a maximum principal stress of 1,696 MPa. This stress occurs at the inside edges of the hexagon and the edges where the connecting bars intersect. This stress value is very large, due to the incredible speed at which it is rotating; 500 rad/sec corresponds to approximately 80 rev/sec.

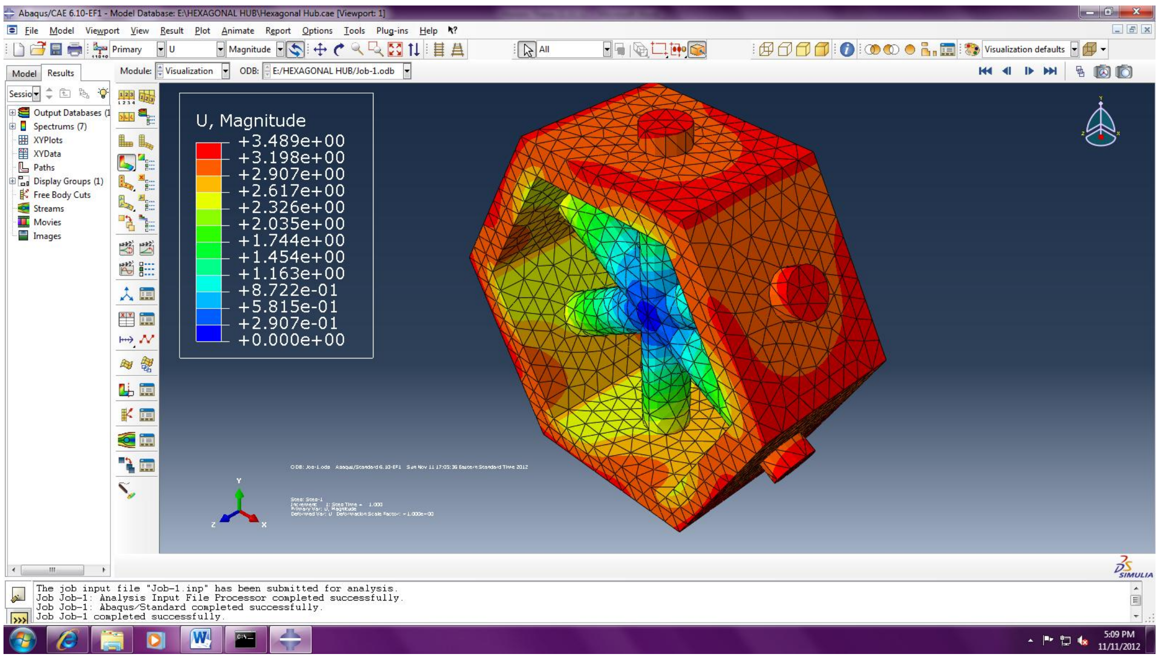

Figure 10 – Deformation for Hexagonal Hub with Carbon Steel Properties Rotating at 500 rad/sec

Figure 10 reports a maximum deflection of 3.489 mm. This deflection occurs at all the edges of the outer portion of the hub. 3.489 mm deflection is large enough to be concerned about, but once again this is corresponding to an incredibly large rotational velocity.

Table 4 records all of the testing results, including those in the previous figures.

Geometry/ Material	Rotational Velocity (rad/sec)	Maximum Principal Stress (MPa)	Location of Maximum Principal Stress	Maximum Deformation (mm)	Location of Maximum Deformation
Circular/Carbon Steel	5	1.22E-01	Intersection of Connecting Bars with Inner Hub and Themselves	2.21E-04	Throughout Circular Hub Halfway Between Each Set of Connecting Bars
	50	1.22E+01		2.21E-02	
	500	1.22E+03		2.21E+00	
Circular/Titanium	5	7.20E-02		2.14E-04	
	50	7.20E+00		2.14E-02	
	500	7.20E+02		2.14E+00	
Square/Carbon Steel	5	3.81E-01	Inside Edges of Square and Where Connecting Bars Intersect	5.08E-03	Outer Part of All Four Corners
	50	3.81E+01		5.04E-01	
	500	3.81E+03		5.05E+01	
Square/Titanium	5	2.22E-01		4.46E-03	
	50	2.22E+01		4.44E-01	
	500	2.22E+03		4.46E+01	
Hexagonal/Carbon Steel	5	1.70E-01	Inside Edges of Hexagon and Where Connecting Bars Intersect	3.49E-04	All Outer Edges
	50	1.70E+01		3.48E-02	
	500	1.70E+03		3.49E+00	
Hexagonal/ Titanium	5	9.98E-02		2.18E-04	Center of Each Outer Hexagonal Side
	50	9.98E+00		2.18E-02	
	500	9.98E+02		2.18E+00	

Table 4 – Total Abaqus Results

The results compiled were very consistent. Increasing rotational velocity by a factor of 10 increased stresses and deflection by a factor of 100 in every case. In an overall comparison of the material properties, Titanium makes for a more efficient central hub. In all similar cases Titanium shows a smaller maximum principal stress and smaller deflection. The best hub shape was circular, followed by hexagonal, and finally square. I was expected the most rounded shapes to perform the best because maximum stresses occur at sharp edges, as occur in the hexagonal and square shapes.

The following graphs concerning the acceleration of a heliogyro solar sail were created through analysis of the equation:

$a = \frac{p*A}{W}$.

The **Methods Employed** section can be referred to for explanation of variable assignment. MacNeal states that the average solar radiation from the sun in space is approximately $1.882 * 10^{-7}\ \frac{lb}{ft^2}$ (5, MacNeal). I analyzed the equation in order to figure out what variables most directly affect the acceleration of an interplanetary craft. It turns out that the equation can be simplified to the following:

$a = \frac{p}{t*\rho}$,

where a is the acceleration of the craft in terms of earth's g's (9.81 m/s), p is the pressure due to solar radiation in $\frac{lb}{ft^2}$, t is thickness in feet, and ρ is density in $\frac{lb}{ft^3}$.

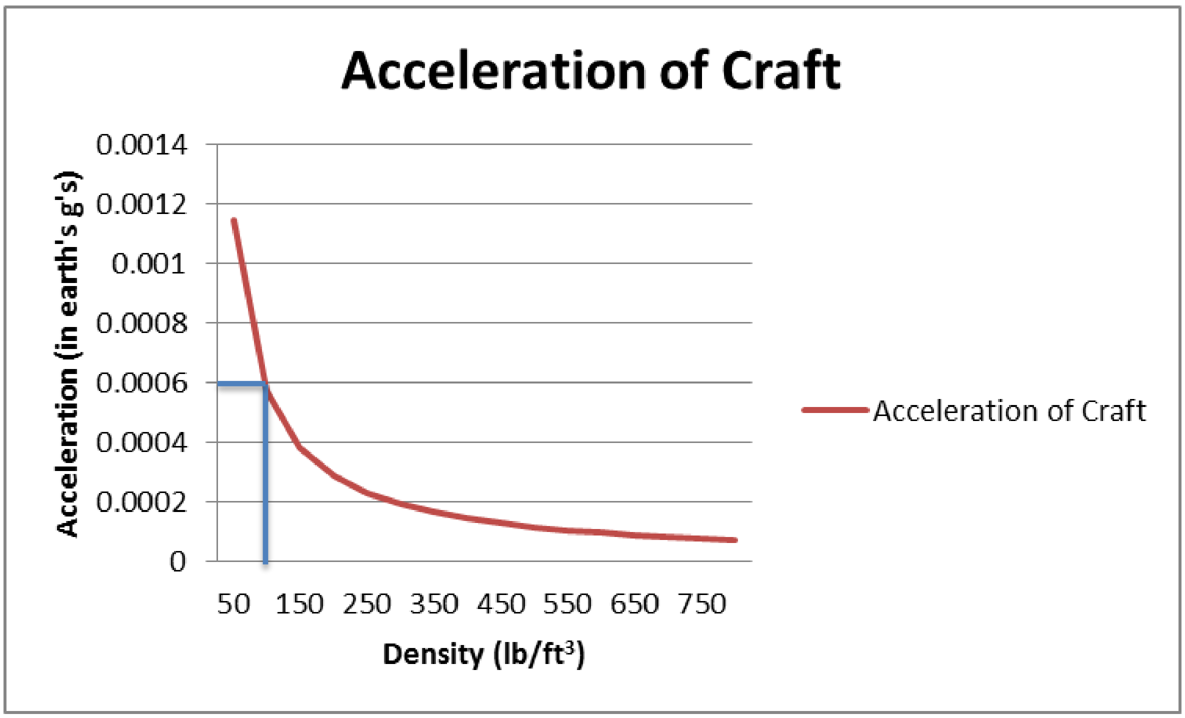

Figure 11 - Acceleration of Craft Given Changing Density

In Figure 11 I used a set thickness of 1 micron. I chose 1 micron because the thickness of solar sail must be extremely small to keep the vehicle light. The data that was obtained from the graph is very useful. Keeping the density of the material below at least 100 $\frac{lb}{ft^3}$ prevents the acceleration at a reasonable value. In Figure 11 100 $\frac{lb}{ft^3}$ corresponds to approximately 0.0006 g's which equals an acceleration of 0.0059 m/s^2.

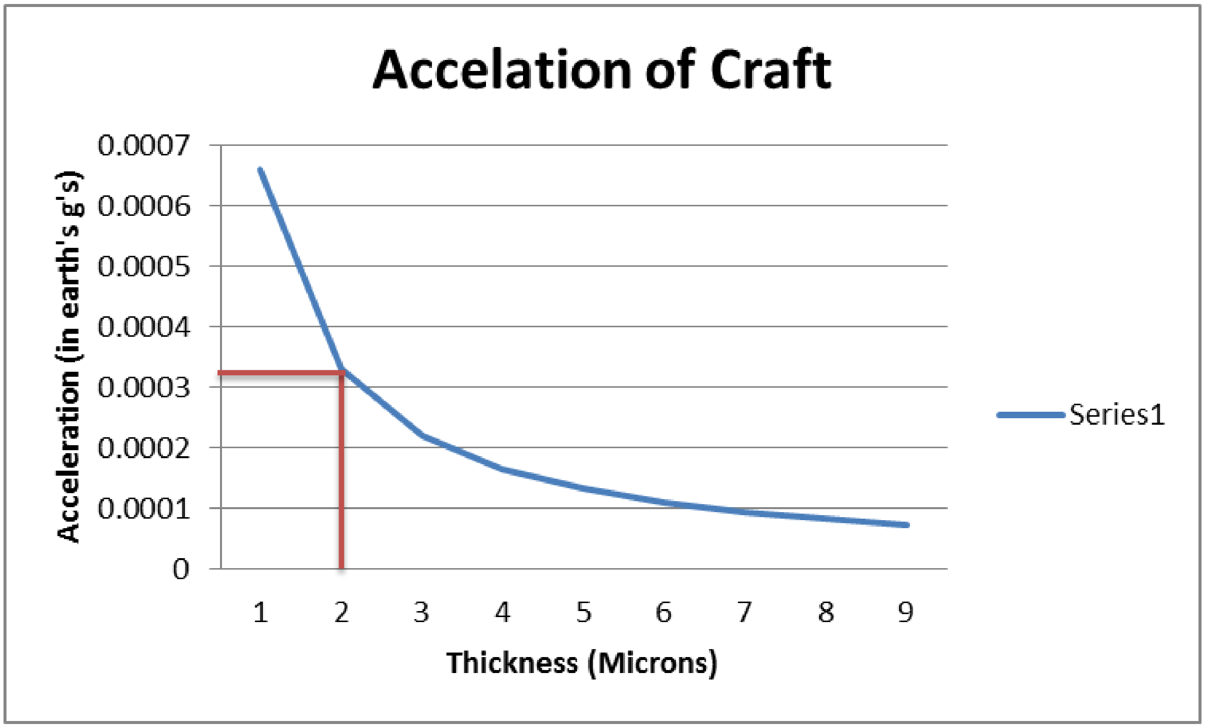

Figure 12 - Acceleration of Craft Given Changing Thickness

In Figure 12 I kept the density the same and altered the thickness of the material. The material Mylar has a density of 86.8 $\frac{lb}{ft^3}$, and I used this value since it fits nicely with the information discovered from the previous graph. This graph is very informative as well. For a material with a density well within the ideal range, keeping the thickness below 2 microns keeps the acceleration at a reasonable value. In Figure 12 2 microns corresponds to approximately 0.00032 g's which equals an acceleration of 0.0031 m/s^2.

In summary, the equation $a = \frac{p}{t*\rho}$ can be used to determine what blade thickness is needed if one already has a set density, or vice versa. It is a very useful analytical tool for solar sail blade material selection.

It is important to keep in mind that a solar sail continually accelerates. For this reason it is not hugely important that the initial acceleration be as high as possible. Once a solar sail is launched it experiences acceleration day in and day out, so it will reach required speeds, it just needs to be made sure that the acceleration is large enough, so that it does not take an unreasonable amount of time to do. Even with an acceleration as small as 0.001 m/s^2, after being in space for a week it would reach a speed of 605 m/s.

It is difficult to grasp the concept of effectively changing the direction of a solar sail simply by turning the blades in an appropriate manner. MacNeal uses a variety of equations to define the movement of a solar sail. The ions from the sun will be partially reflected and partially absorbed by the blade. The amount that is absorbed versus reflected depends on the coefficient of reflectivity of the material. Only the part that is reflected applies pressure and causes motion in a useful way. It turns out that the fraction of pressure reflected and absorbed can be defined by the following equations:

$P_r = P * R * (\cos(\Theta))^2$,

$P_a = \frac{1}{2} * P * (1 - R) * \cos(\Theta)$,

where P_r is component of pressure that is reflected, P_a is the component of pressure that is absorbed, P is total pressure, R is the coefficient of reflectivity, and Θ is the angle between the direction of radiation and normal to the blade surface. The motion of the solar sail can be broken down into lift and drag. Lift is the motion in the direction of orbit and drag is the motion that acts away from the source of radiative pressure, or in our case, the sun. The equation for pressure in the lift direction simply becomes the component of P_r acting in the direction of orbit; only reflected pressure is useful for causing motion in the lift direction. The equation for pressure in the drag direction becomes the components of P_r and P_a acting in the direction directly away from the source of radiative pressure. This analysis performed obtained the following equations:

$P_l = P_r * \sin(\Theta)$,

$P_d = (P_r + P_a) * \cos(\Theta)$,

where P_l is pressure in the lift direction and P_d is pressure in the drag direction (5, MacNeal). These equations allows one to calculate exactly how much pressure is making a solar sail move in the direction of orbit in space with the blade turned to certain angles.

I used the P_l equation to create Table 5. I assumed a high reflectivity coefficient of 0.85, and an average solar pressure of $1.882 * 10^{-7} \frac{lb}{ft^2}$.

P_l ($\frac{lb}{ft^2}$)	Θ (Degrees)	P_l/P
$2.69*10^{-9}$	10	0.142
$4.83*10^{-9}$	20	0.257
$6.00*10^{-9}$	30	0.319
$6.03*10^{-9}$	40	0.321
$5.06*10^{-9}$	50	0.269
$3.46*10^{-9}$	60	0.184
$1.76*10^{-9}$	70	0.093
$4.75*10^{-10}$	80	0.025
$6.00*10^{-41}$	90	$3.19*10^{-33}$

Table 5 – Pressure Lift vs. Angle

Table 5 shows that pressure in the lift direction increases as you increase the blade angle, until about 40 degrees, where the pressure values begin to drop again. I calculated that the exact angle which gives the highest P_l to be 35.3 degrees.

When beginning to analyze methods of controlling a solar sail it was difficult for me to believe that by simply changing blade angles one could efficiently control an entire craft. I began to research helicopter controls in order to find an answer. The blades of a helicopter are controlled in two methods: cyclic pitch and collective pitch. Collective pitch changes all the blades at once, while cyclic pitch turns each blade to a certain angle at certain points in its cycle. For example, if one wanted a helicopter to rise, he/she would use collective pitch, changing the angle of all the blades simultaneously to make them more parallel to the ground, causing more thrust force, and causing lift. If one wanted to move a helicopter forward he/she would use cyclic pitch, the blades would be pitched close to parallel with the ground when in the back of the helicopter causing more thrust in the back and tilting the entire helicopter forward. This would cause forward movement (7, "Helicopter Controls and Components").

The heliogyro solar sail concept can almost be envisioned as a helicopter in space, and the concepts of collective and cyclic pitch can be applied to it as well. If a solar sail was orbiting the earth, and directly in between the earth and the sun, all blades could be turned normal to the sun’s rays in order to cause the sail to move in closer to the earth. Cyclic pitch could be used to turn the blades of a solar sail to a 35.3 degree angle when in the correct position and cause motion in the orbital direction. To make this easier to understand, refer to Figure 13.

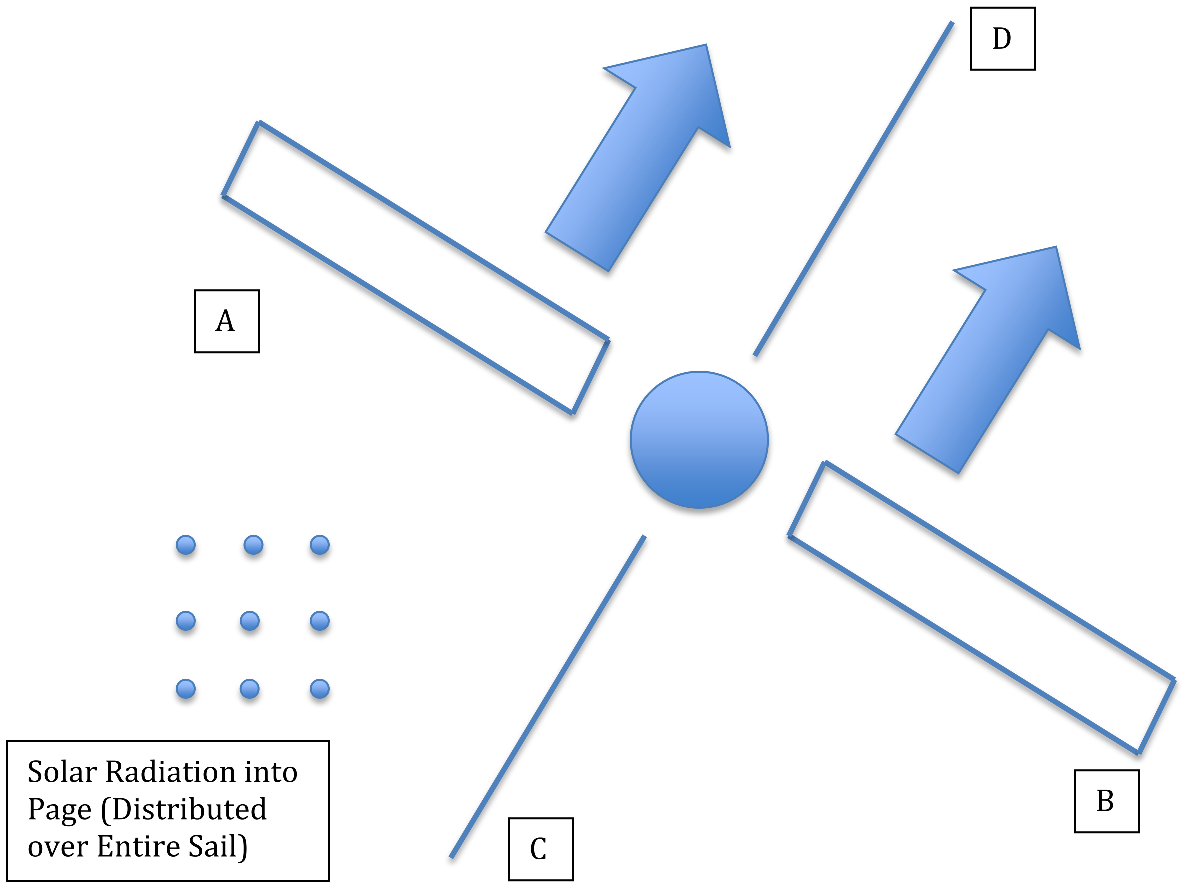

Figure 13 – Overhead View

The above figure represents a four blade solar sail with a center hub. Imagine that the source of radiation is directly above the page, and the body which it is orbiting is under the sail or below the page. Sails C and D are at a 90 degree angle, or normal to the page, while sails A and B are at some angle between 0 and 90 from the page allowing the solar pressure to push the sail in the indicated direction of orbit.

ANSYS was used to prove the concept of centrifugal stiffening as well as begin to model a heliogyro type solar sail. The following image displays a four blade solar sail modeled with the program in attempt to analyze the effects of evenly distributed pressure across the blades.

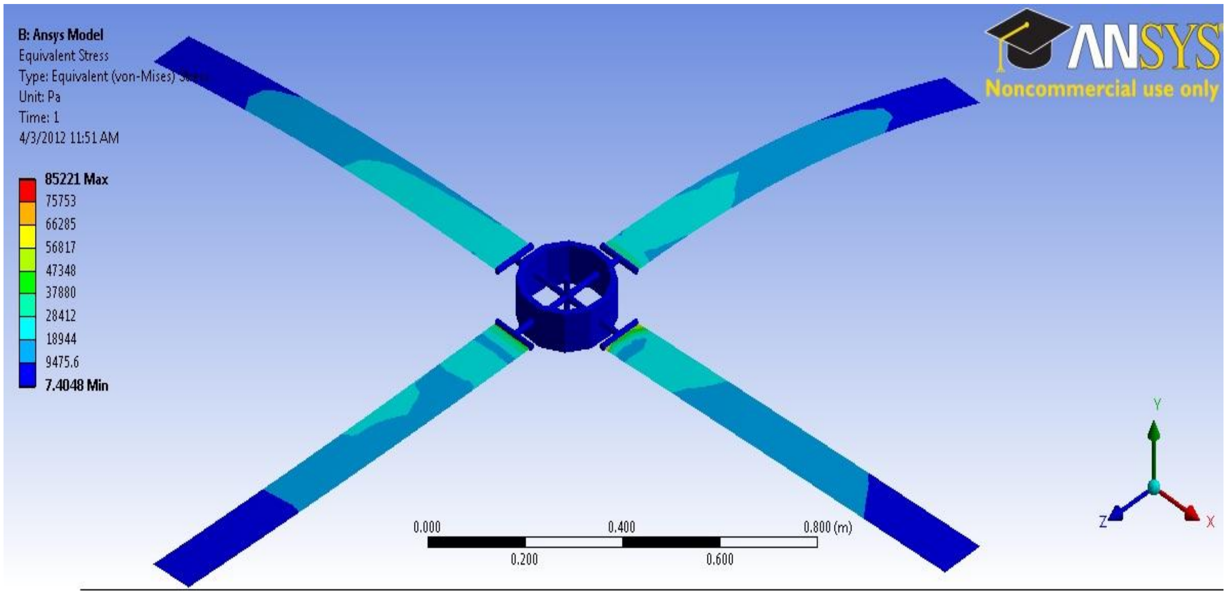

Figure 14 - Four Blade Solar Sail Under Distributed Pressure

As one may notice in the above picture, the four thin blades are simply extended from the hub. Nothing within the mechanical structure is supporting them. What keeps the blades of a heliogyro solar sail unraveled is centrifugal stiffening force. The centrifugal force relies on the rotational velocity of the craft. While the solar sail is flying in space the sails will cone a bit, or deflect downwards. Unfortunately, the group was unable to get the even distribution of stress which we expected in the time which we had access to ANSYS. In the image the two sails furthest to the back are coning further, which should not be the case. Large amounts of progress were however made in terms of coming close to a reasonable representation of a solar sail which could allow for endless amounts of testing and greatly benefit the research of solar sails.

To prove that centrifugal stiffening is a viable concept and that coning angle or the drooping of the blades can be battled by this phenomenon, the group gathered the following data.

Rotational Velocity (rad/s)	Maximum Deflection (m)	Minimum Deflection (m)
1	$2.0349 * 10^{-4}$	$2.5436 * 10^{-5}$
10	$7.0669 * 10^{-5}$	$8.8337 * 10^{-6}$
25	$2.1716 * 10^{-6}$	$2.7145 * 10^{-7}$

Table 6 - The Effect of Centrifugal Force on Coning Angle

For simplicity the program was run with the material properties of steel throughout the entire system. There was a pressure distributed over the blades of roughly $8 * 10^{-6} Pa$, which is the pressure in space at one astronomical unit away from the sun. We chose this value because that is the distance from the earth to the sun. The principles behind this concept carry over to any material. The results show that increasing the rotational velocity from 1 rad/sec to 10 rad/sec to 25 rad/sec decreases the maximum deflection by an order of magnitude each time. This proves that rotational velocity is an effective method of combating coning angle.

Discussion and Conclusion

The work on heliogyro solar sails reported in this thesis explores underlying scientific concepts and proves that one can be designed. Their history begins with Johannes Kepler's observation of blown comet tails, continues on with the discovery of solar pressure, includes a few failed launches and the successful story of IKAROS. Heliogyro solar sails could provide a fuel efficient way of traveling through space as well as create new orbits. The design of a solar sail entails researching many different areas.

Hub design and material choice is of large importance. The hub must withstand rotational body forces and the centrifugal force of however many blades the craft utilizes. Abaqus can be used to compare and contrast hubs of different material and geometry undergoing different rotational velocity. According to the results in Table 4 Carbon Steel and Titanium would both be great candidates for material selection, but Titanium holds up a bit better. It is obvious that a circular hub design would be ideal over any other shape.

Acceleration of the craft is another important facet of the project. Pressure exerted from solar radiation is the driving force of the sail. The two major factors affecting the acceleration that can be applied to the craft is density and thickness of the sail's material. The density of Mylar makes it an excellent choice for blade material, and is manufactured in different thicknesses on the order of microns.

A heliogyro solar sail can be maneuvered by manipulating the pitch or angle of the blades. The portion of radiation which will contribute to acceleration of the craft can be quickly assessed. This allows one to calculate how quickly the craft would obtain necessary speeds. The concepts of cyclic pitch and collective pitch explain how a solar sail can be controlled and forced to move closer or further from the body it's orbiting, or in the direction of orbit.

ANSYS can be used to fully model a heliogyro solar sail. Table 6 proves that increasing rotational velocity and the concept of centrifugal stiffening can be used to combat coning angle. The file that my senior project group worked on was unfortunately incomplete when the ANSYS license was not renewed.

Huge amounts of future work could be conducted in this field. Material research exploring lighter hub materials of similar strength, and possible alternatives to Mylar would be extremely beneficial. The project could also be completed on ANSYS, creating a model of a solar sail with free rotation around its center, and each sail, allowing for simulation of rotational velocity and blade pitch. Lastly ways of testing deployment of a heliogyro solar sail are very much sought after. It is very difficult to simulate a zero-gravity situation.

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